Light gauge steel frame (LSF) walls exposed to fire:

Final report

Real fires project CPD/004/122/039

Prepared for the Building Safety Regulator (BSR)

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

OFR Consultants were engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the "Real Fires" project (CPD/004/122/039) in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run until the 28th of March 2026. The contract has since been novated to the Building Safety Regulator (BSR), originally formed within the Health & Safety Executive (HSE) and now residing as part of the Ministry for Housing, Communities and Local Government (MHCLG). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel frame (LSF) walls.

LSF wall systems are characterised by three main components: cold-formed steel studs for load bearing, sheathing and insulation materials. Concerns have been raised by industry through Collaborative Reporting for Safer Structures UK (CROSS-UK) regarding the expected fire performance of buildings that employ LSF as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal and external loadbearing LSF walls to heating conditions on two sides simultaneously, with typical classification testing concerned with one-sided exposure.

This research project investigated the performance of load bearing LSF walls exposed to fire on two sides and is split into two work packages (WPs) – WP1 and WP2. The first work package (WP1) involved conducting a comprehensive literature review focused on assessing the fire resistance performance of LSF walls when exposed to fire. The review showed that existing experimental and numerical studies have mainly focused on one-sided exposure, and further experimental investigation is needed to understand the structural behaviour of LSF wall systems exposed to fire from both sides. The second work package (WP2) involved generating data and evidence concerning the fire resistance performance of LSF walls under one-sided and two-sided fire exposure. WP2 was arranged into two elements. The first (a) being concerned with fire resistance tests of LSF walls and the second (b) being a subsequent numerical parametric study.

The fire resistance tests (WP2a) involved benchmark furnace tests on LSF walls exposed to fire on two sides to determine whether the loadbearing performance of LSF walls is likely affected by the number of faces simultaneously exposed to fire. A total of four wall specimens were tested at ITB in Poland, two each (with and without cavity insulation) for one- and two-sided fire exposure conditions under the ISO 834 heating regime. The numerical parametric study (WP2b) involved using validated Finite Element (FE) models to provide an understanding of how different factors influence the thermal behaviour of LSF walls and the potential implications for structural performance. The analysis covered a range of critical parameters, including the nature of insulation, the number of sheathing board layers, the type of fire exposure, and the time lag before the second face of the wall is exposed to fire (representative of fire spread).

Overall, the study postulates based on temperature profiles that two-sided fire exposure significantly reduces the loadbearing fire resistance of LSF walls compared to one-sided exposure. While cavity insulation (due to thermal gradient) reduces the load bearing fire resistance under one-sided fire exposure compared to no insulation case, its impact is negligible under two-sided fire exposure. Whilst increasing the number of plasterboard layers can mitigate some reduction in loadbearing fire resistance, the overall structural performance is still notably compromised under two-sided fire conditions.

From a technical policy perspective, it is apparent that walls can be exposed to fire on two sides simultaneously in certain conditions and that this can bring about substantial reductions in structural fire resistance of lightweight wall construction. Therefore, the study recommends that consideration should be given to amending Approved Document B to include recommendations for such cases, including fire resistance classification under conditions where two sides of a wall are exposed simultaneously.

1 Introduction

1.1 Appointment

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR) to deliver the "Real Fires" project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run until the 28th of March 2026. During the period of this engagement, the Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC) (formerly the Ministry for Housing Communities and Local Government), who originally commissioned this project has been novated to the Building Safety Regulator (BSR) who are part of the Government Agency, The Health and Safety Executive (HSE). As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake a research project on the fire performance of light gauge steel frame (LSF) walls.

1.2 Work packages and deliverables

The research project is organised into two work packages (WP) described below:

- WP1: Literature review on the fire resistance performance of LSF walls exposed to fire.
- WP2: Generate data and evidence on the fire resistance performance between one-sided and two-sided exposure of LSF wall elements to support the BSR in understanding the risk to existing buildings and any future changes in fire safety guidance that may be necessary in the future. WP2 is split into two sub packages:
    - WP2a – benchmark furnace tests for LSF walls; and
    - WP2b – desktop / modelling appraisal of the implications of fire resistance specification of LSF walls for their ability to survive burn-out.

All work packages have been completed and separate reports issued to BSR. The individual reports are attached to this final report as appendices:

- Appendix A - WP1: Report ref - 230713-R00-OX21041-WP1-Light gauge steel literature review-RR-CIC. Issued on 13/07/2023.
- Appendix B – WP2a: Report ref - 241007-R00-OX21041-WP2a-Light gauge steel test report-RR-CIC. Issued on 07/10/2024.
- Appendix C – WP2b: Report ref - 241007-R00-OX21041-WP2b-LSF wall parametric study report-RR-CIC. Issued on 07/10/2024.

Refer to the individual reports for full details.

This report is a summary of the three work packages. It covers a brief background to the research project and why it was commissioned, summary of the outcome of the literature review, summary of results of the furnace testing (WP2a), summary of results of the numerical modelling and parametric studies (WP2b), as well as final recommendations to BSR for LSF walls exposed to fire on two sides.

2 RESEARCH BACKGROUND AND MOTIVATION

LSF walls are commonly used in modern building construction, consisting of cold-formed steel studs, sheathing material, and may include insulation. A typical LSF wall system is shown in Figure 1. These walls may be internal architecturally separating elements, but not fire-separating elements, e.g., they do not form part of a compartment boundary. This means that where a compartment is fully involved in a fire, these walls can be exposed to fire on both sides. When used as external loadbearing walls afforded non-fire-resisting cladding, flames emanating from an enclosure fire can heat the external surface of the wall, with the internal face simultaneously heated by the internal fire. A more detailed review of the components of an LSF wall system, types of LSF wall systems, characteristics of LSF wall system, and use of LSF wall in construction was carried out as part of WP1 (Appendix A).

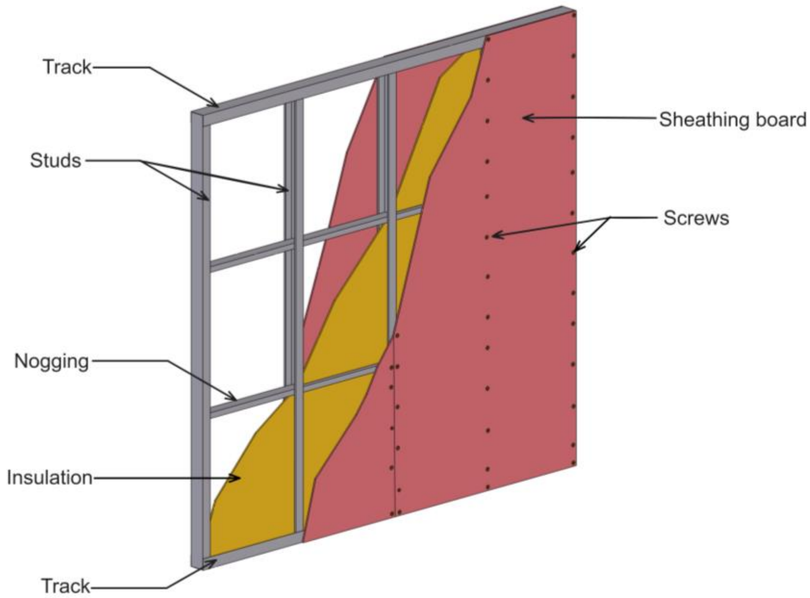

Figure 1. Typical LSF wall system

Concerns have been raised by industry (through CROSS-UK reports 1116 and 1231) regarding the expected fire performance of internal and external loadbearing LSF wall systems exposed to fire on two sides simultaneously. The CROSS-UK reports highlighted the need for research on loadbearing LSF walls when exposed on two sides, as existing studies only address one-sided exposure. Current design guidance (Approved Document B) does not explicitly identify a need to test for two-sided exposure. Finite element modelling (FEM) offers a possible route for engineers for designing loadbearing LSF walls exposed to fire on two sides, but limited test data restricts reliable benchmarking under two-sided heating conditions. Therefore, the research project was set out in three stages: literature review to understand current knowledge on the performance of LSF walls exposed to fire; furnace testing to generate data for benchmarking; and numerical parametric studies using FEM.

3 WP1: SUMMARY OF REVIEW OF PREVIOUS STUDIES ON LSF WALLS EXPOSED

A detailed literature review has been undertaken and a review report issued (refer to WP1 report – Appendix A). A total of 521 articles were systematically screened and reviewed, leading to 92 studies being selected for detailed review. The review showed that there is currently a knowledge gap regarding the expected structural fire performance of LSF elements that are exposed to heating conditions on two sides. Key conclusions arising from the literature review study were:

i. Extensive experimental and numerical studies have been carried out to understand the performance of LSF walls exposed to fire on one side only; but there is lack of test data for two-sided exposure of LSF walls. This justifies the need for two-sided exposure testing.

ii. The one-sided exposure experimental and numerical modelling studies show that the insulation between the studs, number of sheathing board layers, and fire exposure, has a significant impact and, therefore, these are variables that should be considered under two-sided heating.

iii. Evidence from other materials (i.e., masonry and concrete) suggests that the difference between one-sided and two-sided exposure is more significant at higher fire resistance demands. Therefore, to observe the biggest difference between one- and two-sided fire exposure of LSF walls, investigation of 'high' fire resistances is most likely to elucidate that difference.

iv. Furthermore, current design guidance in England (Table B3 of Approved Document B) does not explicitly identify a need to test for two-sided exposure.

4 WP2a: Summary of benchmark furnace test results

To resolve the uncertainty from the lack of data for the performance of LSF walls when exposed to fire on two sides as identified in the literature review studies, and to improve confidence in FEM studies, an experimental programme was conducted in WP2a. The aim was to carry out an experimental investigation of the loadbearing performance of LSF walls with both one- and two-sided fire exposure, to determine whether the loadbearing performance of LSF walls are likely affected by the number of faces simultaneously exposed to fire.

Based on the outcome of the literature review, a total of four wall specimens were tested, two each (with and without cavity insulation) for one- and two-sided fire exposure conditions. The walls were designed to achieve a 'high' (minimum of 90-minute) fire resistance rating under single-sided fire exposure, when afforded cavity insulation.

Each wall specimen was provided with internal thermocouples mounted on the flanges and web of the steel studs at different locations along the length and height of the wall to record the temperature rise of the steel. For the one-sided test, the unexposed wall surface temperature was also measured using external thermocouples attached to the unexposed face of the wall. The deflection of the wall was measured by gauges suitably arranged to measure the vertical deflection (contraction) and horizontal (lateral) deflection of the wall during the test. Horizontal deflection was only measured for the walls exposed to fire on one side. The test was conducted until failure of the steel studs occurred, with failure defined as a loss in loadbearing capacity, indicated by runaway vertical / lateral deflection. For a detailed description of the test programme refer to the WP2a test report (Appendix B).

The main findings / conclusions from the tests were as follows:

i. Two-sided fire exposure results in a more severe heating condition on LSF walls than one-sided fire exposure, as indicated by higher temperatures and rates of temperature increase, particularly beyond 45 – 50 min of standard fire exposure.

ii. The loadbearing fire resistance of LSF walls decreased significantly when exposed to two-sided fire: down to 44% of the one-sided exposure capacity for non-insulated walls and 62% for insulated walls.

iii. One-sided fire exposure leads to a significant thermal gradient within the stud section, especially when insulation is present, resulting in non-uniform heating. In contrast, two-sided exposure generally promotes a more even temperature distribution across the stud section.

iv. Cavity insulation in one-sided fire exposure creates a significant temperature gradient, leading to thermal bowing and earlier structural failure compared to non-insulated walls. For two-sided fire exposure, the influence of cavity insulation on the performance was not significant versus non-insulated walls.

v. Vertical deflection of wall specimen is uniform across various top locations of the wall under all test scenarios, while the centre of the wall exhibits greater lateral deflection, particularly for insulated walls under one-sided exposure.

From the above findings, the following broader design implications were highlighted:

i. The test samples are considered to be representative of common LSF construction practices and, therefore, it is probable that the findings are broadly applicable to the technology i.e. lightweight steel wall construction.

ii. Where there is the potential for two-sided exposure, there is a sufficient reduction in load bearing performance that elements should be specifically designed to address such an exposure condition.

iii. In guidance, there is justification to explicitly request test evidence for two-sided exposure, and the test programme conducted shows that testing such a configuration is achievable.

5 WP2b: Summary of numerical modelling and parametric study

WP2b presented the methodology and findings of the thermal modelling and parametric study of the fire performance of LSF walls exposed to fire on two sides using finite element (FE) analysis. The work comprised two main components.

The first component, FE model development and validation, described the development of the FE model, including the type of finite elements adopted, material properties, and boundary conditions applied. The analysis focused solely on thermal behaviour. To verify the adequacy of the developed model for simulating the behaviour of LSF walls under two-sided fire exposure, the predicted temperature-time profiles were benchmarked against the experimental results obtained from the WP2a experiments.

The second component involved parametric studies of the thermal response of LSF walls exposed to fire on two sides. It examined the influence of key design parameters on the thermal performance of the walls. The parameters investigated, informed by the literature review and experimental results, included the type of insulation (none, cavity, or external), number of sheathing layers, type of fire exposure (ISO 834 standard fire, Eurocode parametric fire, and Eurocode external fire), and the time delay before the second wall face was exposed to fire. Comparative evaluation of the different cases was based on the temperature distribution across the stud section and the time required to reach a specified critical temperature. A total of 133 cases were investigated. For a detailed description of the modelling and parametric study, refer to the WP2b report (Appendix C).

The main findings/conclusions from the parametric study are:

- **Temperature distribution:** Temperature profiles mirrored the experimental results. That is, two-sided fire exposure produces a near-uniform stud temperature, whereas one-sided exposure yields a non-uniform temperature distribution in all configurations.

- **Insulation:** External insulation was found to be the most effective in reducing temperature rise and delaying the onset of critical temperatures under both one-sided and two-sided fire exposures. However, its effectiveness was somewhat reduced under two-sided exposure compared to one-sided exposure, although it still outperformed the other insulation types.

- **Plasterboard layers:** The number of plasterboard layers has a substantial impact on the thermal protection of the steel stud. Each additional layer delays the time at which rapid increase in temperatures are experienced. For a given number of plasterboard layers, two-sided fire exposure remains a more severe scenario, significantly compromising the effectiveness of the plasterboard layers, particularly when fewer layers are used. At extended fire exposure durations under two-sided fire conditions, the number of plasterboard layers has little to no effect on stud temperatures. Specifically, beyond 100 minutes for standard fire exposure, there is no significant difference in temperatures between 1 and 2 plasterboard layers, and after 180 minutes, there is no significant difference among 1, 2, and 3 layers. This may be because they have, in-effect, failed and fallen off.

- **Fire exposure:** ISO 834 heating under two sides simultaneously was shown to be conservative when considering LSF wall stud temperatures under a range of heating and time lag conditions compared to parametric fire curves. Combined ISO/external fire on both faces is less severe than pure two-sided ISO fire but more severe than one-sided ISO fire exposure.

- **Time lag:** Simultaneous two-sided exposure gives the highest stud temperatures. Introducing a 20-minute lag reduces maximum temperature reached and failure time only marginally, and the benefit diminishes as fire duration increases. Time lags exceeding 20 minutes were not investigated in this study, in which case the time lag might have a more significant effect.

- **Loadbearing fire resistance:** Two-sided exposure significantly reduces loadbearing fire resistance compared with one-sided exposure. For instance, with no insulation and a load ratio of 0.6, the load-bearing resistance decreases from 90 minutes under one-sided exposure to 60 minutes under two-sided exposure.
- **Technical policy implication:** It is apparent that walls can be exposed to fire on two sides simultaneously in certain conditions and that this can bring about substantial reductions in structural fire resistance of lightweight wall construction. Therefore, fire resistance classifications for one-sided exposure should not be extrapolated to two-sided exposure, unless evidence of performance subject to two-sided exposure is provided.

6 Recommendations to BSR

The findings of the study have informed a number of technical policy implications and recommendations, which have been submitted by the research authors to the BSR. These are summarised as follows:

- The LSF wall configurations investigated in this study are considered representative of typical LSF construction practices. Consequently, the findings are likely broadly applicable to other lightweight wall systems, such as light-timber frame and cross-laminated timber (CLT) walls.
- Non-separating load-bearing internal and external walls constructed from lightweight construction, should demonstrate fire resistance in line with the anticipated exposure conditions, considering the potential fire spread routes within a building. This may include scenarios where two-sided exposure could reasonably occur. Where such construction forms part of a proprietary or panelised system supplied by a manufacturer, evidence of performance under two-sided fire exposure should be sought from the supply chain. Specific fire testing may not always be required, as guidance such as SCI Publication P442 provides calculation methods for assessing LSF walls under two-sided exposure. In the absence of supply chain evidence, project-specific assessments may be necessary on a case-by-case basis.
- The study has shown that ISO 834 two-sided simultaneous heating provides a conservative estimate of stud temperatures across a range of heating conditions and time-lag scenarios. Accordingly, it may be adopted as a suitable benchmark for developing design recommendations.
- Approved Document B (Table B3) currently specifies that, for fire resistance classification, structural elements forming part of a frame should be tested and designed for fire exposure on all exposed faces. However, loadbearing walls are not explicitly included in this provision. Based on the findings of this study, it is recommended that consideration be given to amending Table 3 of Approved Document B to provide explicit guidance on fire resistance classification where loadbearing walls are simultaneously exposed to fire on two sides. This would align the treatment of loadbearing walls with the existing requirements for other structural elements and provide clearer guidance expectations.

APPENDICES

Appendix A – WP1 REPORT: LITERATURE REVIEW ON THE FIRE PERFORMANCE OF LSF WALLS EXPOSED TO FIRE

Light gauge steel frame (LSF) walls exposed to fire: A systematic review

Real fires project CPD/004/122/039

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TABLE OF CONTENTS

Executive summary / Abstract

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the "Real Fires" project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run for three years from this date. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel framing (LSF) walls.

LSF wall systems are characterized by three main components: cold-formed steel studs for load bearing, sheathing and insulation materials. Concerns have been raised by industry through the Collaborative Reporting for Safer Structures UK (CROSS-UK) regarding the expected fire performance of buildings that employ LSF as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides, which have not been tested for this situation.

The aim of this work package was to systematically review existing studies related to the fire performance of LSF elements that are exposed to different heating conditions to determine whether the fire resistance rating and structural performance of these elements are likely affected by the number of faces exposed to fire. This will help define the framework for any future experimental and numerical studies of LSF walls exposed to fire on both sides.

A total of 932 articles were obtained from three databases, which were narrowed down to 521 after removing duplicates. In the screening stage, 195 potentially relevant studies were selected for full-text search, and in the full-text eligibility assessment stage, 92 studies were included in the detailed review.

Of the 92 studies selected for detailed review, numerical methods were the most used research method in assessing the performance of LSF walls in fire, accounting for approximately 72% of the total number of publications. Studies that used only numerical and only experimental/test methods account were 49% and 27%, respectively, while both experimental and numerical methods were used in approximately 22% of the total number of publications.

Review of the experimental literature revealed that research has focused mainly on single-sided exposure of LSF walls to fire. The presence of insulation in the cavity typically resulted in earlier mechanical failure, whilst steel sheet sheathing was shown to increase structural performance and fire resistance. A larger cavity depth and staggered stud arrangement can also affect fire resistance ratings. From the review, it was concluded that further experimental investigation is needed to understand the structural behaviour of LSF wall systems when exposed to fire from both sides.

From the literature reviewed on numerical studies, it was observed that only one of the existing studies considered cases of the LSF wall exposed to fire on two sides. In the study, it was shown that LSF walls exposed to fire on both sides failed structurally earlier than those exposed to fire on one side only, emphasizing the importance of accounting for fire exposure on both sides in design. Nevertheless, the study had limitations, notably that the finite element (FE) models used were not benchmarked against any tests or experiments and only limited parametric studies were conducted. However, from the other literature reviewed, it was shown that conclusions from the studies on one-sided exposure can be used to inform future finite element (FE) modelling studies and what parameters can potentially influence the behaviour of LSF walls when exposed to fire on two sides. The review showed that for FE models to be able to simulate test and actual design conditions, the FE model should consider the following: LSF wall model idealisation adequate for capturing the LSF wall system; analysis type (transient or steady state analysis); mesh size; boundary condition (number of sides exposed, heat transfer coefficient, emissivity, end restraint conditions); temperature dependent properties of LSF wall components; heat transfer within and through air gap / cavity; initial geometric imperfections of LSF wall studs; screws and fastenings and plasterboard joints; and sheathing material fall-off.

Numerical studies have identified several factors that impact the fire performance of LSF walls, including the fire time-temperature curve, load ratio, stud section, aspect ratio, steel thickness, sheathing board, insulation, wall configuration, sheathing board fall-off time, screw connectivity, noggings, and the presence of loadbearing SHS steel columns located at intervals along the length of LSF walls. Understanding these factors can aid in future parametric studies of LSF walls exposed to fire on two sides.

The review also extended to current fire resistance design approach and guidance expectation for design and testing of walls. It was revealed that design equations exist in guidance documents for assessing the performance of LSF walls exposed to fire on one side. However, there is a need for research on LSF walls exposed to fire on two sides to determine whether current design equations can be used or modified.

Finally, the review discusses different approaches for the fire resistance design of loadbearing walls in different materials. The fire design of masonry structures is set out in EN 1996-1-2, which distinguishes walls as either a “separating wall” or a “non-separating wall”. For concrete structures, fire design guidance is given in EN 1992-1-2, with tabulated wall thicknesses for both single and two-sided exposure. The review shows that walls with higher fire resistance demands require substantially thicker construction when exposure is on two sides versus one.

1 Introduction

1.1 Appointment

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR) to deliver the "Real Fires" project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run for three years from this date. During the period of this engagement, the Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC) (formerly the Ministry for Housing Communities and Local Government), who originally commissioned this project has been novated to the Building Safety Regulator (BSR) who are part of the Government Agency, The Health and Safety Executive (HSE). The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel framing (LSF) walls.

Concerns have been raised by industry (through CROSS) regarding the expected fire performance of buildings that employ light gauge steel framing (LSF) as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides but have not been tested to this situation. These walls may be architecturally separating elements, but not fire separating elements, e.g., they do not form part of a compartment boundary. This means that in case a compartment is fully involved in a fire, then these walls will be exposed to fire on both sides. Currently, there is a knowledge gap regarding the expected structural performance of LSF elements that are exposed to heating conditions on both sides. From this knowledge gap, a technical issue arises; that is whether and how the fire resistance rating of an element is affected by the number of faces exposed to fire.

This report represents the culmination of the first work package of this engagement, which sets out a literature review on the topic.

1.2 Background

LSF walls are typically made of cold-formed steel (CFS) studs and are lined with plasterboard, and typically include cavity insulation [1]. A typical LSF wall system is shown in Figure 1. A more detailed review of the components of an LSF wall system is presented in Section 3. LSF walls are used as fire separating walls to stop the fire spread from one compartment to another and limit temperature increase on the unexposed surface for a specified period in the event of a fire [2]. LSF walls also find application as load bearing walls and building partitions which may not be fire separating.

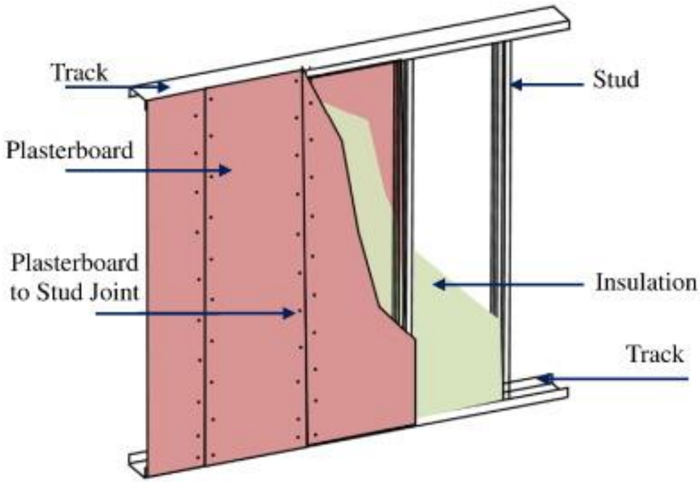


Figure 1. Typical LSF wall system (original figure from [2])

The use of LSF constructions has experienced significant growth lately due to their high strength-to-weight ratio and the availability of a wide range of sizes and shapes for structural engineering specification [2], [3]. According to Abeysiriwardena and Mahendran [4], LSF wall systems became more popular in the last 10 years. However, there are studies dating back to over two decades [5] which reviewed the fire resistance of LSF walls. The thermal bridge created by high thermal conductivity of the CSF steel studs has become a subject of interest due to the substantial amount of energy used in heating and cooling buildings [6]. As LSF construction usage continues to rise and more complex cross-sectional shapes of the studs emerge, researchers are focusing on optimizing CFS members for economic and sustainable building solutions, including improving fire performance.

Concerns have been raised by industry (through CROSS-UK [7]) regarding the expected fire performance of buildings that employ LSF walls as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides but have not been tested to this situation. These walls may be architecturally separating elements, but not fire separating elements, e.g., they do not form part of a compartment boundary. This means that in case a compartment is fully involved in a fire, then these walls will be exposed to fire on both sides and may not perform as expected in terms of loadbearing capacity compared to when heated from just one side. It is understood that some designers have approached this form of construction considering fire testing data from one-sided exposure tests that follow the standard fire curve (testing as a loaded wall). This same concern can be extended to external load-bearing walls, afforded non-fire-resisting cladding, meaning flames emanating from an enclosure fire can heat the external surface of an LSF wall, with the internal face simultaneously heated by the internal fire.

It is understood that there is currently no design approach that is universally seen to be adequate available in industry to account for LSF walls exposed on two faces. This issue has been extensively discussed in CROSS-UK Report 1116. The Steel Construction Institute (SCI), who are producing design guidance on this form of construction, have subsequently responded to CROSS-UK Report 1116. There is the possibility that double-sided exposure can also be an issue for other similar forms of construction too. As far as the authors are aware, there are no recognised national fire testing standards available for testing loadbearing walls subject to fire on both sides, nor have any such tests been proposed. This can be attributed to be a reason for the lack of data on performance of load bearing walls (including LSF walls) exposed to fire on two sides.

Employment of finite element modelling (FEM) is one way designers may attempt to address the lack of a universally accepted design approach for LSF walls exposed to fire on two sides. Whilst this may be a valid means of evidencing performance, given a lack of experimental/test data, the assessment of such modelling remains a cause for concern as there is a limited basis for benchmarking. It is also likely that such modelling studies are limited to a few projects, whilst the issue of multiple sided exposure affects many other projects. To resolve the uncertainty that arises from the lack of data, and to improve confidence in the FEM approach, an experimental programme is deemed necessary. It is hypothesised that both heat transfer processes and the mode of the structural failure of LSF walls can be affected from the change in exposure conditions, both in terms of the duration of heating, e.g., fire resistance rating, or through exposure to realistic fire conditions. It is also assumed that the existence of insulation within the wall section can have an impact on the element's performance, evidenced from existing studies on LSF walls exposed to fire on one side only. To support any future experimental and numerical studies of LSF walls exposed to fire on both sides, it is necessary that a review of existing related studies is carried out to explore current technologies and how they can be applied to form a basis for the definition of experimental conditions and finite element modelling parameters necessary for capturing the effects of fire exposure on two sides.

1.3 Terminologies associated with light gauge steel frame (LSF) construction

Terminologies used to describe light gauge steel frame (LSF) walls vary in the literature. They are commonly referred to as LSF walls (e.g. in [8]–[14]). Some literature (e.g., [4], [15]–[18]) refer to LSF walls as cold-formed steel (CFS) walls, based on the structural material used for the studs in LSF walls. Terms such as lightweight steel frame or light steel framing (e.g., in [19], [20]) and thin-walled steel elements (e.g., in [21], [22]) are also common.

However, wall systems formed by light gauge steel (e.g., cold-formed steel) are predominantly referred to as light gauge steel frame (LSF) walls. This is the terminology adopted in this study when referring to the wall system as a whole and not the individual components that make up the LSF wall system.

1.4 Summary of previous literature review studies on LSF construction in fire

Section 1.1 suggests that limited research exists on the performance of LSF walls exposed to fire on two sides. Literature review studies are one way to evaluate the current state of research and knowledge gaps in the area. There have been some review studies within the existing body of knowledge that provide very useful general insights related to the performance of LSF walls in fire and this section summarises the outcome of previous literature review studies.

Table 1 provides a summary of five previous literature survey studies that reviewed the performance of LSF construction in fire. Liang et al. [6] reviewed existing studies on the structural optimization of CFS sections and their thermal performance in normal conditions. Kesawan and Mahendran [1] reviewed the parameters affecting the fire performance of LSF wall systems and proposed new methods to improve their fire resistance rating (FRR) by considering both thermal and structural performances. Javed et al. [23] focused on recent research on the fire performance of load-bearing CFS beams and columns, while Soares et al. [24] reviewed studies on strategies for reducing thermal bridges and improving the thermal resistance of LSF wall system. Alfawakhiri et al. [5] reviewed available information on the fire resistance of loadbearing cold-formed steel-stud walls clad with gypsum board and the thermal and mechanical properties of their constituent materials at elevated temperatures.

The studies reveal that thermal performance in fire conditions and structural behaviour significantly influence the fire resistance rating of LSF walls. Also, the type, elevated temperature thermal properties and thicknesses of plasterboard and infill insulation used, as well as plasterboard joints affect their elevated temperature performance. Increasing steel thickness of the studs, improving plasterboard joints, and using optimal CFS cross-sectional shape are effective ways of enhancing the fire resistance rating of LSF walls. The reviews show that the elevated temperature performance of LSF walls can be improved through insulation of the LSF wall, optimizing CFS cross-sectional shape, and using phase-change materials (PCM) to increase their thermal inertia and storage capacity.

The reviews highlight that despite the progress in the research on LSF construction, there is still a lack of experimental data on their fire performance and the confidentiality of fire test results impedes the development of knowledge in fire safety engineering of LSF walls systems. Additionally, the literature survey studies concluded that further research is required to understand the behaviour of LSF walls in fire, study the semi-rigid end restraints conditions, and optimize CFS framed walls for better combined structural behaviour and thermal performance improvement. Overall, the studies highlight the importance of considering both thermal and structural performances in improving the fire resistance and of loadbearing LSF systems. However, the key finding herein is that none of the existing literature survey studies reviewed the effect of two-sided fire exposure on the fire performance and fire resistance rating of LSF walls, suggesting an area for future research.

Table 1. Summary of existing literature reviews on light gauge steel construction

Ref.	Title	Year	Scope	Main findings
Alfawakhiri et al. [5]	Fire resistance of loadbearing steel-stud walls protected with gypsum board: A review	1999	• Reviews information available on the topics related to the fire resistance of loadbearing cold-formed steel-stud walls lined with gypsum board. • Reviews previous experimental and analytical studies on loadbearing cold-formed steel-stud walls clad with gypsum board and on the thermal and mechanical properties of the constituent materials—steel, gypsum board, and insulation—at elevated temperatures.	(1) There is a lack of experimental data available on the performance of load-bearing LSF walls exposed to fire. (2) The confidentiality of fire-endurance test results hinders the development of knowledge in fire safety engineering. (3) The available numerical heat transfer models for non-insulated gypsum board cavity walls can predict temperatures with reasonable accuracy as long as the gypsum board stays in place. (4) Previous analytical studies of the structural behaviour of load-bearing LSF walls exposed to fire are based on numerous assumptions and involve crude approximations. (5) The properties of galvanized cold-formed steel, gypsum board, and insulation materials at elevated temperatures are based on limited experimental data.
Javed et al. [23]	Recent research on cold-formed steel beams and columns subjected to elevated temperature: A review	2017	Focused on recent research regarding the fire performance of load-bearing CFS beams and columns	(1) More emphasis is required to understand the behaviour of CFS thin-walled beams in fire by studying the mode interactions to find the real temperature distribution across the section and length of the member. (2) The semi-rigid end restraints conditions should be studied in-depth as the member also undergoes large deflections which leads to member failure. (3) Limited experimental data is available on the performance of different cross-sections.

Ref.	Title	Year	Scope	Main findings
Soares et al. [24]	Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: A review	2017	Reviews the main features of LSF construction with cold-formed elements and strategies for reducing thermal bridges and for improving the thermal resistance of LSF wall components.	The review identified the following to be among the main driving research to improve the thermal performance of LSF construction: (1) Development of single and combined strategies to reduce thermal bridges and to improve the thermal resistance of LSF envelope elements. (2) Increase of the thermal inertia and the thermal storage capacity of LSF constructions, e.g., by using PCMs.
Kesawan and Mahendran [1]	A review of parameters influencing the fire performance of light gauge steel frame walls	2018	• Reviews parameters affecting the fire performance of LSF wall systems under fire conditions. • Proposes new methods to improve the fire resistance rating (FRR) of LSF walls. • Considers the thermal and structural performances of LSF walls in fire.	(1) The FRR of LSF walls is influenced by both the thermal and structural performances. Thermal performance in fire conditions is affected by the type, elevated temperature thermal properties, and thicknesses of plasterboard and infill insulation used, as well as plasterboard-to-plasterboard joints and joints between plasterboard and steel. (2) Improved plasterboard joints can eliminate localised hot flange temperature rise in steel studs. (3) Structural performance is influenced by the thermal performance of LSF walls, steel sections used, and mechanical property reduction factors of cold-formed steel. (4) LSF walls with different cross-section shapes have the same FRR if their depth and flange widths are the same. Increasing steel thickness can improve the FRR of LSF walls. (5) Effects of web depth on the FRR of LSF walls depend on the type of failure mode of the studs, thermal bowing deflections, and local buckling effects. (6) Elevated temperature mechanical property reduction factors vary significantly and can affect the FRR of LSF walls.
Liang et al. [6]	A critical review on optimization of cold-formed steel members for better	2022	Reviews the existing studies on the structural optimization of CFS sections	(1) A significant number of studies have been conducted on optimizing CFS cross-sections for better structural behaviour, considering increasingly

Ref.	Title	Year	Scope	Main findings
	structural and thermal performances		and the thermal performance of such CFS structures. Focus was on thermal bridging and not elevated temperature (i.e., fire) performance.	complex constraints and loading scenarios. System-level optimization studies are rare. (2) Insulation is the most effective way to reduce thermal bridging and energy consumption, but there is also potential for improving thermal performance through optimizing CFS cross-sectional shape and systems. (3) Research on optimization of CFS framed walls for better combined structural behaviour and thermal performance improvement are limited.

1.5 Aim of this study

As already identified in the previous section, there is currently a knowledge gap regarding the expected structural performance of LSF elements that are exposed to heating conditions on both sides. Previous literature review studies on the performance of LSF walls in fire have not covered this issue. From this knowledge gap, a technical issue arises; that is whether and how the number of faces exposed to fire affects the fire resistance rating of an element.

Therefore, the aim of this study is to systematically review existing studies related to the fire performance of light gauge steel framing (LSF) elements that are exposed to different heating conditions to determine whether the fire resistance rating and structural performance of these elements are likely affected by the number of faces exposed to fire. This will help define the framework for any future experimental and numerical studies of LSF walls exposed to fire on both sides.

1.6 Research questions

To achieve the stated aim in Section 1.5, one main research question and six sub-questions were formulated.

Main research question:

> "How does the number of faces exposed to fire affect the fire resistance rating and structural performance of LSF elements?"

The sub-questions were as follows:

i. How do the heat transfer processes and mode of structural failure of LSF elements change under different exposure conditions (such as duration of heating or exposure to realistic fire conditions)?

ii. What are the suitable laboratory fire testing standards for testing loadbearing walls subject to fire on both sides, and how can such tests be proposed and developed?

iii. What are the limitations and validation requirements of Finite Element Modelling (FEM) for predicting the fire performance of LSF elements exposed to fire on two sides, and how can experimental data be used to improve confidence in FEM?

iv. How can the design approach for LSF construction be improved to account for the fire performance of loadbearing walls exposed to fire on two sides?

v. To what extent are other technologies likely to be affected by heating on two sides and what are the most vulnerable?

vi. What are the practical implications and recommendations for industry, designers, and regulators in terms of fire safety and risk management of LSF construction with loadbearing walls exposed to heating conditions on both sides?

2 LITERATURE REVIEW DESIGN

This section details the methodology for reviewing existing related studies through a systematic review. Systematic reviews seek to offer a thorough and unbiased assessment of the evidence that is currently available on a particular research subject.

2.1 Review approach

The approach adopted for this review was based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) procedure [25] to identify related studies on the fire performance of LSF wall systems. The PRISMA procedure ensures that the review covers all studies that match pre-defined eligibility requirements to answer the study research questions as listed in Section 1.6. Selected studies are subjected to an inclusion and exclusion criteria for systematically evaluating whether a study is relevant to the subject been reviewed, from which a reduced number of studies are selected for detailed review.

2.2 Sources and databases

The search was performed on three online databases, namely:

- Scopus (https://www.scopus.com);
- Web of Science (https://www.webofscience.com); and
- Engineering Village (Inspect and Compendex) (https://www.engineeringvillage.com).

These were selected as they are the main bibliographic databases for literature reviews [26], cover a broad range of publications in science and engineering, and have been used in previous literature review studies in fire safety engineering (e.g., by Malagnino et al. [27]).

2.3 Search strategy

Search keywords were selected to capture records that are related to the performance of LSF walls in fire based on the research questions defined in Section 1.6 and terminologies used for describing LSF walls (see Section 1.3). These are presented in Table 2. The advanced keywords searching option of the three databases was used which allows the search to be limited to certain fields, date range, language, publication type, etc.

Studies were identified based on whether the title, abstract and/or keywords had a combination of search keywords that meet the Boolean expression defined in Table 2. The type of publications considered include original journal articles, review papers, conference papers, books (including book sections and chapters), theses and dissertations published up to and including 13th February 2023. The review was limited to only records written in the English language, as most of the studies are written in English.

Table 2. Systematic review search keywords.

Item	Description	
Search keywords	Boolean	Keywords
		("Light gauge steel" **OR** "Lightweight steel" **OR** "Cold-formed steel" **OR** "Cold formed steel" **OR** "Thin-walled steel")
	AND	“fire”
	AND	(“wall” **OR** “walls”)
Search fields	Title, Abstract and Keywords	
Publication type	All (Journal articles, conference articles, conference proceedings, articles in press, book chapters, dissertations)	
Database	Scopus Web of Science Engineering Village (Inspec and Compendex)	
Date of search	13/02/2023	
Publication year	Up to and including 2023	
Language	Limited to publications written in English	

2.4 Inclusion and exclusion criteria

Records returned from the database search were then subjected to further screening and eligibility assessment, based on whether they are directly relevant to answering the research questions listed in Section 1.6 on the performance of LSF walls exposed to fire on both sides. To do this an inclusion and exclusion criteria was formulated as follows:

i. Research must be fire related;

ii. Research focus must be on LSF wall systems or similar applications (e.g., floors). Research focussed on structural elements such as columns, beams, tanks, blocks, and plate girders, were excluded;

iii. Research focus must be on fire performance;

iv. Research focused on other accidental loadings in addition to fire were excluded (e.g., seismic loading, blast loading, etc.); and

v. Full text of research must be available.

2.5 Selection of studies for detailed review

The total number of returned articles for each database search was 932, distributed as follows: Scopus – 473, Web of Science – 151, and Engineering Village – 308. As the databases are all independent, it is possible that one record would appear in more than one database. Therefore, duplicates and triplicates were removed using Endnote reference management software to obtain a final number of studies of 521 for further screening and eligibility assessment.

The 521 studies were then narrowed down using the inclusion and exclusion criteria in two stages, as follows:

I. Screening: In this stage, an initial review of titles and abstracts of all 521 identified studies was carried out to assess their relevance to the research question. This was done by two of the authors, using the pre-defined inclusion and exclusion criteria to determine whether each study meets the eligibility criteria for inclusion in the review. At the end of this stage, 195 potentially relevant studies were selected for full-text search;

II. Full-text eligibility assessment: During this stage, the authors examined the full-text of each of the 195 screened studies to assess whether it met the inclusion and exclusion criteria. Studies whose full text could not be assessed were excluded. This brought the final number of articles to be included in the detailed review to 92.

Figure 2 summarizes the process of selecting the 92 studies relevant to the research questions for detailed review.

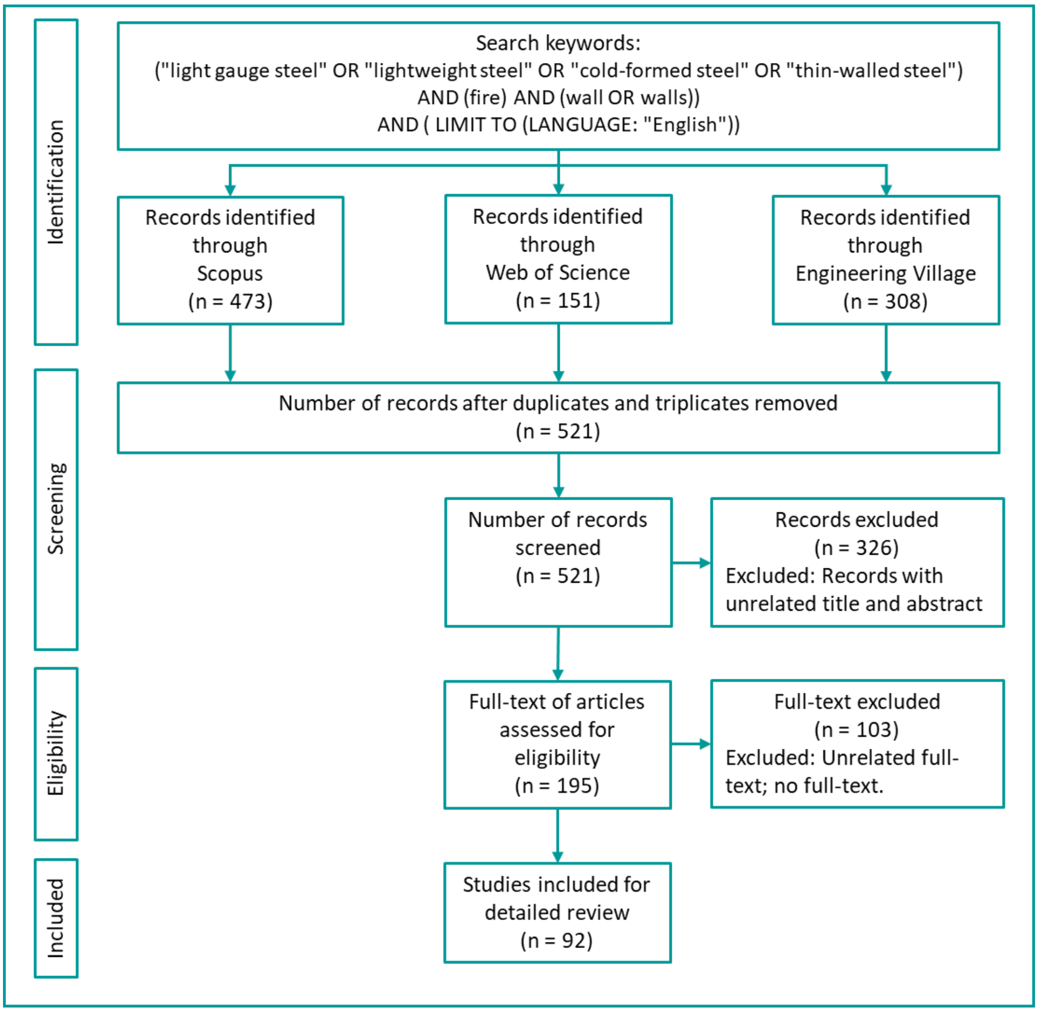


Figure 2. Flow diagram for selection of relevant studies.

2.6 Analysis of bibliographic data of selected studies

This section presents analyses of the bibliometric data of the 92 studies selected for detailed review. This includes analysis of the studies based on year of publication, publication type, co-occurrence of keywords and research method (numerical, experimental or both).

Figure 3 shows the number of publications per year. The data suggests that the number of publications has been generally increasing over the years. In the early years, the number of publications was quite low, with only one or two relevant publications per year. However, there has been a sharp increase in the number of publications since 2013, with the number of publications peaking in 2022 (24 publications). This trend is expected to continue as 2023 already has 5 publications considering records included in the review only cover those published up to midway through the month of February 2023. The increase in the number of publications over the years may be due to several reasons, such as an increase in the number of researchers or funding for research projects related to fire safety engineering in general (and of LSF wall systems exposed to fire) in recent times.

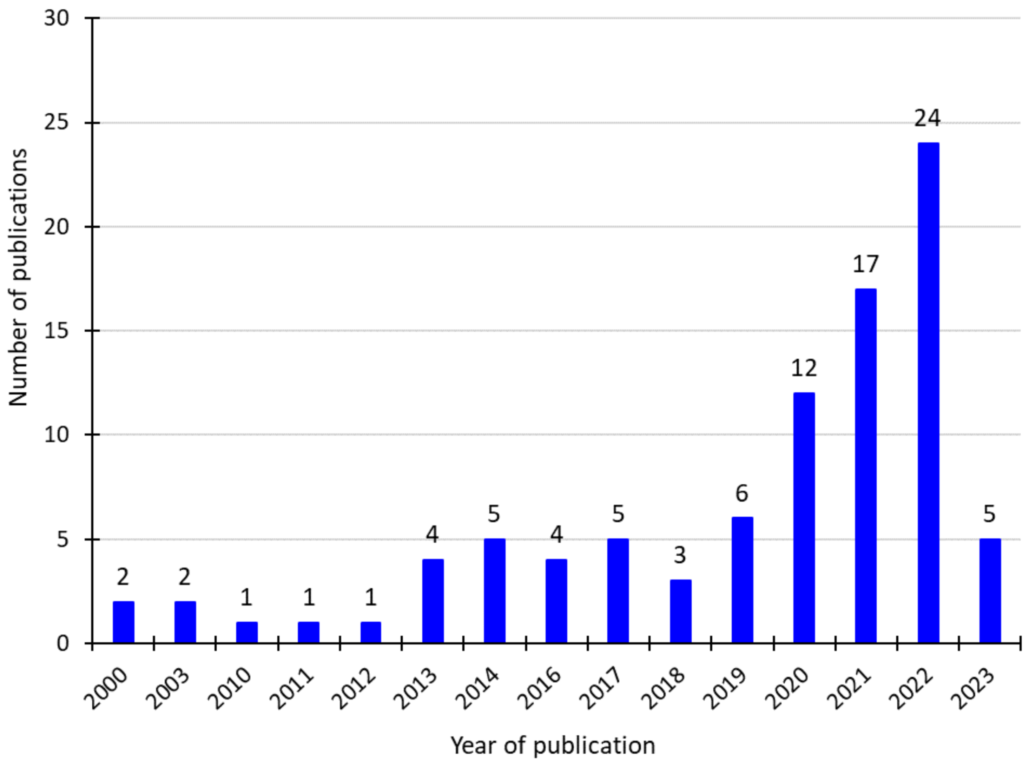


Figure 3. Distribution of studies selected for detailed review based on year of publication.

Figure 4 shows the number of publications by publication type. Most publications are journal articles, with 77 publications, accounting for approximately 85% of the total publications. The other 15% were conference papers with 15 publications, accounting for approximately 17% of the total publications.

This suggests that journal article is the preferred publication type for researchers in the area of LSF walls exposed to fire. Unlike conference papers, journal articles are typically peer-reviewed and provide a platform for researchers to disseminate their findings to a wider audience.

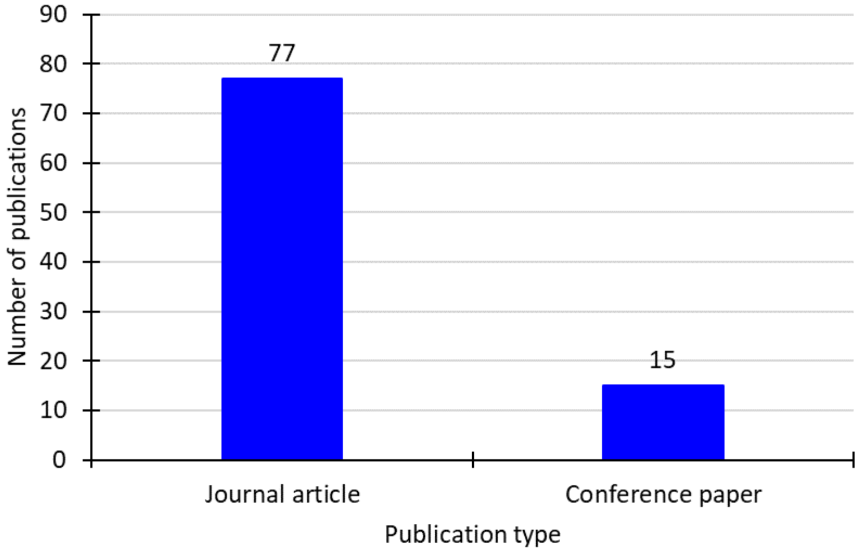


Figure 4. Distribution of studies for selected detailed review based on publication type.

Figure 5 shows the number of publications by research method, with studies that used only experimental/test methods being 25, only numerical methods being 46. This suggests that numerical method is currently the most common method used in assessing the performance of LSF walls in fire, accounting for 67 publications, or approximately 72% of the total number of publications. Studies that used only numerical methods accounted for approximately 49% of the total number of publications while studies that used only experimental /test methods accounted for only 27% of the total number of publications. Both experimental and numerical research methods were used in 20 publications, representing approximately 22% of the total number of publications. The relatively higher percentage of numerical studies may be due to the expensive nature of experiments/tests. As a result, it is common for the FE model used in more than one numerical study to be validated using the result from a single experimental study.

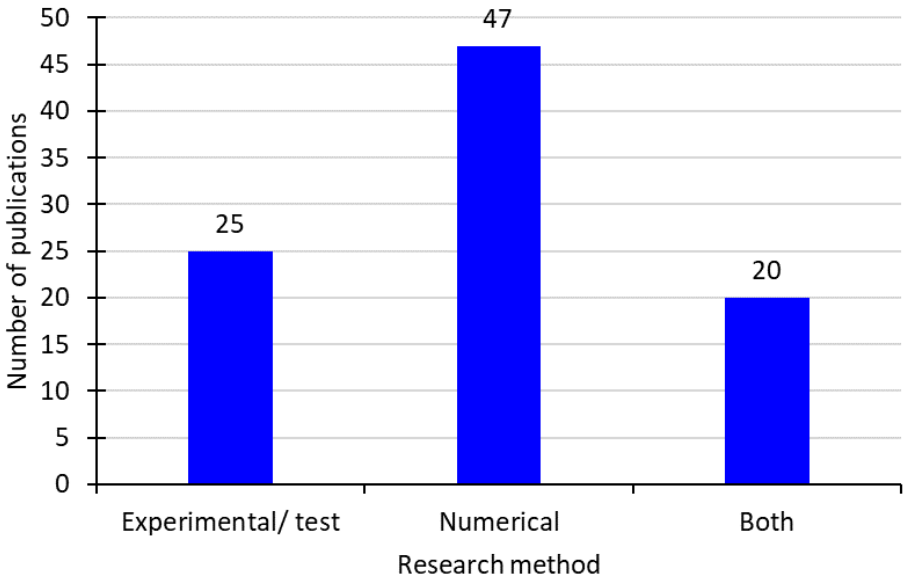


Figure 5. Distribution of studies for selected detailed review based on research method.

Figure 6 shows the co-occurrence analysis of the distribution of keywords used in the selected studies. The VOSviewer software [28], [29] was used to perform the keyword co-occurrence analysis, as it is able to generate visual network maps between the keywords used in the selected studies. The size of the cloud of each keyword is an indication of the number of times it was used in the selected studies, the larger the size and font the higher the frequency of occurrence of the keyword in the selected studies. Figure 6 identifies three main cluster of keywords of studies on the fire performance of LSF walls in fire namely: plasterboard (blue cluster), LSF wall (green cluster) and steel (red cluster). All the clusters are connected, showing an inter-relationship between research focusing on these areas. For example, the red cluster has fire exposure as one of the main keywords, directly connected to keywords such as sheathing, steel, fire resistance time and structural failure. This suggests that connections exist between the different keywords, and that a combination of the keywords they appear in many of the studies. However, there was no keywords related to two-sided fire exposure condition. Hence, indicating that none of the existing studies have simultaneously considered the effects of walls exposed to fire on two sides and the effects on the fire performance of LSF wall systems.

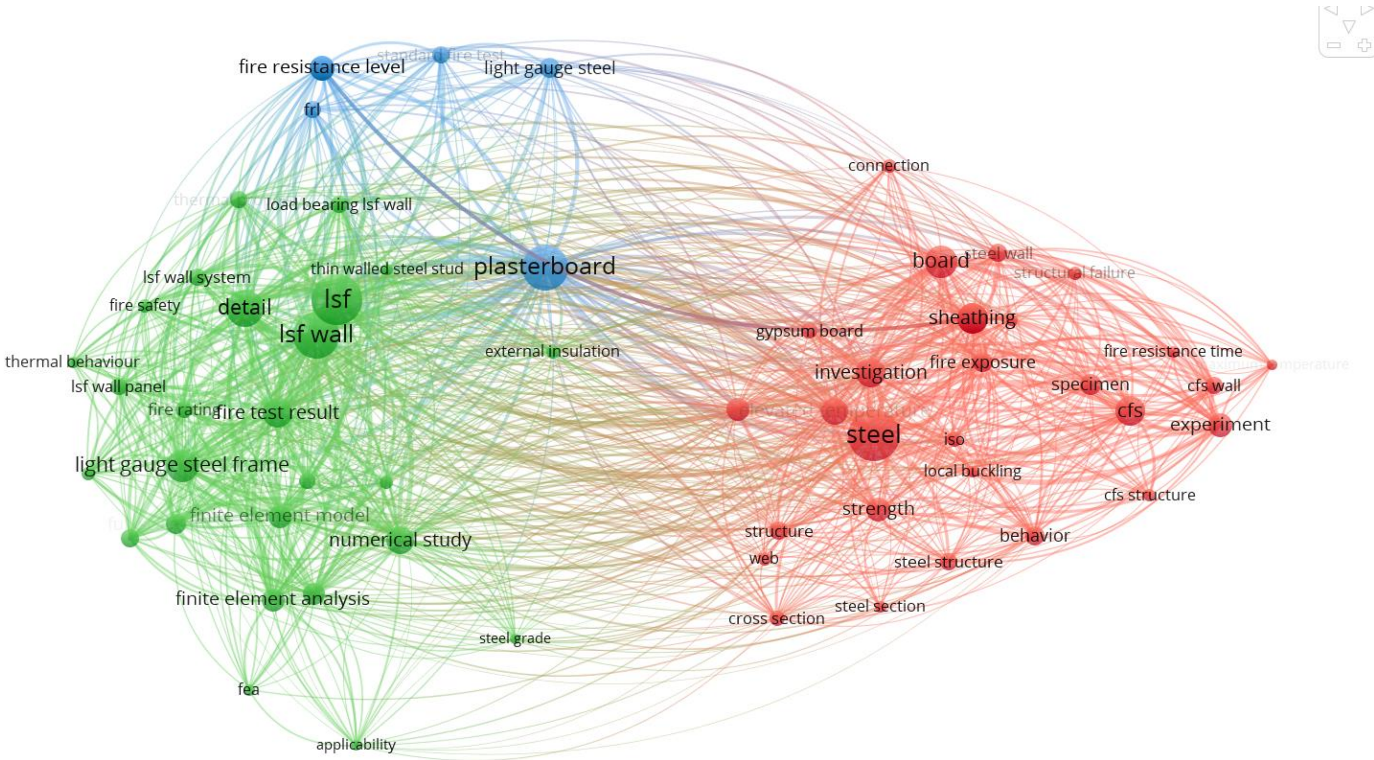


Figure 6. Co-occurrence analysis map of author keywords for all articles.

3 Characteristics of LSF Wall System

LSF wall systems are currently one of the most common forms of walling systems in the building industry [14]. They are utilised in residential, office, and industrial buildings as load-bearing walls or non-load-bearing elements in partition walls. Their high strength-to-weight ratio results in lighter constructions, which significantly reduces construction time, transportation costs, and labour needs. According to [30] substantial portion of the LSF wall system is produced off-site, saving waste and enhancing quality assurance. Figure 7 groups the benefits of LSF wall systems in buildings based on the following aspects: energy saving, ease of construction, sustainability, and value benefits.

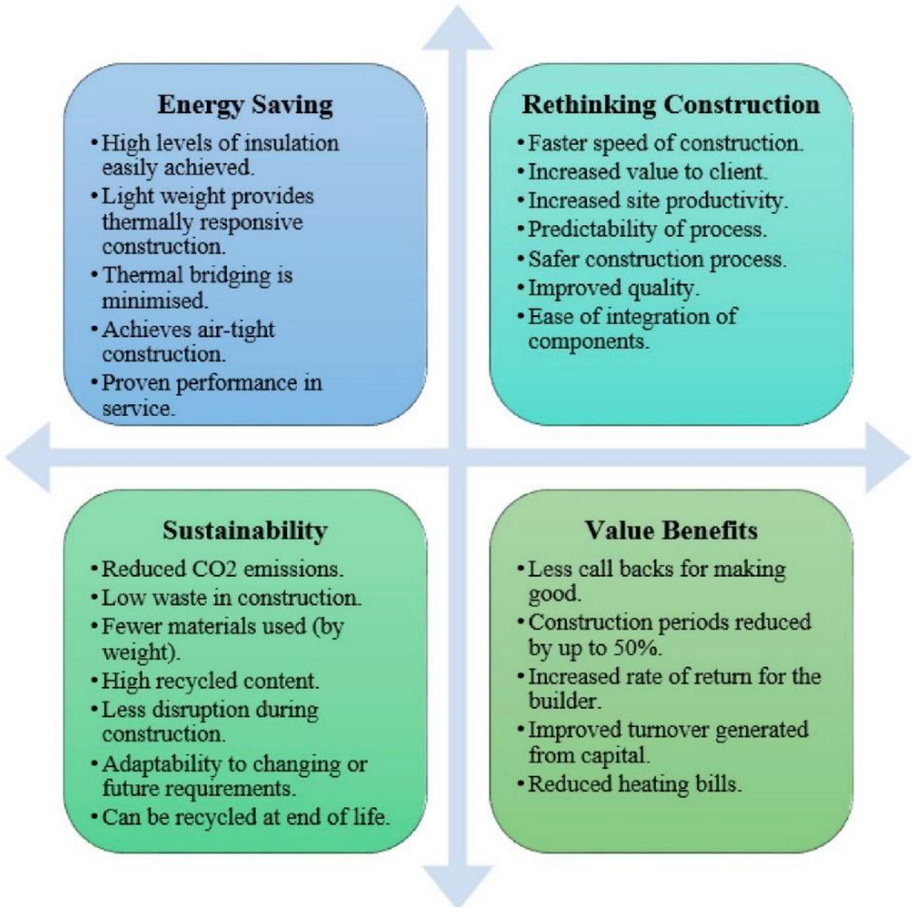


Figure 7. Advantages of using LSF wall system in buildings (original figure from [14])

The following subsections provide a review of the components of an LSF wall system. It covers the description of the different components of an LSF wall system and classification of LSF walls systems based on different criteria used in the literature.

3.1 Components of LSF wall system

LSF wall systems are characterised by three main components: cold-formed steel studs for load bearing; sheathing (e.g., gypsum plasterboard and oriented strand board (OSB)) and insulation materials (e.g., mineral wool). Some LSF wall systems do not have insulation material provided. Each of these components contributes to the structural integrity and/or elevated temperature performance of an LSF wall system. Most modular units are lined with plasterboard or a comparable material and fitted with an external sheathing board before they arrive at the site [30]. Other components of an LSF wall system are materials needed for joining and fastening (e.g., self-drilling screws), waterproof and air tightness membranes, and finishing layers [24]. Figure 8 shows a pictorial view of a typical LSF wall detail.

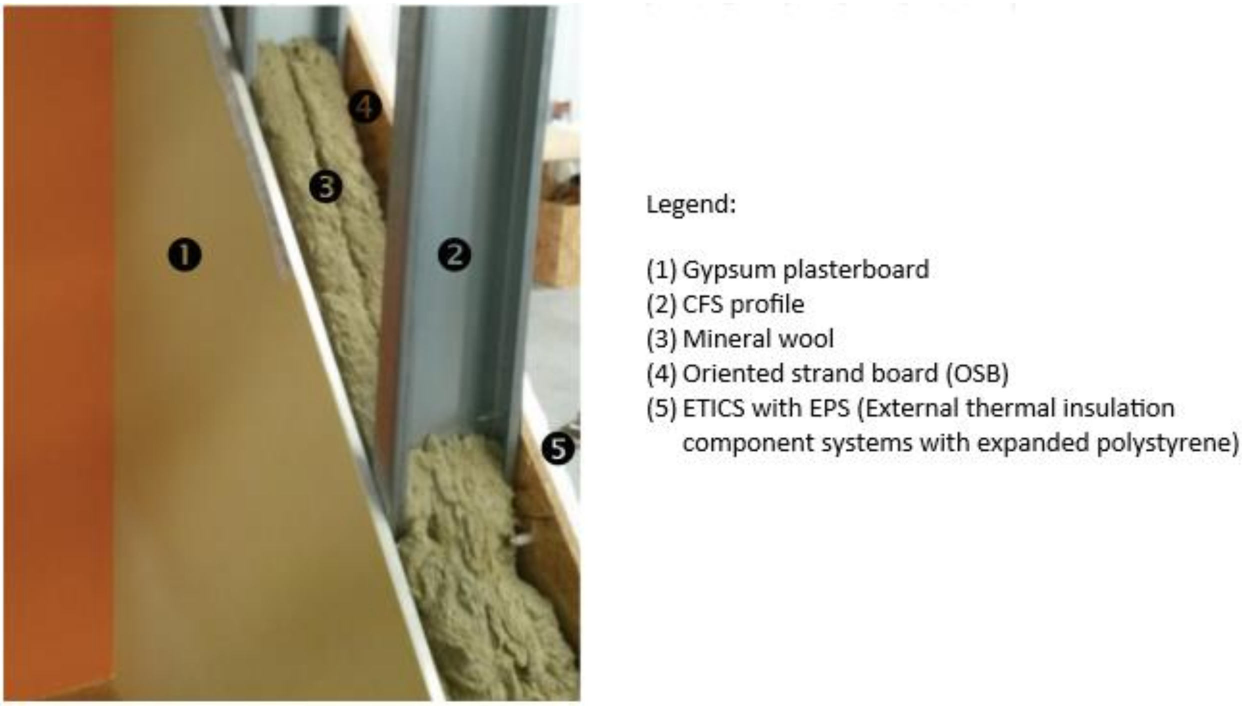


Figure 8. Pictorial view of an LSF wall detail (original figure from [31])

3.1.1 Cold-formed steel studs

Cold-formed steel (CFS) studs are regarded to be the primary load-bearing component in LSF wall systems. Typically, the CFS sections used in load-bearing walls are lipped channel sections, also known as C sections. Other cold-formed cross-section profiles typically used are shown in Figure 9. Due to greater load requirements, standard lipped channel studs cannot meet the structural requirements of many buildings, such as the lower levels of mid-rise buildings. In such situations, cold-formed steel square hollow section (SHS) and rectangular hollow section (RHS) studs are sometimes used instead [32].

CFS sections used in LSF walls are generally 70 to 250 mm in depth and have thickness of between 1 to 4 mm [30]. However, according to Soares et al. [24] the thickness of CFS sections used in LSF walls cover a slightly wider range, from as low as 0.45 to up to 6 mm.

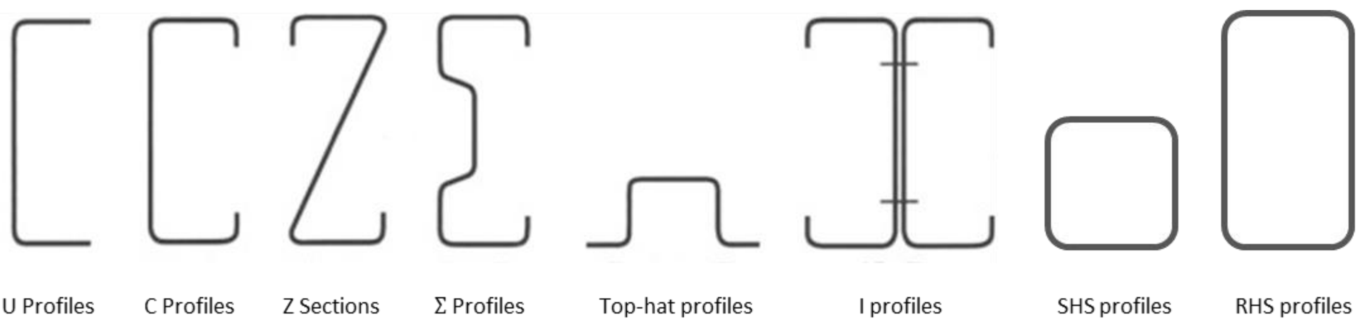


Figure 9. CFS section profiles used as studs in LSF walls (modified from [24])

Some LSF wall build-ups also include horizontal members known as noggings (or noggins) made of the same CFS section as the stud and typically spaced at regular intervals along the height of the wall. Whereas tracks are horizontal members at the top and bottom boundaries of the wall build-up connecting the tops and bottoms of the vertical studs, noggings are intermediate horizontal members. Figure 10 shows an LSF wall build-up indicating the vertical studs, the top and bottom horizontal tracks and two intermediate horizontal noggings. The spacing of noggings (typically 1 m [33]) depend on factors such as size of the wall, type and thickness of sheathing material and expected loads on the wall. Noggings help to provide restraints to studs when they bow as a result of thermal gradient caused by non-uniform heating, and resist the out-of-plane deflection of LSF walls in fire [33].

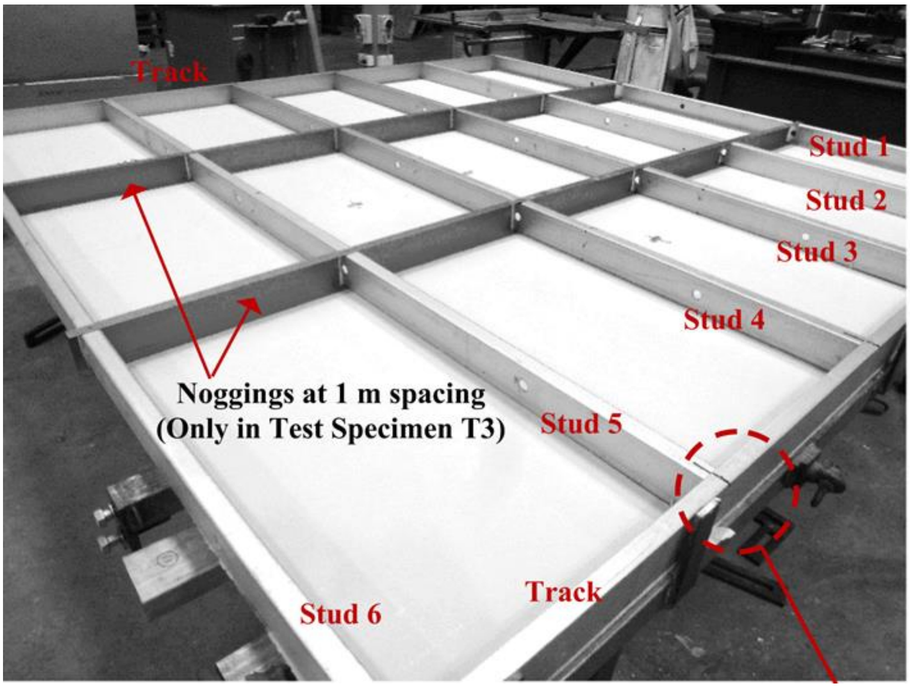


Figure 10. LSF wall build-up showing the studs, tracks and noggings (original figure from [33]).

3.1.2 Sheathing boards

LSF wall systems are lined with sheathing materials on both sides to enhance aesthetics, structural stability (through diaphragm action often termed racking resistance [34]), heat loss and energy performance, and protection to the steel frame from fire exposure. Examples of materials used are gypsum plasterboard, oriented strand board (OSB), calcium silicate board, magnesium oxide board, particle cement board, and steel sheets [24], [30], [35]–[37]. In most applications, LSF walls are used as load bearing walls, and adequate fire resistance levels are important [33]. Sheathing boards contribute to the fire protection of the LSF wall through their insulating properties and inherent chemically-bonded water content [30]. Different types of boards will provide different levels of protection [30]. Among the different types of sheathing board used in LSF walls, gypsum plasterboard is the most common due to its superior fire performance [38].

The fire protection in terms of fire resistance period provided by the boards also depends on the thickness of the board and number of layers used. Lawson and Way [30] gave examples of the thickness of gypsum plasterboard required for different fire resistance ratings of load bearing LSF walls ranging from single layer 12.5 mm board for 30 minutes fire resistance to three layers of 15 mm thick board for a 120 minute fire resistance. It is noted that these thicknesses are for the specific LSF walls assessed by Lawson and Way [30].

A new class of advanced composite materials used as sheathing material for LSF walls known as functionally graded materials (FGMs) have been used in some studies (e.g., in Ali et al. [22]). FGMs are characterized by continuous variation of material properties. FGMs are considered ideal for high strain rate and thermal shock loading applications due to their resistance to debonding, crack initiation, and reduced stress concentration and residual stress.

3.1.3 Insulation materials

The use of insulation materials in LSF wall systems is optional. Insulation is typically provided to improve the thermal performance (i.e., heat release and absorption) [13]. It also serve as an acoustic insulator [31]. The insulation materials are often placed between the steel studs (known as cavity insulation, full or partial depth) or in-between layers of plasterboard (known as external insulation) as shown in Figure 11. External insulation forms a composite panel of plasterboard and insulation material.

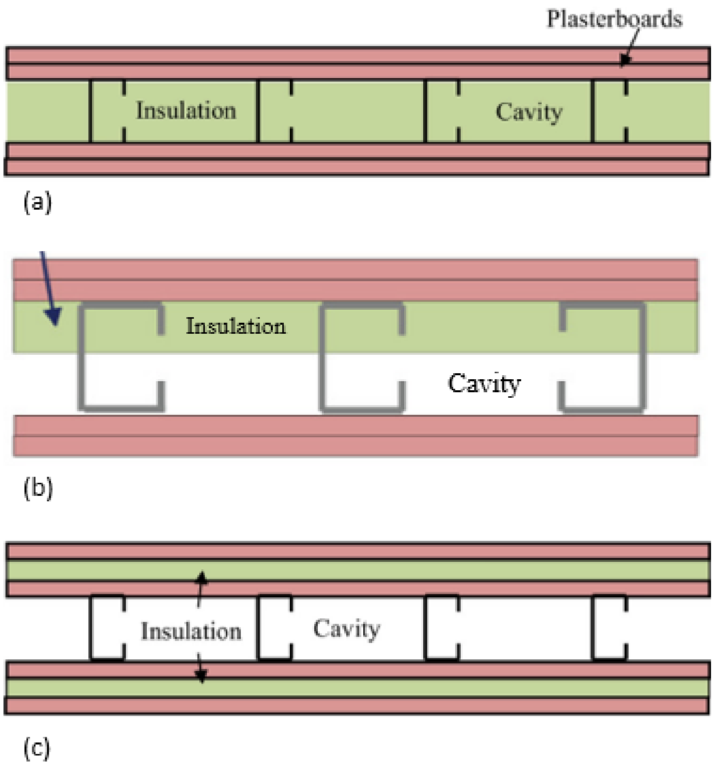


Figure 11. LSF wall systems with (a) full depth cavity insulation; (b) partial depth cavity insulation (c) external insulation (modified from [39])

Insulation materials used in LSF wall systems can be grouped into two types: organic and inorganic insulation materials [14]. Organic insulation materials are derived from natural or synthetic organic sources [40] and examples include XPS (extruded polystyrene), EPS (expanded polystyrene), PUF (polyurethane foams). On the other hand, inorganic insulation materials are derived from minerals usually in fibrous and porous forms [40]. Examples of inorganic insulation materials include mineral wool (e.g., rock mineral wool also known as rock wool and glass mineral wool), calcium silicate, glass fibre, and foam concrete. The thermal conductivity of inorganic thermal insulation materials is higher than that of organic thermal insulation materials. This makes inorganic thermal insulation materials less effective as insulation [14]. On the other hand, organic insulating materials have poorer fire resistance performance [14].

Mineral wool is the most common thermal insulation material used in LSF construction as it offers additional fire resistance to LSF elements and is regarded as the traditional insulation material for LSF walls [13]. To help minimise the impact of thermal bridges, it is also common construction practice to use a thermal insulation that comprises of expanded polystyrene (EPS) with an External Thermal Insulation Composite System (ETICS). Vacuum Insulation Panels (VIP) are used where due to space constraint, reduced wall thickness is required. This is because VIP exhibits up to five times the thermal resistance of traditional insulation materials, therefore requiring less thickness to achieve the same thermal performance [14].

3.1.4 Joining and fastening

Figure 12 illustrates different methods for joining and fastening components of an LSF wall system. Welding is mostly avoided due to the high residual stress it induces on light gauge steel sections, riveting is a time-consuming method as it requires prior drilling, and nails are not very durable. As a result, self-drilling screws are the most common fastening method because they provide a much stronger and more durable connection and are easy to use [31].

Adjacent panels of sheathings are typically filled and finished with jointing compounds to create a smooth, seamless surface [4].

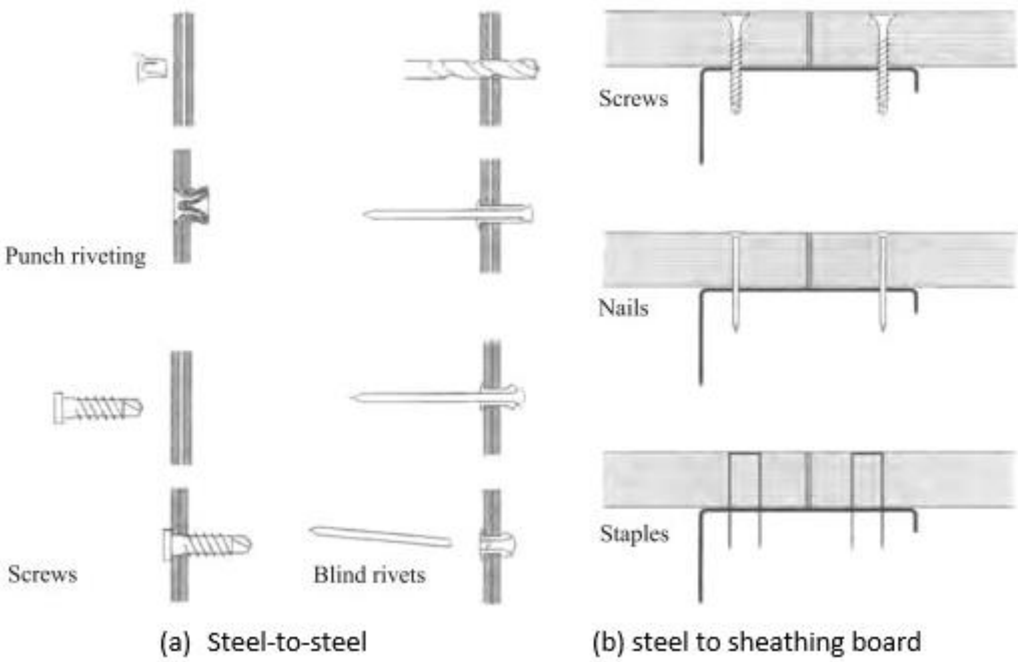


Figure 12. Joining and fastening options for LSF walls

3.2 Classification of LSF construction

LSF walls have two broad classifications based on their loading condition and whether they are insulated.

Based on loading condition, LSF walls are either load-bearing or non-load bearing. Several studies have investigated the fire performance of LSF walls of load-bearing versus non-load bearing applications (e.g., [9], [41]–[45]). Determination of whether an LSF wall will be load-bearing or not has implication on how the LSF wall is designed and what performance criteria it is required to meet.

Based on insulation condition, LSF walls are classified as insulated and non-insulated LSF walls. Insulated LSF walls have insulation materials provided either as cavity insulation or external insulation (see Section 3.1.3 for description of cavity and external insulation of LSF walls). Non-insulated LSF walls have no insulation material provided.

A further classification of LSF walls exists for insulated LSF wall systems based on the location of the insulation material. These are: cold-frame, warm-frame and hybrid-frame LSF wall systems [46]. The cold-frame LSF wall is designed with all its thermal insulation within the cavity, resulting in a thinner wall panel (see Figure a). However, this design makes the wall more vulnerable to hygrothermal issues and leads to higher thermal transmittance. On the other hand, the warm-frame LSF wall has the thermal insulation located outside the cavity, which increases the wall thickness and offers better hygrothermal and energy performance (see Figure 13c). The hybrid-frame LSF wall is a combination of the cold-frame and warm-frame designs, where half of the insulation is placed inside the cavity and the other half outside the wall (see Figure b).

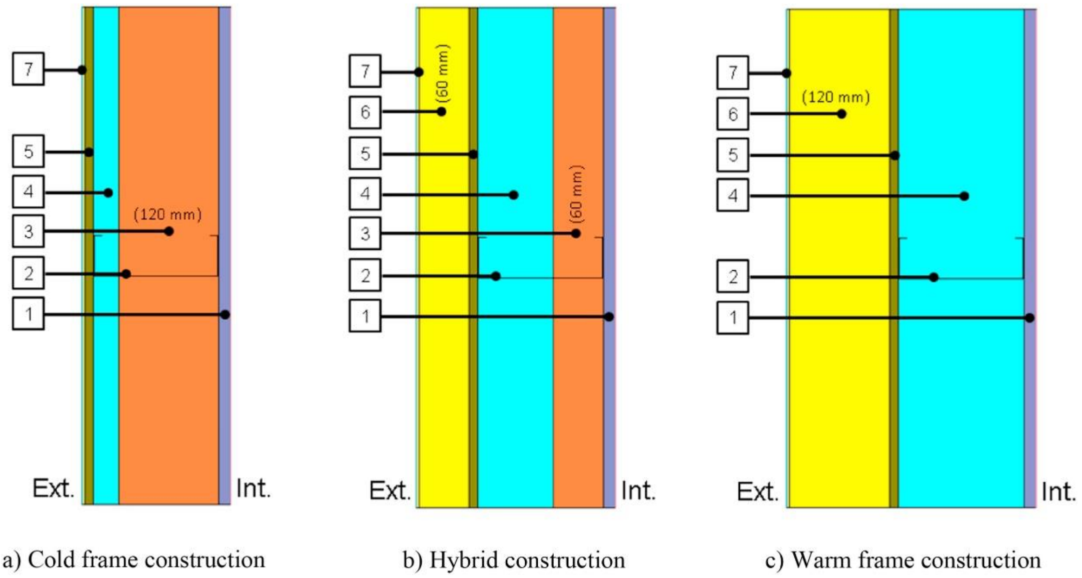


Figure 13. Classification of LSF constructions depending on the position of insulation materials (1- Gypsum; 2- LSF; 3- Mineral wool; 4- Air gap; 5- OSB; 6- EPS; 7- ETICS) (original figure from [24])

4 EXPERIMENTS

4.1 Overview

A primary goal of this systematic literature review is to identify the ways in which earlier research has used experiments to understand how LSF walls perform when exposed to fire or elevated temperatures. The focus of this chapter is on the experimental work undertaken in the literature and findings that shape the current state-of-the-art on light gauge steel framing wall systems.

A total of 99 studies were screened for this purpose, which contained references to LSF walls and/or fire/elevated temperature conditions. Out of these, information from 30 studies is included in this chapter. Studies that were included from literature needed to fit the questions set in Section 1.6. This was established by examining the documents and identifying whether the scope of the study was relevant to the set questions or not.

4.2 Results

4.2.1 System/material properties for ambient and elevated temperatures

Several studies reported material/product used in the LSF wall assembly. A list of studies that reported the assembly material properties is shown in Table 3.

The majority of the reported yield strengths are in the range of 355 MPa to 550 MPa. It is interesting to note that the reported yield strengths for some types of steel are different depending on the application. For example, the yield strength for steel sheathing is reported as low as 235 MPa, while the yield strength for studs and tracks is reported as 355 MPa.

The data provided shows the different types of sheathing used in construction. Gypsum plasterboard (GP) is the most commonly used sheathing material, appearing in the majority of cases listed. Magnesium board (Mg), calcium silicate board (CS), vermiculux, and bio-based PCM were used in the same experimental programmes alongside GP in some cases. Steel sheet and oriented strand board (OSB) were also used as sheathing materials. In one case, a study examined corrugated steel as a sheathing material [8]. Brick veneer and steel plate were also used as sheathing materials in different cases.

The most common insulation material used was glass fibre and Rockwool. Less common insulation used in the cavity included cellulose, silica aerogel fibreglass blanket, Earthwool, autoclaved aerated concrete, and foam concrete.

Table 3. Materials used in the LSF wall assembly.

Authors	Steel type [a]	Sheathing materials	Insulation materials
Roy et al. [47]	G550	Gypsum plasterboard (GP)	None
Ariyanayagam and Mahendran [44]	min 300 MPa	Gypsum plasterboard	None, glass fibre
Chen et al. [48]	550 MPa	Gypsum plasterboard	Not reported
Gnanachelvam et al. [49]	G550	Gypsum plasterboard, magnesium board (Mg), calcium silicate board (CS), vermiculux, bio-based PCM	Not reported
Batista Abreu et al. [50]	345 MPa	Gypsum plasterboard, oriented strand board (OSB), fire rated gypsum plasterboard	None
Andres et al. [51]	Not reported	Steel sheet, oriented strand board	Not reported
Gnanachelvam et al. [13]	G550 [b]	Gypsum plasterboard	Not reported
Tao et al. [32]	C450 [c]	Gypsum plasterboard	Glass fibre
Liu et al. [52]	G550	Gypsum plasterboard, CS, autoclaved lightweight concrete (ALC)	Rockwool
Tao and Mahendran [53]	C450	Gypsum plasterboard, aerogel blanket (sheet form)	Silica aerogel fibreglass blanket
Liu et al. [54]	G550	Gypsum plasterboard, Rockwool, calcium silicate board, autoclaved lightweight concrete	Not reported
Chen et al. [55]	G550	Not reported	Rockwool
Hassan et al. [56]	Not reported	Not reported	Cellulose insulation
Pancheti and Mahendran [57]	G550	Not reported	Glass fibre insulation
Abeysiriwardena et al. [4]	G550 (single web stiffened) / G500 (double web stiffened)	Gypsum plasterboard	Not reported
Chen et al. [16]	G550	Gypsum plasterboard	Not reported
Pancheti et al. [8]	G550	Gypsum plasterboard, corrugated steel	Earthwool
Upasiri et al. [12]	Not reported	Plasterboard	Rockwool, Autoclaved aerated concrete, Foam concrete
Gnanachelvam et al. [58]	G550	Not reported	Not reported
Liu et al. [17]	G550	Not reported	Not reported
Liu et al. [18]	345 MPa	Not reported	Not reported
Pancheti et al. [45]	G550	Brick veneer/plasterboard	Glass fibre
Liu et al. [15]	Q355 [d]	Gypsum plasterboard	Not reported
Xing et al. [59]	Q235 (sheathing) / Q355 (tracks/studs)	Steel plate as a central member	Not reported

[a] All numbers in the reported steel types refer to the yield strength of the steel profile quoted (in MPa)
[b] The letter G indicates hot-dipped aluminium/zinc alloy-coated structural steel with a regular spangle surface and a guaranteed minimum yield strength of 550MPa [60]
[c] The letter C indicates the steel hollow section was manufactured in accordance with AS 1163 [61]
[d] The letter Q indicates the steel profile manufactured according to the Chinese GB/T 1591 -2018 standard [62]

4.2.2 Properties of materials commonly used in LSF wall experiments

In certain cases, the material properties of the wall assembly were reported in the studies conducted. The properties of materials/products most-commonly found in LSF experimental literature are included in Figure 14 to Figure 17.

Plasterboard and gypsum plasterboard are the most used materials. Experimental properties are provided by various researchers [4], [8], [13], [15], [45], for ambient and elevated temperature conditions.

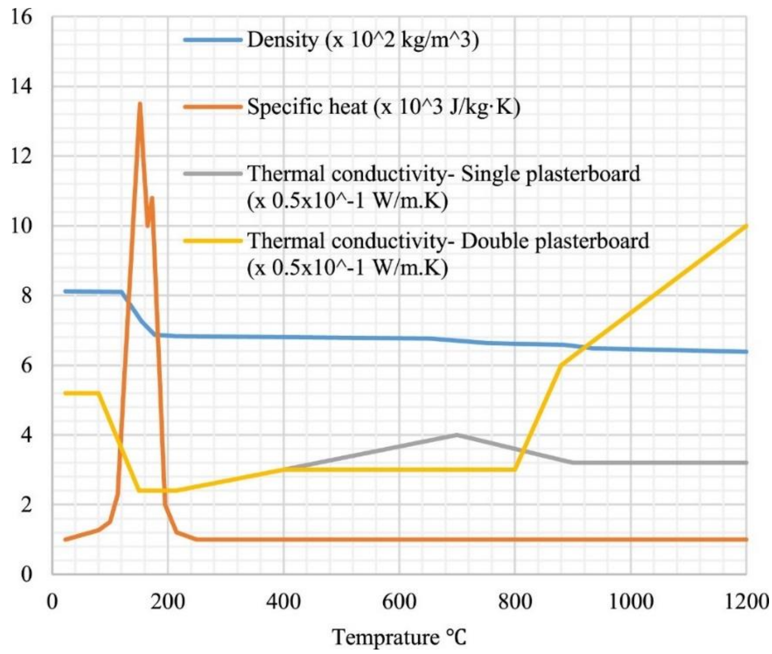


Figure 14. Thermal properties of gypsum plasterboard (original from [4]).

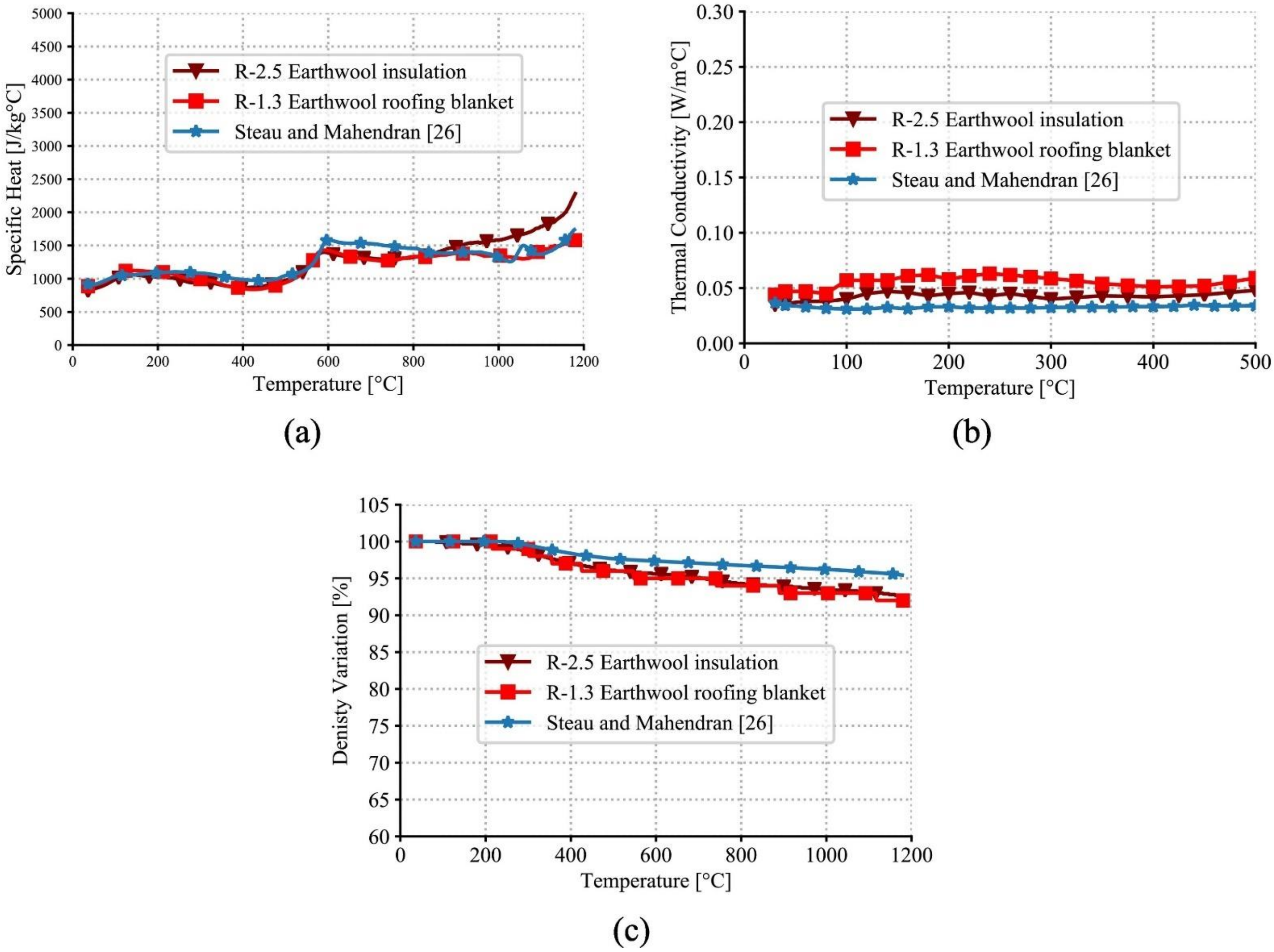


Figure 15. Thermal properties of glass fibre (Earthwool) insulation (original from [8]).

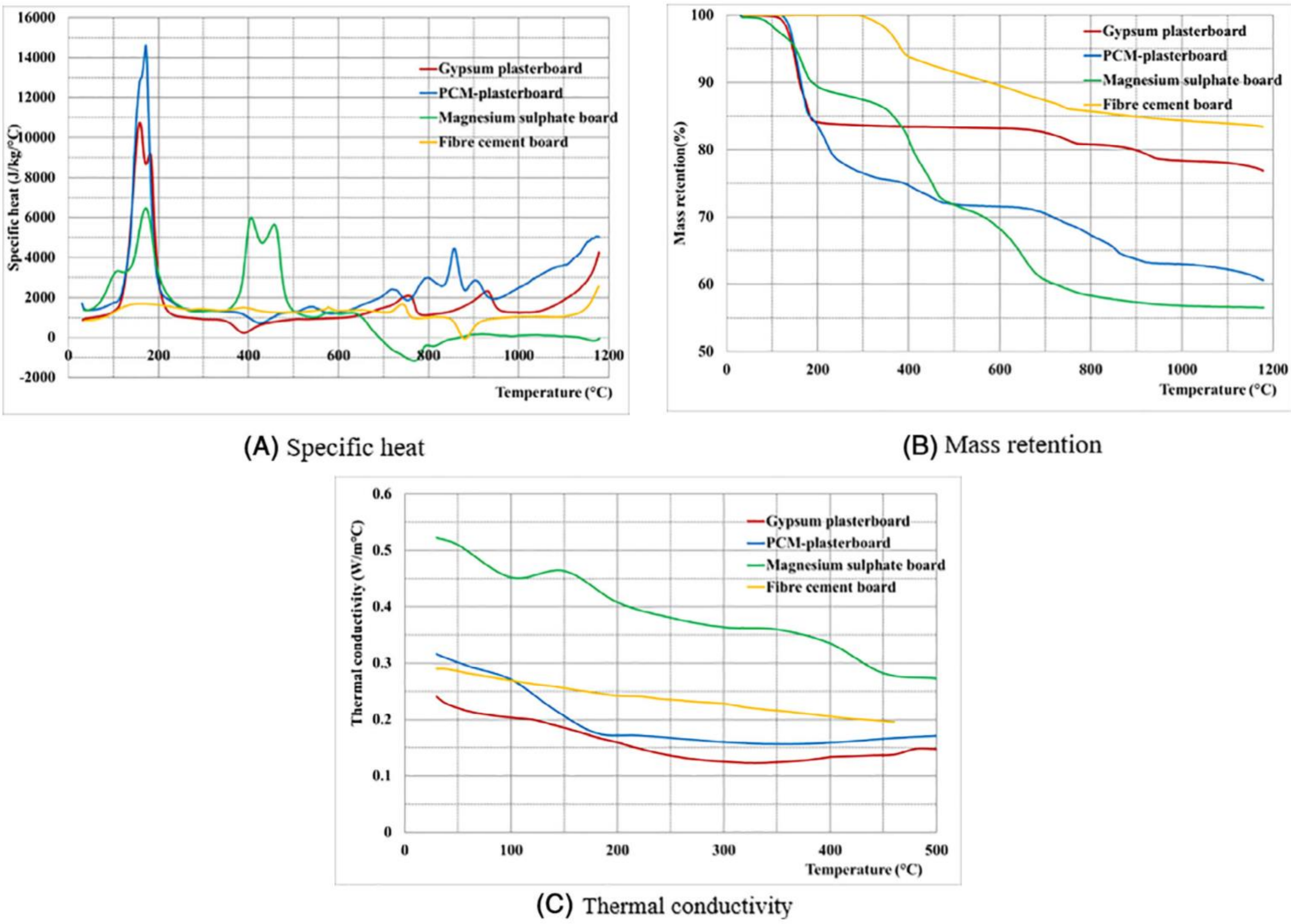


Figure 16. Thermal properties of different sheathing materials (modified from [58]).

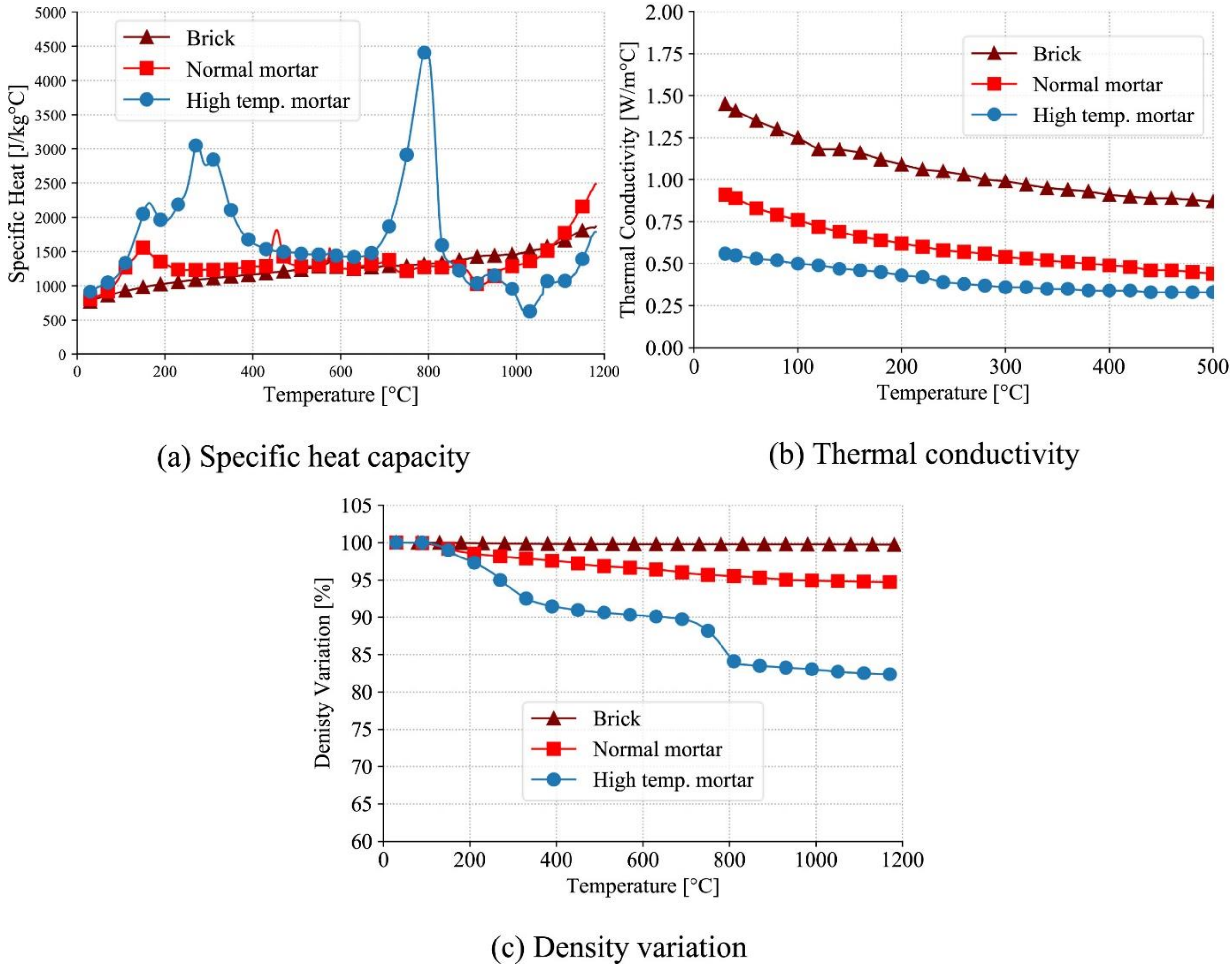


Figure 17. Thermal properties of brick veneer (modified from [45]).

Based on the type of steel used, different material properties (such as conductivity, specific heat, etc.) are reported by researchers [4], [12], [59]. The main identifier of steel used in the different research is the yield strength. The most common steel used has a yield strength of 550 MPa and that refers to C-channel type sections.

4.2.3 One-sided/two-sided exposure

The basic mechanisms for heat transfer for LSF wall systems are shown in Figure 18. This is an example of one-sided heating, as there is the assumption that one flange is being heated, as indicated in the figure.

The literature appears to consider one-sided exposure for LSF walls, almost exclusively. The majority of the experiments/tests used furnaces, either medium scale (c. 1.0–1.5 m) (e.g., [15], [18], [59]) or large scale (c. 3.0 m) (e.g., [32], [37], [63]), exposing the LSF wall systems to the standard fire time-temperature curve (ISO 834 [64]). A picture from an experimental setup similar to most of the work in the literature is shown in Figure 19.

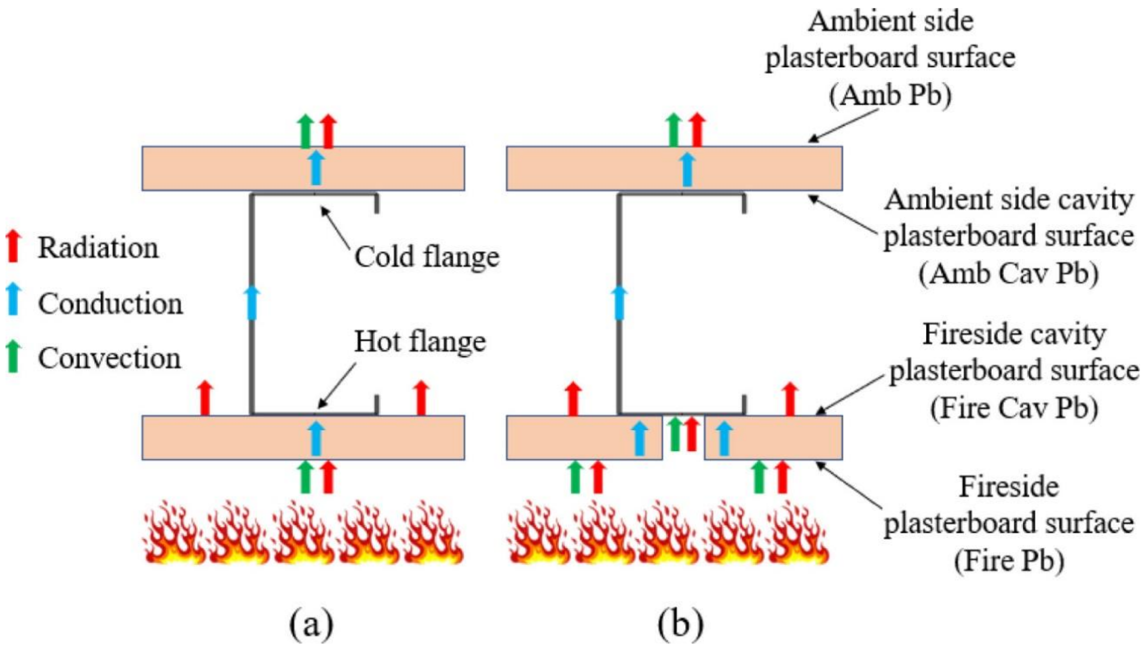


Figure 18. Heat transfer through LSF wall panel (a) without and (b) with plasterboard joint opening (original from [4]).

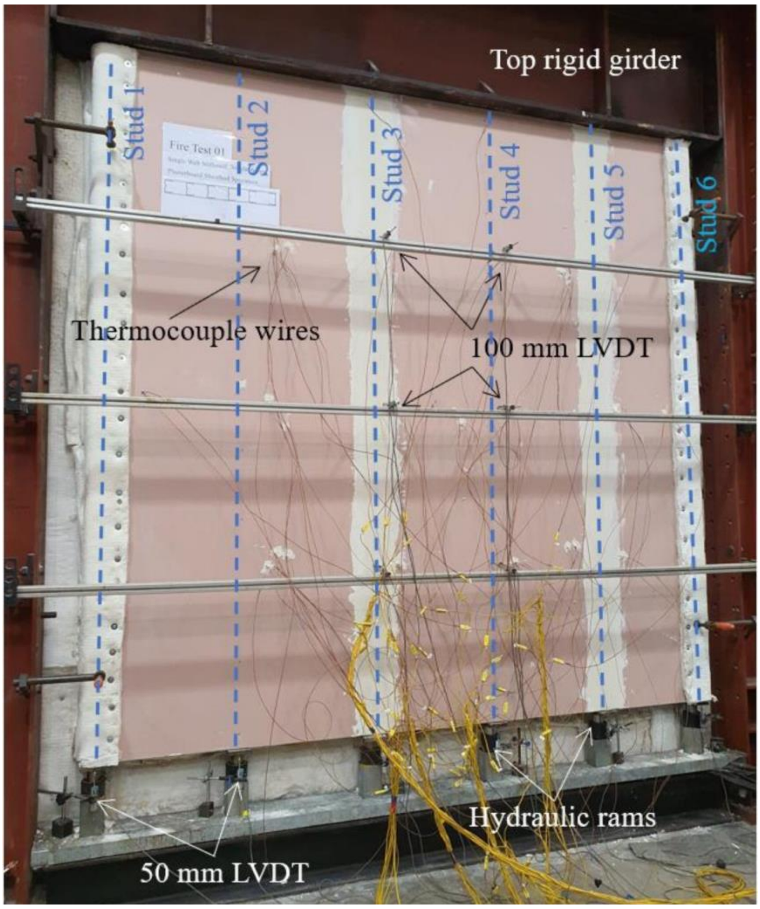
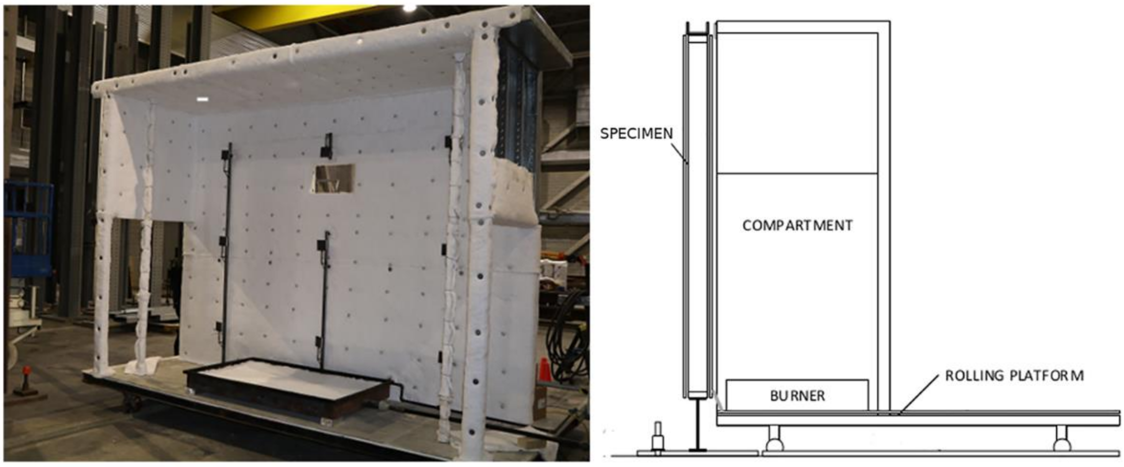


Figure 19. Full scale arrangement of LSF wall assembly (original figure from [4]).

For instance, analysing the experimental programme of Figure 19, three configurations were used: (T1) single web-stiffened stud, with a single plasterboard layer; (T2) double web-stiffened stud, with a single plasterboard layer; and (T3) single web-stiffened stud, with two plasterboard layers. It was demonstrated that the additional web-stiffening provided to the studs in T2 had little impact on R. Failure of T1 and T2 due to distortional buckling occurred at 34 and 43 minutes of one-sided exposure to the standard time-temperature, respectively. The failure occurred at locations with plasterboard joint openings. Additionally, it was shown that the second plasterboard layer led to more than doubling the failure time, as T3 failed at 107 minutes.

In some cases [51], LSF walls were exposed to a realistic fire scenario in an enclosure (e.g., a kitchen fire); this provided information of the LSF wall performance in a compartment fire scenario. The experimental setup used is shown in Figure 20 and Figure 21. The experiments carried out in the ad-hoc compartment-like apparatus of Figure 20 were subjected to the time-temperature curves of Figure 22(a); these approximated the ISO 834 fire, along with a mild fire and a severe fire scenario. The kitchen fire scenario in Figure 21 followed a natural fire curve development, as shown in Figure 22(b), with a heating curve similar to the mild fire in duration but closer to the magnitude of the severe fire. Again, as in the case of experiments in furnace testing, the wall assembly was exposed to fire on only one side, while the temperature exposure on the other side remained ambient.



(A) (B)

Figure 20. Experimental setup for gas burner compartment-like fire experiments (A) photograph and (B) sketch (original figure from [51]).

Figure 21. Compartment fire in a kitchen enclosure (original figure from [51]).

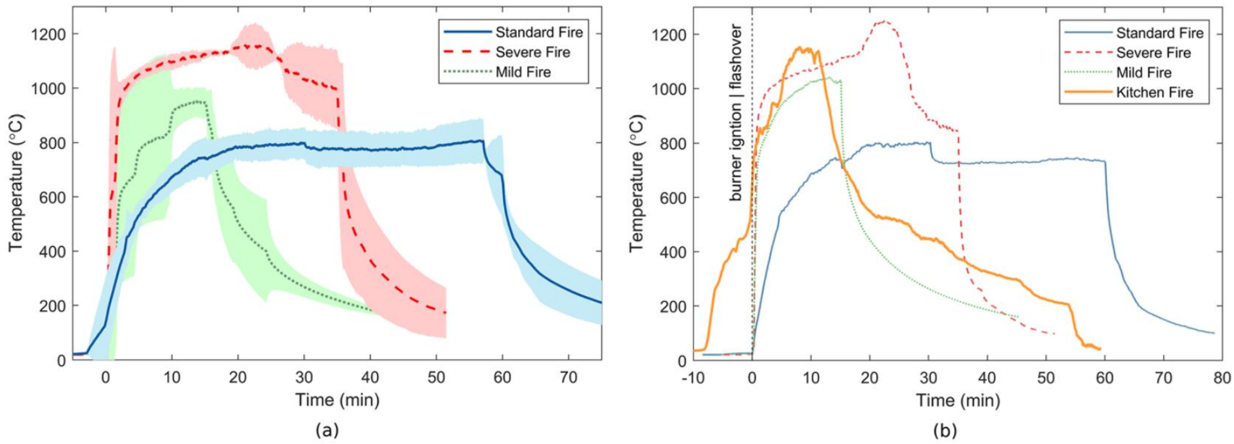


Figure 22. Time-temperature curves (a) for mean values (lines) and one standard deviation (shaded area) for three design fire scenarios and (b) the upper layer gas temperatures for design fires and the kitchen fire scenario, for tests that included an OSB sheathing board (original figure from [51]).

Figure 23 shows the distribution of heat fluxes in the compartment-like space during the design fires established previously. The heat fluxes were estimated using the temperature data of plate thermometers used during experimentation; adjacent gas temperatures were measured and accounted for in the calculation [51]. It is demonstrated that the standard fire resulted in lower heat fluxes compared to the Mild and Severe design fires.

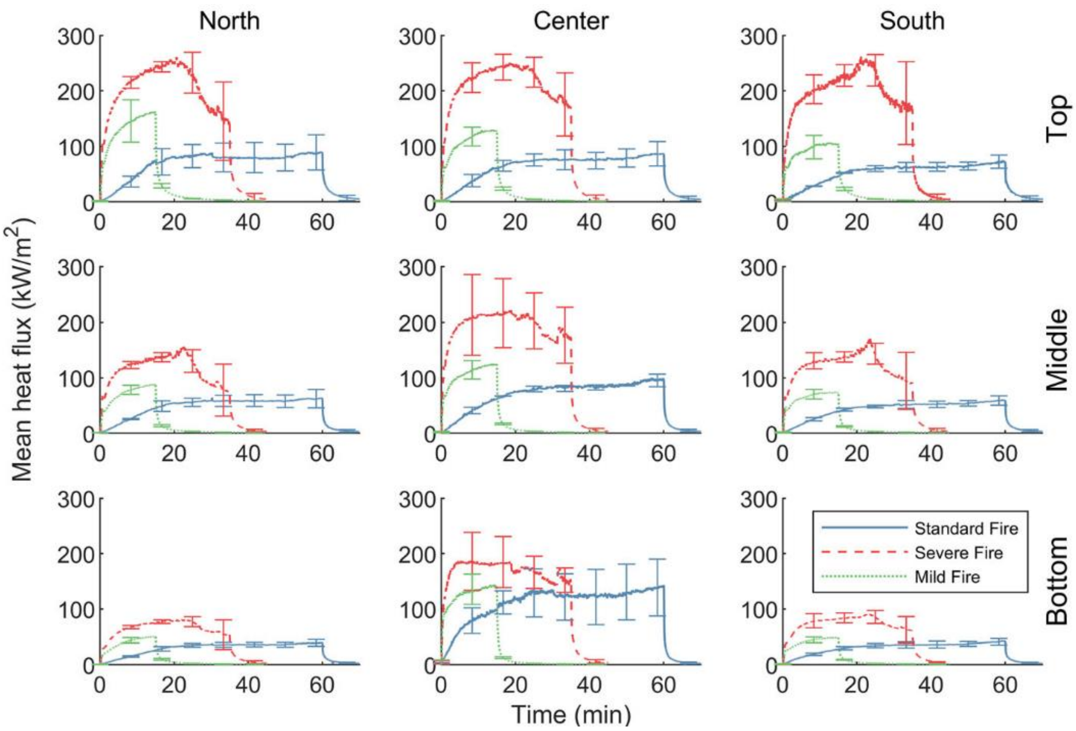


Figure 23. Mean and standard deviation of heat flux in the compartment at different locations/heights for the three design fires.

Roy et al. performed an enclosure fire experiment on a single-storey LSF wall and roof building [47]. The experimental setup used timber cribs in the enclosure, as the movable, imposed fuel load. The building and fuel arrangement are shown in Figure 24. The building represents a typical form of construction in Malaysia, for single-storey units like the one illustrated. The timber cribs were ignited on one side, to provide a non-uniform heating to the structure, as it could be expected in a natural fire; this was the intended heating for the structure by the research team.

Figure 24. LSF building experiment using a natural fire (original from [47]).

Despite the fact that this experiment could have resulted in external flaming, and therefore exposure of the LSF wall to fire from two sides, the fuel load was not sufficient to achieve that. In this experiment, only the southern side wall was covered internally by gypsum plasterboard. This resulted in its collapse later in the test, compared to the northern side wall, and therefore demonstrated improved performance, due to plasterboard protection.

Other work from a team of researchers in China has used several different heating curves (in a furnace) to expose mid- and large-scale wall assemblies to fire conditions [48]. The different heating curves are shown in Figure 25. The LSF assembly used two layers of gypsum plasterboard, with an insulation layer sandwiched in between, as sheathing material; the cavity was empty.

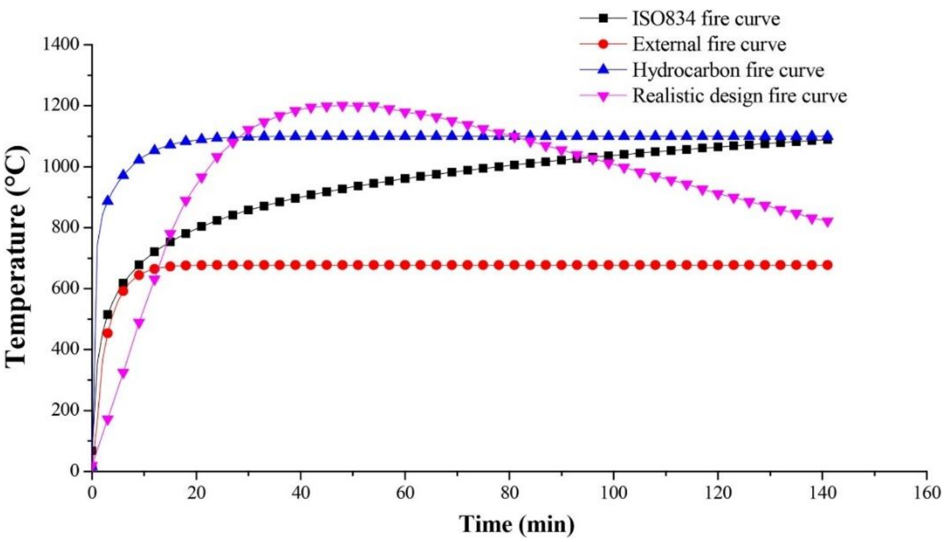


Figure 25. Time-temperature curves of four types of fire exposure (original figure from [48]).

This experimental work followed from previous experiments by the same researchers [65], in which insulation was used in the cavity. They demonstrated that the insulation in the cavity resulted in an earlier failure of the studs. The authors of the current report believe this is due to the insulation reducing the stud's heat losses in the cavity, and resulting in the temperature of the hot flange rising faster, and therefore leading to earlier failure of the system.

In the screened literature, only one project considered double sided exposure on a LSF wall assembly. Batista Abreu et al. [50] used an electric furnace to apply a constant temperature to the assembly. Heating was uniform around the LSF wall, i.e., exposing both sides of the wall to heating, with the temperature difference of the bottom of the specimen relative to the top having been within 10 °C. The experiments were at medium scale, using LSF walls of 0.6 m and 1.0 m height. The experimental setup is shown in Figure 26.

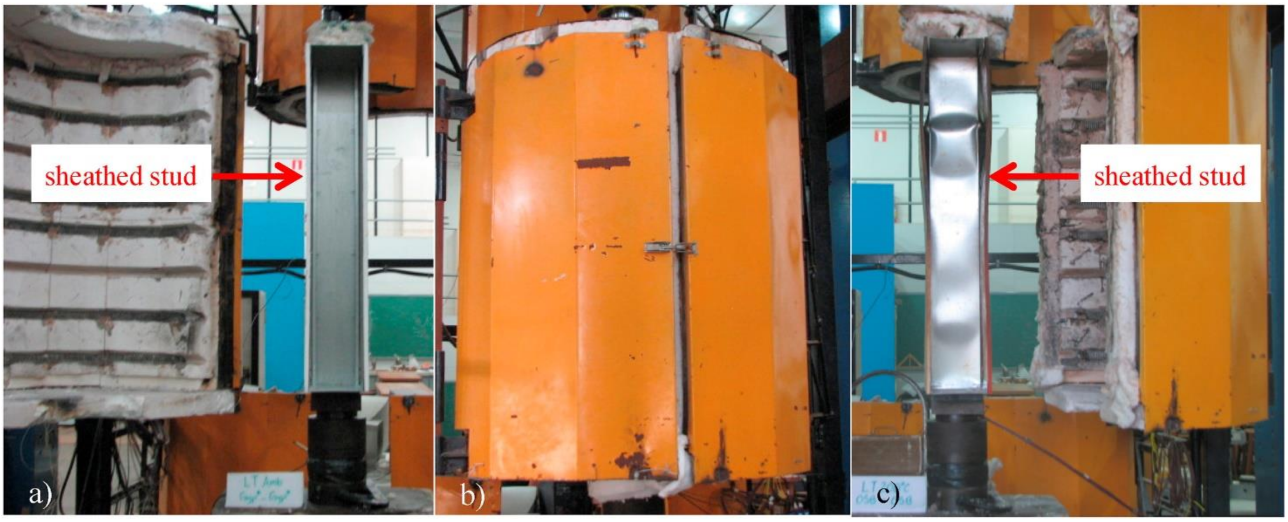


Figure 26 – Experimental setup of medium scale LSF wall assembly (a) pre-experiment; (b) during testing, when the electric furnace was wrapped around the sample; and (c) post-experiment buckled sample (original figure from [50])

This experimental programme demonstrated that, at ambient temperatures, sheathing could increase the ultimate axial load of the LSF walls. This is due to the sheathing providing restraint to the studs, thus preventing early failure due to distortional and global buckling. At elevated temperatures, the mechanical properties of the sheathing and the steel frame decrease; this is dependent on the time the sheathing fails:

- in the case of GP due to dehydration of the board and burning of the paper face; and
- in the case of OSB due to burning of the board, effectively exposing the stud to the fire.

Furthermore, the Direct Strength Method was applied to predict the LSF wall's behaviour. The predictions for the 1 m length specimens had good agreement with the experimental results. It was shown through this study that the use of the method could be extended to uniformly heated assemblies, as opposed to its current use only for one-sided exposure to fire; that is, provided accurate material and connection retention factors are known [50].

4.2.4 Structural loading conditions

This review considers loaded LSF walls in experimental studies reported in the literature. Experiments that did not report loaded LSF wall specimens were not considered at this stage of the literature review. The structural load is most commonly applied to the wall assembly in the form of hydraulic jacks; the load is kept constant during the experiment, assessing the failure time of the system due to both the fire exposure and load.

The concept of load ratio is introduced in the literature, when reporting the applied load that the wall assemblies could successfully carry, prior to failure due to elevated temperatures. The load ratio is a comparison of the ultimate applied load that the member can carry in ambient conditions and the applied load at elevated temperatures.

For cases that had loaded walls, the values of the load ratio used in the studies ranged from 0.2 to 0.85 [16]. Most studies reported load ratios between 0.2 and 0.4 ([4], [8], [12], [17], [18], [32], [37], [44], [47], [48], [53], [63]. A distribution of the reported load ratios in literature is illustrated in Figure 27.

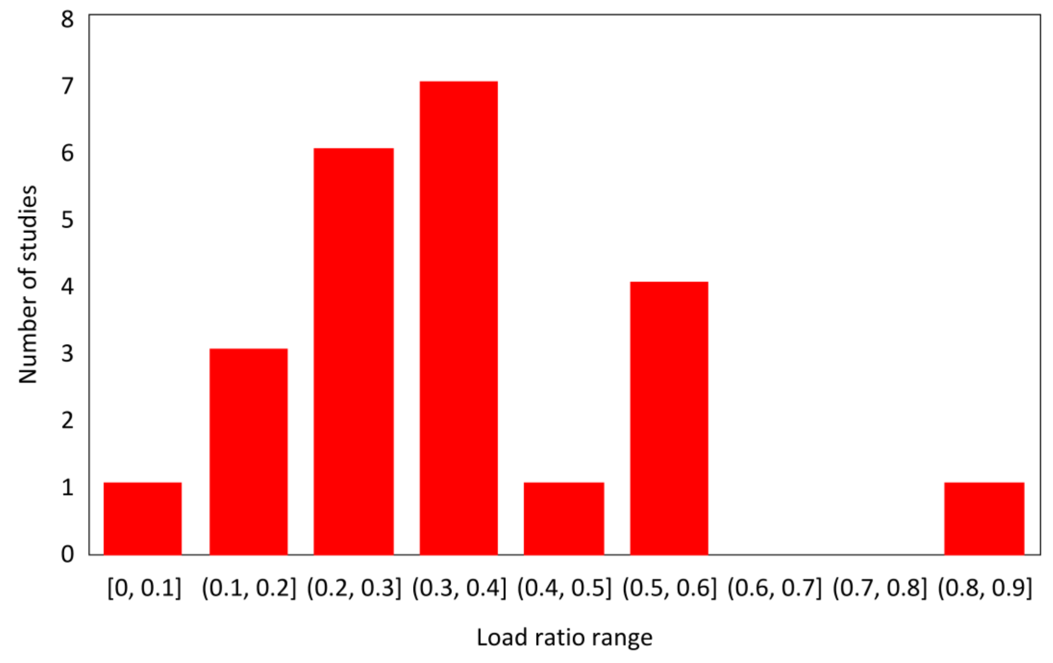


Figure 27. The number of studies reporting the applied load ratio to LSF walls.

The majority of experiments used a constant loading and applied transient heating to the LSF walls. Unlike most of the examined work, one of the studies did not use a constant load applied to the LSF wall. Instead, the researchers applied an increasing displacement of 0.01 mm/s until failure of the members [50]. The applied heating was constant during each experiment.

4.2.4.1 Parts of an LSF wall system affecting the structural capacity

As it can be expected, from a mechanical response, the structural performance of an LSF wall system is dependent on the constituent materials or products (when considering e.g., sheathing) of the system, and the way these are connected to form the system. Primarily, the applied loads are carried through the steel frame (tracks and studs of the system), as loads are transferred from the top track of the system to the studs and then the base track.

In some occasions where steel sheathing [59] and/or web-stiffened elements [4] are included in the LSF wall system, these act as reinforcement. Such elements effectively provide additional stiffness to the system, leading to a more robust LSF wall assembly. Studies that did not consider additional reinforcement have most commonly reported a lower load ratio (0.2 – 0.4), as indicated in the prior section. On the other hand, as the load ratio values are dependent on the expected structural capacity of the assembly in question, other studies had significant variations from such values, due to the fact that the tested assembly was more robust. A few notable cases are those where a steel sheet was used as a sheathing material [59], effectively providing some reinforcement to the system, and cases where hollow sections were used instead of channel sections [32], as hollow sections have a higher capacity for a similar footprint. In addition to these, web-stiffened steel studs demonstrated a higher load bearing capacity, compared to the most common C-channel (lipped) cross section of steel studs commonly reported in the literature.

4.2.4.2 Sheathing mechanical performance

It was identified that gypsum sheathing panels experience thermal expansion both in cases where axial load was applied or not [48], when exposed to elevated temperatures. Chen and co-workers interpreted this as an indication that the thermal expansion of gypsum plasterboards happens irrespective of any axial load applied to a wall system, in which the gypsum boards are components of.

4.2.5 Fire resistance of assembly

The three components of a fire resistance rating are: (1) loadbearing capacity (indicated with R); (2) integrity (indicated with E); and (3) insulation (indicated with I). When one of these criteria fails, this results in its quoted rating. For the system in question in this literature review, only R is required (and of interest to the study). This is due to the fact this literature review is investigating the exposure of both sides of the LSF wall; therefore, E and I are not properties the system can possess, as both sides are subjected to fire.

The resulting fire resistance of an LSF wall assembly is shown to present significant variations. As the current literature review investigates exposure of LSF walls on two sides, only values of R (stability) were considered as failure of the system. On the one hand, values of reported fire resistance (R) were are as low as 26 minutes [48]. On the other hand, in some cases, researchers reported values of fire resistance (R) of 240 minutes, as the LSF walls did not fail during testing, therefore were given the highest test value [45], [57].

4.2.5.1 Sheathing products

In the case of single-sided heating the sheathing boards are shown to be the primary barrier between the side of wall system exposed to fire and the side of the wall at ambient temperature. Failure of the sheathing board can rapidly affect the heat transfer through the wall, and lead to failure of the aforementioned three components of the fire resistance rating – all at once, or failure of each component at a different time. As it is the system that fails, not just the sheathing board, all other constituents of the LSF wall (e.g., the type of studs used, spacing, etc.) have a significant impact on the final reported numbers of fire resistance in literature.

It is observed that the highest fire resistance values are reported for non-combustible sheathing products of large thickness (e.g., autoclaved aerated concrete [57], brick veneer [45]). These are typically products that are expected to have an inherent high performance in fire resistance testing; this is due to these products being less susceptible to degradation, when exposed to heat.

Aside from more complex products discussed above, the most common sheathing product used in LSF wall systems is gypsum plasterboard. Potentially, the extensive use of the gypsum plasterboard in literature is due to its application in construction, as it is relatively light and a common product to sheath/encapsulate materials that require protection from exposure to heat (e.g., steel, timber). Depending on the number of layers and the performance criteria set to assess the LSF wall system's failure, a system using gypsum plasterboard could fail as early as 26 minutes of fire resistance testing (for high load ratios of 0.54 [48]) to as late as 235 minutes (for a load ratio of 0.2) [32].

Dias et al. [37] identified the influence of steel sheathing, used either inside the cavity or exposed on the outside of the LSF wall, for web-stiffened steel studs. At ambient temperature, the LSF walls with steel sheathing resulted in a higher structural performance when subject to axial compressive load, compared to: (a) LSF walls without steel sheathing and web-stiffened studs; or (b) LSF walls with lipped channel studs. However, at elevated temperatures, the steel sheathing had a limited contribution on the overall fire resistance of the system, as the fire rating was determined by the loadbearing capacity; the loadbearing capacity was approximately the same when comparing LSF walls with or without steel sheathing. Despite the fact the sheathing initially provided a time-lag to the heat wave propagation into the section, once the sheet buckled (and heat passed through the cracks formed on the GP and the steel sheet edge joints), it resulted in a more rapid temperature increase. The three systems tested achieved around the same fire resistance levels, with respect to their loadbearing capacity. In a separate study, which did not account for loads applied to the LSF walls, the steel-sheathed walls scored c. 16% higher on the insulation criterion (I), when one sheet was used (same values for internal or external use); and c. 41% higher on the insulation criterion (I), when two sheets (internal and external together) were used.

4.2.5.2 Wall cavity and insulation

Ariyanayagam and Mahendran [44] investigated the impact of using insulation materials in the cavity; the insulation material used was glass fibre. Out of the four tests run in total, two were loaded, with a load ratio of 0.2, and two were unloaded; in both sets (i.e., loaded and unloaded sets), one of the tests had an empty cavity, and the other one had glass fibre insulation in the cavity.

In the case of the unloaded tests, the failure criterion was insulation (I). The experiment that had an empty cavity failed, due to the average temperature passing the insulation threshold, at 94 minutes of fire resistance test time. The experiment that included glass fibre insulation in the cavity failed later in the fire resistance test, at 106 minutes of fire resistance test time. Therefore, it was shown that the time to reach the insulation failure criterion during fire resistance testing was increased when there was an insulation material in the cavity.

For the loaded tests, the failure criterion was loadbearing capacity (R). In this case, the specimen without an insulated cavity failed at 77 minutes. Contrary to the unloaded tests, for the loaded LSF wall, the wall assembly with an insulated cavity failed earlier, at 47 minutes. The hot flange of the steel presented a quicker temperature rise, leading to an earlier failure of the fire resistance test. It is speculated by the authors of this literature review that this is due to a decrease of heat losses from the steel to the air in the cavity (through convection) and the surrounding boards and other steel profiles (through radiation). This effectively meant that the steel studs heated up faster, therefore leading to decrease in stiffness and strength, and eventually failure. Similar observations were made by Chen et al., who investigated the influence of insulation in the cavity in two separate studies [48], [65].

Magarabooshanam et al. [63] performed full-scale fire tests of double-stud LSF walls and compared them to conventional single-stud LSF walls. Double-stud walls, according to the researchers, are used when higher acoustic insulation levels and load bearing capacities are desired. The study found that the presence of a wider cavity alone does not influence the delayed heat transfer mechanism. This was made evident through a comparison of failure under exposure to the standard fire resistance time-temperature curve.

The characteristics of the LSF walls tested were as follows:

- The cavity depths were a) 150 mm, for a single stud with a deep web; b) 92 mm, for a single stud with a shallow web; and c) 200 mm for the double stud, with studs of 90 mm webs.
- The steel thickness for the single-stud walls was the same for both the shallow and deep web studs, and equal to 1.15 mm; the steel thicknesses for the double-stud LSF walls were 0.95 mm and 0.75 mm.
- The load ratios used for comparison here are equal to 0.4.

The resulting times of failure for the above were a) 127 minutes for the single stud with a deep web; b) 162 minutes single stud with a shallow web; and c) 176 and 132 minutes for the double-stud walls.

The discontinuous stud arrangement in double-stud walls is the main contributor to the delayed heat transfer, as more material requires a larger amount of energy to propagate heat from the fire side to the ambient side. The fire-side studs showed higher heat losses in the larger cavity. The lateral deflections and the axial displacements of the double-stud walls were smaller compared to the single-stud walls, despite the fact these were provided with lateral support for both flanges. The fact that the studs were thinner in the double-stud experiments did not affect the heat transfer mechanism in double-stud walls.

4.2.6 Additional items

Chen et al. did a series of coupon specimen experiments [66]. In this experimental programme, the specimens were cut from the longitudinal direction of the flat parts of the web and the flange of the steel studs. The specimens were tested in tension and under different thermal exposure (both in heating and cooling); the thermal exposure was achieved through a high temperature furnace which enclosed the sample. The experimental programme resulted in yield strength, ultimate strength, and modulus of elasticity reduction factors for heating and cooling, compared to the ambient temperature values, for G550 steel. These are shown in Figure 28.

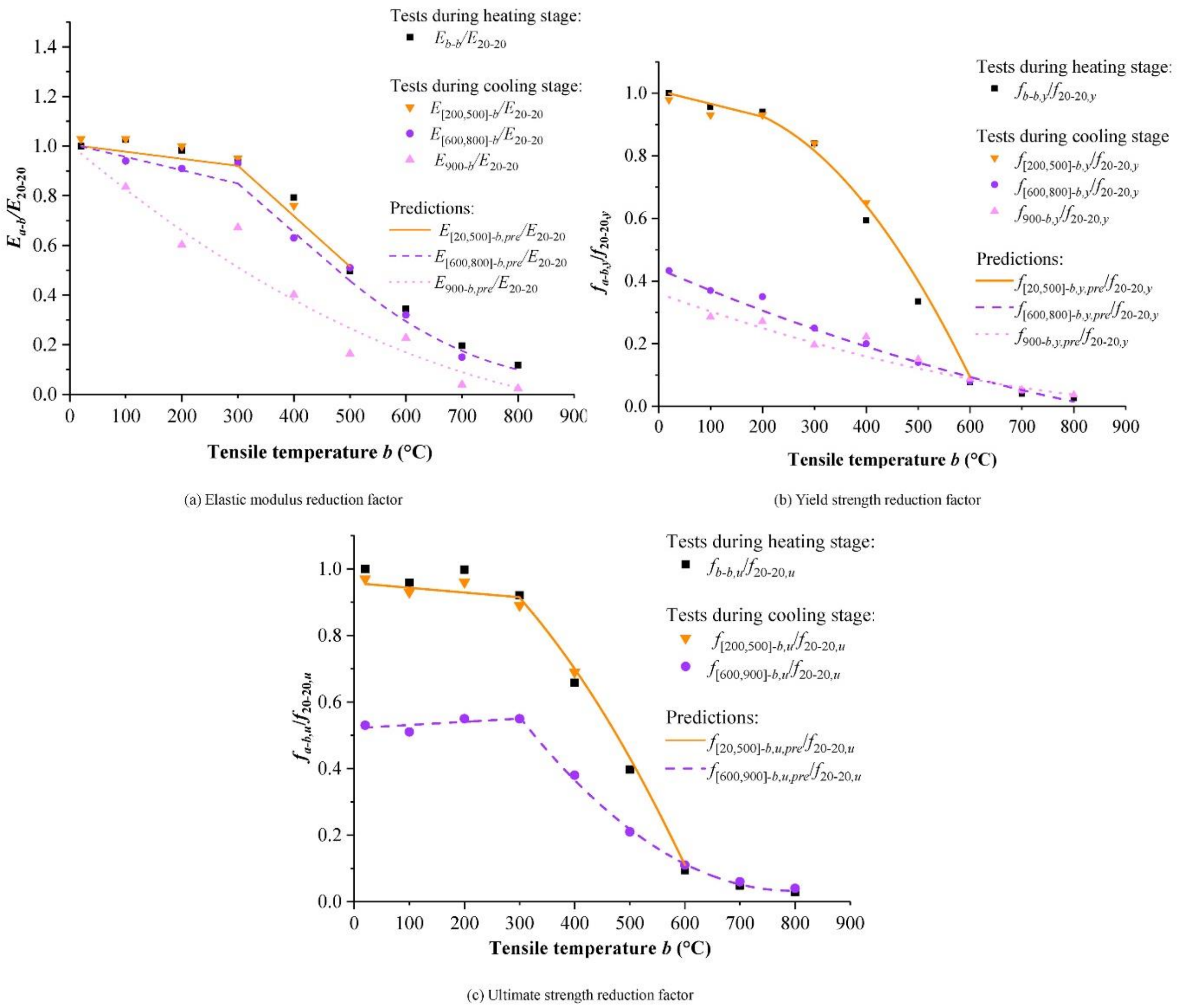


Figure 28. Predicted curves of the material property reduction factors for G550 CFS during heating and cooling stages (a) Elastic modulus; (b) Yield strength; (c) ultimate strength (modified from [66]).

Members of the same team also studied the exposure to different compartment fire curves of Q345 steel coupon specimens [67]. Like the aforementioned project, they released reduction factors for the yield and ultimate strength, and the modulus of elasticity of the tested steel.

A research team investigated the use of different sheathing boards to assess their insulation properties [49]. The different types of boards were made of gypsum plaster (GP), magnesium sulphate, fibre cement, vermiculux, and bio-based phase changing material (PCM). It was identified that the GP boards provided a higher insulation (in the sense of fire resistance testing) compared to the rest of the boards; it was also shown that a combination of the GP and bio-based PCM boards provided more consistent results and almost equal insulation rating to the wall systems that only used GP boards.

Magarabooshanam et al. ran a series of full scale tests exploring different cavity depths [43]. The LSF walls were supported on the furnace by applying a small load, effectively restricting them freely expanding; despite this low external load, these were considered unloaded samples, as the hydraulic rams were only restraining movement. They explored using a single and double layer of studs (single-stud and double-stud walls); additionally, they tested a staggered system of studs, which they were set in two layers, as shown in Figure 29.

The tested arrangements included:

- One plasterboard layer and single studs of:
  - 76 mm (failed at 69 minutes due to the insulation criterion, exceeding the maximum temperature);
  - 150 mm (failed at 84 minutes due to the insulation criterion, exceeding the maximum temperature);
  - 92 mm (failed at 95 minutes due to the insulation criterion, exceeding the average temperature);
- Two plasterboard layers:
  - Staggered-stud, with an effective cavity of 150 mm (failed at 190 minutes due to the loadbearing capacity, all studs buckled);
  - Double-stud, with an effective cavity of 90 mm (did not fail after 240 minutes); and
  - Single-stud, with an effective cavity of 92 mm (failed at 197 minutes due to the insulation criterion, exceeding the maximum temperature).

They demonstrated that a deeper cavity resulted in a lower distribution of temperatures within the cavity, and, in some cases, a higher fire resistance level (irrespective of the failure criterion used). Additionally, the discontinuity created in the double-stud cavity (due to a plasterboard subdividing the cavity) was more effective than the larger continuous cavity in the staggered stud assembly test. Furthermore, the lack of lateral restraint to both flanges of the staggered stud LSF wall arrangement led to higher lateral deflections compared to the double-stud LSF wall. This resulted in local (and global) buckling of the studs, and failure due to loss of loadbearing capacity, as the limiting rate of deflection was exceeded. Magarabooshanam et al. suspected this was due to the ambient-side plasterboards retaining their stiffness and effectively acting as a restraint to expansion of the whole LSF assembly, inducing a stress to the system. The studs, which were significantly softened and lacked bilateral restraint, failed in buckling [43].

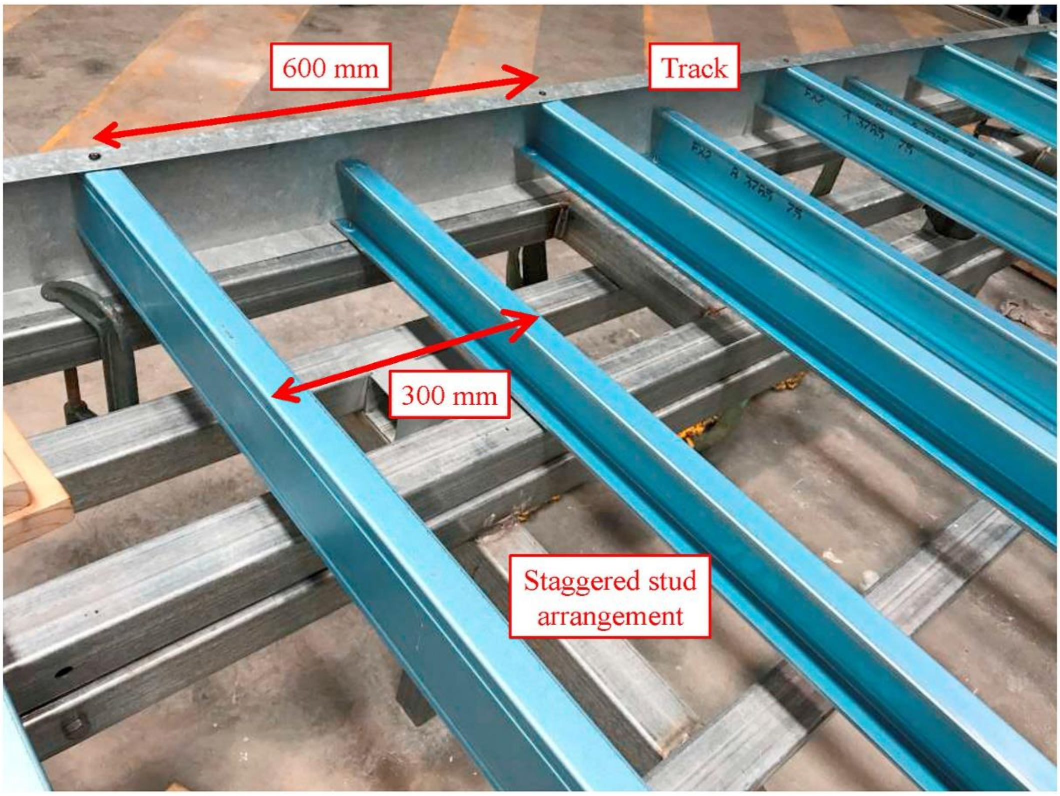


Figure 29. Staggered arrangement of studs in LSF wall (original from [43]).

4.3 Comparison and synthesis of the results

The previous sections have summarised the state-of-the-art of experimental studies for loadbearing, LSF wall systems when exposed to elevated temperatures. It is shown that:

- Research has focused extensively on single-sided exposure to fire. This indicates that researchers approach the use of the element as a separating element. Therefore, assuming that the element will only be exposed to fire from one side (as the assumption used in design is that a fire will be involving only one compartment);
- Insulation in the cavity can lead to earlier failure due to loss of loadbearing capacity of the LSF wall, as the temperature of the hot flange increased at a faster rate. The authors of the review are speculating this is due to lower heat losses of the hot flange, as the insulation eliminates convection and radiation losses;
- Steel sheet, when used as a sheathing material, can provide mechanical reinforcement to the LSF wall (increased loadbearing capacity of the LSF assembly) and also delay heat transfer to the hot flange. However, due to buckling of the steel sheathing and formation of openings, the loadbearing fire resistance was approximately the same;
- A larger cavity depth does not lead to increased fire resistance ratings, when R is examined. The discontinuity of the cavity of the double-stud LSF walls led smaller lateral deflections and the axial displacements, compared to a deeper single-stud LSF wall;
- Staggered arrangement of the studs (in a wider cavity arrangement) can lead to failure due to thermal expansion and loss of loadbearing capacity, as it was demonstrated through non-loadbearing LSF wall experiments. The lack of lateral support to both flanges has been shown to make that type of wall prone to buckling, even in non-loadbearing conditions.

In the recent CROSS-UK report [7], the fire engineer of the reported project took the view that when the LSF wall system is used for load-bearing purposes, and not as an element of the compartmentation line, two-sided exposure can sometimes be expected and should be examined.

In the examined literature for experimental studies, there is a single paper that considers heat exposure of LSF wall systems (in medium scale) from two sides [50]. For these reasons, and specifically accounting for the CROSS-UK report in question, further experimental investigation is warranted. A proposed experimental programme should aim to understand the structural behaviour of the LSF wall system and investigate the differences between heat exposure of the system from one side only and both sides simultaneously. This will build up on the previous knowledge for exposure on one side only and aid to observations of differences in structural behaviour, when the system’s thermal boundary conditions change.

5 Numerical Modelling of LSF Wall Systems

One of the main aims of this systematic literature review is to identify how previous studies have used numerical methods (finite element method) to assess the performance of LSF walls exposed to fire on both sides.

This section presents a summary of studies on the numerical modelling of LSF walls in fire and implications for modelling the fire performance of LSF walls exposed to fire on two sides. Where the studies do not address double sided fire exposure, the existing studies are reviewed to explore how the literature can be adapted and form a basis for the definition of finite element modelling parameters and conditions necessary for capturing the effects of fire exposure on two sides. How different factors affect the performance of LSF walls exposed to fire are also reviewed to support future parametric studies. A total of 67 studies (numerical studies only – 47, both experimental and numerical studies – 20) were reviewed for this as shown in Figure 5.

The review of existing numerical studies presented in this section are discussed under the following subsections: overview of finite element modelling approach used in existing studies (Section 5.1), key parameters used in finite element modelling studies of LSF walls in fire (Section 5.2), finite element modelling of LSF walls (Section 5.3), and factors that influence the performance of LSF walls in fire (Section 5.4).

5.1 Overview of finite element modelling approach used in existing studies

The advanced calculation methods in Eurocode 3 [68] can be used to design steel structures for fire safety. However, the LSF walls are typically composite structures made up of cold-formed steel studs and different types of sheathing and insulation materials. Large-scale fire testing is expensive, so validated numerical models are often used to predict the performance of LSF walls in fire, typically under standard fire conditions. Once the time–temperature profiles of the studs are known, non-linear transient or steady-state structural finite element (FE) analysis is used to predict their failure times [4]. So, when designing the structural fire resistance of LSF panels, an FE model for a similar LSF panel that has been tested in a full-scale test has to be developed and validated to predict the performance and fire resistance level of the specific LSF panel with different parametric values [69]. As a result, several studies have focussed on developing FE models to study the influence of different parameters on the fire performance of LSF walls in fire.

According to Abeysiriwardena and Mahendran [4] finite element models are solved through either transient or steady-state coupled temperature-displacement analysis. In transient analysis, a pre-determined load is applied at the start and held constant while the non-uniform temperature distribution is raised until the failure of the stud. On the other hand, in steady-state analysis, the non-uniform temperature distribution is kept constant while the load is gradually increased until the stud fails. Studies have revealed that both methods yield comparable fire resistance outcome (i.e., for transient state, the time (and corresponding temperature) to failure for a given load ratio is comparable to the steady state temperature (and corresponding time) that will cause failure when the steady state reaches the same load ratio). However, transient analysis closely simulates fire testing and provides additional valuable data such as the temporal variation of lateral displacement.

Peiris and Mahendran [70] identified the key modelling parameters used in the structural FE modelling of LSF walls in fire to include finite element type, model size / mesh size, mechanical properties of LSF wall components, consideration for geometric imperfections, residual stress and analysis type (i.e., steady state or transient state or both). The key modelling parameters used in the selected studies are discussed in Section 5.2.

5.2 Summary of key parameters used in finite element modelling studies of LSF walls in fire

A summary of modelling parameters used in existing finite element modelling studies of LSF walls in fire in the last decade (2013 – 2023), covering a total number of 22 of the selected studies are shown in Table 4. The table summarises the exposure conditions (fire type and number of sides of the LSF wall exposed to fire), material types, loading condition, load ratio, FEM software used, a summary of the FE model and how the FE was validated.

From the literature reviewed as shown in Table 4, it was observed that only one of the existing studies (a 2019 conference paper by Ariyanayagam and Mahendran [71]) considered cases of the LSF wall exposed to fire on two sides. However, conclusions from the other studies on one-sided exposure can be used to inform future finite element modelling studies and what parameters can potentially influence the behaviour of LSF walls when exposed to fire on two sides.

Regarding the insulation material used in LSF walls, the review shows that many studies include cases where there was no insulation material provided in the LSF wall (see Figure 30). Among the studies where insulation was used, glass fibre, rock wool, rock fibre and cellulose fibre were the most common types. This includes studies where only one insulation material was considered and studies where multiple insulation materials were considered, and their relative performance compared. This suggests that a variety of insulation materials are being studied.

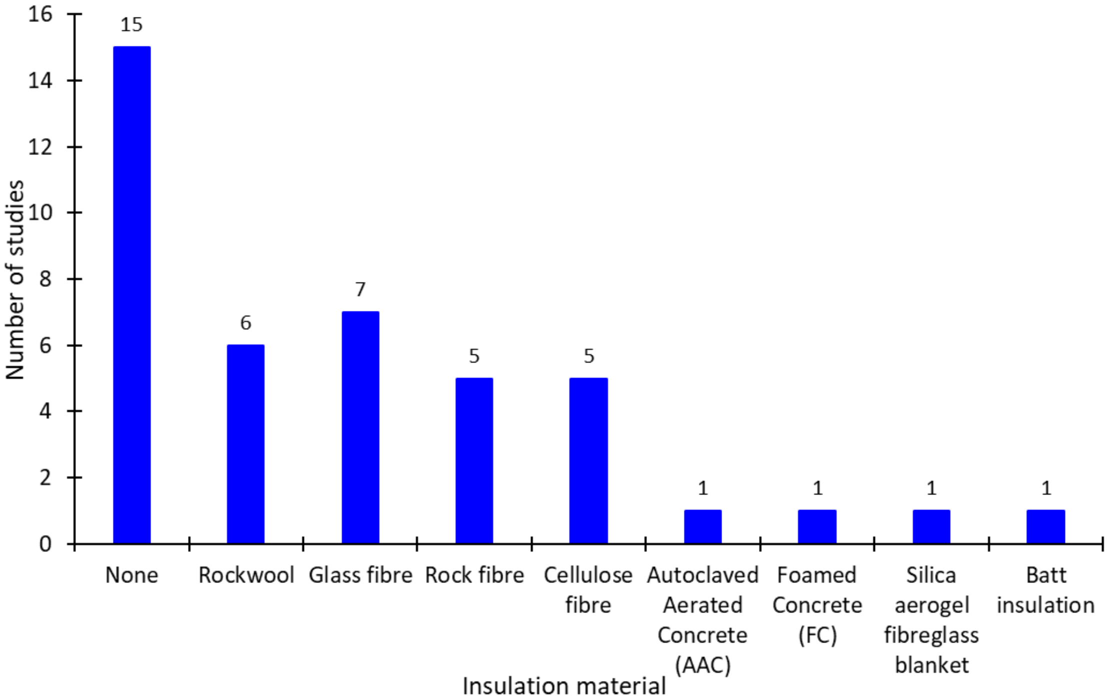


Figure 30. Distribution of Insulation material used in the different studies.

From the review, 22 studies (81%) considered the standard fire condition as shown in Figure 31. In contrast, only 5 studies (19%) considered a natural (parametric) fire as the fire condition. This suggests that most of the research on the behaviour of LSF walls in fire has been conducted using the standard fire rather than a realistic fire model. This could be because a standard fire is easier to reproduce and compare across different studies and existing test data, while a realistic fire requires more input parameters and may not be directly comparable to other studies.

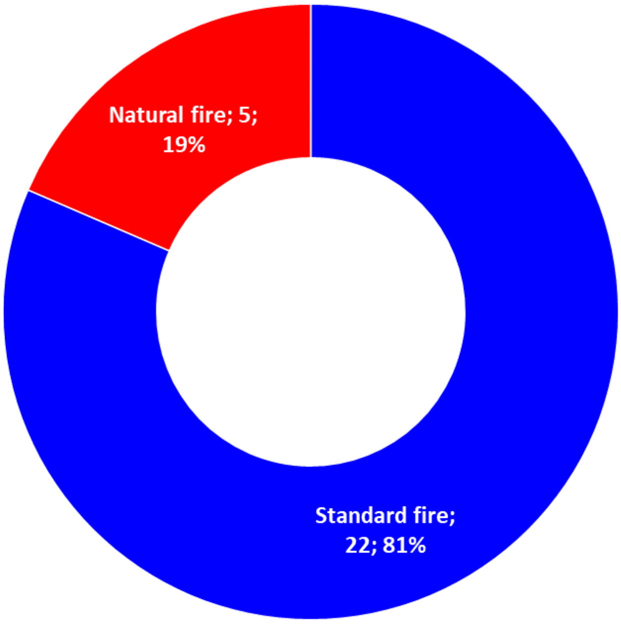


Figure 31. Distribution of fire model used in different studies.

Out of the 22 studies reviewed in Table 4, 19 studies used gypsum as the sheathing material. Only one study used functionally graded material (FGM) as the plasterboard material (see Figure 32). This suggests that gypsum is the predominant sheathing material. Two of the studies, did not include the sheathing material, only the LSF wall studs were modelled.

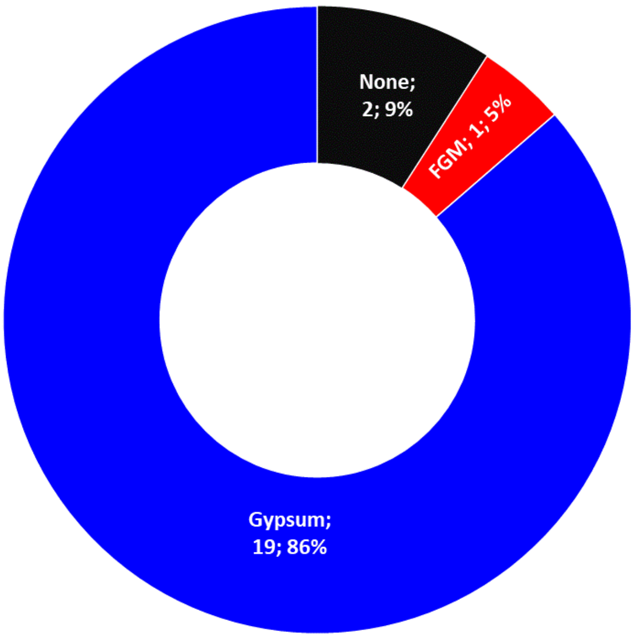


Figure 32. Distribution of plasterboard material used in different studies.

Figure 33 shows that lipped C section is the most used stud section profile type in the studies of LSF walls (used in 16 of the 22 studies). SHS, RHS, and sigma sections were used in 3, 2, and 2 studies, respectively. Hollow flange channel (HFC), channel (C) section, and hat-shaped section were each used in one study.

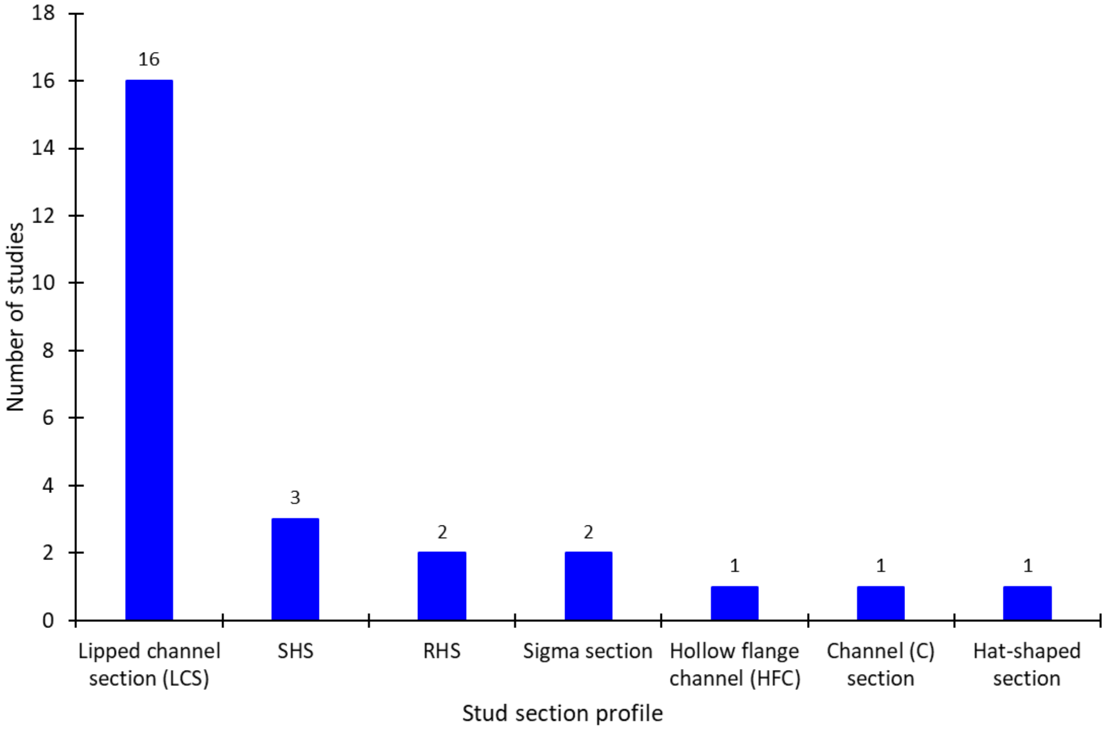


Figure 33. Distribution of LSF wall stud section profile type used in different studies.

Figure 34 shows that the software used in most of the studies was ABAQUS, with SAFIR and ANSYS also used in the literature.

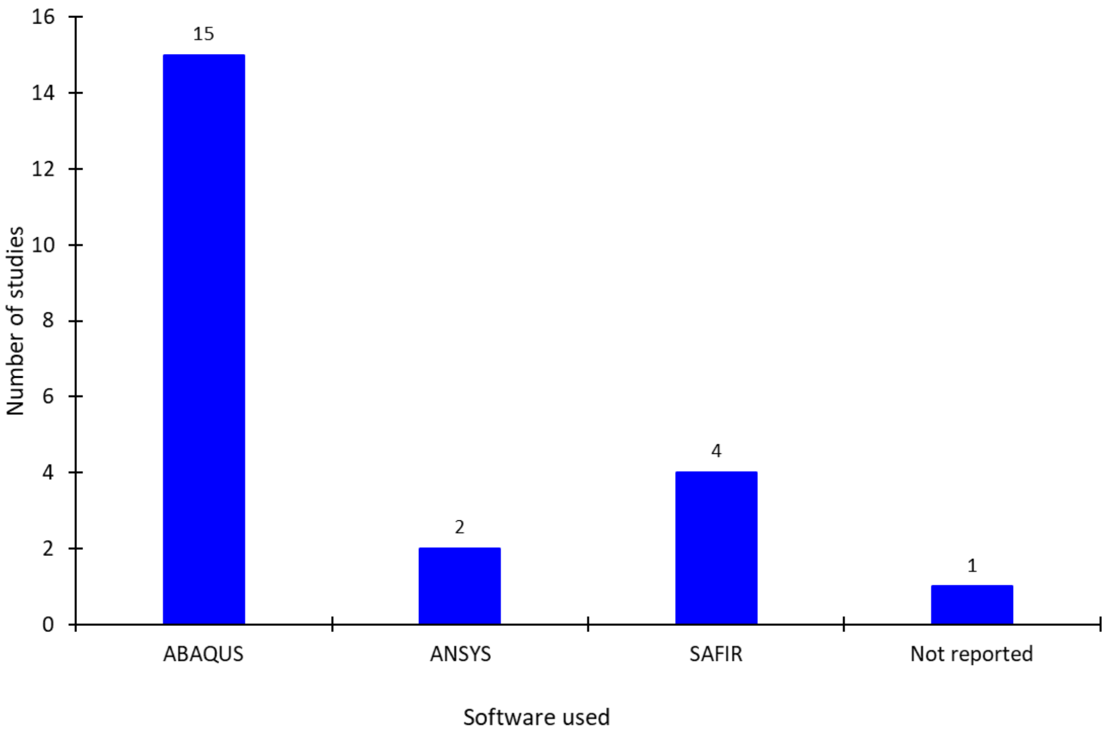


Figure 34. Distribution of finite element software used in different studies.

In most of the studies reviewed in Table 4, the loading condition considered was axial load. Only one study considered combined axial and lateral loads condition [70]. The load ratio used in the studies vary widely from 0.1 to 1.0, with most in the range of 0.2 – 0.6.

The FE models in the literature used 2D or 3D thermal analysis to investigate the cross-section and incorporated tie constraints, surface-to-surface tie constraints, and general contact to prevent mutual penetration of components. In almost all the studies, the residual stresses in the studs were ignored or details on how it was accounted for were not mentioned. FE validation was carried out by comparison with full-scale fire test results, furnace tests, and thermal validation against reduced scale specimens and thermo-mechanical validations against full-scale specimens.

Table 4. Summary of key parameters of existing FE studies on LSF walls in fire.

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Ariyanayagam and Mahendran [71]	Two sides	CFS / G550	Lipped C section	None	Gypsum	Axial load	0.2 – 0.7	Standard fire	ABAQUS	• Plasterboard and stud temperatures in LSF walls were obtained using thermal finite element (FE) analyses. • 8-node linear heat transfer brick elements (DC3D8) were used for modelling LSF walls in the thermal model. Heat transfer modes, including conduction, convection, and radiation, were considered through appropriate boundary conditions and material property values. • Transient heat transfer analysis was performed using a standard fire curve as amplitude, assigned to the fire-exposed surface of the plasterboard. For the initially unexposed surface, the standard fire curve was applied with a time lag of 15 and 30 minutes. • Shell element type S4R with a 4 mm x 4 mm mesh size was used for modelling the stud in the structural model. • Transient state FE analyses were carried out, subjecting the stud to a predetermined axial compression load and increasing stud temperatures until failure.	-
Peiris and Mahendran [70]	One side	CFS	Lipped C section	None	Gypsum	Combined axial and lateral loads	Axial: 0.2-0.4 Lateral: (0.24 – 0.72)	Standard fire	ABAQUS	• The plasterboard and stud were modelled using Diffusion Continuum 3D 8-node linear heat transfer solid brick elements (DC3D8). • A 4-node thermally coupled temperature-displacement shell element was utilized for the structural finite element (FE) model. • The model incorporated material and geometric non-linearities, contact interactions, idealized in-plane restraints, and explicit modelling of gypsum plasterboard sheathing.	Comparison with full-scale fire test results
Xing et al. [59]	One side	Q235	Hat-shaped section	Batt insulation	-	Axial load	0.3 – 0.7	Standard fire	ABAQUS	• CFS simulated using the DS4 shell element. • The "Beam" connector was used to model the properties of the fasteners because no slippage or cracking of screws was observed during the test. • The end studs were connected to the hold-downs using surface-to-surface tie constraints because there was no separation during the test. • General contact was adopted in the model to prevent mutual penetration of the components.	Comparison with furnace test

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Abeysiriwardena and Mahendran [4]	One side	CFS	Lipped C section	None	Gypsum	Axial load	0.4	Standard fire	ABAQUS	• The model was developed using 8 node linear heat transfer brick elements (DC3D8). • The model included the simulation of heat transfer through solid surfaces in contact. • Tie constraints were used to simulate the heat transfer.	Comparison with full-scale fire test results
Ni et al. [72]	One side	CFS / G500	Lipped C section	Rock fibre; glass fibre; cellulose fibre	Gypsum	Axial load	0.2 – 0.4	Standard fire	SAFIR	• A 2D thermal analysis was carried out to investigate the cross-section. • Solid conductive elements were used for the analysis. • The specific heat of the gas inside the cavity was not taken into account. The gas in the cavity was assumed to be transparent.	Comparison with furnace test
Perera et al. [10]	One side	CFS / G500; G550	C section	Rockwool; none	Gypsum	Axial load	0.2 – 0.8	Standard fire	ABAQUS	• The LSF wall was modelled using 'DC3D8' heat transfer brick elements. • The thermal behaviour of gypsum plasterboard was simulated using apparent thermal properties. • Two steps were defined in the program to conduct heat transfer analysis on the FEM: steady state and heat transfer step.	Comparison with full-scale fire test results
Perera et al. [73]	One side	CFS	RHS	None	Gypsum	Axial load	0.2 – 0.8	Standard fire	ABAQUS	• Meshing of all parts was done using structured hexahedron shaped, 8-node heat transfer brick elements (DC3D8). • To enable conduction mode heat transfer from one element to the next inside the same part, heat transfer brick finite elements were assigned. • Tie constraints were used between adjacent parts in contact to enable conduction mode heat transfer. • Convection and radiation mode interactions were introduced between the fire exposed surface and the unexposed side surface. • HT inside the cavity surfaces was simulated by defining closed cavity radiation interactions with 0.9 emissivity.	Comparison with full-scale fire test results

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Piloto et al. [11]	One side	S280; C350	SHS section	Rockwool; none	Gypsum	Axial load	0.2 – 0.8	Standard fire	-	• The FEM models are based on multi-layer shell finite elements and solid finite elements that use linear interpolation and full Gauss integration methods. • The thermal analysis is decoupled from the structural analysis for the calculation of fire resistance. • The model is partially restrained with respect to all displacement directions in the single fixed surface, and in-plane restraints in the horizontal direction due to the screw connections between the LSF elements and between the protection layers. Out of plane direction is not restrained. • Screws are not included in the thermal model.	Thermal validation against reduced scale specimens and Thermo-mechanical validations against full-scale specimens
Samiee et al. [74]	One side	CFS	Lipped C section; sigma profiles	None	Gypsum	Axial load	0.2-0.9	Standard fire	ABAQUS	• Surface-to-surface tie constraints were incorporated between contact pairs to allow for heat transfer through conduction in thermal analysis. In heat transfer analysis, a temperature boundary condition was established. • To minimize the time and space requirements of the analysis, only a quarter of the wall height was modelled in thermal analysis.	Comparison with full-scale fire test results
Upasiri et al. [75]	One side	CFS	Lipped C section	Rockwool; Autoclaved Aerated Concrete (AAC); Foamed Concrete; (FC); none	Gypsum	Axial load	0.2-0.6	Standard fire; EC parametric fire	ABAQUS	• 3D and 2D heat transfer FEMs were developed. The LSF wall model was created by assembling plasterboard, LCS, and insulation parts separately. • Fire load was assigned as a time-temperature amplitude boundary condition on the exposed surface of the LSF wall. • Heat loss due to convection and radiation was incorporated using interactions surface film coefficient and surface radiation.	Comparison with full-scale fire test results
Ali et al. [22]	One side	CFS	Lipped C section	None	Functionally graded material (FGM)	Axial load	0.1 – 1.0	Standard fire	ABAQUS	• A finite element model was developed for an FGM wall using heat transfer shell elements. The components of the wall were connected using fasteners and modelled as rigid beams. • A sequentially coupled thermal-stress analysis was performed by solving the pure heat transfer problem first and then reading the temperature solution into a stress analysis. • The sheathing boards used in the wall system were not included in the FE model but their effects were considered in terms of additional boundary conditions and actual temperature distribution on the stud.	-

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Samiee et al. [76]	One side	CFS / G500	Lipped C section	None	Not modelled	Axial load	0.3-0.7	Standard fire	ABAQUS	• Numerical analysis of the wall under fire conditions was done in steady and transient states. • In the steady state, non-uniform temperature distribution in the steel section was kept constant and then load was applied to the structure until failure. • In the transient state, the load was first applied to the structure at a certain ratio and then non-uniform temperature distribution was applied to the steel section until wall failure. • Solid-to-solid tie constraints were assigned to contact pairs for heat transfer through conduction in thermal analysis. • Plasterboard restrains were simulated by restraining appropriate translational displacement at both flanges.	Comparison with full-scale fire test results
Tao and Mahendran [53]	One side	CFS / C450	SHS	Silica aerogel fibreglass blanket; none	Gypsum	Axial load	0.4	Standard fire	ANSYS	• 3D transient thermal models were developed and validated to simulate heat transfer in tested wall specimens. • Multi-step transient analysis and element birth/death method were used to model plasterboard fall-off. • The plasterboard fall-off criterion was based on an average critical temperature at the unexposed board surface.	Comparison with small-scale and full-scale fire test results
Tao et al. [77]	One side	CFS/ C350; C450	SHS; RHS	None; Glass fibre insulation	Gypsum	Axial load	0.2 – 0.4	Standard fire	ANSYS	• Shell elements are to model CFS studs. • 3D solid elements were utilized to model plasterboards and insulation materials in fire, and the mesh size was varied for these wall components to reflect their interaction with steel studs. • The nodal movement at plasterboard-stud connections were restricted in the FE model to provide adequate lateral restraint. • An idealized residual stress distribution for the SHS/RHS was used to calculate membrane residual stress.	Comparison with full-scale fire test results

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Perera et al. [69]	One side	CFS/ G500	Lipped C section	Glass fibre; rock fibre; cellulose fibre; none	Gypsum	Axial load	0.4, 0.6, 0.8	Standard fire	ABAQUS	• The LSF wall components were modelled as DC3D8 solid elements, and 8-node linear heat transfer brick elements were used for mesh creation. • Tie constraints were applied to contacting surfaces to enable perfect conduction heat transfer between instances. • Two steps were used for heat transfer FEA. The initial step applied ambient temperature to the model. The heat transfer step applied the standard fire curve and interactions as a transient step.	Comparison with full-scale fire test results
Ariyanayagam and Mahendran [78]	One side	CFS	Lipped C section	Glass fibre	Gypsum	Axial load	0.2 – 1.0	Standard fire	ABAQUS	• The study utilized sequentially coupled thermal and structural FE modelling on wall panels. • The thermal FE analysis was conducted first to obtain the plasterboard and stud time-temperature curves. • The obtained time-temperature curves were then used as input in the structural FE analysis. • The wall was modelled using a DC3D8 type element, which is a diffusion continuum three-dimensional eight node brick element.	Comparison with full-scale fire test results
Dias et al. [79]	One side	CFS	Lipped C section; Hollow flange channel (HFC); web-stiffened channel section (SCS) or sigma	Rockwool	Gypsum	Axial load	0.2 – 0.7	Standard fire	ABAQUS	• A sequentially coupled 3-D analysis was conducted to study the thermal and structural behaviour of a wall. • DC3D8, a 3-D eight-node linear heat transfer brick element with one degree of freedom per node, was used to model steel studs, plasterboards, and insulation materials in the thermal analyses. • Surface-to-surface tie constraints were used to allow for solid-to-solid heat transfer between contact pairs. • The plasterboards were not explicitly modelled, but the effect of screws was simulated as translational restraints. • S4R, a general-purpose four-node quadrilateral conventional shell element with linear interpolation and reduced integration, was used to model the plasterboard and the insulation materials in the structural analysis.	Comparison with full-scale fire test results

Ref	Number of sides of LSF wall exposed to fire	Stud material type / grade	Stud section profile type	Insulation material	Sheathing material	Loading condition	Axial Load ratio	Fire condition	Software	FE model (key modelling details)	FE validation
Ariyanayagam et al. [80]	One side	CFS	Lipped C section	Rock fibre	Gypsum	Axial load	0.2, 0.4	Standard fire; EC parametric fire	SAFIR	• 2D analysis with triangular or quadrilateral solid elements. • Conduction is used to model heat transfer within a body of elements. • Convection and radiation transfer modes are used to model heat transfer from boundary elements. • Three voids were created in the numerical model. • Radiation and convection were used to define heat transfer in the voids between the boundaries.	Comparison with full-scale fire test results
Rusthi et al. [81]	One side	CFS	Lipped C section	Glass fibre; rock fibre; cellulose fibre; none	Gypsum	Axial load	0.2, 0.6	Standard fire	ABAQUS	• A 3D finite element analysis (FEA) was conducted for LSF wall components. • Heat transfer solid elements (DC3D8) were used to model the components, and tie constraints were used to ensure heat transfer between them. • The models without interior cavity insulation materials were created using closed cavity radiation in enclosures.	Comparison with full-scale fire test results
Ariyanayagam and Mahendran [82]	One side	CFS / G500	Lipped C section	Rock fibre; none	Gypsum	Axial load	0.2, 0.4	Standard fire; EC parametric fire	ABAQUS	• Both steady and transient conditions were conducted. • The transient state method involved applying the axial compression load to the stud and then increasing the stud temperatures every minute until failure. • In the steady state method, the axial compression load was applied to the stud after the stud temperatures were increased to the required levels. • Shell element type S4R was used to model the LSF wall stud, while rigid body element R3D4 was used to model the rigid end plates.	Comparison with full-scale fire test results
Keerthan and Mahendran [83]	One side	CFS / G500	Lipped C section	Glass fibre; rockwool; cellulose fibre, none	Gypsum	Axial load	0.4	Standard fire; EC parametric fire	SAFIR	-	Comparison with full-scale fire test results
Keerthan and Mahendran [84]	One side	CFS / G500	Lipped C section	Glass fibre; rockwool; cellulose fibre, none	Gypsum	Axial load	0.4	Standard fire; EC parametric fire	SAFIR	-	Comparison with full-scale fire test results

5.3 Finite element modelling of LSF walls in fire

This section summarises the modelling details and how the different factors that affect the performance of LSF walls in fire were captured in the FE models of the selected studies.

5.3.1 Modelling idealisations

Three numerical modelling idealisations have been considered in the literature to evaluate the fire performance of LSF walls under fire conditions. The three numerical idealisations are as follows [74], [77]:

i. "Single-stud" model, only the critical stud selected from the wall frame is modelled. The plasterboard restraint is simulated by restraining the translational displacement of the hot and cold flange in screw location (Figure 35(a)).

ii. "Steel frame with lateral restraint" model consists of a group of studs and the wall panel tracks connected by screws. In this model, like the single stud model, the effect of plasterboard restraint is considered as a lateral restraint on the two flanges of the stud at screw location (Figure 35(b)).

iii. "Complete wall" model consists of the steel frame and sheathings and any insulation material. In this model, all wall components are considered. The sheathings are attached to the steel frames with screws like the experimental details (Figure 35(c)).

According to Samiee et al. [74], the purpose of examining three types of modelling methods is to better understand the behaviour of walls under fire conditions and to identify which model gives the most accurate behaviour when compared to experimental results. In their study, it was reported that the comparison provides insights into the failure mechanisms of walls under fire conditions and aid in the development of more reliable models for predicting their performance.

According to the study conducted by Tao et al. [77], the comparison of the sheathed and single-stud FE models revealed that they produced similar results in terms of fire resistance levels (FRL) and lateral and axial displacement versus time plots. Therefore, it was recommended to use the simplified stud model to predict the FRL of cold-formed steel SHS/RHS stud walls in a fire as it is both adequate and efficient. Furthermore, the study showed that the simplified stud model has the potential to predict the load-bearing capacity of walls made of steel studs that are subject to local buckling failure. However, when steel studs are subject to major axis global buckling failure, the simplified model does not accurately estimate the wall capacity as it fails to consider the out-of-plane restraint. In this case, it was recommended to use the sheathed stud model, which includes explicit modelling of the sheathing material.

In another study by Peiris and Mahendran [70], an improved structural finite element (FE) model for steel stud walls was used because the conventional stud-only model available was found to be limited as it does not account for the bending stiffness provided by sheathing and was not capable of accurately predicting the FRLs of LSF walls subjected to combined axial compression and lateral loads. This was done by extending the stud-only model to incorporate sheathing. The improved model included material and geometrical nonlinearities, contact interactions, and idealised in-plane restraints. The hot and cold flange temperatures obtained from the fire tests were used as temperature boundary conditions to the stud. The improved single-stud model was validated by comparing its results with FRLs, failure modes, load versus axial shortening, and lateral deflection curves obtained from full-scale fire tests. The results of the improved model showed good agreement with the test results.

The above studies suggest that the boundary and loading conditions of the LSF wall, as well as the output parameter required, influences what model idealisation might be best in representing the experimental condition.

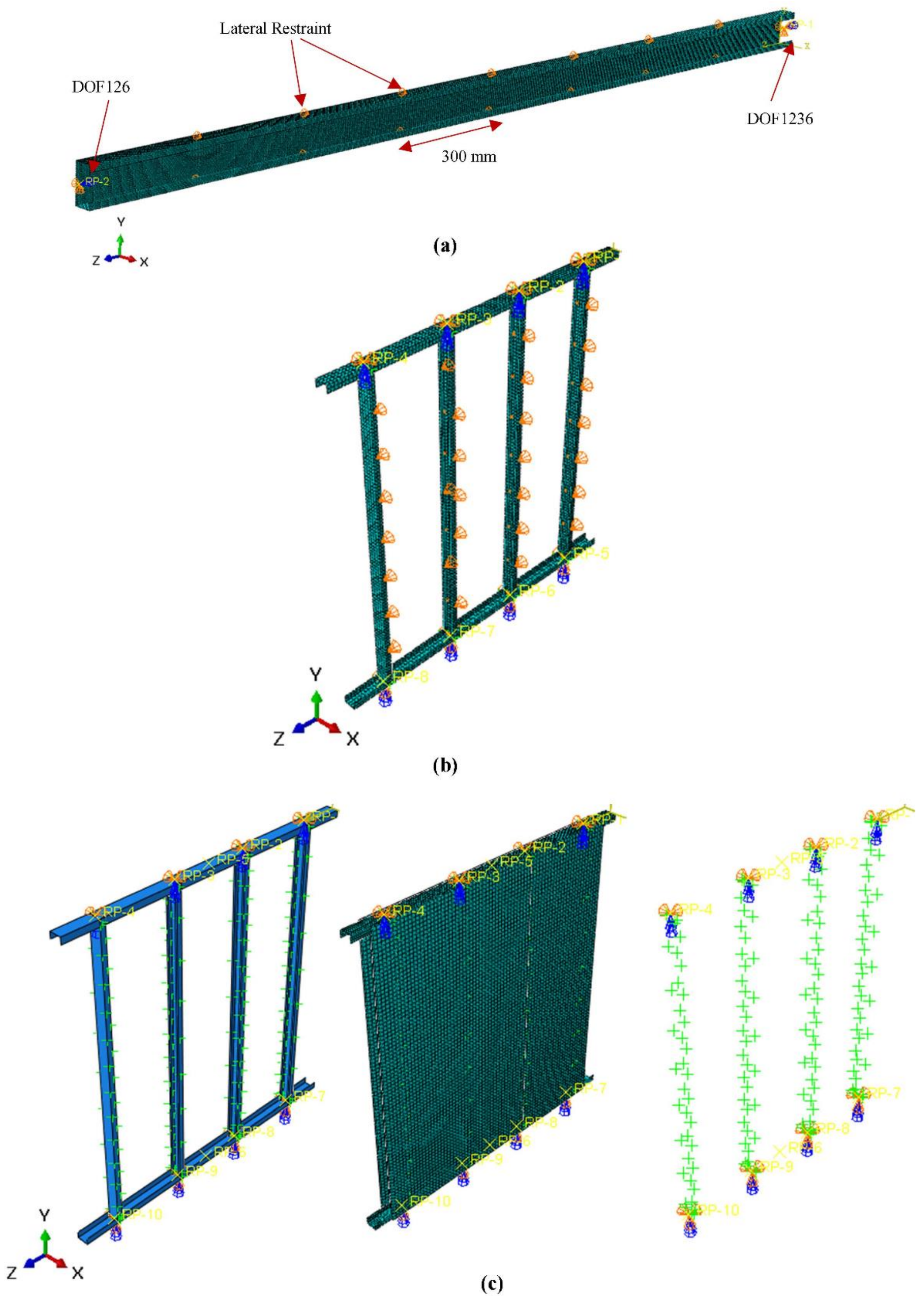


Figure 35. FE structural model of wall (a) single stud (b) steel frame with lateral restraint (c) complete wall (Original figure from [74]).

5.3.2 Modelling technique and analysis type

Two types of modelling techniques are typically used in the literature. These are fully coupled (or directly coupled) thermal and structural FE modelling and sequentially coupled thermal and structural FE modelling. In fully coupled or directly coupled FE modelling, both thermal and structural analyses are conducted at the same time, while sequentially coupled FE analysis is based on a two-step approach. In sequentially coupled FE modelling, thermal analysis is conducted first, assuming that the structural behaviour of the wall does not affect the thermal behaviour. The time-temperature curves obtained from the thermal analysis are then used as input to the structural FE model to obtain the stud failure times. Both fully coupled and sequentially coupled approaches have advantages and limitations [78]. According to Perera et al. [73], fully coupled thermal and structural FE modelling offers advantages such as simulation of exact experimental conditions including any two-way interaction between thermal and mechanical effects and capturing of transient effects. However, it has limitations including increased computational cost and increased complexity in modelling. On the other hand, sequentially coupled FE modelling offers advantages such as computational efficiency, simplified modelling, and flexibility in choosing the order of solving the thermal and mechanical problems. However, it has limitations including reduced accuracy and difficulty in capturing transient behaviour.

In most studies on LSF walls exposed to fire, the sequentially coupled FE model approach was used (e.g., [22], [78]). Ariyanayagam and Mahendran [78] conducted a sequential thermal and structural finite element (FE) modelling of LSF wall panels. The analysis involved a thermal FE analysis to obtain plasterboard and stud time-temperature curves, which were then used as input for the subsequent structural FE analysis. A sequentially coupled thermal-stress analysis that solved the pure heat transfer problem was employed before using the temperature solution as a predefined field for stress analysis. The temperature was allowed to vary with time and position but was not affected by the stress analysis solution, making it ideal for stress/displacement solution that relied solely on temperature field.

For any given modelling technique used, two analysis types are possible. These are: steady state and transient state analysis [70]. Steady state FE modelling involves modelling the steady state temperature distribution in a structure subjected to a constant heat source. Transient FE modelling, on the other hand, involves solving a dynamic problem, where the load or boundary conditions change with time. In the context of thermal analysis, this could include modelling the transient heating and cooling of a structure subjected to a fire. According to the review conducted by Peiris and Mahendran [70], studies on the performance of LSF walls in fire use both or only the transient state analysis type.

On dimensionality of the model, according to Rusthi et al. [81], while simplified FE analysis for studying the fire performance of LSF wall systems using 1-D and 2-D uncoupled FE models have shown reasonable agreement with the full-scale fire test results, they are not suitable for simulating non-uniform time-temperature profiles across the LSF wall during a fire event due to factors such as noggings, service holes in studs, partially fire exposed LSF walls, and different boundary conditions. To address these limitations, Rusthi et al. [81] developed and validated a 3-D FE model. The developed FE thermal models were fully coupled to the structural modelling of the wall studs, providing an advantage over simplified FEA approaches. However, the limitation of 3-D FE models is that they can be computationally expensive.

On residual stress, many studies on the performance of LSF walls in fire do not consider residual stress. Chen and Ye [41] reported that the residual stress in cold-formed lipped channels can cause a reduction in stiffness and premature yielding. However, it has a minor impact on ultimate stress. Furthermore, as temperature increases, the effect of cold bending also decreases. Therefore, the effect of residual stress reduces with temperature and as such not considered in many studies of LSF walls in fire (e.g., [70], [79], [82], [85]–[87]).

5.3.3 Software used

Various finite element software programs including ABAQUS, ANSYS, and SAFIR are available for simulating heat transfer processes. Accurately calculating heat transfer processes using commercial finite element software can provide a basis for thermal-mechanical coupling simulation [41]. Table 4 and Figure 34 showed that ABAQUS is the most popular software.

According to Ali et al. [22], the heat transfer analysis in ABAQUS can be done using two methods: time-dependent and both time and space-dependent. In time-dependent analysis, the temperature varies with time across the cross-section, but remains uniform along the length of the longitudinal member. On the other hand, in both time and space-dependent analysis, the temperature varies both across and along the longitudinal member in time and location. In Ali et al. [22], only the temperature variation across the cross-section was considered, assuming a uniform temperature along the length of the member.

Despite the advanced computing tools and options available in the ABAQUS CAE package for FE analysis of LSF walls in fire, Perera et al. [69] reported that limitations exist such as modelling of plasterboard shrinkage behaviour and initiation of cracks. When exposed to fire, gypsum plasterboards undergo ablation resulting in a loss of mass and a reduction in cross-sectional dimensions. However, the thinning effect cannot be simulated using the ABAQUS software. This can result in an increase in heat transfer through the plasterboard via conduction. To account for this, the measured thermal properties have to be modified (to apparent thermal properties) to produce accurate heat transfer through the plasterboard.

From Table 4 and Figure 34, SAFIR is also commonly used to model LSF walls in fire. SAFIR can use various elements to accurately simulate material response and stress-strain behaviour. In SAFIR, the analysis is undertaken with triangular (3 node) or quadrilateral (4 node) elements. The heat transfer within a body of elements is modelled through conduction, whereas heat transfer from boundary elements is modelled with both convection and radiation transfer modes [80].

According to Keerthan and Mahendran [84], SAFIR also has some limitations in its ability to model gypsum plasterboard assemblies. SAFIR does not allow the user to eliminate any elements from the section to simulate ablation of plasterboard. Hence, like ABAQUS, the ablation process is taken into account through the use of suitable apparent thermal properties of plasterboard. Modelling moisture movement across the cavity is a complex problem. However, this is usually neglected as it only influences heat transfer across the cavity at low temperatures (below 120^{o}C) [80], [84].

5.3.4 Mesh Size

As reported in Tao and Mahendran [53], the use of shell elements is common for CFS studs as they provide better modelling convergence and efficiency than 3D solid elements. Typical mesh size of CFS studs and sheathing board in the literature are in the range of 4 mm to 10 mm. However, it was further reported that where display of temperature gradient along the thickness direction is required, 3D solid elements must be used to simulate sheathing and insulation materials. For these wall components, slightly larger mesh sizes are recommended to increase the modelling efficiency. However, mesh size in the thickness direction is usually finer because they control the heat transfer through the thickness of plasterboard and insulation [81], and typically range from 2 – 4 mm [69], [74], [79].

In many of the studies reviewed, the mesh size of elements used to model the LSF wall components vary from as low as 2 mm to as high as 25 mm (see [4], [22], [59], [74], [79], [80]).

5.3.5 Boundary conditions

In the studies reviewed, different approaches have been followed to assign the boundary conditions used in finite element modelling of LSF walls in fire. Abeysiriwardena and Mahendran [4] and Gunalan and Mahendran [85] both emphasized the importance of simulating the support provided by the sheathing board in the finite element models. They considered pinned-ended boundary conditions at the top and bottom of the studs, with the axial compression loading applied to the studs at the bottom of the wall panel, to replicate test conditions. Lateral restraints provided by plasterboard sheathing were modelled as point in-plane restraints at the screw locations. The same approach was adopted in [76].

Perera et al. [10] conducted a heat transfer analysis (HTA) by defining two steps in their finite element model (FEM): the steady state, where the model is at ambient temperature (20°C) with no heat transfer mechanisms, and a heat transfer step with defined boundary conditions and interactions. They adopted convection coefficients of 25 $W/m^2/K$ and 10 $W/m^2/K$ for fire and ambient sides of the wall, respectively, and an emissivity coefficient of 0.9 for all surfaces. They neglected convection mode heat transfer inside the cavities due to restricted air movement. Figure 36 shows the thermal boundary conditions assigned in the heat transfer model.

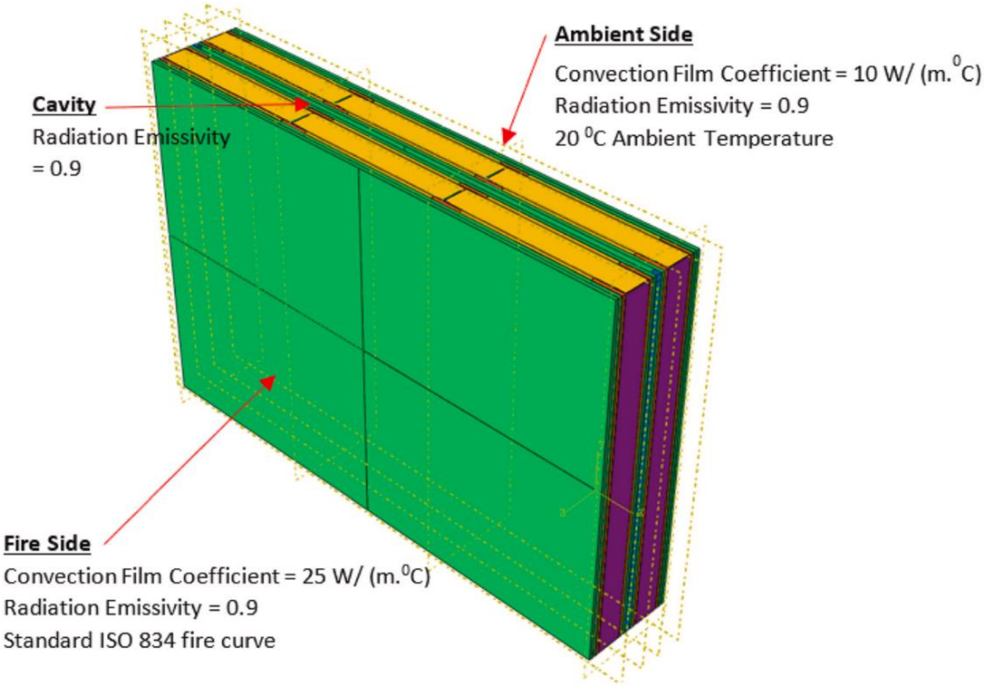


Figure 36. Boundary conditions assigned in the heat transfer model (original figure from [10]).

Piloto et al. [11] utilized a hybrid model to specify the temperature evolution inside the empty cavity region, assuming heat transfer by convection and radiation. Samiee et al. [74] also considered radiative heat flux using an emissivity factor of 0.9 for cavity, fire, and ambient sides of plasterboards, and convection with heat transfer coefficients equal to 25 and 10 $W/m^2/K$ for fire and ambient sides of the wall, respectively. They neglected convection inside the wall cavities due to restricted airflow.

In their structural analysis, Samiee et al. [74] applied pinned end conditions at both the top and bottom of the walls, with axial compression loads modelled as nodal concentrated forces. They assumed a non-uniform temperature distribution and used time–temperature profiles obtained from thermal analysis. Xing et al. [59] input air temperature obtained from the test into ABAQUS, defining convective heat transfer coefficients of 25 $W/m^2/K$ and 10 $W/m^2/K$ on fire-exposed and cold sides of the wall, respectively, with emissivity of 0.7 for both sides.

Ali et al. [22] defined conduction, convection, and radiation as the three major thermal boundary conditions used in their FEA. They assigned convective film coefficients of 25 and 10 $W/m^2/K$ on the fire and ambient sides, respectively, and emissivity values of 0.8 and 0.3 on fire and ambient sides, respectively.

In modelling boundary conditions for double-sided fire exposure, Ariyanayagam and Mahendran [71] assigned the standard fire condition to the fire exposed surface of the plasterboard, while the “ambient surface” (i.e., the initially unexposed surface) was assigned the standard fire conditions with two different time lag, 15 minutes and 30 minutes. The time lag was applied to simulate the time it takes for the fire to spread (though openings) from the compartment of fire origin to the adjoining compartment sharing the same wall. An emissivity of 0.9 was used for both faces of the LSF wall model. Section 5.4.1.1 reviews the influence of double-sided fire exposure on the fire performance of LSF walls.

In summary, the boundary conditions in the finite element modelling of LSF walls in fire involve simulating the support provided by plasterboards, considering pinned-ended conditions, axial compression loads, lateral restraints, and various thermal boundary conditions including conduction, convection, and radiation. The heat transfer coefficients and emissivity values used in the studies can be summarized as follows:

- Convection coefficients:
  - Fire side: 25 $W/m^2/K$
  - Ambient side: 10 $W/m^2/K$
- Emissivity coefficients:
  - Fire side: 0.7; 0.8; 0.9
  - Ambient side: 0.3; 0.7; 0.9

5.3.6 Temperature dependent properties of LSF wall components

The use of accurate thermal and mechanical properties is an important issue in numerical analysis [74]. Properties of the main components of LSF walls are discussed in the following subsections.

5.3.6.1 Steel

The temperature-dependent properties of steel play a crucial role in finite element modelling of LSF walls in fire conditions. Several studies have utilized Eurocode 3 (EN 1993-1-2:2005) [68] to obtain these properties for their models (e.g., [10], [59], [70], [72], [74]). The Poisson's ratio of cold-formed steel (CFS) is assumed to be 0.3 at room temperature and remains constant at elevated temperatures [59], [74]. The elastic modulus and yield strength of steel decrease with increasing temperature, with reduction coefficients determined by Eurocode 3 (EN 1993-1-2:2005). Furthermore, the thermal expansion, specific heat, and thermal conductivity of CFS are determined based on the formula recommended by Eurocode 3 (EN 1993-1-2:2005). The density of steel, as per Eurocode 3, is 7850 kg/m^3. Figure 37 shows typical curve of thermal and material properties at elevated temperatures.

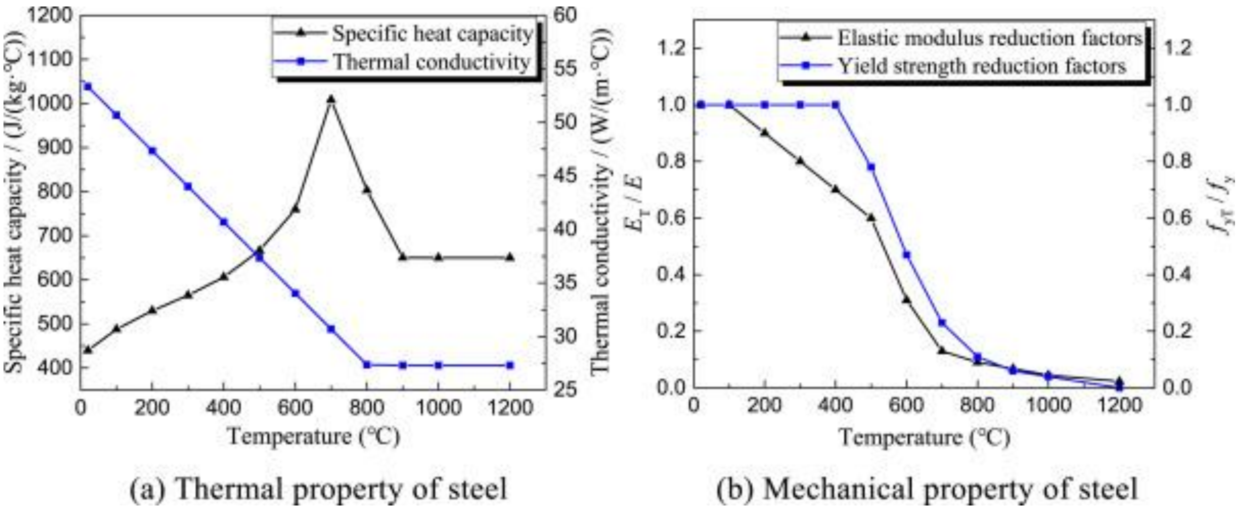


Figure 37. Relationships of steel material properties versus temperature (original figure from [59], [74]).

However, in some studies, these properties are derived from tests. Samiee et al. [74] in their work used the stress-strain curve and thermal coefficient of G500 steel with a thickness of 1.15 mm obtained from experimental test (see Figure 38). Two stress-strain models, namely elastic-perfect plastic and strain hardening models, were employed in finite element analysis. Due to the absence of a clear elastic region in the stress-strain curves of steel at elevated temperatures obtained from tensile coupon tests, the strain hardening model is utilized to simulate the behaviour of cold-formed steel. Samiee et al. [74] did not state the reason for using experimental results of stress-strain properties of steel instead of existing models defined in standards or other literature. There may be several reasons for this including where accurate properties for a specific material grade are required which differ from material grades the models in standards are applicable to.

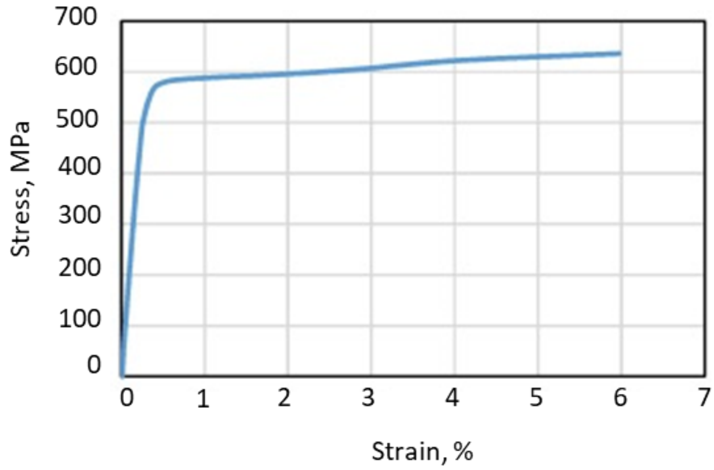


Figure 38. Stress-Strain curve of 1.15 mm G500 cold-formed steel from tensile coupon test (original figure from [74]).

5.3.6.2 Sheathing board

As shown in Table 4 and Figure 32, gypsum is the most common sheathing material used in LSF walls.

The temperature-dependent properties (thermal conductivity, density and specific heat capacity) of gypsum plasterboard in several finite element studies of LSF walls exposed to fire (e.g., [10], [70], [72], [74]) have been extracted from series of tests and FE validation programme by Keerthan and Mahendran [88] as shown in Figure 39.

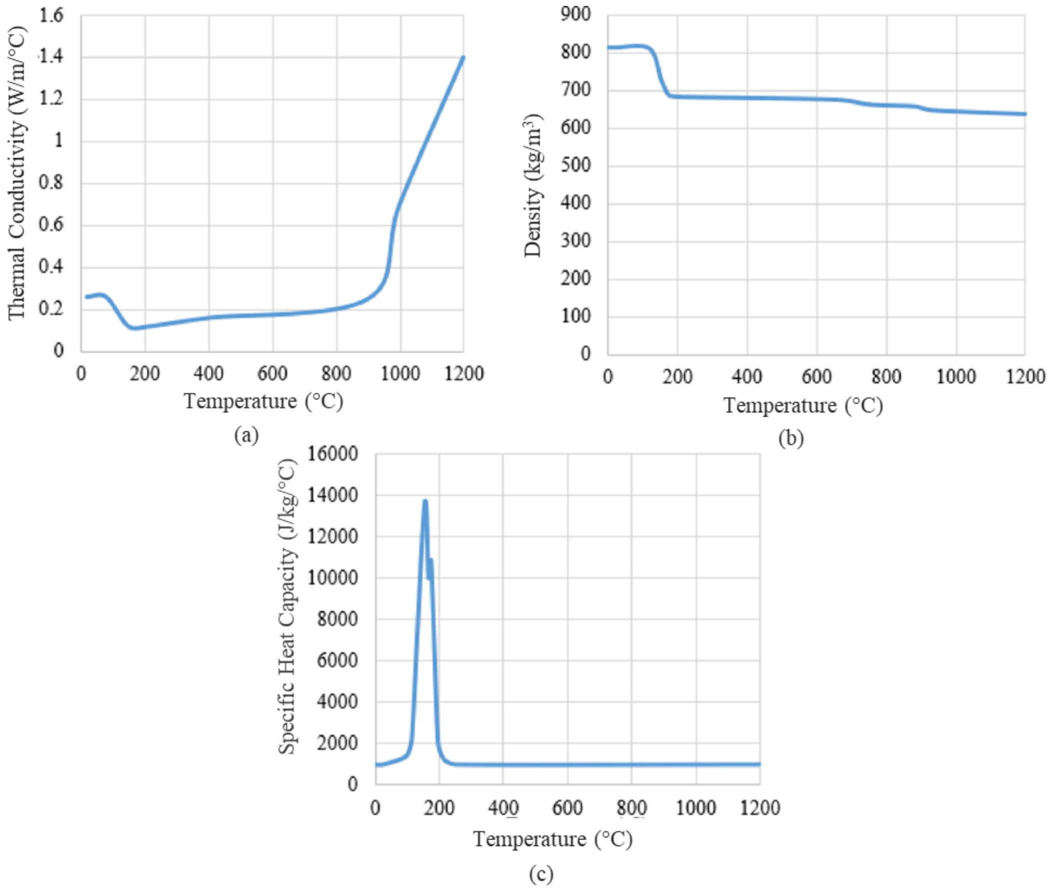


Figure 39. Elevated temperature thermal properties of gypsum plasterboard (a) thermal conductivity (b) density (c) specific heat (original figure from [70]).

Several researchers have also investigated the thermal properties of gypsum plasterboard fabricated in different countries (Canada, New Zealand, Europe, Australia, and China) through direct testing or property calibration from fire tests of wall panels. Yu et al. [89] summarized the representative thermal properties of gypsum plasterboards in those studies as shown in Figure 40.

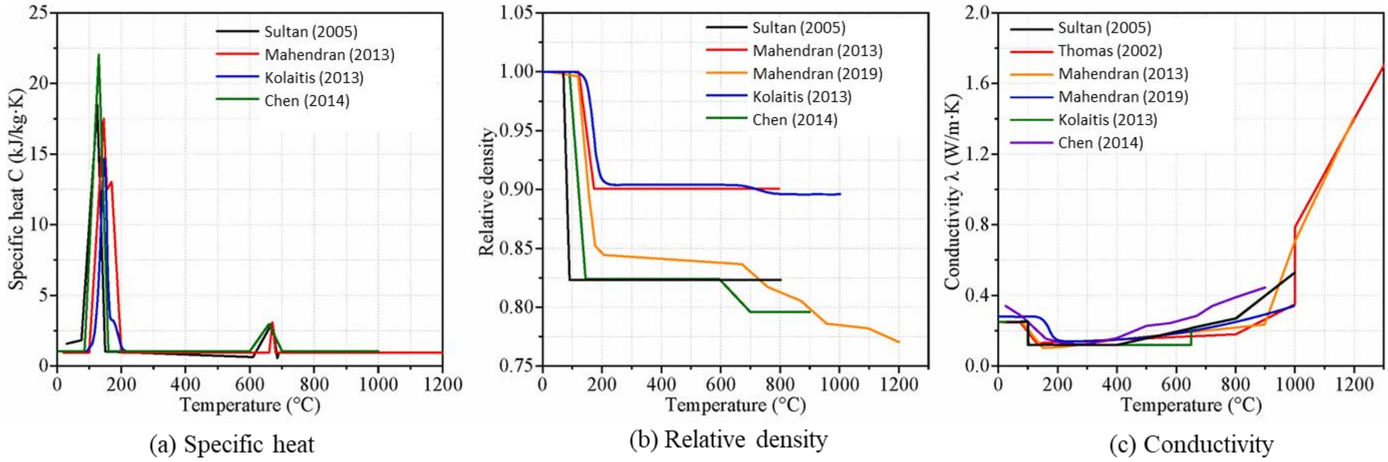


Figure 40. Thermal properties of gypsum boards from different studies (original figure from [89]).

In the study of the thermal and structural behaviour of LSF walls under fire condition by Samiee et al. [74], the modulus of elasticity at ambient temperature and the Poisson ratio for gypsum materials were assumed to be 2470 MPa and 0.2, respectively.

To account for ablation, cracking, and moisture movement, the thermal conductivity of gypsum plasterboard is modified at elevated temperatures [70]. Figure 41 shows an example of the modification of the thermal conductivity of gypsum plasterboard, with the solid line representing the original gypsum plasterboard thermal conductivity-temperature curve, and the dashed line representing the modified curve.

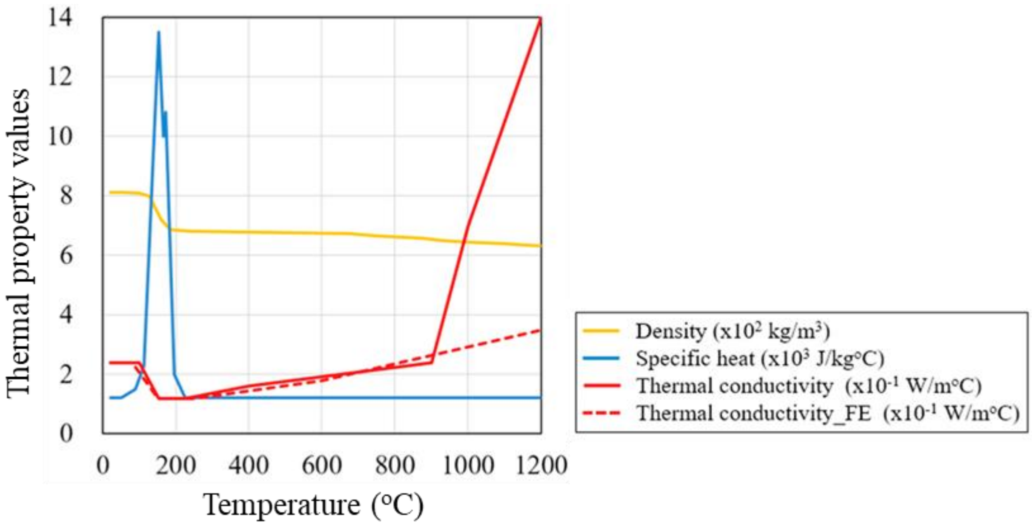
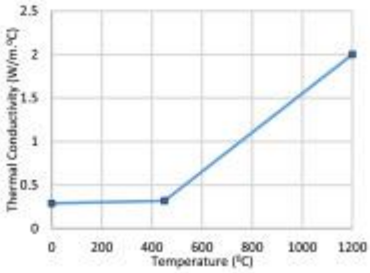
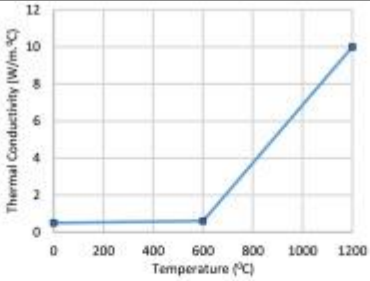
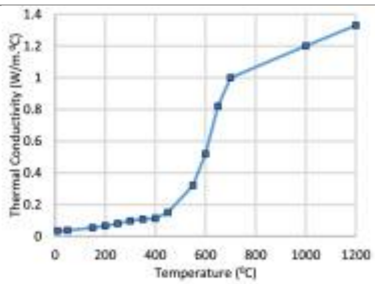


Figure 41. Thermal properties of gypsum plasterboard showing modified thermal conductivity-temperature relationship (original figure from [53]).

5.3.6.3 Insulation

Perera et al. [10] (based on the work of others) gave temperature dependent thermal conductivity, specific heat and density of different of insulation materials over temperatures ranging from 20 °C to 1200 °C. These are presented in Table 5. While the density and specific heat of the insulation materials are often taken as constant values, the thermal conductivity is temperature dependent [89].

Table 5. Elevated temperature thermal properties of different LSF wall insulation materials (Original table from [18]).

Material	Density (kg/m^3)	Thermal Conductivity (W/m.°C)	Specific Heat (J/kg.°C)
Rock wool	100 kg/m^3		840 J/kg.°C
Glass fibre	15.42 kg/m^3		900 J/kg.°C
Mineral wool	80 kg/m^3		840 J/kg.°C

Like gypsum plasterboard, to account for the ablation effect of insulation materials, the thermal conductivity values are adjusted. One method of achieving this was reported by Yu et al. [89], where to simulate the effect of ablation of mineral wool insulation, the thermal conductivity of the mineral wool insulation is increased at high temperatures. Figure 41 shows an example of the modification of the thermal conductivity of silica aerogel fibreglass insulation, with the solid red line representing the original insulation thermal conductivity-temperature curve, and the dashed line representing the modified curve.

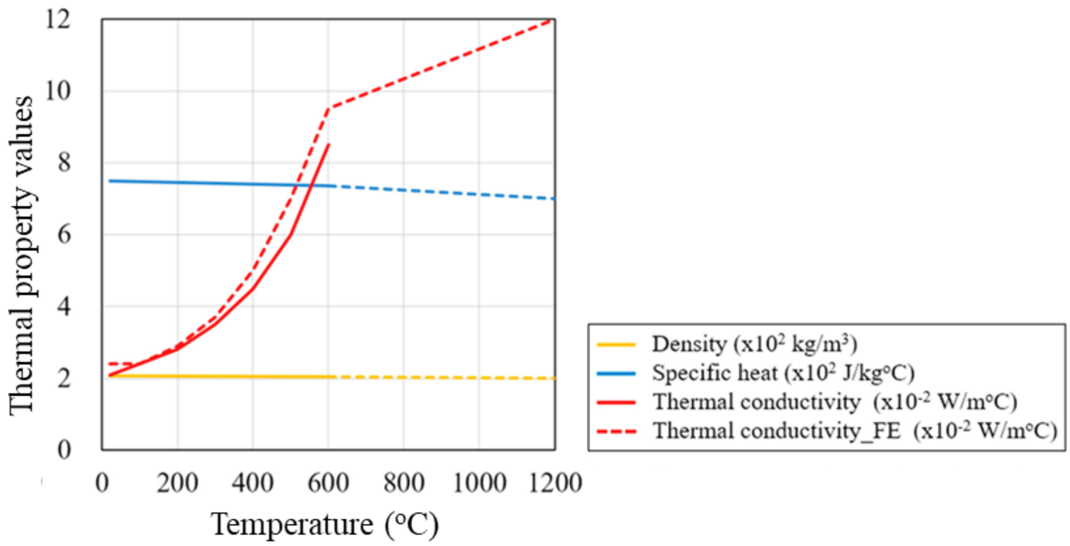


Figure 42. Thermal properties of silica aerogel fibreglass insulation showing modified thermal conductivity-temperature relationship (original figure from [53]).

5.3.6.4 Temperature dependent properties considering natural fires

Most numerical studies are validated with tests based on standard time-temperature curves as shown in Table 4. Sections 5.3.6.1 through 5.3.6.3 demonstrate that previous research on the fire performance of LSF walls subjected to fire employed finite element models (FEM) with temperature-dependent material properties. However, Upasiri et al. [75] point out that these temperature-dependent properties are primarily applicable during the heating phase, as they have been validated against standard fire conditions, and that incorporating the same temperature-dependent properties during the cooling phase of realistic fires may lead to inaccurate FEM results. For example, the specific heat and thermal conductivity of materials, which are treated as temperature-dependent properties during the heating phase, may not be suitable for the cooling phase. This is because the heating process can cause irreversible changes in the material, such as decomposition, phase transitions, and alterations in chemical composition, and the properties used during the heating phase may not be appropriate for the cooling phase in most materials.

Thus, comprehensive experimental research is needed to determine the thermal and mechanical properties during the cooling phase. Incorporating these properties into the FEM will enhance the accuracy of the results for LSF walls exposed to fire. Section 5.4.1 reviews the effect of using material properties validated against standard fire conditions on the performance of LSF walls exposed to realistic fires.

5.3.7 Modelling air gap / cavity

In studies reviewed of LSF walls without cavity insulation, the heat transfer through the cavity is taken to be predominantly governed by radiation, and the cavity is assigned an emissivity value of 0.9 and treated as a closed system. For example in Upasiri et al. [75] , surface radiation was applied to the cavity of the wall configurations, employing an emissivity coefficient of 0.9 and the closed cavity method for the cavity surfaces. Also, Perera et al. [69] considered the minimal thermal conductivity of air and the relatively static staged air inside the cavity, the heat transfer contribution from convection and conduction was deemed negligible compared to cavity radiation. This approach aligns with previous research that successfully simulated experimental structural fire tests on LSF wall panels as reported in Perera et al. [69].

5.3.8 Modelling geometric imperfections

Initial geometric imperfections commonly exist in CFS studs used in LSF walls. The initial geometric imperfection is thus a critical factor for CFS studs as it can reduce the load-bearing capacity of LSF walls [77].

These imperfections include local and global imperfections that influence local or distortional buckling capacities and the buckling load of the member, respectively [70], [74]. Initial geometric imperfections are often introduced based on deformation modes from linear buckling analysis [77].

In their studies, Gunalan and Mahendran [85] and Peiris and Mahendran [70] used AS/NZS 4600 [90] (Australia and New Zealand standard for cold formed steel structures) to determine suitable magnitudes of initial geometric imperfections for nonlinear analyses of CFS members. Xing et al. [59] used the thickness of the end stud to derive the magnitude of local buckling, while Abeysiriwardena and Mahendran [4] calculated the magnitude of geometric imperfections according to AS/NZS 4600.

Different values of geometric imperfection have been studied by researchers as reported in Samiee et al. [74], where they also introduced geometric imperfections in the nonlinear analysis of "steel frame with lateral restraint" and "complete wall" models of LSF walls in fire using a combination of local and distortional buckling modes.

Initial geometric imperfections have a significant impact on the behaviour of CFS sections used in LSF walls. However, at high temperatures, thermal bowing deformation may dominate the structural performance, reducing the influence of initial imperfections [76], [77].

5.3.9 Modelling screws and fastenings and sheathing board joints/restraints

In the selected studies, various methods of modelling screws and fastenings in LSF walls exposed to fire have been employed.

According to Xing et al. [59], fasteners do not impact heat transfer between shell elements, leading to the adoption of tie constraints for shell-to-shell heat transfer. Consequently, screws are excluded from the thermal model [11]. However, in Samiee et al. [74], mesh-independent fasteners have been utilized to model screw connections between sheathing boards and the steel frame or stud to track. Ali et al. [22] modelled connectors as rigid beam, tying nodes at the centre of CFS flanges and adjacent nodes on the sheathing board.

Due to the complexity and limitations of FEM, some simplifications were made in some of the studies, including neglecting the effects of sheathing board joints and screw fasteners, and assuming uniform thermal loading [53].

Tao et al. [77] reported that past studies have demonstrated that lining materials provide sufficient lateral restraint to prevent steel studs from globally buckling about their minor axis, even under fire conditions. This can be achieved in FE models by restricting nodal movement at sheathing-stud connections or screw locations. For example, sheathing material were not modelled explicitly Dias et al. [79], but the effect of screws was simulated as translational restraints in the lateral direction. In Upasiri et al. [75], perfect connections were assumed between plasterboard, CFS lipped channel section, and insulation materials, and tie constraints were assigned between all contacting surfaces.

Section 5.4.4 reviews the influence of plasterboard joints and restraints conditions on the performance of LSF walls in fire.

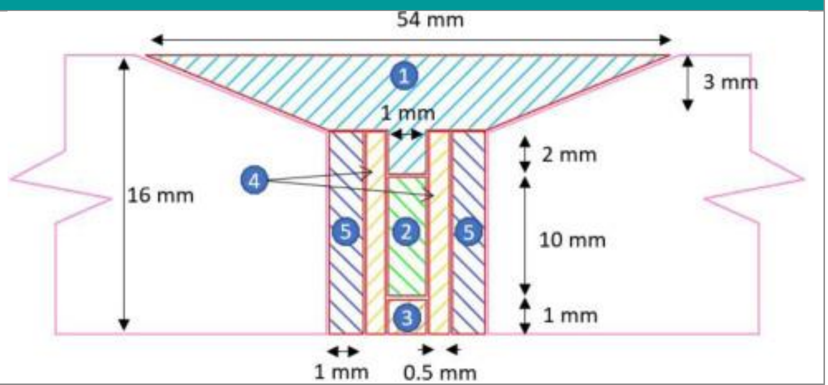
5.3.10 Modelling sheathing fall-off and insulation material failure

When exposed to fire, modelling heat transfer through LSF walls becomes more complex due plasterboard joint opening, wall panel cracking, and localized fire side plasterboard fall-off [53]. To achieve realistic simulations, these wall behaviours must be considered.

Gypsum board cracking and fall-off typically occur when exposed to fire, as reported in Liu et al. [91]. Liu et al. [91] employed a model change method to simulate gypsum board fall-off by deactivating fire-exposed elements at a specific time determined by the onset of material fall-off.

To accurately determine stud temperature profiles in single plasterboard sheathed walls, Abeysiriwardena and Mahendran [4] emphasized the necessity of incorporating plasterboard joint opening effects. In their study, Abeysiriwardena and Mahendran [4] observed that the plasterboard joint compound detached and fell off after approximately 17 minutes, with the average gap in plasterboard joints reaching 4-5 mm at undisturbed locations. They proposed a six-step sequence (Table 6) to simulate plasterboard joint fall-off and opening-up, visualized by corresponding element blocks.

Table 6. Sequence simulating plasterboard joint fall-off and opening-up (Original table from [4]).

Step	Function	Total time [min]	Element blocks
1	No element deletion	–	
2	Delete element block 1	17	
3	Delete element block 2	20	
4	Delete element block 3	25	
5	Delete element block 4	30	
6	Delete element block 5	35	

Liu et al. [91] simulated gypsum plasterboard and insulation material failure using the birth-death element technique based on test data. The birth-death element technique involves introducing elements within the FE model that represents parts of the material that fails, such that the elements are removed from the simulation when specific conditions are reached. It is a reasonable method for simulating material failure or fall-off due to fire as it provides a flexible approach to model the dynamic nature of fire-induced material failure or fall-off. However, this method relies on non-independent test data and subjective visual observations of failure moment [74]. Instead, Samiee et al. [74] incorporated the ablation process and plasterboard cracking indirectly through suitable apparent thermal properties of plasterboard, such as thermal conductivity and specific heat.

Tao and Mahendran [53] criticised the adjustment of thermal conductivity values in previous studies where case-by-case definition was required and did not account for the heat transfer mechanism variations among different wall components after fall-off. They proposed a more realistic modelling prediction using a multi-step transient analysis and element birth/death method [36]. Similar to Liu et al. [91], the fall-off time was defined based on fire test results.

Section 5.4.7 reviews the influence of plasterboard joints opening and fall-off on the performance of LSF walls in fire.

5.4 Factors that influence performance of LSF walls in fire

This section reviews the influence of different factors affecting the performance of LSF walls in fire as reported in the literature. It is noted that all the studies reviewed herein considered only one-sided exposure of LSF walls. However, this review is important to determine which parameters the performance of LSF walls in fire are more sensitive to and to form a basis for future parametric studies of LSF walls exposed to fire on two sides using FE models.

5.4.1 Influence of fire type and exposure condition

Table 4 and Figure 31 have shown that limited research has been conducted on the fire performance of structural elements exposed to realistic design fires. Standard fires do not accurately simulate real fire situations, as they do not consider factors such as fuel load, environmental conditions, ventilation, and material thermal properties [75]. Parametric fire curves, which represent more realistic temperature variations, include both heating and cooling phases, unlike standard and hydrocarbon fires, which only consider the heating phase. Due to the variation of the heating rate and influence of the cooling phase, it is reported that the fire performance of a structural element is different when exposed to realistic fire compared to standard fire [75]. Numerical models should incorporate both temperature and phase-dependent properties due to the heating and cooling phases present in realistic design fires.

In Upasiri et al. [75], it was reported that prolonged realistic fires and standard fire ratings were found to be similar for most LSF wall configurations, while rapid-fire exposure was more severe within the first 50 minutes compared to standard fire exposure.

Similarly, Ariyanayagam et al. [80] observed that stud temperature rise and fire resistance rating (FRR) were significantly influenced by the type of fire time-temperature curve, with rapid fires causing faster temperature increases than prolonged fires. Furthermore, LSF wall stud temperatures continued to rise in the decay phase, indicating that LSF wall studs could fail during this phase if they reached critical failure temperatures.

Kesawan and Mahendran [92] showed that the FRR of LSF walls was significantly affected by using realistic design fire curves instead of standard fire curves. In another study by Keerthan and Mahendran [84], Eurocode design fires were also found to cause more severe damage to LSF walls than standard fires.

Chen and Ye [41] found that the temperature rise rate is inversely proportional to the buckling temperature at the cold flange of the stud.

According to Ariyanayagam et al. [80], many studies have investigated the fire performance of load-bearing LSF walls under standard fire conditions, but the relevance of these scenarios to modern buildings is questionable. According to them, modern buildings contain materials with higher heat release rates, which could increase fire severity and compromise life safety.

LSF wall assemblies are usually subjected to fire from one side of the wall, which results in a non-uniform temperature distribution across the stud cross-section [1], [93]. Thermal bowing deformations and non-uniform strength and stiffness distribution within LSF wall studs result from the temperature gradient across cold-formed steel studs during fires [94]. Therefore, it is important to investigate the influence of two-sided exposure and how it affects the temperature distribution within LSF wall components and ultimately its fire performance.

5.4.1.1 Influence of double-sided fire exposure

Only one numerical study (Ariyanayagam and Mahendran [71]) was found in the literature to have investigated the effects of LSF walls exposed to fire on two sides on the fire performance of LSF walls. The fire model used was the standard fire curve. The study examined two configurations: single and double layer 16 mm thick gypsum plasterboards lined walls. FE models were developed with one side exposed to fire from the onset, and the initially unexposed surface of the wall exposed to fire with a time lag of 15 and 30 minutes. The investigation included thermal and structural finite element analyses to obtain time-temperature curves for plasterboard and stud, and to determine the load-bearing capacity of 3 m long LSF wall panels in fire.

Results of thermal FE analysis revealed that at initial fire stages, the sheathing delays temperature rise in all LSF walls, with plasterboard and stud temperatures being nearly uniform. For LSF walls exposed to fire on one side, distinct temperature profiles are observed, with fire side surfaces being hotter than ambient side surfaces, and stud hot flange (HF) temperatures being higher than web and cold flange (CF) temperatures. However, for LSF walls exposed to fire on both sides, ambient plasterboard surface temperatures rapidly increase after 15 and 30 minutes due to fire exposure on the ambient side surface as well. Non-uniform temperature distribution in stud HF and CF temperatures observed in one-sided fire exposure does not exist for two sides exposed to fire, with HF and CF temperatures becoming nearly the same after 35 and 55 minutes of fire exposure. However, web (mid-point) temperatures are less than the stud HF and CF temperatures for the entire duration of the fire (120 minutes for single plasterboard model and 240 minutes for the double plasterboard model). This creates two temperature gradients across the stud section, one being from HF to web (mid-point) and another from web (mid-point) to CF. This is different to that of LSF walls exposed to fire on one side with a single temperature gradient from HF to CF across the stud.

Using the stud temperatures from the thermal finite element analyses and mechanical properties at elevated temperatures, transient state finite element analyses were conducted to determine stud failure times and temperatures. LSF walls exposed to fire on both sides failed structurally much earlier than those exposed to fire on one side only, highlighting the importance of incorporating fire exposure on both sides in design. Studs exposed to fire on one side failed at lower HF and CF temperatures than those exposed to fire on both sides due to one-sided fire exposure resulting in higher thermal gradients, thermal bowing, neutral axis shift, eccentric loading, and higher second-order deflections caused by bending. Studs in LSF walls exposed to fire on both sides experience more uniform temperatures across the cross-section, resulting in reduced contribution from bending action. Consequently, the stud HF temperatures in single plasterboard lined walls exposed to fire on both sides are significantly higher for load ratios ranging from 0.3 to 0.5 (see Figure 43). This temperature difference is less pronounced in double plasterboard lined walls due to the presence of an additional gypsum plasterboard layer that delays stud temperature rise. This temperature difference is not noticed in load ratios less than 0.2 and above 0.6, since with lower loads and associated longer fire duration, the stud temperature distribution across the cross-section will become nearly uniform even in walls exposed to fire on one side. At higher load ratios, gypsum plasterboard delays the stud temperature rise and thus the stud HF temperatures are the same for walls exposed to fire on one side and both sides.

However, the study had some limitations, notably that the FE model developed in the study was not benchmarked against any tests / experiments. Therefore, the temperature distribution across the LSF wall when exposed to fire on two sides has not been well established. Also, the effects of other factors such as steel section details, different sheathing and insulation, end restraints conditions, etc., were not investigated. These are useful to be able to make recommendations for the design of LSF walls exposed to fire on two sides.

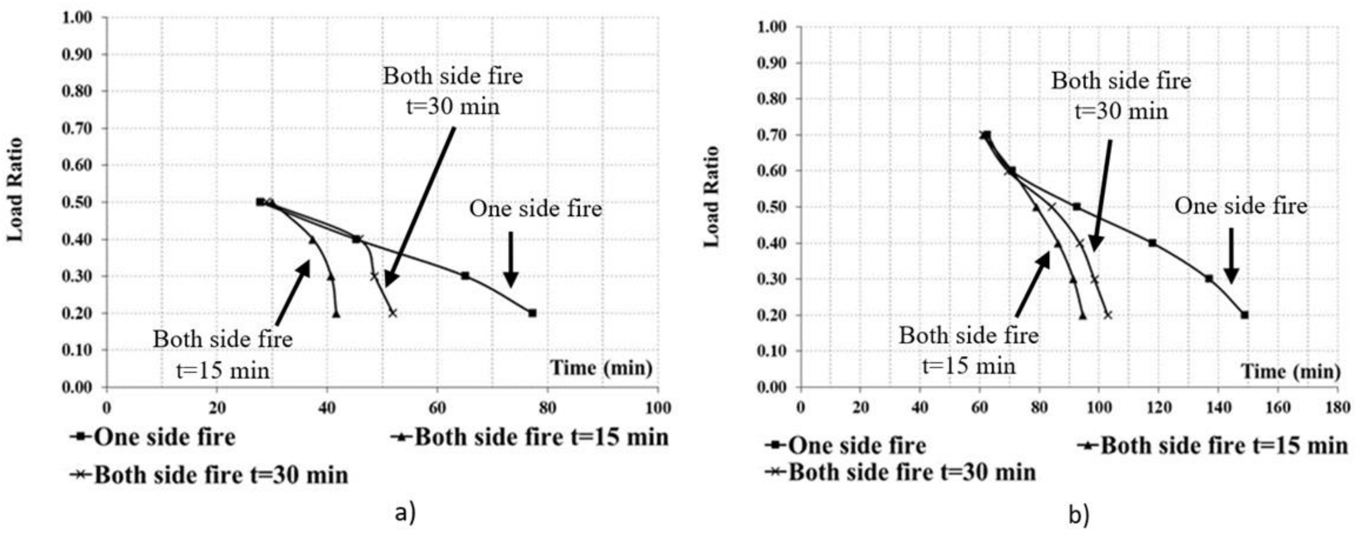


Figure 43. Load ratio versus time a) single plasterboard b) double plasterboards lined walls (original figure from [71])

5.4.2 Influence of load ratio

The load ratio plays a significant role in the fire performance of load-bearing and non-load bearing LSF walls [70]. Load ratios for load-bearing LSF walls typically range between 0.2 and 0.7 [79].

A parametric analysis by Xing et al. [59] found that critical temperature and time decreased as the load ratio increased, with an average decline rate of 11.64% in response to a 0.1 increase in load ratio. A maximum drop in the critical time was observed when the load ratio increased from 0.6 to 0.7. Axial displacement was also found to be significantly affected by the load ratio. The study concluded that a load ratio beyond 0.4 contributed to a considerable loss of wall ductility.

Chen and Ye [41] found that the load ratio was related to the overall buckling of the stud, with overall buckling occurring when the load ratio was larger (between 0.4 and 0.8 for walls without cavities, and above 0.6 for walls filled with aluminium silicate wool).

Perera et al. [69] noted a relationship between the load ratio (LR) and hot flange (HF) temperature of wall studs in load-bearing LSF walls exposed to fire, which was derived from results of previous studies (see Figure 44). It was highlighted that the HF temperature would be the maximum steel temperature at all times during fire exposure, and when it reached the critical temperature related to the LR, the steel stud would undergo thermal bowing due to reduced strength at the HF.

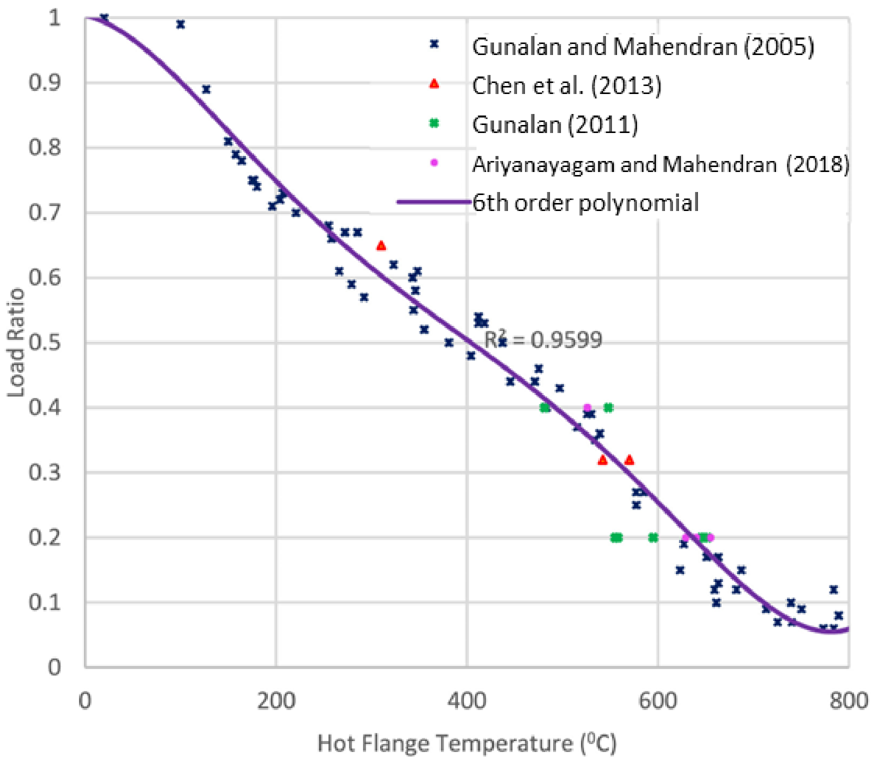


Figure 44. Load ratio (LR) versus hot flange (HF) Temperature at the structural failure of LSF wall, based on previous studies (original figure from [69]).

5.4.3 Influence of steel section details

5.4.3.1 Effect of profile type

Dias et al. [79] investigated the performance of LSF walls constructed with three different steel stud sections (lipped channel section (LCS), welded hollow flange section (LiteSteel Beam or LSB), and web-stiffened channel section (SCS)) under both ambient and fire conditions. In fire conditions, the stud geometry had minimal impact on LSF wall stud performance, with the SCS matching the thermal and structural fire performance of LCS and LSB sections in LSF wall applications.

Similarly, Kesawan and Mahendran [92] found that the enhanced plasterboard-to-stud connectivity in hollow flange channel (HFC) studs did not influence the structural fire performance of LSF walls. The use of HFC studs did not provide an advantage over other stud sections with similar overall sizes and thicknesses in terms of retaining the ambient temperature load-carrying capacity of LSF wall studs exposed to fire conditions.

However, for hollow sections, Tao et al. [77] reported that there is an advantage of using hollow section (SHS/RHS) studs in cavity-insulated walls. The hollow cavity of SHS/RHS studs accelerated the heat transfer process between the stud hot and cold flanges, helping to avoid excessive flange temperature differences and reduce thermal bowing deformations. This characteristic led to an increased structural adequacy-based fire resistance level (FRL).

5.4.3.2 Effect of section size and aspect ratio

In the study conducted by Xing et al. [59] on the experimental and numerical studies of fire behaviour of cold-formed steel centre-sheathed walls subjected to gravity loading, it was found that increasing the aspect ratio of LSF walls marginally improved fire behaviour. The critical temperature growth rate slowed down when the aspect ratio exceeded 2.5, as the slenderness ratio of end studs increased, causing a change in the failure mode from local to global buckling. Axial displacement increased monotonically with the increased aspect ratio due to the increased expansion force, which was consistent with fire test observations.

Samiee et al. [74] demonstrated that increasing the stud web depth led to an increased fire resistance rating (FRR) of LSF walls, with the highest FRR difference observed at a load ratio of 0.9. Walls with higher stud web depth failed due to local buckling of the web, as these thin-walled sections were more prone to local buckling due to their high slenderness. The primary failure mode for walls with wide stud flange widths was distortional buckling, as wider flanges resulted in lower rotational stiffness at the web-flange junction.

Similar results to Samiee et al. [74] were obtained by Tao et al. [77], where it was shown that increasing the depth of steel studs improved the fire resistance level (FRL), as higher stud depths provided higher bending capacity and reduced lateral displacement. Overall, the influence of steel section size and aspect ratio on the fire performance of LSF walls involves complex interactions between factors such as stud web depth, flange width, aspect ratio, and failure modes.

5.4.3.3 Effect of stud thickness

Xing et al. [59] observed that increasing the end stud thickness did not consistently improve the fire behaviour of cold-formed steel-concrete sandwich walls (CFSCSSWs). Although the critical temperature decreased by 3.38% and 2.54% when the thickness increased from 1.5 to 3.0 mm, the wall with a 2 mm end stud thickness exhibited better fire behaviour and was recommended for use in CFSCSSWs.

Samiee et al. [76] conducted parametric studies on the impact of steel grade and cross-section thickness on the fire behaviour of cold-formed steel shear walls. Their findings revealed that increasing steel thickness led to a decrease in the temperature of steel sections, particularly in the hot flange. Increasing the stud thickness up to 1.55 mm resulted in an increase in the fire resistance rating (FRR).

Kesawan and Mahendran [92] concluded that steel stud thickness significantly influenced the fire performance of light steel frame (LSF) walls, both with and without cavity insulation. Walls with thicker studs exhibited higher FRRs due to slower hot flange temperature development and reduced local buckling effects in their plate elements.

5.4.3.4 Effect of steel grade

Samiee et al. [76] investigated the fire performance of LSF walls with different steel grade and thicknesses and found that increasing the grade of steel led to an increase in the ultimate compression capacity of studs in structural analysis at room temperature. Additionally, using high strength steel in a load ratio range of 0.3–0.7 resulted in an increased fire resistance rating (FRR). The section type of the stud used by Samiee et al. [76] was lipped channel sections. In contrast, Tao et al. [77] observed no significant difference in the fire resistance levels (FRLs) of cold-formed steel square/rectangular hollow section (SHS/RHS) stud walls made of C350 and C450 grade steels for a given load ratio.

5.4.4 Influence of sheathing board material

Samiee et al. [74] observed that local buckling in the flange of the studs caused damage to LSF walls with different sheathing materials, with the plasterboard material type not affecting the failure modes. Ali et al. [22] explored functionally graded materials (FGMs), a new class of advanced composite materials used as sheathing material for LSF walls and characterized by continuous variation of material properties. FGMs are considered ideal for high strain rate and thermal shock loading applications due to their resistance to debonding, crack initiation, and reduced stress concentration and residual stress. The study found that using FGM as a sheathing material for fire protection increased the failure time for all load ratios compared to traditional gypsum board. However, further research is needed to examine the behaviour of FGMs in various geometries, loading, and boundary conditions under elevated temperatures and optimize their use in fire conditions, including double sided exposure of the parent LSF walls.

Abeysiriwardena and Mahendran [4] investigated the effect of out-of-plane restraints provided by sheathing boards on the fire resistance of LSF wall studs under non-uniform elevated temperature distributions. The results showed that out-of-plane restraints significantly reduced lateral deflections of the walls and improved their fire resistance levels, especially when double layers of gypsum plasterboards were used. FE analysis with and without out-of-plane restraints showed a difference in failure times up to 40%, emphasizing the importance of considering these effects in structural FE modelling of LSF walls under fire conditions. The study also found that the out-of-plane restraints provided by gypsum plasterboards depend on the fire exposure time, with the values decreasing as material properties and stud-to-sheathing screw connection performance deteriorate.

5.4.5 Influence of insulation material and insulation location / type

Ariyanayagam and Mahendran [78] in their study noted that cavity insulation in LSF walls serves as a thermal barrier during fire events, resisting temperature rise and preventing flame penetration. Perera et al. [10] investigated the influence of cavity insulation ratio on fire resistance in both conventional (separate assembly of LSF walls, floors, and primary frame structures at the construction site) and modular (whole volumetric units fully completed and transported to the construction site) LSF wall panels. The study found that increasing the insulation ratio (depth of cavity insulation to depth of cavity) led to higher insulation fire resistance levels (FRLs), with modular LSF walls demonstrating superior insulation FRLs due to their double skin nature.

Perera et al. [10] further observed that the most efficient cavity insulation ratio for achieving insulation and structural fire resistance, as well as energy efficiency, was found to be 0.4. Perera et al. [69] concluded that shifting rock wool insulation to the fireside of the wall in modified warm-frame configurations or partially moving it to the fireside in partially modified warm-frame and modified cold-frame configurations enhanced the fire performance of LSF walls (see Section 3.2 for the description of cold-frame and warm-frame LSF wall configurations).

Ariyanayagam and Mahendran [78] demonstrated that cavity insulation increased the FRL of non-load bearing walls, but reduced the FRL of load-bearing walls with load ratios below 0.7. Kesawan and Mahendran [92] found that uninsulated and externally insulated LSF walls exhibited better fire performance than cavity-insulated LSF walls.

Conventional cavity insulation materials, such as glass wool, rock wool, and cellulose fibres, have been found to reduce the fire resistance of load-bearing LSF walls by acting as heat barriers and increasing the hot flange temperature, temperature gradient across the steel stud cross-section, and large thermal bowing deformations, causing premature structural failures of studs. Upasiri et al. [75] proposed a novel approach to enhance both structural and fire performances in LSF walls by using lightweight concrete filling.

Insulating fire performance improved with the introduction of rock wool insulation, but a significant enhancement was observed when lightweight concrete filling was incorporated into LSF walls. The best insulation fire performance was exhibited when foamed concrete with 1,000 kg/m^3 density (FC1000) was used under both prolonged and rapid-fire conditions. Although lightweight concrete filling improved fire performance, it increased the total weight of the wall panel, suggesting that lightweight concrete AAC and FC could be utilized as filling materials in LSF walls with improved fire performance, with careful consideration of the structure's weight.

Upasiri et al. [75] further demonstrated that silica aerogel fiberglass blanket, used as external insulation, enhanced fire resistance by delaying stud temperature development and reducing the stud flange temperature difference compared to cavity insulated LSF walls. However, the aerogel blanket accelerated the temperature development of fire protective gypsum boards, potentially leading to early failure and reduced fire resistance of LSF walls.

5.4.6 Influence LSF wall configuration type

Kesawan and Mahendran [92] evaluated the performance of LSF walls under standard fire conditions with different configurations made of hollow flange channel section studs. The study found that LSF walls lined with three plasterboard layers had the highest fire resistance rating, making them the recommended choice when higher fire performance is required. However, cavity insulated LSF walls performed poorly due to the insulation acting as a heat barrier. On the other hand, the externally insulated LSF walls had a better fire performance than the uninsulated and cavity insulated LSF walls. The study also revealed that the number of plasterboard layers and insulation location significantly affected the fire performance of LSF walls.

In a similar study, Perera et al. [69] used benchmarked finite element models to assess the fire performance of six different LSF wall configurations (as shown in Figure 45) exposed to standard fire conditions in terms of structural and insulation criteria. It was found that modified warm-frame construction exhibits the maximum fire resistance level (FRL) irrespective of the applied load ratio (LR). The FRL values at a load ratio of 0.6 for cold-frame, warm-frame, hybrid-frame, partially modified warm-frame, and modified cold-frame LSF walls were around 60 min, while that of the modified warm-frame was 150 min, indicating approximately 150% better performance than original wall frame constructions. Therefore, the authors propose incorporating the novel LSF wall configurations to enhance the fire performance of LSF walls.

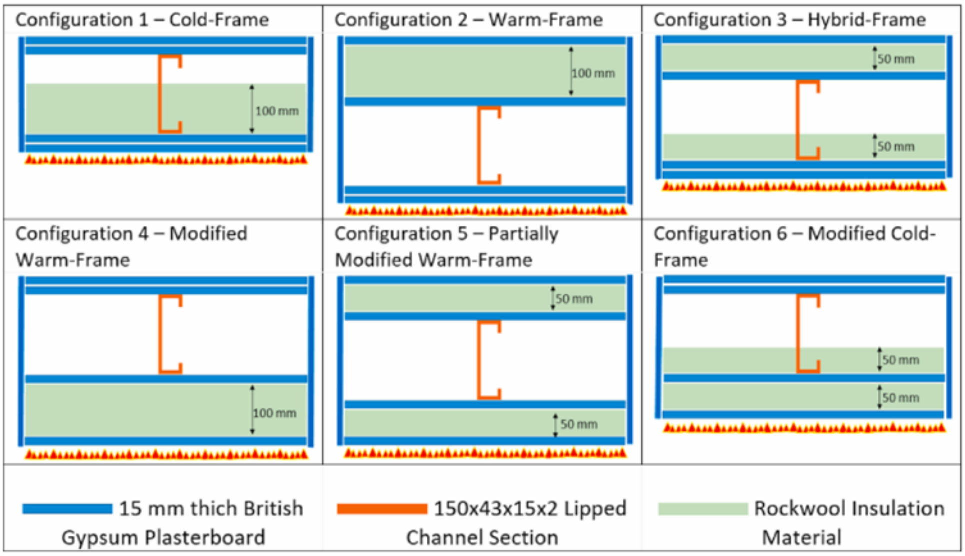


Figure 45. LSF wall configurations studied by Perera et al. [69] (original figure from [69]).

In another study, Perera et al. [95] conducted a numerical analysis of the fire performance of modular LSF wall panels with different configurations. Numerical models benchmarked against fire tests were used to investigate the fire performance of 16 different types of modular LSF wall panels under standard fire conditions. The results showed that the numerical models are an effective tool to predict the fire resistance time of modular LSF wall panels. The type of insulation material had little influence on the hot flange (HF) temperature of the wall. The critical HF temperature variation barely varied between single to double layer plasterboard LSF walls, and therefore, there was no noticeable difference in the structural fire resistance rating between the modular LSF wall panels and the corresponding mapped conventional LSF wall configurations. However, the modular LSF wall panels experience up to 170% higher insulation fire rating for single-lined plasterboards and up to 80% higher insulation fire rating for double-lined plasterboard configurations compared to the mapped conventional LSF wall configurations.

5.4.7 Influence sheathing board joint opening and fall-off

When LSF walls are exposed to fire, plasterboard joints open up, and plasterboard pieces fall off [4]. In Abeysiriwardena and Mahendran [4] and Peiris and Mahendran [70], improvements were made to heat transfer finite element (FE) modelling to incorporate these phenomena based on visual observations from full-scale fire tests. The effects of plasterboard fall-off and joint opening are accounted for by using the apparent thermal properties of plasterboard. Gypsum plasterboard fall-off when exposed to fire was observed in a test by Liu et al. [91]. In all cases, it was reported that gypsum plasterboard fall-off resulted in an increased rate of temperature rise at the stud section.

This finding highlights the significant impact of gypsum board fall-off on the fire resistance performance of light-gauge slotted stud steel walls. Liu et al. [91] compared different fall-off times, including 1000 s, 1500 s, 2000 s, 2500 s, and 3000 s, to examine their influence on temperature rise. It was found that earlier gypsum board fall-off led to a faster temperature increase. However, after 60 minutes, the fall-off time had an insignificant effect on temperatures. The fall-off time also notably affected the temperature of the unexposed surface, suggesting that gypsum board fall-off significantly reduces fire resistance of LSF walls.

5.4.8 Influence of noggings and columns located at intervals

As discussed in Section 3.1.1, when exposed to fire, LSF wall studs bow towards the hotter side due to the temperature gradient across the stud depth, and the plasterboards on the fire side lose strength, causing the studs to lose their lateral and torsional restraints over time. However, noggings placed at 1m intervals can provide continued support to the studs and resist out-of-plane deflection, resulting in reduced thermal bowing deflections and less cracking on the fire side plasterboards. Ariyanayagam and Mahendran [94] investigated the effect of noggings on the fire performance of LSF wall systems. Structural finite element models of fire-tested walls were developed and benchmarked using the fire test results. The use of noggings increased the FRR of LSF walls due to the reduced lateral deflections. This effect was found to be the same for both low and high strength steel stud walls.

To improve the load carrying capacity of LSF walls, previous studies have investigated the effect of integrating SHS steel columns in LSF walls at intervals. The integrated columns become the loadbearing components of the wall, while the studs of the wall are designed as non-loadbearing. Perera et al. [73] conducted a detailed numerical analysis of a modular wall panel with loadbearing SHS steel columns located at intervals along the length of the wall and different section/material options for the non-loadbearing LSF wall studs (RHS steel, LCS steel and softwood solid rectangular timber studs). The loadbearing SHS columns are separately sheathed with 32 mm thick gypsum plasterboard and the LSF wall sheathing boards are of the same material but only 12 mm thick in the original wall panel (see Figure 46).

The results of the study showed that as the non-load bearing stud type was changed from RHS CFS stud to LCS CFS stud and to softwood solid rectangular timber stud, no effective influence was seen against the structural or insulation FRL. The sheathing thickness of the loadbearing SHS column located at intervals was found to have a significant effect on the structural FRL, but not on the insulation FRL. On the other hand, the cavity insulation resistance linearly influenced the insulation FRL, but not the structural FRL.

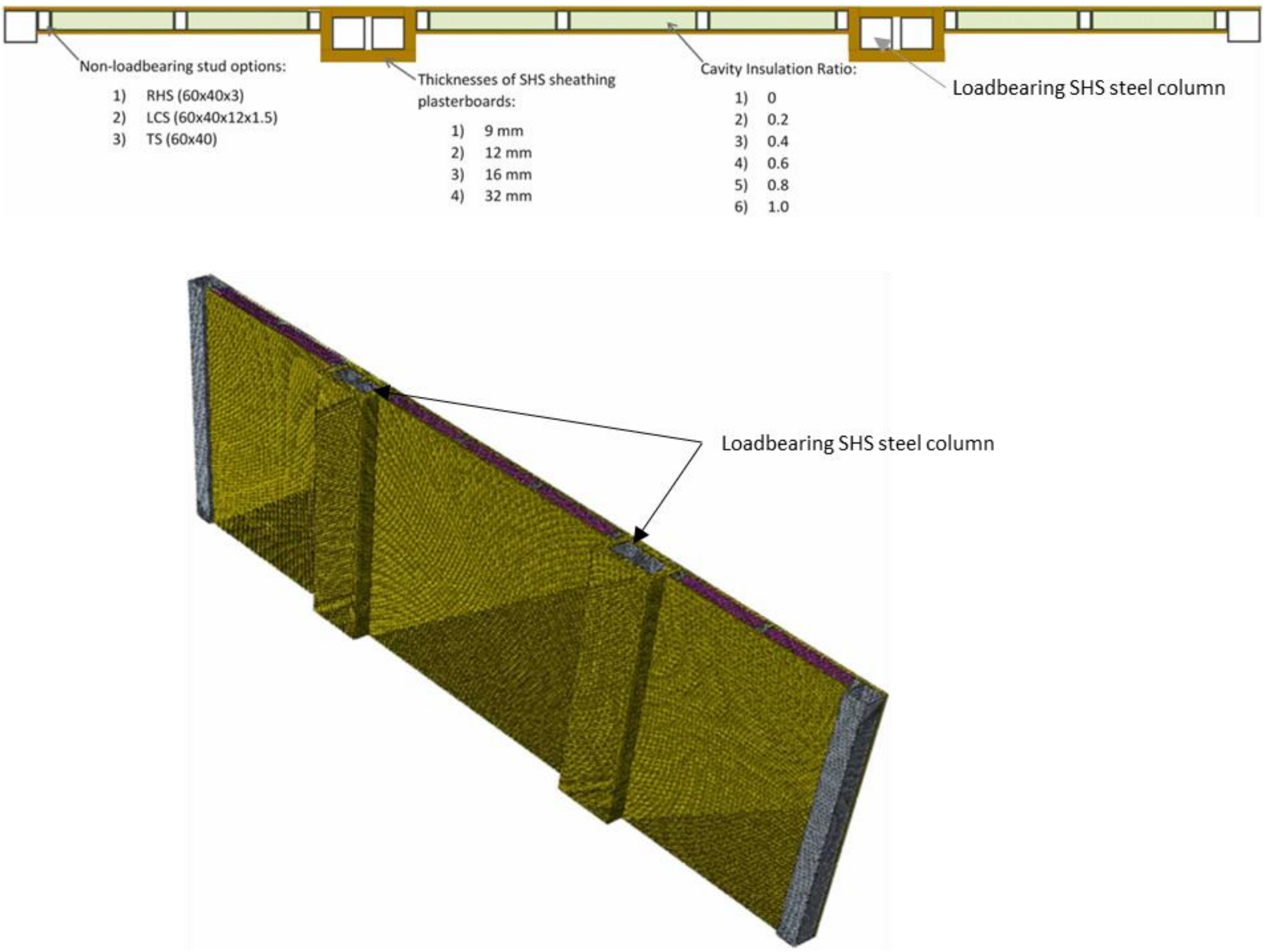


Figure 46. Plan and FE model of LSF wall showing loadbearing SHS steel columns at intervals (original figure from [73]).

5.5 Summary

In this section a review of existing studies on finite element modelling of LSF walls in fire and its implications for modelling fire performance when exposed to fire on two sides has been carried out. The key findings are summarised in this section.

From the literature reviewed, it was observed that only one of the existing studies considered cases of the LSF wall exposed to fire on two sides. In the study, it was shown that LSF walls exposed to fire on both sides failed structurally earlier than those exposed to fire on one side only, emphasizing the importance of accounting for fire exposure on both sides in design. Nevertheless, the study had limitations, notably that the finite element (FE) models used were not benchmarked against any tests or experiments and only limited parametric studies were conducted. However, from the other literature reviewed, it was shown that conclusions from the studies on one-sided exposure can be used to inform future finite element modelling studies and what parameters can potentially influence the behaviour of LSF walls when exposed to fire on two sides.

The literature review also showed that FE models need to be validated against test/experimental results of similar detail and application to ascertain their suitability to be used in parametric studies.

For FE models to be able to simulate test and specific design conditions, the FE model should consider the following: LSF wall model idealisation adequate for capturing the LSF wall system (i.e., single stud, steel frame with lateral restraint, or complete wall models); analysis type (transient or steady state analysis); mesh size; boundary condition (number of sides exposed, heat transfer coefficient, emissivity, end restraint conditions); temperature dependent properties of LSF wall components; heat transfer within and through air gap / cavity; initial geometric imperfections of LSF wall studs; screws and fastenings; plasterboard joints; and sheathing material fall-off.

The existing numerical studies have demonstrated that the above considerations necessary for FE modelling of LSF walls can be reasonably accounted for in FE models. Recommendations on good practices for modelling LSF walls from the existing studies are summarised as follows:

- Three numerical modelling idealisations exist to evaluate the fire performance of LSF walls (i.e., single stud, steel frame with lateral restraint, or complete wall models). The simplified single-stud model is recommended for predicting the fire resistance level of cold-formed steel SHS/RHS stud walls in a fire as it is both adequate and efficient. However, the sheathed stud model is recommended when steel studs are subject to major axis global buckling failure;

- The literature on fire performance of LSF walls uses two modelling techniques: fully coupled and sequentially coupled thermal and structural FE modelling. Most studies use sequentially coupled FE modelling. Two analysis types are possible: steady state and transient state analysis, with studies using both or only the transient state analysis type. 3-D FE models are developed to address limitations of 1-D and 2-D models but can be computationally expensive. Residual stress is not considered in many studies on LSF walls in fire;

- Software used frequently for FE modelling of LSF walls in fire are Abaqus and SAFIR, both have similar limitations;

- The mesh size of CFS studs and sheathing board used in modelling LSF walls typically ranges from 4 mm to 10 mm, but could be as low as 2 mm and as high as 25 mm. Mesh sizes for plasterboard and insulation elements in the thickness direction are usually finer, ranging from 2 – 4 mm;

- The boundary conditions in the finite element modelling of LSF walls in fire involve simulating the support provided by plasterboards, considering pinned-ended conditions, axial compression loads, lateral restraints, and various thermal boundary conditions including conduction, convection, and radiation. The heat transfer coefficients and emissivity values used in the studies can be summarized as follows:

- Convection coefficients:
  - Fire side: 25 W/m2/K
  - Ambient side: 10 W/m2/K
- Emissivity coefficients:
  - Fire side: 0.7; 0.8; 0.9
  - Ambient side: 0.3; 0.7; 0.9

- The use of accurate thermal and mechanical properties of LSF wall components is an important issue in numerical analysis. These properties are well established in the literature;

- LSF walls without cavity insulation are modelled by assuming the heat transfer through the cavity to be mainly governed by radiation with an emissivity value of 0.9;

- Various methods of modelling screws and fastenings in LSF walls exposed to fire have been used in the literature, including mesh-independent fasteners, tie constraints, and modelling connectors as rigid beams. Some simplifications were made in some studies, such as neglecting the effects of plasterboard sheathing board joints and screw fasteners, and assuming uniform thermal loading;

- Different methods have been proposed in modelling sheathing board cracking, fall-off, and joint opening. The methods include the model change method, element birth/death technique, and indirect incorporation through apparent thermal properties of sheathing board. A multi-step transient analysis and element birth/death method have been suggested for more realistic modelling predictions.

Several factors were observed from past numerical studies to influence the performance of LSF walls exposed to fire on one side. These factors can be used to form a basis for selecting parameters for future parametric studies of LSF walls exposed to fire on two sides. The factors and their influence on the performance of LSF walls in fire are summarised as follows:

- The fire performance of LSF walls was found to be significantly affected by the type of fire time-temperature curve. Many studies have investigated the fire performance of loadbearing LSF walls under standard fire conditions, but the relevance of these scenarios to actual building conditions is questionable;

- The load ratio plays a significant role in the fire performance of load-bearing and non-load bearing LSF walls. The hot flange temperature of wall studs in loadbearing LSF walls is related to the load ratio and is critical to the steel stud's thermal bowing due to reduced strength at the hot flange. As the load ratio increases, critical temperature and time to failure decrease, and axial displacement is significantly affected. A load ratio beyond 0.4 contributes to a considerable loss of wall ductility, and global buckling occurs when the load ratio is larger;

- The type of steel stud sections used have minimal impact on LSF wall stud performance under fire conditions. However, hollow sections such as Square and Rectangular Hollow Sections (SHS/RHS) have an advantage in cavity-insulated walls as they help reduce thermal bowing deformations and increase structural fire resistance level;

- Increasing the aspect ratio and stud web depth marginally improved the fire behaviour of LSF walls. Increasing stud web depth led to an increased fire resistance rating, with higher depths providing higher bending capacity and reduced lateral displacement. However, higher stud depths also increased the risk of local buckling failure mode;

- Increasing steel thickness can lead to improved fire performance of LSF walls, with higher fire resistance rating and reduced hot flange temperatures;

- The type of sheathing board used did not affect the failure modes of LSF walls. However, out-of-plane restraints provided by sheathing boards significantly improved the fire resistance of LSF wall studs under non-uniform elevated temperature distributions;

- Cavity insulation can enhance the insulation fire resistance level of non-load bearing walls but reduces the fire resistance level of load-bearing walls. Lightweight concrete filling can improve fire performance but increases the weight of the wall panel;

- The fire performance of LSF walls was significantly affected by wall configuration, including the number of plasterboard layers and insulation provision and location;

- The performance of LSF walls under standard fire conditions can be improved by using specific wall configurations, such as modified warm-frame construction and modular LSF wall panels, with recommended choices for plasterboard layers and insulation location;

- Sheathing board fall-off from LSF walls during fire exposure increases the rate of temperature rise at the stud section, and it significantly impacts the fire resistance performance of LSF walls;

- Screw connectivity does not influence the fire performance of LSF wall studs, but improved connectivity may reduce plasterboard fall-off;

- Use of noggings can reduce thermal bowing deflections and improve the fire performance of LSF walls;

- Use of loadbearing SHS steel columns located at intervals along the length of LSF walls can increase the load carrying capacity of LSF walls. When the loadbearing SHS steel columns are utilized in the LSF wall build-up, the non-load bearing LSF wall stud section and material type used has no effect on the fire resistance level.

6 Fire resistance design approach for LSF walls

6.1 Guidance expectations for the fire resistance of walls

In England, Part B of the Building Regulations 2010 ("the Regulations") [96] have the following requirement:

Internal fire spread (structure)

(1) The building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period.

(2) A wall common to two or more buildings shall be designed and constructed so that it adequately resists the spread of fire between those buildings. For the purposes of this sub-paragraph a house in a terrace and a semi-detached house are each to be treated as a separate building.

(3) Where reasonably necessary to inhibit the spread of fire within the building, measures shall be taken, to an extent appropriate to the size and intended use of the building, comprising either or both of the following –

a. Sub-division of the building with fire-resisting construction;

b. Installation of suitable automatic fire suppression systems.

(4) The building shall be designed and constructed so that the unseen spread of fire and smoke within concealed spaces in its structure and fabric is inhibited.

At present, it is reasonable to expect compliance with the Regulations can be achieved through guidance documents; these are the Approved Document B (ADB) [97] and BS 9999:2017 (BS 9999) [98]. However, it is noted that the application of guidance documents does not guarantee compliance and alternative ways may be necessary to meet the Regulations for uncommon building situations.

6.1.1 ADB

ADB proposes different periods of fire resistance for elements of structures and different exposures, depending on the end use of the element:

(a) Elements classified as structural frame (i.e., beam or column) are to be tested on all exposed faces;

(b) loadbearing walls are to be tested on each side separately;

(c) compartment walls are to be tested on each side separately;

(d) enclosure walls (that is not a compartment wall) next to a protected lobby or corridor are to be tested on each side separately.

Depending on the use of an LSF wall, its fire resistance period could fit one of the above descriptions. For example, if the element is not loadbearing, it will either fit description I or (d); if the element is loadbearing, it will either fit (a) or (b). The latter would result in a case-dependent fire resistance period (which will be equal to (c) and/or (d) or more onerous). In case the LSF wall is not classified as part of the structural frame, testing on each side separately is advised. However, if it is considered to be included in a building and perform as a column (i.e., not part of a wall, separating two enclosures of the building), then it should be tested on all faces that are anticipated to be exposed at the same time.

Based on the above, it is suggested through ADB that the designer should consider the end use of the system. Judgement should be used on which type of description best represents the expected fire scenarios for the application of the LSF wall system. Fire resistance will be dependent on this decision as well.

6.1.2 BS 9999

As with ADB, BS 9999 assigns the same four categories for the same exposure conditions. Therefore, it can be reiterated that it is the designer's responsibility to identify the appropriate application of the system and use the exposure necessary to test the LSF wall's behaviour.

6.2 Overview of design methods for LSF wall systems

Standards and guidelines for structural fire design of steel-based structures, such as Eurocode 3 and the Australian and New Zealand Standard, define three basic criteria: 1) structural, 2) integrity, and 3) insulation. Structural failure occurs when a component cannot support the design load under fire conditions. Integrity failure refers to the inability to prevent the transfer of hot gases and flames from the fire-exposed side to the unexposed side through the structure. Insulation failure takes place when the temperature on the unexposed surface of the structure exceeds an average of 140 °C or 180 °C at any point.

AS/NZS 4600 gives two methods for determining the load bearing capacity of LSF walls exposed to fire on one side. These are effective width method (EWM) fire design equations and the Direct Strength Method (DSM), both given in Appendix G of AS/NZS 4600. The Direct Strength Method (DSM) is widely used due to its simplicity.

In the work of Ariyanayagam and Mahendran [94], the residual compression capacities of fire exposed short columns were predicted with both effective width method and Direct Strength Method and compared with finite element analysis results. The analysis confirmed that current design rules can be used to predict the axial compression capacity of wall studs with non-uniform mechanical properties caused by exposure to a non-uniform temperature distribution across the wall thickness in a fire event on one side.

AS/NZS 4600 EWM and DSM give accurate predictions of the load ratio versus failure time curves for LSF wall studs exposed to non-uniform elevated temperature distributions. However, studies (e.g., [99]) have proposed improvements to the equations. These improvements aim to streamline the calculation process without compromising accuracy and to maintain consistency in considering weighted average mechanical properties and temperature variation for compression capacity calculations, while mid-web temperature mechanical properties and uniform temperature are considered for bending capacity calculations. However, these improvements did not include consideration of effects of fire exposure on two sides of the LSF wall. Therefore, studies on the fire performance of LSF walls exposed to fire on two sides are required to ascertain whether existing design equations can be used or modified to account for conditions when there is double-sided exposure.

6.3 Classification testing for walls exposed to fire on two sides

In England, fire testing applicable for load bearing and non-loadbearing LSF walls are as per European Standard BS EN 1364-1 [100] and BS EN 1365-1 [101]; and British Standard BS 476-21 [102] and BS 476-22 [103].

Clause A.6.1 of BS 476-21 notes that some walls, used in practice, act as wide columns which are not designed to provide fire separation, but are required for their loadbearing capacity and that situations can develop where a wall that acts as a wide column can be exposed either partially or fully to fire on both faces simultaneously. BS 476-21 further notes that, where the facility for testing such walls does exist, the basic methodology used in evaluating the single face exposure specified in clause 8 of BS 476-21 (which makes reference to BS 476-20 [104]) is appropriate for testing such walls exposed to fire on both faces.

Similar recommendation for testing of non-separating loadbearing walls is given in BS EN 1365-1, which notes that non-separating load bearing walls with potential to be exposed to fire on both sides can be tested as columns in accordance with EN 1365-4. Clause 6.3 of BS EN 1364-1:2015 and BS EN 1365-1:2012 notes that the test specimen be "fully representative of the construction intended for use in practice or be designed to obtain the widest applicability of the test result to other similar constructions". Both BS EN 1364-1:2015 and BS EN 1365-1:2012 further note that the tests shall be carried out using equipment and procedures in accordance with BS EN 1363-1 [105].

6.4 Extending the field of application of LSF wall systems

SCI publication P424 [106] provides guidance on how light steel framed buildings should be designed and detailed to provide fire resistance in accordance with the Building Regulations. It notes that light steel framing can be used in buildings up to 15 storeys high and uses cold-formed steel sections for loadbearing walls and floors. Floors in light steel framed buildings may also use composite slabs formed from profiled steel decking and in-situ concrete.

The publication is an update and extension to SCI publication P129 [107] "Building design using cold formed steel sections: Fire protection" and SCI Technical Information Sheet ED016 [30] "Fire safety of light steel construction". The publication includes calculation methods which may be used to extend the tested fire performance of a light steel wall or floor construction to a wider range of design parameters. The motivation for these methods is said to relate to limitations on the loads that can be practically applied in tests, for example, for a six-storey building, the loads acting at the ground floor may be 30 to 40 kN per C section, which leads to use of C sections that may be twice as thick as those used in a fire test (where maximum achievable loads in the test facility are typically in the range of 12 to 20 kN per C section). Further, calculation methods are provided that allow for extended fields on application in respect of the height / span of walls and floors which may be larger or reduced relative to that subject to fire resistance testing.

In the context of single vs. two-sided exposure to walls, SCI P424 notes that loadbearing light steel walls should meet the following minimum provisions:

- Loadbearing capacity dictated by its function as part of the 'structural frame'.
- Integrity and insulation dictated by the worst case of any other function it performs.
- Type of exposure for tests as appropriate for the same functions performed.

Regarding the first bullet, ADB sets out an expectation that the structural frame achieve fire resistance considering each exposed face. Therefore, a non-fire-separating but loadbearing LSF wall, e.g., between rooms within an apartment, would have to achieve loadbearing fire resistance when subject to two-sided exposure. By extension, any calculations undertaken following the methods in SCI P424 would be on the prerequisite of relevant test data being available for the purpose of providing temperature profiles, etc., necessitating test data for two-sided exposure be available.

6.5 Approaches for other materials

It is apparent from the summary in Section 6.1 that some ambiguity exists regarding the fire resistance expectations of loadbearing walls. If considered as part of the structural frame, the walls should achieve loadbearing fire resistance considering each exposed face. If considered as a loadbearing wall, the guidance calls for fire resistance considering fire exposure to each side separately. Given this ambiguity, design methods in material specific design codes vary in terms of provisions for single vs. two-sided exposure. Material specific guidance / approaches are set out below based on OFR's understanding of the current Eurocode framework.

6.5.1 Masonry

The fire design of masonry structures is set out in EN 1996-1-2 [108] and the corresponding national annex (NA) [109]. EN 1996-1-2 distinguishes walls as either a "separating wall", which is a wall exposed to fire on one side only, versus a "non-separating wall", which is a loadbearing wall exposed to fire on two or more sides. Separating walls can be either loadbearing or non-loadbearing.

Table NA.1.2 of the NA to EN 1996-1-2 sets out clay masonry minimum thicknesses for separating loadbearing single-leaf walls (criteria REI). For Group 1S units, i.e., containing less than 5% of formed voids by volume, walls subject to a load-ratio of 60% require a thickness of 90 mm to achieve REI 60 minutes and 100 mm to achieve REI 120 minutes. Per Table N.B.1.3 of EN 1996-1-2, this increases to 100 mm to achieve R 60 minutes and 240 mm to achieve R 120 minutes, when considering fire exposure on two sides, i.e., non-separating walls.

This indicates that to maintain the same load-bearing fire resistance, walls with higher fire resistance demands generally require substantially thicker construction when exposure is on two sides versus one. As fire resistance demands reduce, e.g., 30 to 60 minutes, this uplift in thickness is less substantial.

6.5.2 Concrete

Fire design guidance for concrete structures is given in EN 1992-1-2 [110], where tabulated wall thicknesses in function of fire resistance are given for both single and two-sided exposure. An extract is provided in Figure 47.

Per the masonry case shown in Section 6.5.1, as the fire resistance demand increases, walls exposed on two sides require a greater thickness than those exposed on one side. For example, to achieve 60 min fire resistance at a load-ratio of 70%, walls exposed on one side need be 130 mm thick which increases to 140 mm thick when exposed on two sides. At 120 min, the difference in wall thickness for single versus two-sided exposure increases from 10 mm to 60 mm (160 mm versus 220 mm).

Standard fire resistance	Minimum dimensions (mm) Wall thickness/axis distance for			
	μ_{fi} = 0,35		μ_{fi} = 0,7	
	wall exposed on one side	wall exposed on two sides	wall exposed on one side	wall exposed on two sides
1	2	3	4	5
REI 30	100/10*	120/10*	120/10*	120/10*
REI 60	110/10*	120/10*	130/10*	140/10*
REI 90	120/20*	140/10*	140/25	170/25
REI 120	150/25	160/25	160/35	220/35
REI 180	180/40	200/45	210/50	270/55
REI 240	230/55	250/55	270/60	350/60

* Normally the cover required by EN 1992-1-1 will control.

Note: For the definition of μ_{fi} see 5.3.2 (3).

Figure 47. Extract from EN 1992-1-2, setting out wall thicknesses for load-bearing walls based on fire resistance demand and exposure condition

6.6 Summary

The review conducted in this section has revealed that the fire resistance of LSF walls can be affected by exposure to fire on both sides. However, it is believed that this concern is not exclusive to LSF walls and is applicable to other wall types such as masonry, concrete, and timber.

The fire design standards for masonry structures (EN 1996-1-2) classify walls as either "separating" or "non-separating" and provide specific guidance for fire design. Similarly, EN 1992-1-2 offers fire design recommendations for concrete structures, including wall thicknesses for both single and two-sided exposure scenarios. These guidelines indicate that walls with higher fire resistance requirements need to be constructed with thicker materials when exposed to fire on both sides, compared to single-sided exposure. However, gaps exist on design methods for assessing the performance of LSF walls when exposed to fire on two sides. It is, therefore, crucial to investigate the implications of double-sided fire exposure of LSF walls and other construction methods where this knowledge gap also exists such as panelised systems like cross-laminated timber (CLT) and other lightweight construction methods, like light timber frame.

7 Conclusions

7.1 Summary of findings

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Department for Levelling Up, Housing and Communities (DLUHC) to deliver the “Real Fires” project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run for three years from this date. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel framing (LSF) walls.

Concerns have been raised by industry (through CROSS-UK) regarding the expected fire performance of buildings that employ light gauge steel framing (LSF) as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides but have not been tested to this situation.

The aim of this study was to systematically review existing studies related to the fire performance of light gauge steel framing (LSF) elements that are exposed to different heating conditions to determine whether the fire resistance rating and structural performance of these elements are likely affected by the number of faces exposed to fire. This will help define the framework for any future experimental and numerical studies of LSF walls exposed to fire on both sides.

A total of 932 articles were obtained from three databases, which were narrowed down to 521 after removing duplicates. In the screening stage, 195 potentially relevant studies were selected for full-text search, and in the full-text eligibility assessment stage, 91 studies were included in the detailed review.

Of the 91 studies selected for detailed review, numerical methods were the most commonly used research method in assessing the performance of LSF walls in fire, accounting for approximately 72% of the total number of publications. Studies that used only numerical and only experimental/test methods account were 49% and 27%, respectively, while both experimental and numerical methods were used in approximately 22% of the total number of publications.

7.1.1 Experimental review

In the examined literature, there is a single paper that considers heat exposure of LSF wall systems (in medium scale) from two sides [50]. However, in addition to this, other studies on LSF walls exposed to fire on one side were reviewed. The following summarises the main conclusions from the review:

- Research has focused extensively on single-sided exposure to fire. This indicates that researchers approach the use of the element as a separating wall, therefore assuming that the element will only be exposed to fire from one side;
- Insulation in the cavity can lead to earlier mechanical failure of the LSF wall, as the temperature of the hot flange increased at a faster rate. The authors of the review are speculating this is due to lower heat losses, as the stud section is insulated;
- Steel sheet, when used as a sheathing material, can provide mechanical reinforcement to the LSF wall (increased structural performance) and also act as a heat sink, delaying heat transfer to the hot flange. This results in longer fire resistance ratings, when R is concerned;
- A larger cavity depth leads to increased fire resistance ratings. This is also applicable for double-stud walls (as the cavity is larger);
- A staggered arrangement of the studs (in a wider cavity arrangement) can lead to failure due to thermal expansion, as was demonstrated through non-loadbearing LSF wall experiments.

For these reasons, and specifically accounting for the CROSS-UK report in question, further experimental investigation is warranted. A proposed experimental programme should aim to understand the structural behaviour of the LSF wall system and investigate the differences between heat exposure of the system from one side only and both sides simultaneously. This will build on the previous knowledge for exposure on one side only and aid to observations of differences in structural behaviour, when the system's thermal boundary conditions change.

7.1.2 Numerical review

From the literature reviewed on numerical studies, it was observed that only one of the existing studies considered cases of the LSF wall exposed to fire on two sides. In the study, it was shown that LSF walls exposed to fire on both sides failed structurally earlier than those exposed to fire on one side only, emphasizing the importance of accounting for fire exposure on both sides in design. Nevertheless, the study had limitations, notably that the finite element (FE) models used were not benchmarked against any tests or experiments and only limited parametric studies were conducted. However, from the other literature reviewed, it was shown that conclusions from the studies on one-sided exposure can be used to inform future finite element modelling studies and what parameters can potentially influence the behaviour of LSF walls when exposed to fire on two sides.

The review showed that for FE models to be able to simulate test and actual design conditions, the FE model should consider the following: LSF wall model idealization adequate for capturing the LSF wall system; analysis type (transient or steady state analysis); mesh size; boundary condition (number of sides exposed, heat transfer coefficient, emissivity, end restraint conditions); temperature dependent properties of LSF wall components; heat transfer within and through air gap / cavity; initial geometric imperfections of LSF wall studs; screws and fastenings and plasterboard joints; and sheathing material fall off.

Several factors were observed from past numerical studies to influence the performance of LSF walls exposed to fire on one side. These factors can be used to form a basis for selecting parameters for future parametric studies of LSF walls exposed to fire on two sides. The factors and their influence on the performance of LSF walls in fire are summarised as follows:

- The fire performance of LSF walls was found to be significantly affected by the type of fire time-temperature curve. Many studies have investigated the fire performance of loadbearing LSF walls under standard fire conditions, but the relevance of these scenarios to actual building conditions is questionable;

- The load ratio plays a significant role in the fire performance of load-bearing and non-load bearing LSF walls. The hot flange temperature of wall studs in loadbearing LSF walls is related to the load ratio and is critical to the steel stud's thermal bowing due to reduced strength at the hot flange. As the load ratio increases, critical temperature and time to failure decrease, and axial displacement is significantly affected. A load ratio beyond 0.4 contributes to a considerable loss of wall ductility, and global buckling occurs when the load ratio is larger;

- The type of steel stud sections used have minimal impact on LSF wall stud performance under fire conditions. However, hollow sections such as Square and Rectangular Hollow Sections (SHS/RHS) have an advantage in cavity-insulated walls as they help reduce thermal bowing deformations and increase structural fire resistance level;

- Increasing the aspect ratio and stud web depth marginally improved the fire behaviour of LSF walls. Increasing stud web depth led to an increased fire resistance rating, with higher depths providing higher bending capacity and reduced lateral displacement. However, higher stud depths also increased the risk of local buckling failure mode;

- Increasing steel thickness can lead to improved fire performance of LSF walls, with higher fire resistance rating and reduced hot flange temperatures;

- The type of sheathing board used did not affect the failure modes of LSF walls. However, out-of-plane restraints provided by sheathing boards significantly improved the fire resistance of LSF wall studs under non-uniform elevated temperature distributions;
- Cavity insulation can enhance the insulation fire resistance level of non-load bearing walls but reduces the fire resistance level of load-bearing walls. Lightweight concrete filling can improve fire performance but increases the weight of the wall panel;
- The fire performance of LSF walls was significantly affected by wall configuration, including the number of plasterboard layers and insulation provision and location;
- The performance of LSF walls under standard fire conditions can be improved by using specific wall configurations, such as modified warm-frame construction and modular LSF wall panels, with recommended choices for plasterboard layers and insulation location;
- Sheathing board fall-off from LSF walls during fire exposure increases the rate of temperature rise at the stud section, and it significantly impacts the fire resistance performance of LSF walls;
- Screw connectivity does not influence the fire performance of LSF wall studs, but improved connectivity may reduce plasterboard fall-off;
- Use of noggings can reduce thermal bowing deflections and improve the fire performance of LSF walls;
- Use of loadbearing SHS steel columns located at intervals along the length of LSF walls can increase the load carrying capacity of LSF walls. When the loadbearing SHS steel columns are utilized in the LSF wall build-up, the non-load bearing LSF wall stud section and material type used has no effect on the fire resistance level.

7.1.3 Potential challenges for other forms of construction

The review conducted herein have shown that the effect of double-sided exposure could have implications for the fire resistance of LSF walls exposed to fire. However, it is postulated that this is also a concern for other wall types (masonry, concrete and timber). The fire design of masonry structures as set out in EN 1996-1-2, distinguishes walls as either a “separating wall” or a “non-separating wall”. For concrete structures, fire design guidance is given in EN 1992-1-2, with tabulated wall thicknesses for both single and two-sided exposure. In these documents, walls with higher fire resistance demands require thicker construction when exposure is on two sides versus one. This indicates that double-sided exposure is more severe than single-sided exposure and should be investigated for all forms of construction, i.e., it is also likely to have implications for other light framing solutions, such as timber frame, as well as panelised forms of construction, like cross laminated timber (CLT) and other lightweight construction methods, like light timber frame.

7.2 Limitations and areas for future research

This review has examined the fire performance of light gauge steel framing (LSF) elements exposed to different heating conditions. The review shows that existing experimental and numerical studies have mainly focused on one-sided exposure, and further experimental investigation is needed to understand the structural behaviour of LSF wall systems exposed to fire from both sides. The review also highlights several factors that impact the fire performance of LSF walls and discusses different approaches for fire resistance design of loadbearing walls in different materials. Therefore, further experimental studies that specifically address the issue of double-sided exposure of LSF walls are required. Due to the expensive nature of experiments/tests, it is not possible to investigate all possible factors that could influence the performance of LSF walls when exposed to fire on two sides simultaneously. Therefore, validated FE models may offer utility in supporting detailed and extensive parametric studies.

Furthermore, design equations exist in guidance documents for assessing the performance of LSF walls exposed to fire, however, these are for one-sided fire exposure. There is a need for research on LSF walls exposed to fire on two sides to determine whether current design equations can be used or modified.

8 FUTURE WORK PACKAGES / NEXT STEPS

The research project to study the fire resistance performance of LSF walls exposed to fire is organised in two work packages (WP) described below:

- WP1: Literature review on the fire resistance performance of LSF walls exposed to fire.
- WP2: Generate data and evidence on the fire resistance performance between single-sided and double-sided exposure of LSF wall elements to support the department understand the risk to existing buildings. WP2 is split into two sub packages:
    - WP2a – benchmark furnace tests for LSF walls; and
    - WP2b – desktop / modelling appraisal of the implications of fire resistance specification of LSF walls for their ability to survive burn-out.

The literature review (WP1) presented in this report is the first of the two work packages and forms the foundation for the second work package (WP2).

The review shows that extensive experimental and numerical studies have been conducted on LSF walls exposed to fire on one side. However, studies on the performance of LSF walls exposed to fire on two sides are very limited. As detailed in Sections 4 - 6, the review identifies experimental and numerical modelling options for assessing the performance of LSF walls in fire and factors that influences the performance of LSF walls when exposed to fire.

Three key observations from the review informing decisions on the testing programme and numerical parameters to be considered in carrying out WP2 include:

i. There is lack of test data for two-sided exposure of LSF walls. This justifies the need for two-sided exposure testing to be carried out in WP2a.

ii. Where experimental and numerical modelling data exists, they show that the insulation between the studs has a significant impact and, therefore, this is a variable that should be considered.

iii. Evidence from other materials suggests that two-sided exposure is more significant at higher fire resistance demands. Therefore, to observe the biggest difference between single- and two-sided fire exposure of LSF walls, investigation of high fire resistances is most likely to elucidate that difference.

Furthermore, findings from the review suggest that the performance of LSF walls exposed to fire on two sides can be reliably modelled when benchmarked against tests.

Based on the findings of the literature review stage, the next step is to progress to the second work package (WP2), which is split into two sub packages, WP2a and WP2b.

WP2a involves furnace tests to compare the fire resistance achieved by LSF walls under the same mechanical loading conditions, but subject to fire on one side, or both sides simultaneously. A research report setting out what was tested, why, how it was designed and what was observed / measured will be produced at the end of this sub work package.

WP2b involves development of a numerical representation (using finite element method) that can reproduce the thermal and mechanical performance observed in tests undertaken during WP2a, followed by parametric studies investigating how sensitive or otherwise LSF walls exposed on two sides are to potential delays in thermal exposure associated with internal or external fire spread. Factors to consider in the parametric studies will be based on those identified in this literature review (see Section 5) as having impact on the performance of LSF walls exposed to fire.

At the completion of WP2, a final research report will be produced which will combine the findings from WP1, WP2a and WP2b.

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Appendix B – WP2A REPORT: BENCHMARK FURNACE TESTS FOR LSF WALLS

Light gauge steel frame (LSF) walls exposed to fire: Fire test report (WP2a)

Real fires project CPD/004/122/039

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR), who are part of the Government Agency, The Health and Safety Executive (HSE), to deliver the "Real Fires" project in support of fire safety technical policy. The Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC, formerly the Ministry for Housing Communities and Local Government, MHCLG, and now BSR), originally commissioned this project on the 22nd of October 2021. The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date for three years. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel framing (LSF) walls.

LSF wall systems are characterised by three main components: cold-formed steel studs for load bearing, sheathing and insulation materials. Concerns have been raised by industry through Collaborative Reporting for Safer Structures UK (CROSS-UK) regarding the expected fire performance of buildings that employ LSF as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides, with typical classification testing concerned with single sided exposure.

This research project to investigate the performance of load bearing LSF walls exposed to fire on two sides is split into two work packages. The first work package (WP1) involved conducting a comprehensive literature review focused on assessing the fire resistance performance of LSF walls when exposed to fire. The findings of this study have been issued to the BSR. The second work package (WP2) involved generating data and evidence concerning the fire resistance performance of LSF walls under one-sided and two-sided fire exposure. WP2 was arranged into two elements. The first (a) being concerned with fire resistance tests of LSF walls and the second (b) being a subsequent numerical parametric study.

This report is the first part of WP2 to conduct benchmark furnace tests on LSF walls exposed to fire on two sides to determine whether the loadbearing performance of LSF walls is likely affected by the number of faces simultaneously exposed to fire. A total of four wall specimens were tested at ITB in Poland, two each (with and without cavity insulation) for single- and two-sided fire exposure conditions under the ISO 834 heating regime. During the tests, internal and external temperatures, as well as vertical and lateral (where feasible to do so) deflection of the wall specimens were measured and recorded. The test was conducted until failure of the steel studs occurred, with failure defined as a loss in loadbearing capacity, indicated by runaway vertical / lateral deflection.

The main findings from the tests are that exposure of LSF walls to fire on two sides markedly intensifies heating compared to one-sided exposure, evidenced by higher stud temperatures and accelerated rates of increase particularly at higher fire resistance periods. The loadbearing capacity of LSF walls is considerably reduced under two-sided fire, dropping to 44% for non-insulated and 62% for insulated walls, relative to one-sided exposure. While cavity insulation precipitates a notable temperature gradient and subsequent early failure in one-sided exposure, its impact is negligible in two-sided scenarios. Furthermore, fire resistance classifications for single-sided exposure should not be extrapolated to two-sided exposure.

1 INTRODUCTION

1.1 Appointment

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR) to deliver the "Real Fires" project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run for three years from this date. During the period of this engagement, the Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC) (formerly the Ministry for Housing Communities and Local Government), who originally commissioned this project has been novated to the Building Safety Regulator (BSR) who are part of the Government Agency, The Health and Safety Executive (HSE). The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake a research project on the fire performance of light gauge steel framing (LSF) walls.

The research project is organised into two work packages (WP) described below:

- WP1: Literature review on the fire resistance performance of LSF walls exposed to fire.
- WP2: Generate data and evidence on the fire resistance performance between single-sided and double-sided exposure of LSF wall elements to support the BSR in understanding the risk to existing buildings and any future changes in fire safety guidance that may be necessary in the future. WP2 is split into two sub packages:
    - WP2a – benchmark furnace tests for LSF walls; and
    - WP2b – desktop / modelling appraisal of the implications of fire resistance specification of LSF walls for their ability to survive burn-out.

The literature review work package (WP1) has been completed, and report issued to BSR on 13/07/2023[1]. The review formed the foundation for the second work package (WP2).

This report represents the culmination of WP2a and summarises the results of the fire tests of LSF walls exposed to fire. It sets out what was tested, why, how it was designed and what was observed / measured. The testing was conducted by a third-party lab, Building Research Institute (ITB), Poland. The results from the test will be used to validate numerical models in support of parametric studies to be carried out in WP2b.

1.2 Background

LSF walls are commonly used in modern building construction [1]. They consist of three main components: cold-formed steel studs, sheathing material, and may include insulation [2]. LSF walls may be used as fire-separating walls to mitigate fire and smoke spread from one compartment to another and limit temperature increase on the unexposed surface for a specified period [3]. LSF walls also find application as both loadbearing and non-loadbearing walls which may not have a fire-separating function. A typical LSF wall system is shown in Figure 1. A more detailed review of the components of an LSF wall system, types of LSF wall systems, characteristics of LSF wall system, and use of LSF wall in construction has been carried out as part of WP1.

[1] Report ref: 230713-R00-OX21041-Light gauge steel literature review-RR-CIC; Date of issue: 13/07/2023.

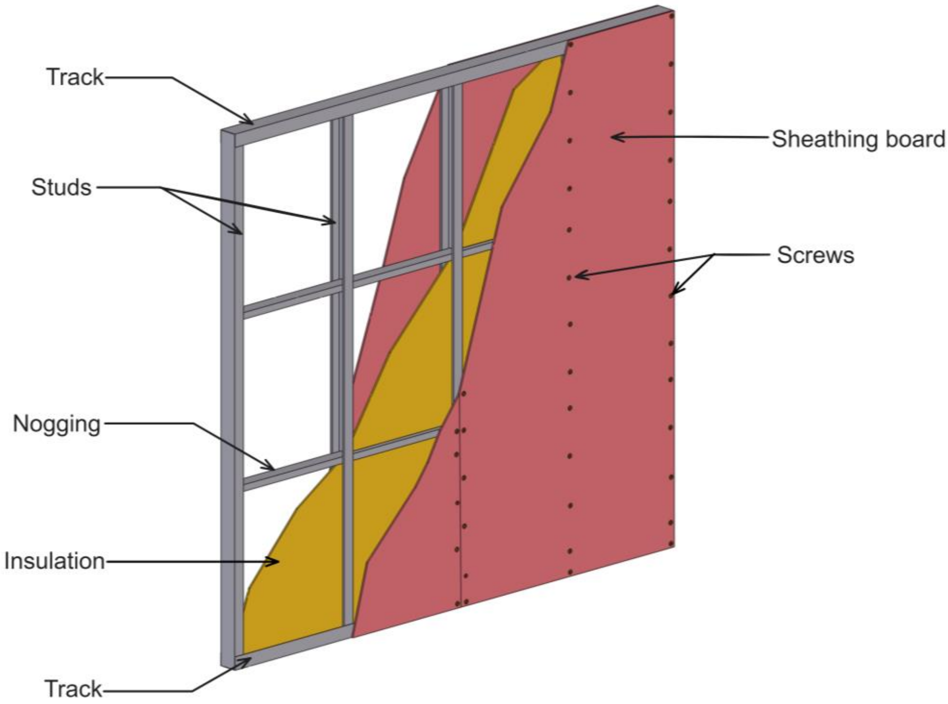

Figure 1. Typical LSF wall system

Concerns have been raised by industry regarding the expected fire performance of internal loadbearing LSF wall systems [4]. There is a level of uncertainty arising from the potential exposure of internal loadbearing walls to heating conditions on both sides. These walls may be architecturally separating elements, but not fire-separating elements, e.g., they do not form part of a compartment boundary. This means that where a compartment is fully involved in a fire, these walls will be exposed to fire on both sides and may not perform as expected in terms of loadbearing capacity compared to when heated from just one side. A similar concern has also been raised by industry [5] for external loadbearing walls afforded non-fire-resisting cladding, where flames emanating from an enclosure fire can heat the external surface of an LSF wall, with the internal face simultaneously heated by the internal fire.

The literature review undertaken in WP1 showed that there is currently a knowledge gap regarding the expected structural performance of LSF elements that are exposed to heating conditions on both sides. Three key observations made from the literature review study are:

i. There is lack of test data for two-sided exposure of LSF walls. The review showed that there have been no experiments carried out on LSF walls simultaneously exposed to fire on both sides. This justifies the need for two-sided exposure testing.

ii. Where experimental and numerical modelling data exists (i.e., for one-sided exposure), they show that the insulation between the studs has a significant impact and, therefore, this is a variable that should be considered.

iii. Evidence from other materials suggests that two-sided exposure is more significant at higher fire resistance demands. Therefore, to observe the biggest difference between single- and two-sided fire exposure of LSF walls, investigation of high fire resistances is most likely to elucidate that difference.

Furthermore, current design guidance in England (Table B3 of Approved Document B [6]) does not explicitly identify a need to test for two-sided exposure.

Finite element modelling (FEM) has been used extensively to investigate the performance of LSF walls exposed to fire on one side, e.g. [7]. FEM is one way designers may attempt to address the lack of a universally accepted design approach for LSF walls exposed to fire on two sides. Whilst this may be a valid means of evidencing performance, given a lack of experimental/test data, the assessment of such modelling remains a cause for concern as there is a limited basis for benchmarking.

To resolve the uncertainty that arises from the lack of data, and to improve confidence in future FEM studies, an experimental programme was deemed necessary.

1.3 Aim of the experiments

The aim of the study presented in this report was to carry out an experimental investigation of the loadbearing performance of LSF walls with both one- and two-sided fire exposure, to determine whether the loadbearing performance of LSF walls are likely affected by the number of faces simultaneously exposed to fire.

Based on the outcome of the literature review as highlighted in Section 1.2, a total of four wall specimens were tested, two each (with and without cavity insulation) for single- and two-sided fire exposure conditions. The walls were designed to achieve a high (minimum of 90-minute) fire resistance rating under single-sided fire exposure, when afforded cavity insulation.

This report aims to compare the performance of the LSF walls under one-sided and two-sided fire exposure from the experiments conducted and described herein. It only covers what was observed / measured during the tests and does not discuss the relationship of the test results with (or make reference to results of) existing literature on the loadbearing performance of LSF walls in fire. Comparison of the outcomes of the experimental investigation with previous studies will be presented in the final report to be issued as part of WP2b.

1.4 Structure of the report

The subsequent sections of this report details how the report is structured to deliver on the aim of the experimental programme, as set out below:

- **Experimental programme (Section 2):** This section describes the test setup, fire exposure conditions, specimen characteristics and material properties, and parameters investigated and how they were measured/observed.
- **Results and analysis (Section 3):** This section presents observations from the experiments, temperature-time plots, deflection measurements during the test, and failure times.
- **Discussion (Section 4):** This section provides a comparative examination of single vs two-sided fire exposure conditions, and the impacts of cavity insulated versus non-insulated LSF walls. It also discusses the structural responses of the different LSF wall systems tested and the implications of the test outcomes.
- **Conclusions (Section 5):** This section provides a synthesis of the key findings for each test scenario, suggests practical design implications and proposes areas for future experimental and numerical research.
- **Future work packages / Next steps (Section 6):** Based on the outcome of the experimental programme, this section briefly discusses the final (outstanding) work package (WP2b) on the numerical modelling and parametric studies of LSF walls exposed to fire on two sides.
- **Appendices:** This section contains supplementary material such as additional measurements from the tests (Appendix A) and the ITB test reports (Appendix B).

2 EXPERIMENTAL PROGRAMME (ONE-SIDED VS TWO-SIDED FIRE EXPOSURE)

This section present details of the experimental programme to determine the impacts of two-sided fire exposure on the loadbearing performance of LSF walls. It covers the test method (Section 2.1), description of test specimens (Section 2.2), test setup for the one-sided and two-sided tests (Section 2.3), load application (Section 2.4), test instrumentation and measurements (Section 2.5), criteria for termination of the tests (Section 2.6), and summary of test parameters (Section 2.7).

Four wall build-ups were tested. These are:

- Test 1: Two-sided fire exposure, no insulation
- Test 2: One-sided fire exposure, no insulation
- Test 3: Two-sided fire exposure, with cavity insulation
- Test 4: One-sided fire exposure, with cavity insulation

2.1 Test method

In England, fire testing applicable for load bearing LSF walls are as per European Standard BS EN 1365-1:2012 '*Fire resistance tests for loadbearing elements - Part 1: Walls*' [8], and British Standard BS 476-21:1987 '*Fire tests on building materials and structures – Part 21: Methods for determination of the fire resistance of loadbearing elements of construction*' [9]. Both standards are generally applicable to one-sided fire exposure. BS EN 1365-1 notes that non-separating load bearing walls with potential to be exposed to fire on both sides can be tested as columns in accordance with BS EN 1365-4:1999 '*Fire resistance tests for loadbearing elements – Columns*' [10]. Similar recommendations for testing of loadbearing walls with potential to be exposed on both sides simultaneously as columns is also given in BS 476-21:1987.

The test methods adopted for the testing of the LSF walls in this project are as per BS EN 1365-1:2012 for the one-sided fire exposure test, and BS EN 1365-4:1999 for the two-sided test. Both BS EN 1365-1:2012 and BS EN 1365-4:1999 further note that the tests shall be carried out using equipment and procedures in accordance with BS EN 1363-1 '*Fire resistance tests – Part 1: General requirements*' [11].

2.2 Description of test specimens

The tested LSF wall system comprised of cold-formed steel studs and sheathing boards, with the addition of insulation material within the cavity for the insulated wall.

The steel stud section used was a lipped channel section with nominal dimensions as follows: depth of 89 mm, width of 41 mm, thickness of 1.2 mm and stiffener depth of 11 mm; and a specific mass of 1.75 kg/m. The steel grade was S350GD.

The sheathing material was 2 layers (nominal thickness of 15 mm each) of fire rated gypsum board with a measured density ranging from 12.6 kg/m² to 13.0 kg/m² for the four different tests, ambient temperature thermal conductivity of 0.2 W/mK and measured moisture content of between 0.2% and 0.3%. The gypsum boards were attached to the studs with self-drilling screws at 300 mm centres at each board edge and each board mid-width over a stud. The screws used were TB 3.5×35 mm for the first layer and TB 3.5×55 mm for the second layer. The free vertical side edges of the wall were covered with two layers of the boards, the same as the 'wall' surfaces. Gypsum filler was used as the jointing compound to seal the joints between plasterboards.

The insulation material used (for the cavity insulated wall specimens) was mineral wool insulation completely filling the cavity between the studs and the sheathing boards, with density of 35.1 kg/m³, ambient temperature thermal conductivity of 0.036 W/mK and 0.8% moisture content.

The tested wall build-up was 3 m wide by 3 m high with 6 studs spaced at 600 mm centres. Figure 2 and Figure 3 show a section of the tested wall specimen with no insulation and with cavity insulation provided, respectively. The tested walls were expected to achieve a minimum of 90-minute fire resistance rating under one-sided fire exposure when afforded cavity insulation.

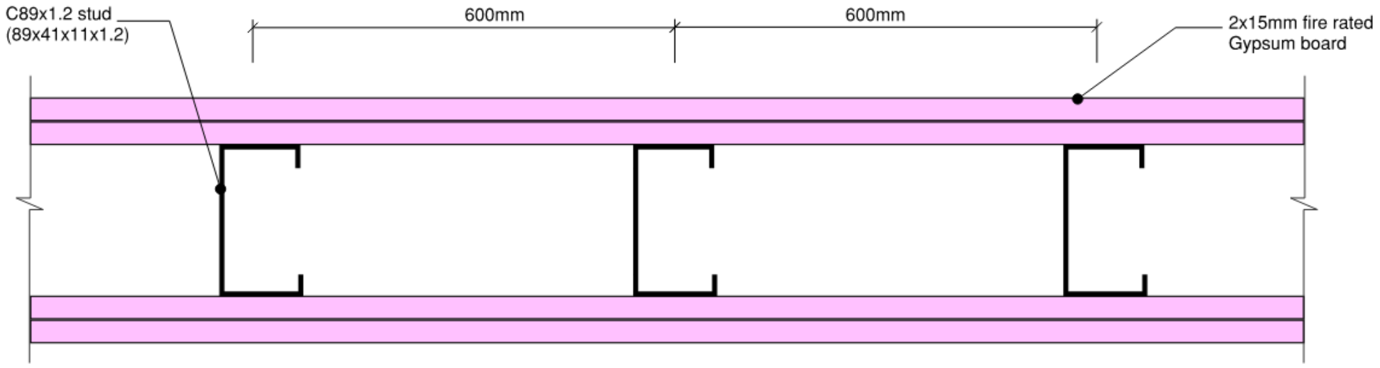

Figure 2. Section of tested LSF wall (no insulation)

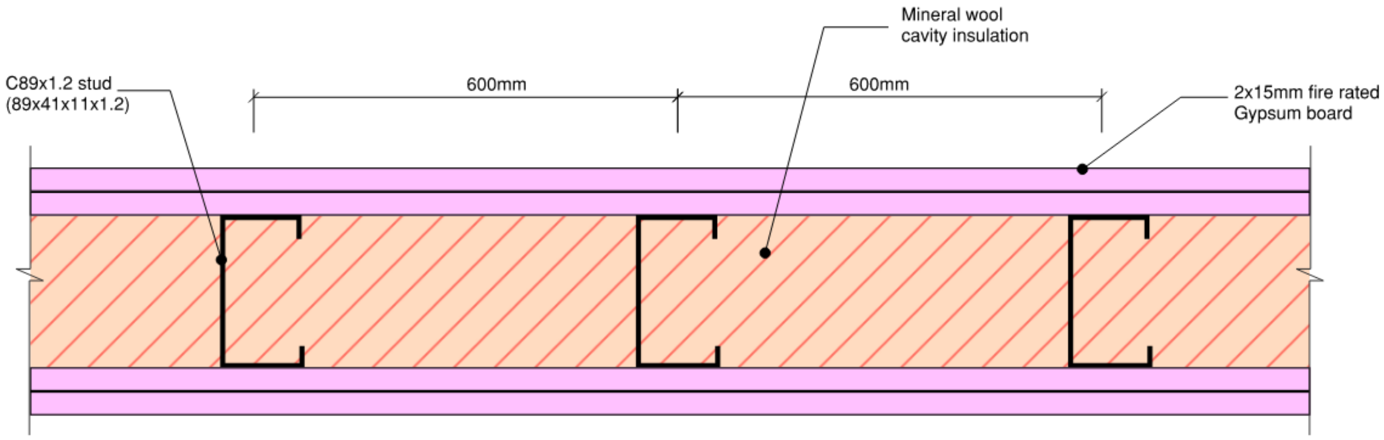

Figure 3. Section of tested LSF wall (with cavity insulation)

2.3 Test setup

The wall specimens were constructed outside of the furnace and then lowered into the furnace via a gantry crane and mounted vertically to enable it to be exposed to heating as required.

The test was conducted in a furnace with dimensions able to accommodate the wall specimen. Internal dimensions of the furnace chamber were 3.3 m x 4.3 m. For the one-sided test, the wall was placed at the end of the furnace and heated on one side only. For the two-sided test, the wall placed at the centre of the furnace along the longer side (resulting in approximately 0.65 m of free space at both ends of the wall) and heated on both sides simultaneously. In both cases, the wall was fixed to a masonry plinth at the bottom and loaded at the top. The furnace followed the ISO 834 heating regime [12], which was achieved through the use of propane gas burners. Figure 4 – Figure 6 show a sketch of the plan and elevation of the wall specimen inside the furnace for both exposure conditions.

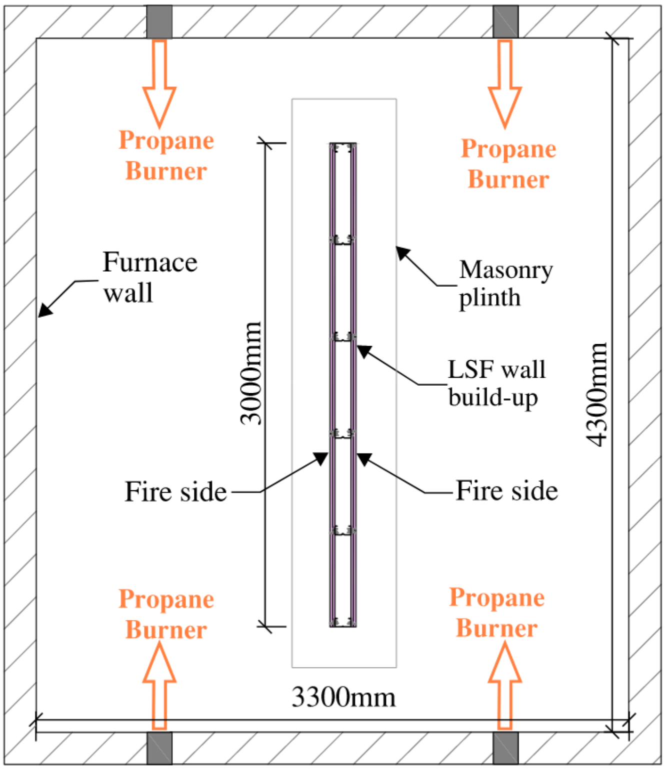

Figure 4. Sketch plan of test setup (two-sided test)

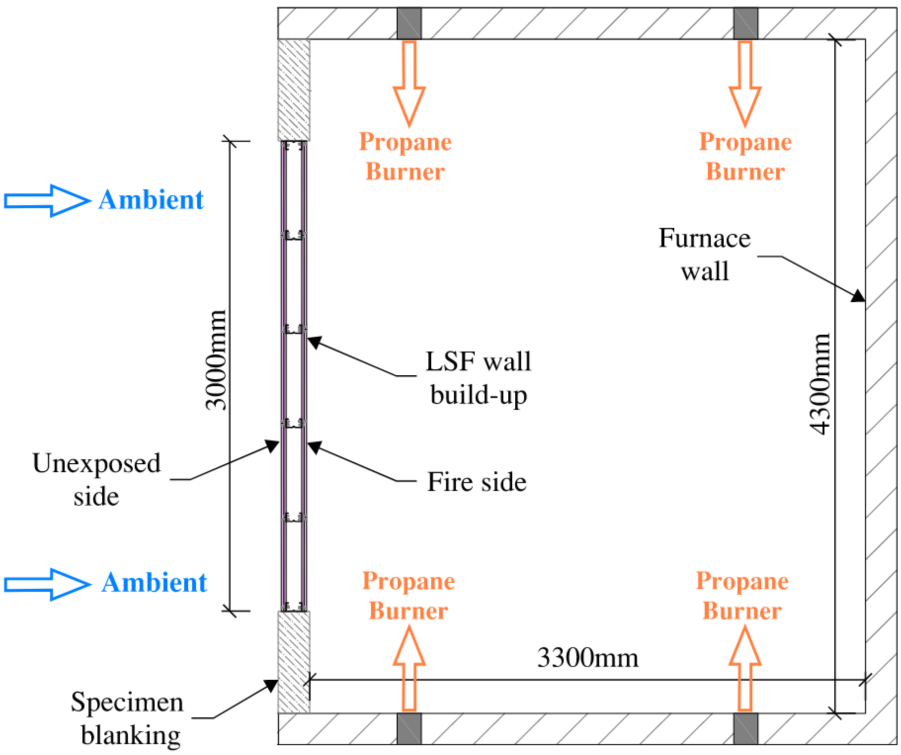

Figure 5. Sketch plan of test setup (one-sided test)

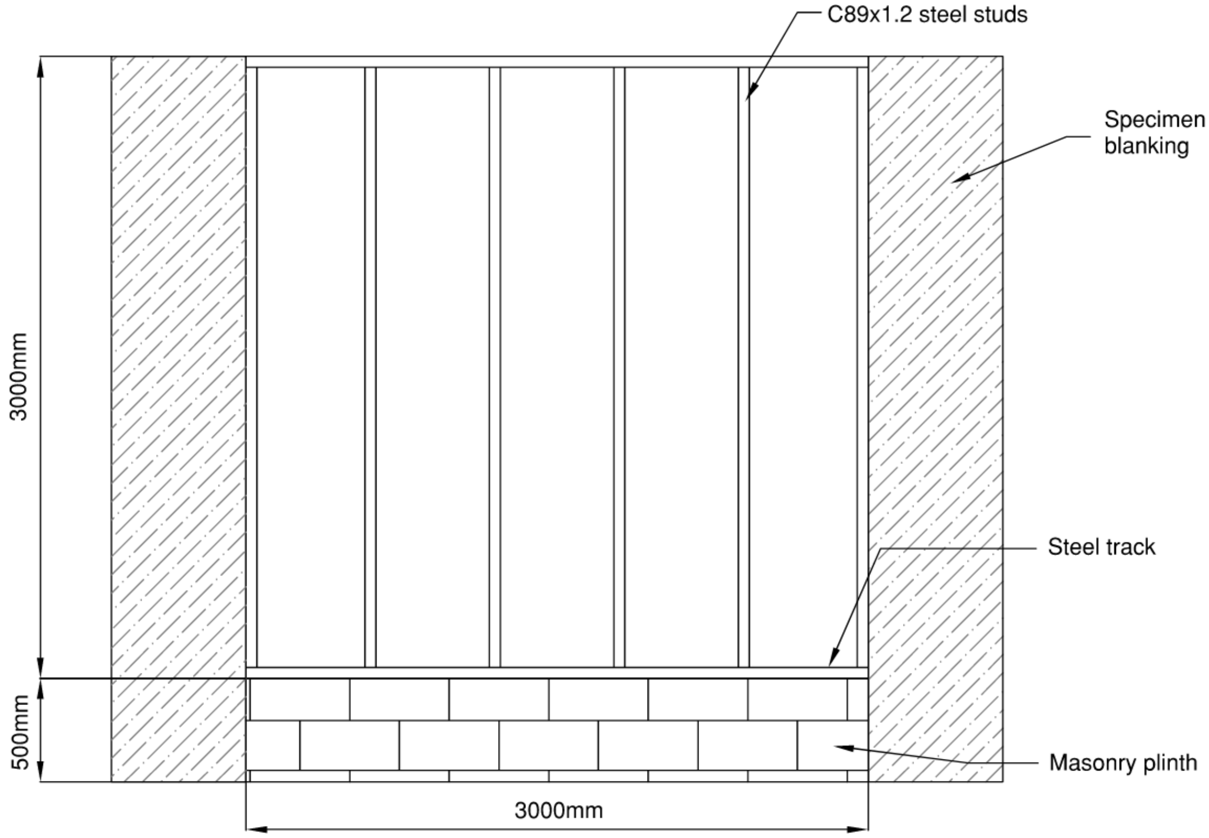

Figure 6. Elevation of test setup (one-sided test)

2.4 Load application

The load was applied axially to the wall specimen by means of a beam and actuator at the top edge of the wall. The total load applied to the wall was 80 kN i.e., 13.3 kN per stud. The load on the test specimen was increased gradually from 0 kN to 80 kN in 10 minutes and then sustained at the full test load (80 kN) for 20 minutes before the commencement of the test.

2.5 Test instrumentation and measurements

2.5.1 Furnace temperature measurements

The furnace was provided with plate thermometers to record the gas temperature during the experiments. The plate thermometers were distributed to give a reliable indication of the average temperature in the vicinity of the test specimen and positioned so that they are not in contact with flames from the furnace burners and that they are at least 450 mm away from any wall, floor or roof of the furnace. Figure 7a) and Figure 7b) show a picture of the test setup and the location of the plate thermometers, for the two sided and one-sided fire exposure tests, respectively.

(a) Two-sided fire exposure (b) One-sided fire exposure

Figure 7. Picture of test setup showing location of plate thermometers for gas temperature measurements

2.5.2 Internal temperature measurements of steel studs

Each wall specimen was provided with 20 internal thermocouples mounted on the flanges and web of the steel studs at different locations (the two middle studs and adjacent studs) to record the temperature rise of the steel. For the two middle studs, thermocouples were provided at three different locations along the height of each stud (top ¼ height, mid-height, and bottom ¼ height) with thermocouple group TE1 to TE6. The adjacent studs were provided with thermocouples at mid-height of the stud (thermocouple group TE7 and TE8). Each of TE1 to TE6 have three thermocouples provided (at the two flanges – flange 1 and flange 2, and the web)[2] at each location of the studs. TE7 and TE8 have one thermocouple located at the web of the section. Figure 8 is a section drawing of the wall showing the location of the internal thermocouples and Figure 9 shows a picture of one of the test specimens with fixing of the internal thermocouples in progress.

The siting of thermocouples was such that information on the temperature profile of the studs could be gained. The internal thermocouples were fixed so as not to affect the performance of the test specimen.

[2] As shown in Figure 8, for the one-sided test, Flange 2 is the flange near the unexposed face of the wall.

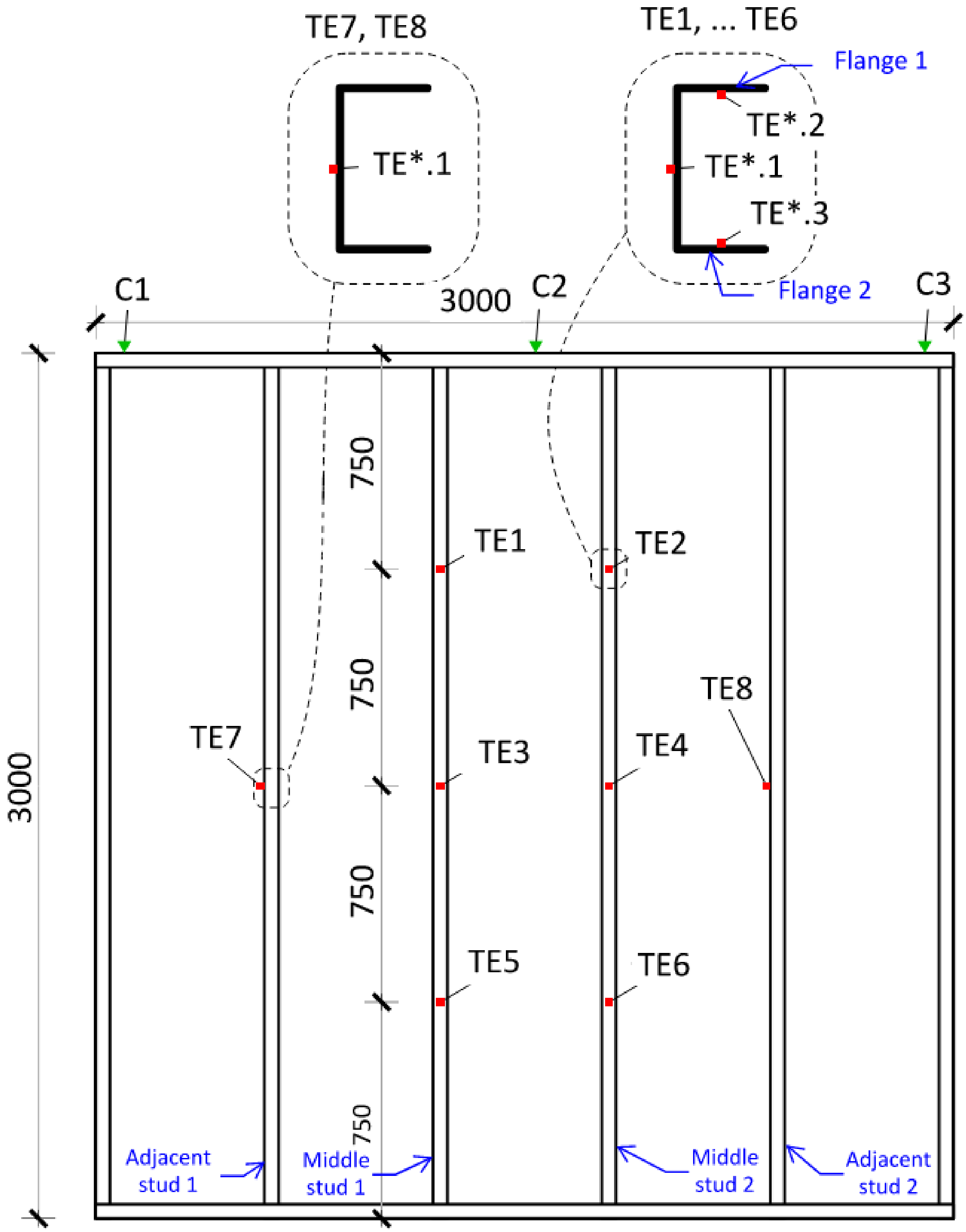

Figure 8. Section drawing showing location of internal thermocouples and deflection gauges

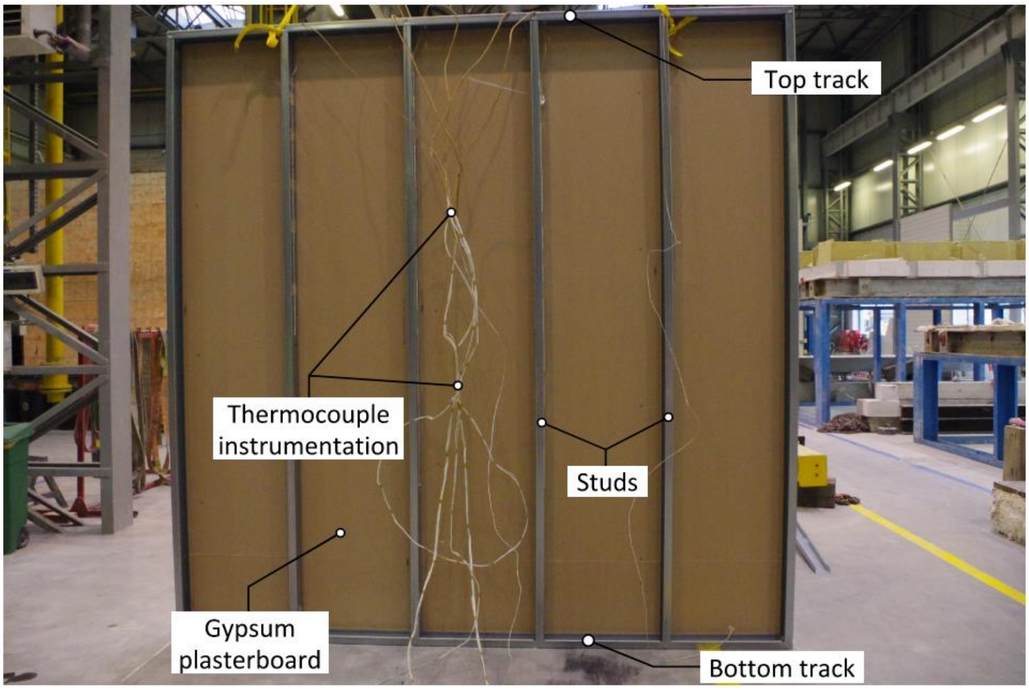

Figure 9. Fixing of internal thermocouples in progress

2.5.3 Unexposed surface temperature (one-sided test)

For the one-sided test, the unexposed wall surface temperature was also measured. Thermocouples (21 nos. – TE1 to TE21) were attached to the unexposed face to measure the average (TE1 to TE6) and the maximum (TE1 to TE21) temperature rise. The purpose of the average unexposed face temperature measurement was to determine the general level of insulation of the test specimen while disregarding hotspots. The average temperature rise on the unexposed surface was thus based upon measurements obtained from surface thermocouples located at or near the centre of the test specimen and at or near the centre of each quarter section of the wall. The purpose of maximum unexposed face temperature measurement was to determine the level of insulation at those locations where higher temperatures are expected to occur. Figure 10 is an elevation drawing and Figure 11 is a picture of the mounted test specimen, both showing the location of the external thermocouples.

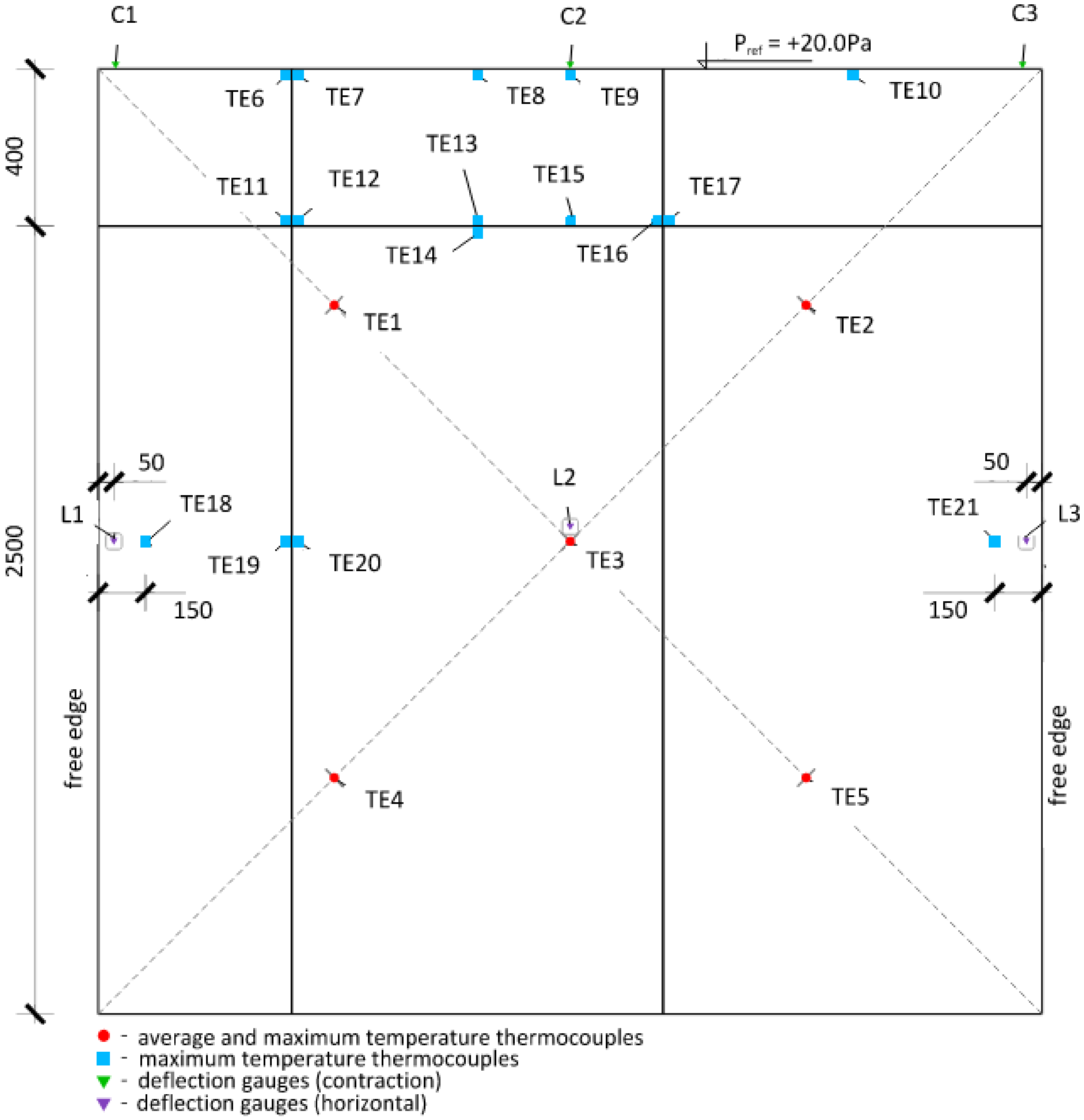

Figure 10. Location of external thermocouples, deflection gauges and pressure reference

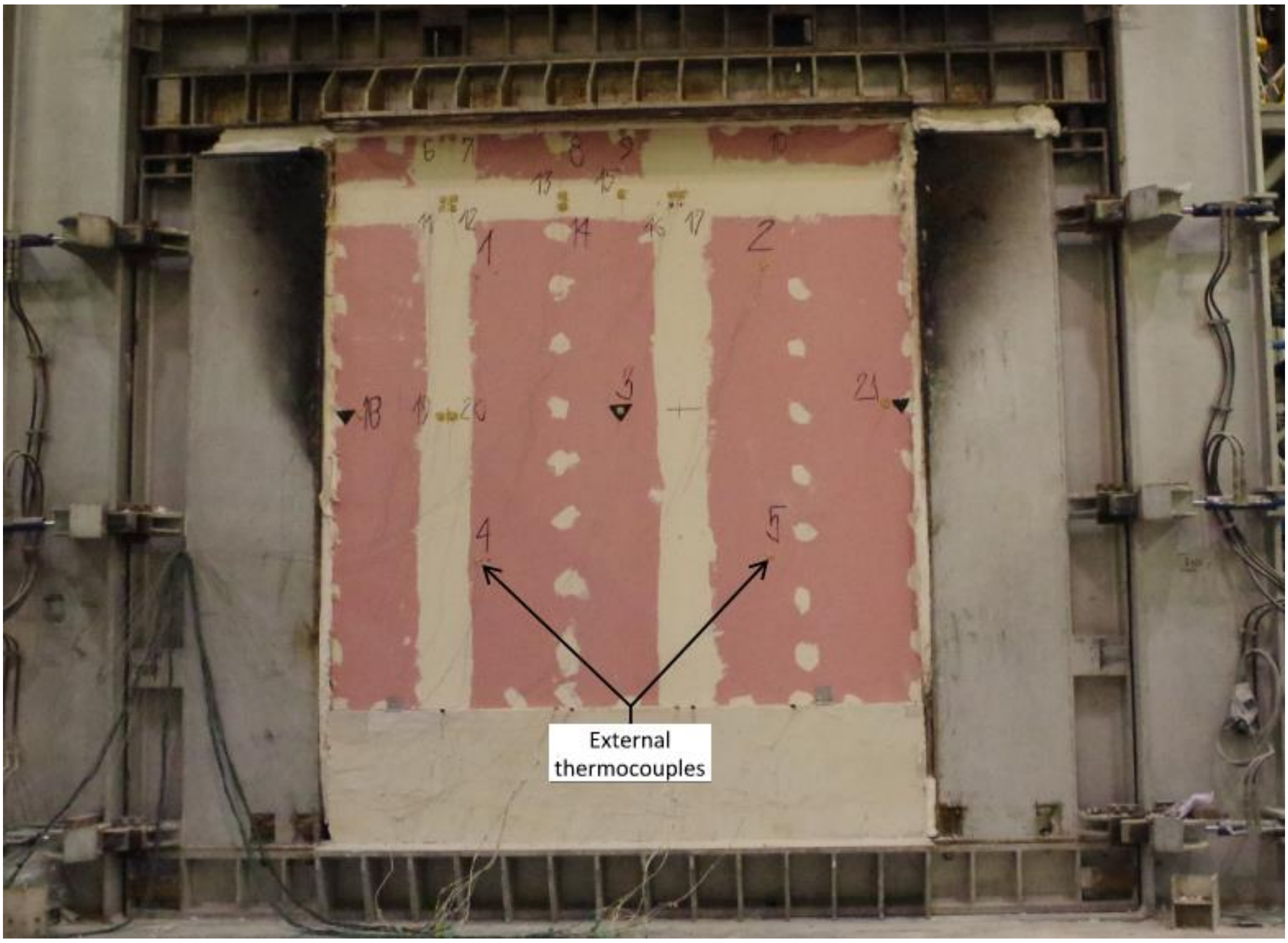

Figure 11. Picture of mounted wall specimen showing location of external thermocouples

2.5.4 Deflection measurements

The axial deflection of the wall was measured by gauges suitably arranged to measure the vertical deflection (contraction) and horizontal (lateral) deflection of the wall during the test. The zero point for the deflection is measured after applying the (full) load at the beginning of the test and before the commencement of heating. Horizontal deflection was only measured and recorded for the walls exposed to fire on one side with the gauges fixed on the surface of the unexposed plasterboard. Horizontal deflection was not measured for the two-sided tests because the instrumentation will be exposed directly to furnace heating and damaged in the process, as it involves fixing a wire and transducer to the mid-height of the wall inside the furnace. Location of the deflection gauges (contraction gauges – C1, C2 and C3; horizontal deflection gauges – L1, L2 and L3) are shown in Figure 8 and Figure 10.

2.5.5 Furnace pressure and power measurements

Pressure within the furnace was measured as described in EN 1363-1 by pressure gauges located 0.1 m below the top edge of the wall specimen. The furnace power (i.e., the rate at which the furnace releases heat energy such that the furnace temperature follows the gas temperature-time relationship of ISO fire) was also measured.

2.6 Commencement and termination of test

At the commencement of the test, the initial temperatures recorded by all thermocouples were checked to ensure consistency and the datum values were established. Similar datum values were also obtained for the deflection gauges. Ambient temperature and humidity were also measured and recorded.

The test was conducted until failure of the steel studs occurred, with failure defined as a loss in loadbearing capacity, indicated by runaway vertical / lateral deflection.

All measurements (temperature, applied load, deflection, furnace pressure and furnace power) were made and recorded at 15 s interval for the duration of the test.

2.7 Summary of test parameters

A summary of the test parameters discussed in Sections 2.1 - 2.6 are presented in Table 1.

Table 1. Summary of test parameters

Parameter		Test ID			
		LZP01	LZP02	LZP03	LZP04
Number of faces exposed		Two-sided	One-sided	Two-sided	One-sided
Insulation type		None	None	Cavity insulation	Cavity insulation
Test method		EN 1365-4:1999	EN 1365-1:2012	EN 1365-4:1999	EN 1365-1:2012
Heating regime		ISO 834	ISO 834	ISO 834	ISO 834
Steel stud	Section type	Lipped channel	Lipped channel	Lipped channel	Lipped channel
	Dimensions [mm]	89x41x11x1.2	89x41x11x1.2	89x41x11x1.2	89x41x11x1.2
	Specific mass [kg/m]	1.75	1.75	1.75	1.75
	Grade	S350GD	S350GD	S350GD	S350GD
Sheathing board	Material	Gypsum plasterboard	Gypsum plasterboard	Gypsum plasterboard	Gypsum plasterboard
	No. of layers	2	2	2	2
	Thickness of each layer [mm]	15	15	15	15
	Density [kg/m²]	12.6	12.6	13.0	12.9
	Thermal conductivity [W/mK]	0.2	0.2	0.2	0.2
	Moisture content [%]	0.3	0.3	0.3	0.2
	Fixing to steel frame (first layer)	TB 3.5×35 mm screws at 300 mm c/c	TB 3.5×35 mm screws at 300 mm c/c	TB 3.5×35 mm screws at 300 mm c/c	TB 3.5×35 mm screws at 300 mm c/c
	Fixing to steel frame (second layer)	TB 3.5×55 mm screws at 300 mm c/c	TB 3.5×55 mm screws at 300 mm c/c	TB 3.5×55 mm screws at 300 mm c/c	TB 3.5×55 mm screws at 300 mm c/c
Insulation	Material	--	--	Mineral wool	Mineral wool
	Density [kg/m³]	--	--	35.1	35.1
	Thermal conductivity [W/mK]	--	--	0.036	0.036
	Moisture content [%]	--	--	0.8	0.8
Applied load [kN]		80	80	80	80
Ambient conditions	Temperature [°C]	19.6	19.5	17.3	19.1
	Humidity [%]	35	53	35	31
Initial furnace temperature [°C]		19.2	21.7	21.2	18.2
Date of test		19/10/2023	31/10/2023	09/11/2023	24/11/2023

3 Results and analysis

This section presents the results of the tests in the form of plots of the furnace temperature, temperature of the steel studs, deflection measurements and temperature of the unexposed surface (for the one-sided test).

Plots of force (load application), furnace pressure and furnace power are presented in the appendix (Appendix A) for reference purpose and are not discussed further in this report as they are not directly relevant for assessing the impact of two-sided fire exposure on the load bearing capacity of LSF walls compared to one-sided exposure condition.

3.1 Furnace temperature

Figure 12 plots the average, minimum and maximum furnace temperatures recorded during the tests and compares it with the ISO fire curve. For all four test cases, the average furnace temperature mirrors the ISO fire curve. The range between the maximum and minimum furnace temperature is relatively small, indicating that the furnace temperatures were consistent with the ISO fire curve.

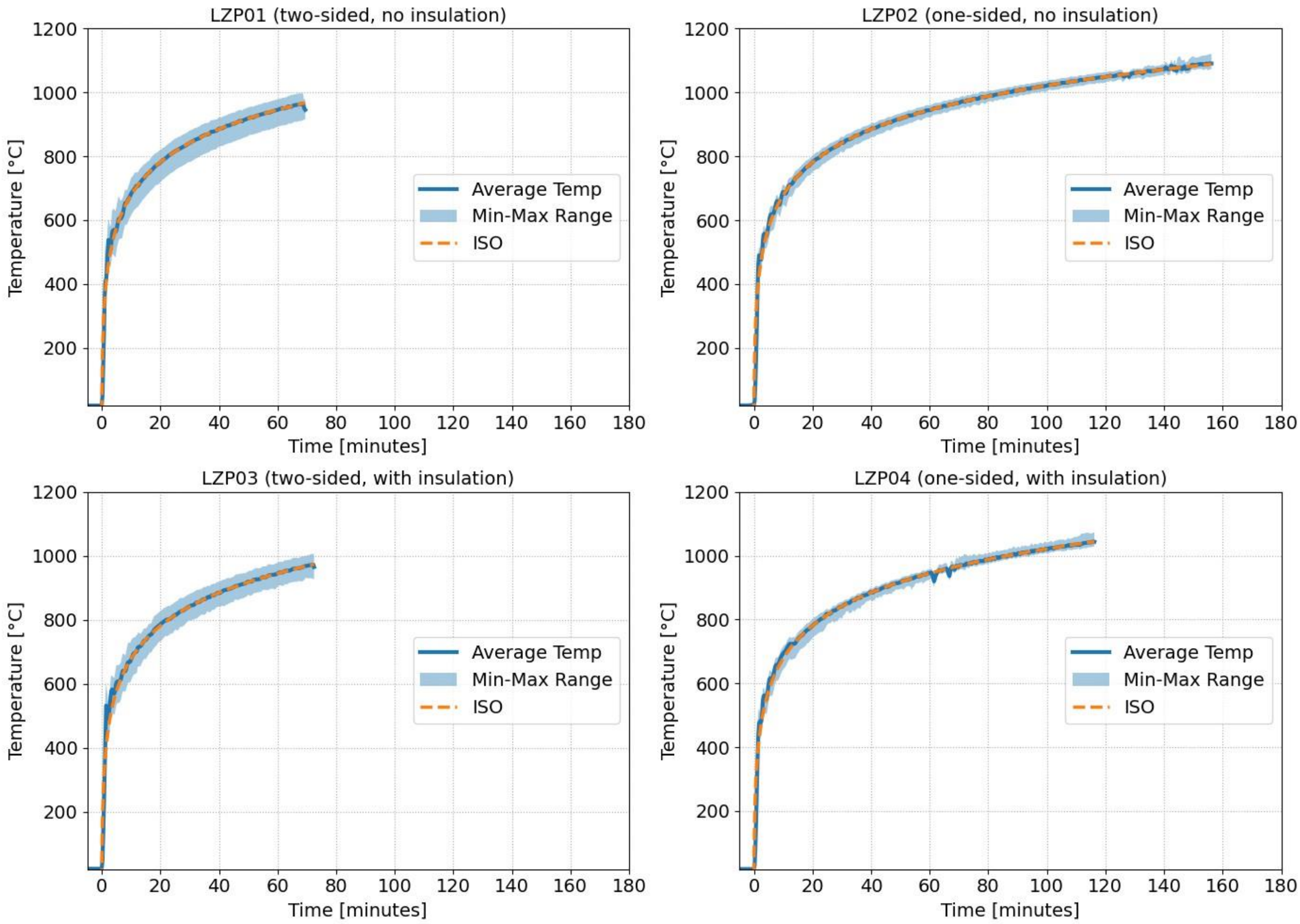

Figure 12. Comparison of furnace temperature with ISO fire curve

3.2 Steel stud temperature distribution

Figure 13 shows the temperature distribution across the steel section at the mid-height of the wall for the four test cases. The graph shows that the two-sided test generally results in a higher temperature across all parts of the stud section (flange 1, web, flange 2) compared to the one-sided test. This indicates that the LSF wall is subjected to more intense heating when both sides are exposed to fire. As shown in Figure 8, for the one-sided test, the flange 2 is the flange near the unexposed wall surface. In both no insulation and with insulation scenarios, the two-sided fire exposure had a higher rate of temperature increase, compared to the one-sided test, leading to a quicker time to failure. However, the difference in temperature rise across the section for two-sided vs one-sided exposure is greater at higher fire resistance periods. The maximum flange temperature observed (prior to failure of the wall specimen based on criteria defined in Section 2.6) is c. 546 °C and 697 °C for two-sided and one-sided fire exposure, respectively, with no insulation. For the insulated walls, the maximum flange temperature at mid-height of the wall section is 614 °C and 985 °C for two-sided and one-sided fire exposure, respectively. Table 2 summarises all the stud temperatures at different locations of the wall at failure.

Furthermore, Figure 13 shows that the temperature gradient across the stud section (from flange 1 through the web to flange 2) is greater for the one-sided fire exposure condition and cases where insulation is present. This indicates that uniform heating is more likely for two-sided fire exposure, while non-uniform heating is expected for one-sided fire exposure.

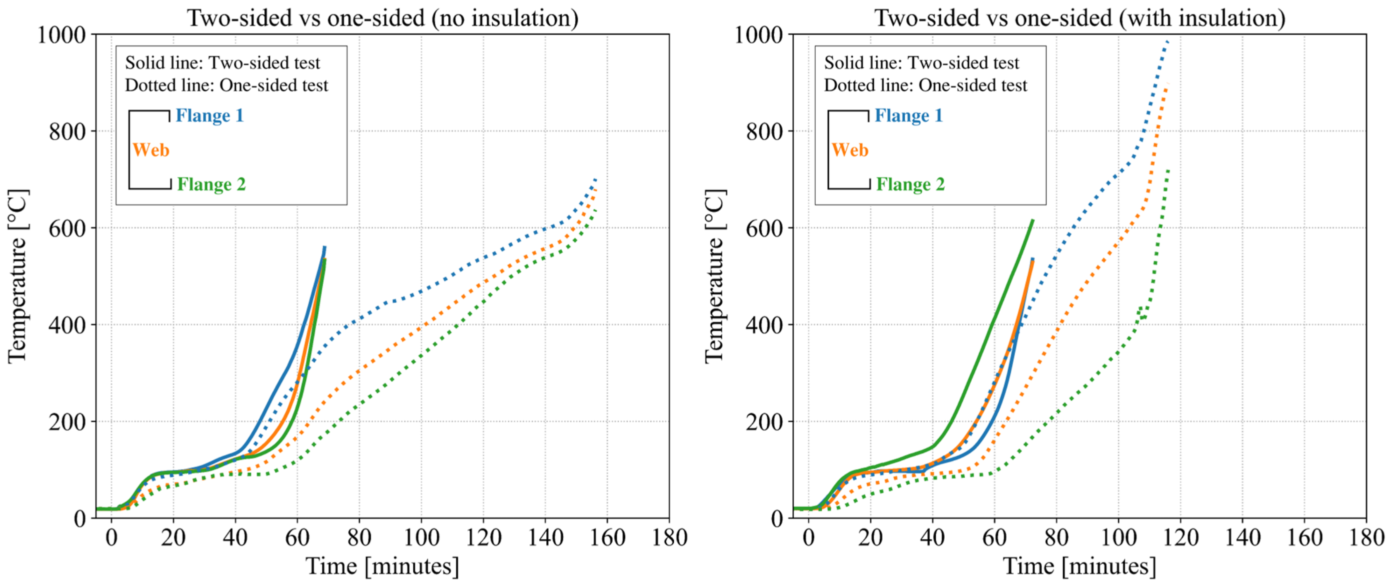

Figure 13. Stud temperature distribution at mid-height section (middle stud – TE3 in Figure 8)

Table 2. Summary of stud temperatures at failure at different locations of the wall

Location ref. (Figure 8)	Steel stud temperature at failure [°C]											
	Test ID: LZP01 (Two-sided, no insulation)			Test ID: LZP02 (One-sided, no insulation) *			Test ID: LZP03 (Two-sided, with insulation)			Test ID: LZP04 (One-sided, with insulation) *		
	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2
TE1	487	459	502	622	597	569	432	433	526	924	786	501
TE2	476	461	491	615	569	550	537	488	673	994	931	548
TE3	546	521	515	697	675	635	535	529	614	985	900	723
TE4	550	539	573	864	790	758	620	528	538	1043	1014	1001
TE5	486	494	462	727	710	677	463	473	564	1045	1026	979
TE6	508	510	537	788	709	722	532	455	471	1050	1041	1017
TE7	--	460	--	--	741	--	--	465	--	--	812	--
TE8	--	512	--	--	595	--	--	468	--	--	865	--
*Note: For the one-sided test, Flange 2 is the flange near the unexposed face of the wall.												

Figure 14 compares the stud section temperature variation at different points along the height of the wall (top ¼ height, mid-height, and bottom ¼ height). The results show that the temperature distribution along the height of the stud can be described as uniform as the flange and web temperatures do not vary significantly along the height of the stud. This is expected as the furnace temperature is uniform. As observed in Figure 13, Figure 14 also shows that the temperature gradient across the section of the stud at a particular height is higher for LSF walls exposed to fire on one side only vs two-sided fire exposure and higher for insulated LSF walls vs non-insulated LSF walls.

Figure 15 compares the stud web temperature variation along the (horizontal) length of the wall. Four locations were considered as shown in Figure 8 (the two middle studs and adjacent studs i.e., TE3, TE4, TE7 and TE8). The results show that there is no significant variation along the length of the wall for all the wall specimens tested with temperature variation not exceeding 50 °C across the four locations for the two-sided test. The temperature variation was higher for the one-sided test with a maximum temperature variation of approximately 150 °C for the one-sided test with insulation.

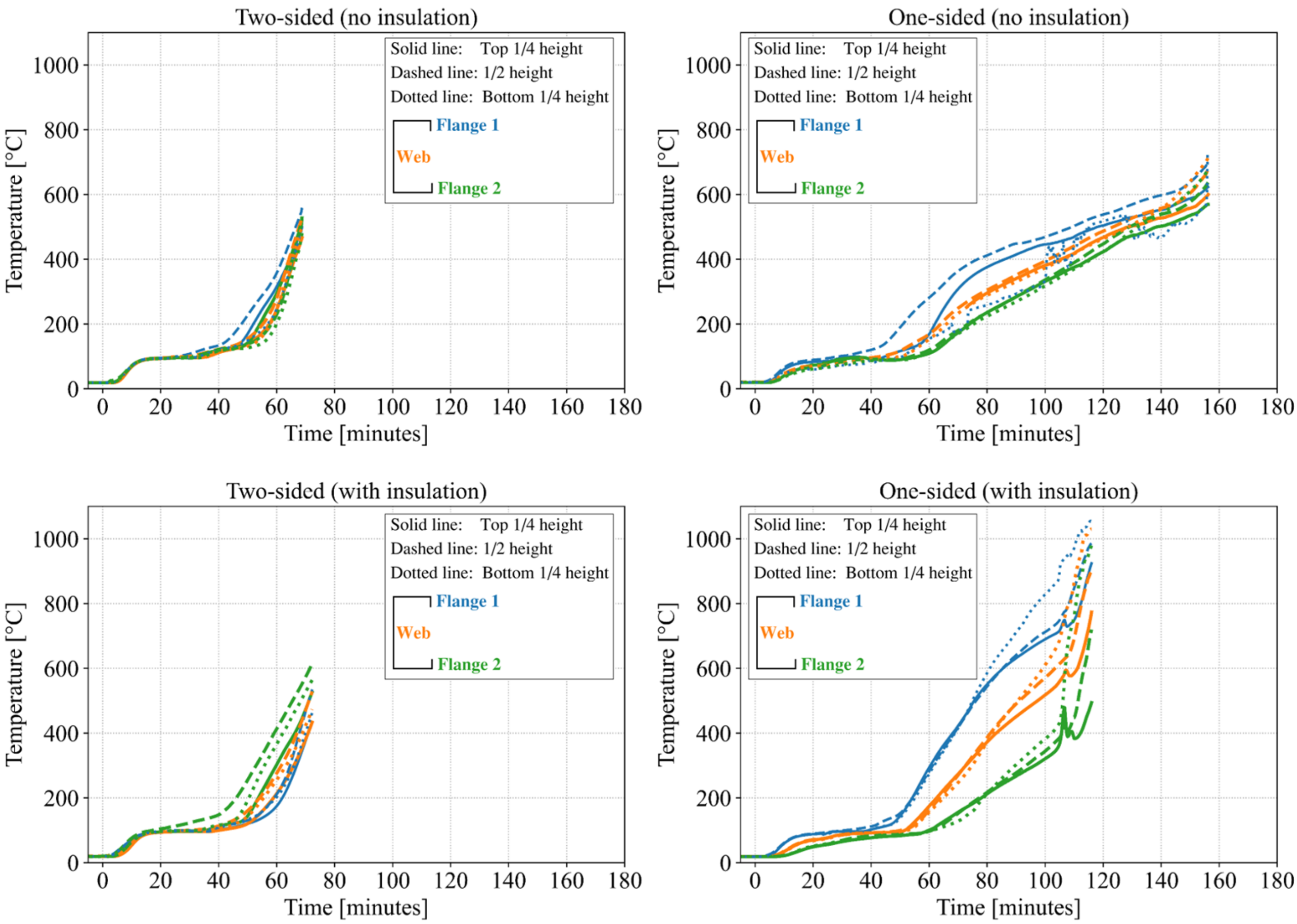

Figure 14. Comparison of stud temperature distribution at different points along the height of the stud (middle stud – TE1, TE3 and TE5 in Figure 8)

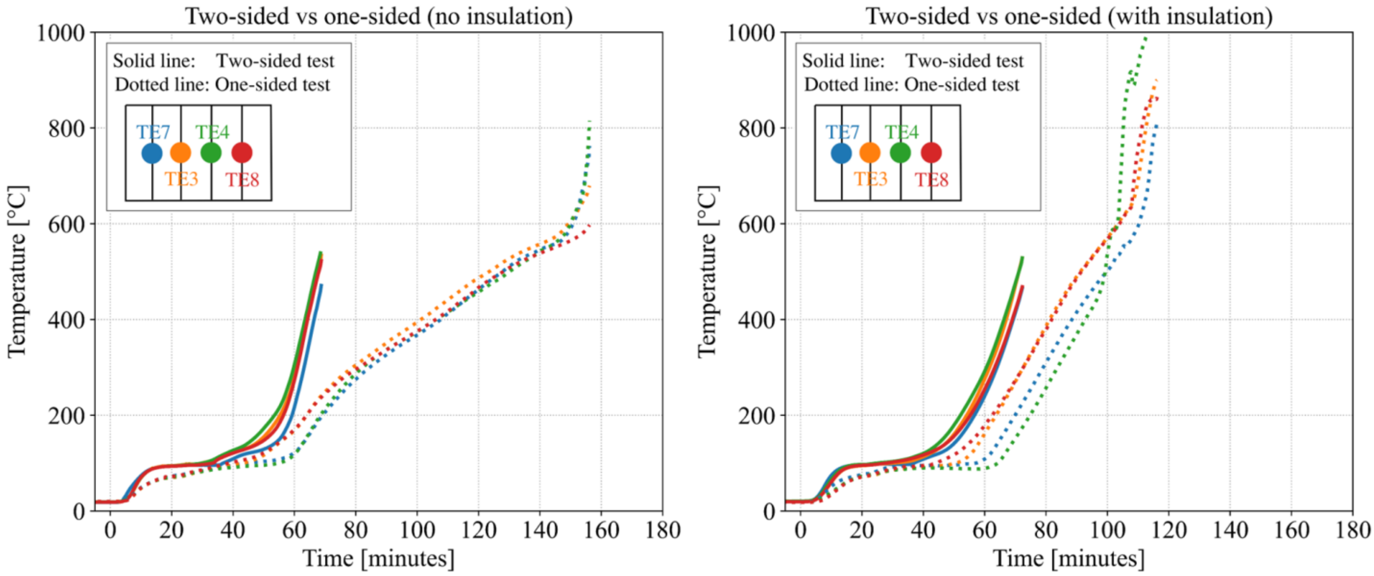

Figure 15. Comparison of stud web temperature variation along the length of the wall (TE3, TE4, TE7 and TE8)

3.3 Deflection

Figure 16 compares the vertical deflection of the wall specimens at three locations at the top of the wall i.e., near both ends – C1 and C3, and at the centre – C2 (see Figure 8). The results show that, for all the tested scenarios, the vertical deflection (contraction) across the top of the wall was approximately uniform.

Figure 17 shows the lateral deflection on the unexposed face of the wall at three locations at the mid-height of the wall i.e., near both ends – L1 and L3, and at the centre – L2 (see Figure 10) for both no insulation and with insulation scenarios. The result show that the lateral deflection at the centre of the wall was higher than that observed near the ends of the walls. The results show that walls with no insulation exposed to fire on one side have more capacity in resisting lateral deflection compared to LSF wall with cavity insulation. This indicates that the temperature gradient across the wall section, which is amplified by the presence of insulation, significantly contributes to the lateral deflection of LSF walls.

The loadbearing failure criteria is based on observation of runaway vertical / lateral deflection. From Figure 16 and Figure 17, for LSF walls with no insulation, runaway vertical / lateral deflection was observed at 68 minutes and 156 minutes for the two-sided and one-sided fire exposure, respectively. For insulated wall specimens, runaway vertical / lateral deflection was observed at 72 minutes and 116 minutes for the two-sided and one-sided fire exposure, respectively. Noting that the wall specimens were designed to achieve a minimum loadbearing capacity of 90 minutes under one-sided fire exposure, the one-sided test results show that the walls achieve this fire rating and that the wall build-up (and material selection) were adequately designed. However, the results of the two-sided tests show that the walls did not achieve the required fire resistance rating as failure occurred before 90 minutes of standard fire exposure.

Figure 18 shows pictures of the wall specimens after the test indicating the extent of vertical and lateral deflections of the walls. Significant sheathing material fall-off was also observed during the test following the runaway deflection which likely caused the failure in the jointing material and screws used for fixing the sheathing boards to the stud. Complete wall collapse was observed at the end of the test for the two-sided fire exposure and one-sided fire exposure, with more damage observed in the two-sided scenario.

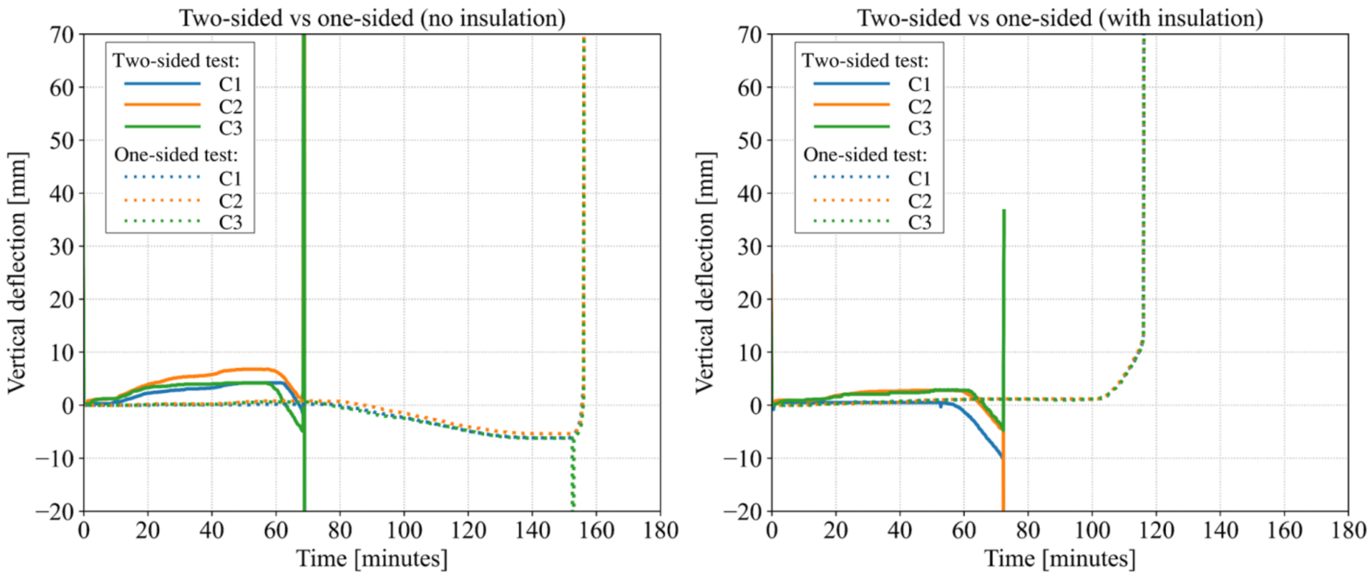

Figure 16. Vertical deflection of wall specimen (positive values = contraction; negative values = expansion)

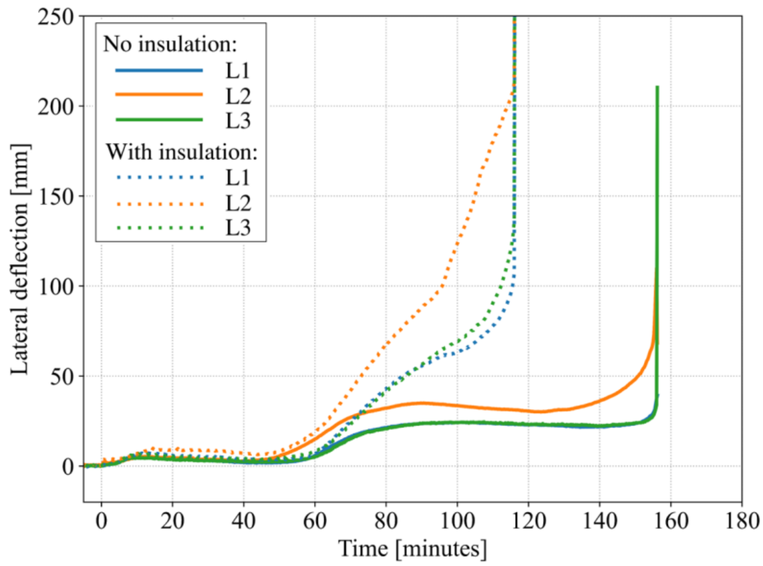

Figure 17. Lateral deflection (into the furnace) of unexposed face of walls exposed to fire on one side (no insulation vs with insulation)

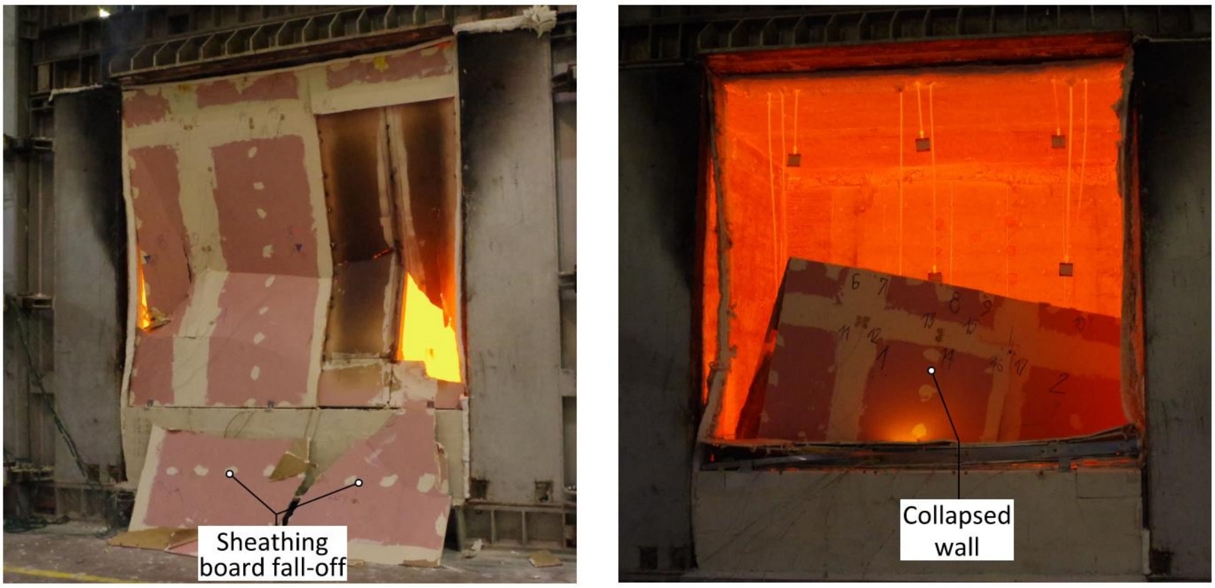

Figure 18. Pictures of LSF wall under testing showing extent of deflection for the one-sided fire exposure condition

3.4 Unexposed surface temperature

Figure 19 plots the average and maximum temperature readings on the unexposed face of the LSF wall (with and without insulation) exposed to fire on one side. The plots are presented in the form of a range graph of readings of all the average thermocouple elements (TE1 to TE6) and maximum thermocouple elements (TE1 to TE21). The result of TE8 for the scenario with cavity insulation was not included as the temperature measurements were significantly different from those of the other thermocouples, likely due to fall-off of the thermocouple during the test.

As expected, temperatures at unexposed face of the wall were lower and with a more gradual increase for the wall with cavity insulation than for the wall without insulation due to delayed heat transfer associated with the insulation. At 90 minutes of fire exposure, the upper bound of average and maximum temperatures observed were 74 °C and 78 °C, respectively, for the scenario with no insulation; and 50 °C and 55 °C, respectively, for the scenario with cavity insulation. Through the duration of the test, the maximum unexposed surface temperature did not exceed 100 °C for both cases.

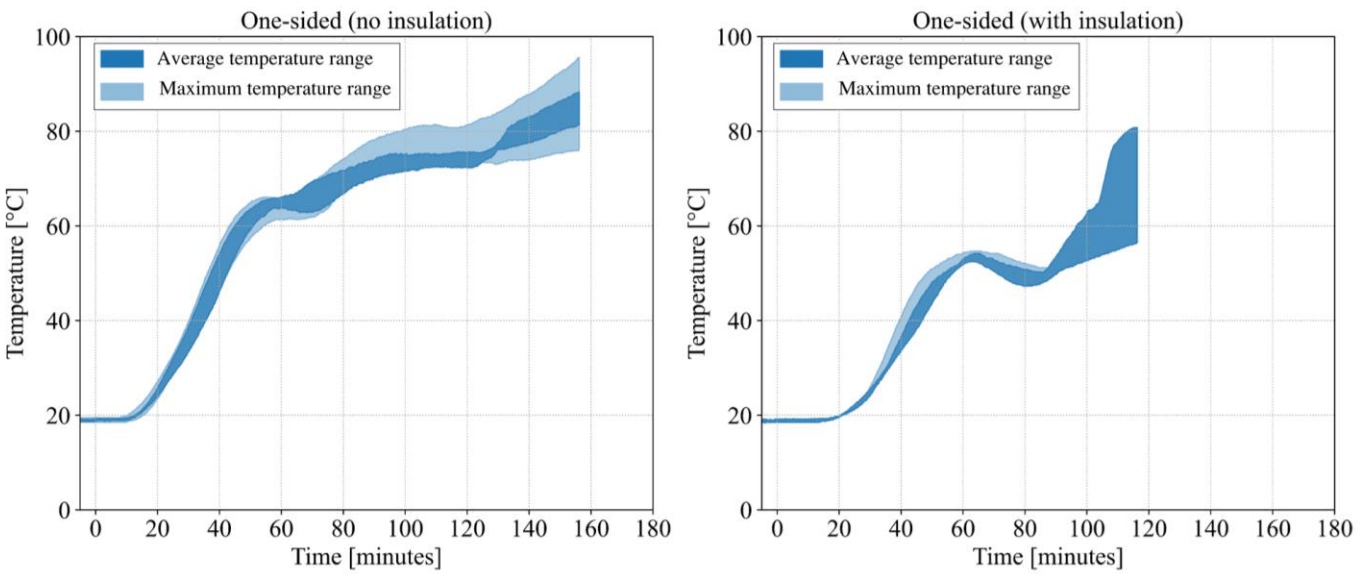

Figure 19. Average and maximum temperature on unexposed face of wall (one-sided fire exposure)

4 Discussion

The results of the tests presented in Section 3 demonstrate that two-sided fire exposure generally imposes a more severe heating condition on the LSF walls. This is evidenced by the higher temperatures and rate of temperature rise recorded across all components of the stud section – flanges and web – when compared to one-sided exposure. However, the impact of two-sided fire exposure is more significant at higher fire resistance periods (> 45 minutes).

The results also show that one-sided fire exposure creates a thermal gradient within the stud cross-section, which is heightened when the wall is insulated. This suggests that non-uniform heating is a significant characteristic of one-sided exposure, especially when insulation is present. Conversely, two-sided exposure tends to promote more uniform heating across the stud section.

The distribution of temperature along the stud's height, was relatively consistent, irrespective of the wall being subjected to one- or two-sided fire exposure. This uniformity across the vertical axis is attributable to the even distribution of furnace temperatures. In the horizontal direction, temperature variations along the wall length are minimal for two-sided fire exposure, not exceeding 50 °C. This contrasts with the one-sided exposure scenario, particularly with insulation, where temperature variations can reach up to 150 °C, underscoring the influence of fire exposure patterns and insulation on temperature distribution along the length of the wall.

The deflection results reveal that, for all tested scenarios, vertical deflection at various locations atop the wall were uniform. In contrast, lateral deflection (measured for the one-sided fire exposure scenarios) was greater at the wall's centre compared to its ends. The higher central lateral deflection was more pronounced in insulated walls, indicating that insulation amplifies the temperature gradient, contributing to the lateral deflection of LSF walls.

Table 3 summarises the main findings from the experiments. The loadbearing performance of LSF walls is significantly reduced to 44% with no insulation and 62% with insulation, when exposed to fire on both sides compared to one-sided exposure. This can have notable implications for the design of loadbearing LSF walls, particularly those with high utilisation ratios. The results further show that for one-sided exposure, cavity insulation creates a significant temperature gradient in the studs which induces thermal bowing and earlier failure. For two-sided exposure, the results indicate that the impact of cavity insulation is not significant.

Furthermore, for the two-sided tests (with and without cavity insulation), the fire resistance rating achieved were lower than that the walls were designed to achieve under one-sided fire exposure (i.e., less than 90 minutes). This implies that classifications achieved for single-sided exposure should not be extrapolated to two-sided exposure.

Table 3. Summary of time to failure for one-sided vs two-sided fire exposure conditions

Test ID	Fire exposure condition	Cavity insulation	Time to failure [minutes]	Ratio of two-sided to one-sided
LZP01	Two-sided	No	68	0.44
LZP02	One-sided		156	
LZP03	Two-sided	Yes	72	0.62
LZP04	One-sided		116	

The unexposed surface temperature measurements taken during the tests of LSF walls exposed to fire on one side allowed the insulation performance of the walls to be assessed. The results showed that walls with cavity insulation generally exhibit lower temperatures on the unexposed surface of the wall over the same period compared to those with no insulation due to the insulation amplifying the thermal gradient across the wall section. The results suggest that cavity insulation can improve the insulation performance on the unexposed face of LSF walls in a fire event, but may exacerbate the temperature gradient and therefore could worsen the loadbearing performance. It is noted that the average and maximum unexposed surface temperature recorded were below 100 °C throughout the duration of the tests. This is well below the insulation performance criteria defined in BS EN 1363-12020 [11] and BS 476-20:1987 [14], where it is stated that increase in the average temperature on the unexposed surface should not exceed 140 °C above ambient, and the maximum temperature at any location of the unexposed surface should not increase more than 180 °C above ambient.

5 Conclusions

This report has presented the results of experiments conducted to assess the impact of the exposure condition (single- or two-sided) on the fire resistance of LSF walls. A total of four wall specimens were tested, two each (with and without cavity insulation) for single- and two-sided fire exposure conditions under the ISO fire regime.

The main findings / conclusions from the experiments are as follows:

- Two-sided fire exposure results in a more severe heating condition on LSF walls than one-sided fire exposure, as indicated by higher temperatures and rates of temperature increase, particularly beyond 45 minutes of exposure.
- The loadbearing fire resistance of LSF walls decreases significantly when exposed to two-sided fire: down to 44% of the one-sided exposure capacity for non-insulated walls and 62% for insulated walls.
- Cavity insulation in one-sided fire exposure creates a significant temperature gradient, leading to thermal bowing and earlier structural failure. For two-sided fire exposure, the influence of cavity insulation on the performance is deemed not significant.
- Walls were designed to achieve at least 90 min fire resistance for one-sided exposure. Given walls exposed on two-sides failed to achieve this, fire resistance classifications for one-sided exposure should not be extrapolated to two-sided exposure.
- One-sided fire exposure leads to a significant thermal gradient within the stud section, especially when insulation is present, resulting in non-uniform heating. In contrast, two-sided exposure generally promotes a more even temperature distribution across the stud section. The former typically results in reduced load-bearing fire resistance.
- The temperature distribution along the height of the stud is largely uniform, regardless of whether the exposure is one-sided or two-sided, due to the uniform furnace temperatures. Temperature variations along the length of the wall are minimal for two-sided fire exposure but can be substantial for one-sided exposure with insulation, reaching variations of up to 150 °C.
- Vertical deflection of wall specimen is uniform across various top locations of the wall under all test scenarios, while the centre of the wall exhibits greater lateral deflection, particularly for insulated walls under one-sided exposure.
- Insulated LSF walls maintain lower temperatures on their unexposed surfaces compared to non-insulated walls. However, presence of insulation may exacerbate the temperature gradient and therefore could worsen the loadbearing performance.
- Both average and maximum unexposed surface temperatures recorded during the one-sided fire exposure tests remained well below the threshold set out by BS EN 1363-1:2020 and BS 476-20:1987, indicating that the walls met the stipulated insulation performance criteria.

6 FUTURE WORK PACKAGES / NEXT STEPS

The research project to study the fire resistance performance of LSF walls exposed to fire is organised in two work packages (WP) described below:

- WP1: Literature review on the fire resistance performance of LSF walls exposed to fire.
- WP2: Generate data and evidence on the fire resistance performance between single-sided and double-sided exposure of LSF wall elements to support the department understand the risk to existing buildings. WP2 is split into two sub packages:
    - WP2a – benchmark furnace tests for LSF walls; and
    - WP2b – desktop / modelling appraisal of the implications of fire resistance specification of LSF walls for their ability to survive burn-out.

The literature review work package (WP1) has been completed. This report represents the culmination of WP2a and summarises the results of the fire tests of LSF walls exposed to fire. It sets out what was tested, why, how it was designed and what was observed / measured.

The next step is to use the results from the test to validate numerical models in support of parametric studies to be carried out in WP2b.

WP2b involves development of a numerical representation (using the finite element method) that can reproduce the thermal and mechanical performance observed in tests undertaken during WP2a, followed by parametric studies investigating how sensitive or otherwise LSF walls exposed on two sides are to potential delays in thermal exposure associated with internal or external fire spread. Factors to consider in the parametric studies will be based on those identified in the literature review report as having impact on the performance of LSF walls exposed to fire.

At the completion of WP2, a final research report will be produced which will combine the findings from WP1, WP2a and WP2b.

References

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[2] S. Kesawan and M. Mahendran, 'A Review of Parameters Influencing the Fire Performance of Light Gauge Steel Frame Walls', *Fire Technology*, vol. 54, no. 1, pp. 3–35, Jan. 2018, doi: 10.1007/s10694-017-0669-8.

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[7] D. Perera *et al.*, 'Fire performance of cold, warm and hybrid LSF wall panels using numerical studies', *Thin-Walled Structures*, vol. 157, Dec. 2020, doi: 10.1016/j.tws.2020.107109.

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[9] BSI, 'BS 476-21:1987 Fire tests on building materials and structures. Methods for determination of the fire resistance of loadbearing elements of construction', BSI, London, 1987.

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[11] BSI, 'BS EN 1363-1:2020 Fire resistance tests. General requirements', BSI, London, 2020.

[12] ISO, 'ISO 834-1:1999 Fire-resistance tests — Elements of building construction — Part 1: General requirements', International Organization for Standardization, Geneva, 1999.

[13] BSI, 'BS EN 1993-1-3:2006 Eurocode 3. Design of steel structures. Part 1-3: General rules - Supplementary rules for cold-formed members and sheeting. (Incorporating corrigendum November 2009)', BSI, London, 2010.

[14] BSI, 'BS 476-20:1987 Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles)', BSI, London, 1987.

APPENDICES

Appendix A – Furnace power, furnace pressure, and test loading

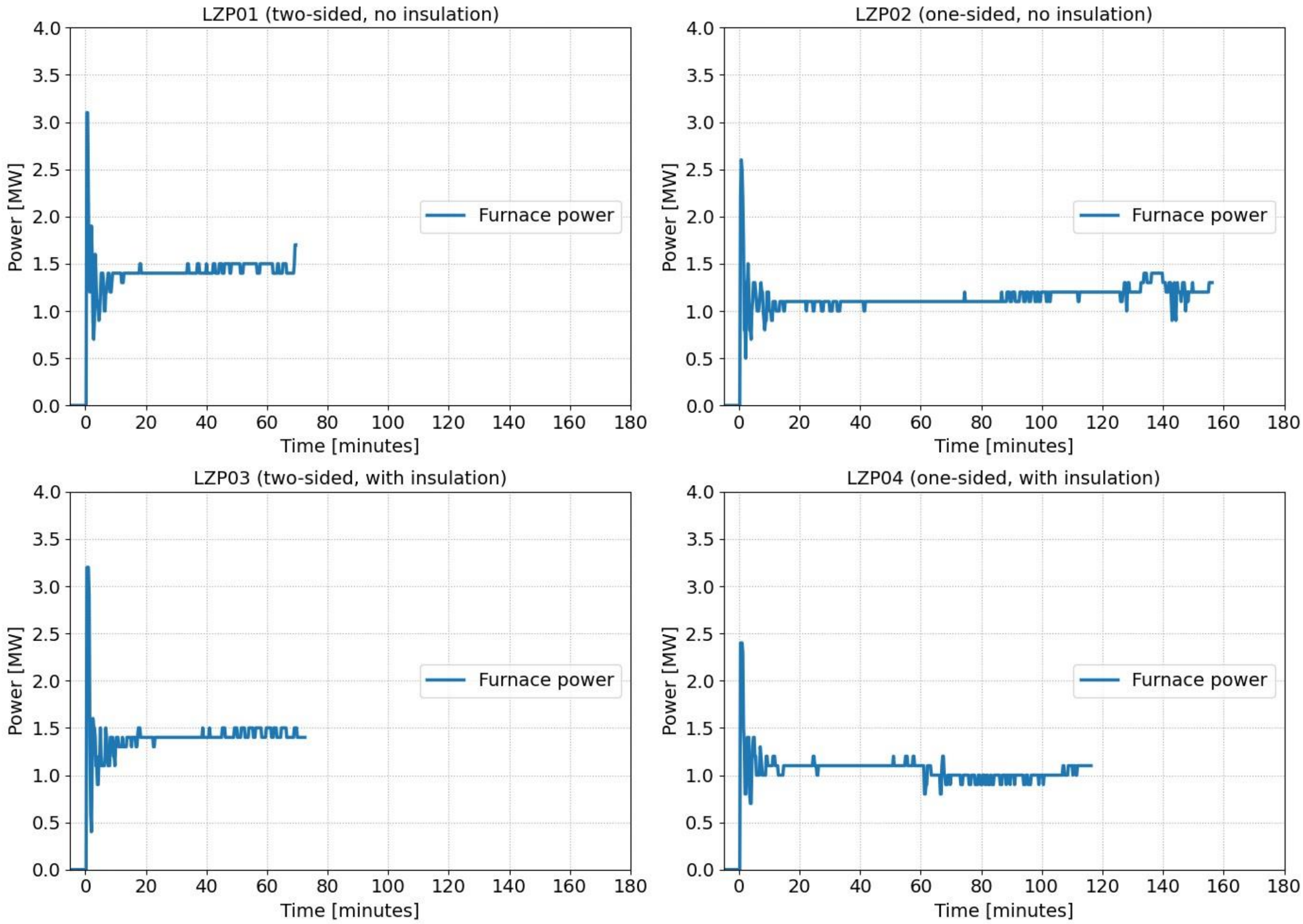

Figure 20. Furnace power during test

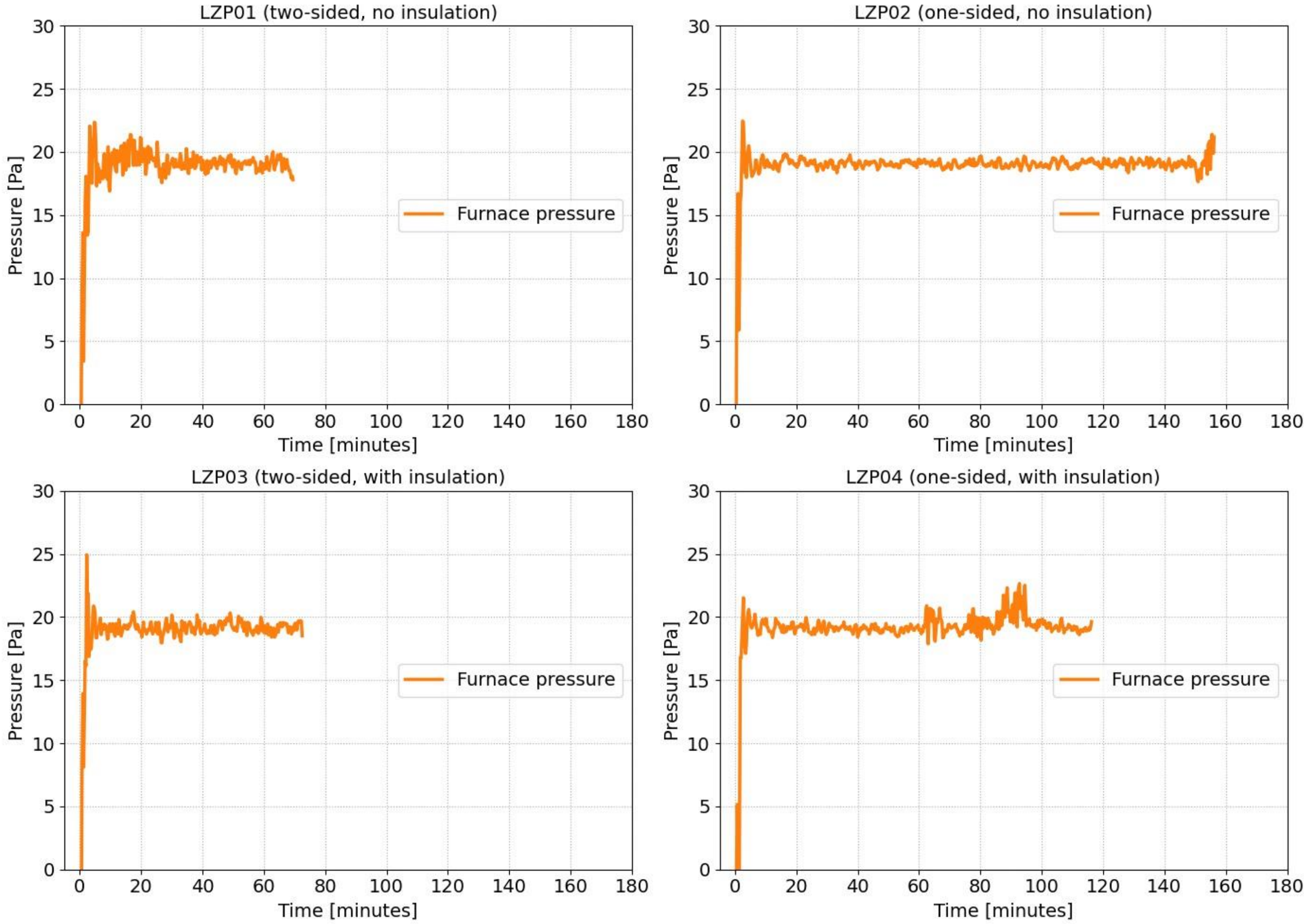

Figure 21. Furnace pressure during test

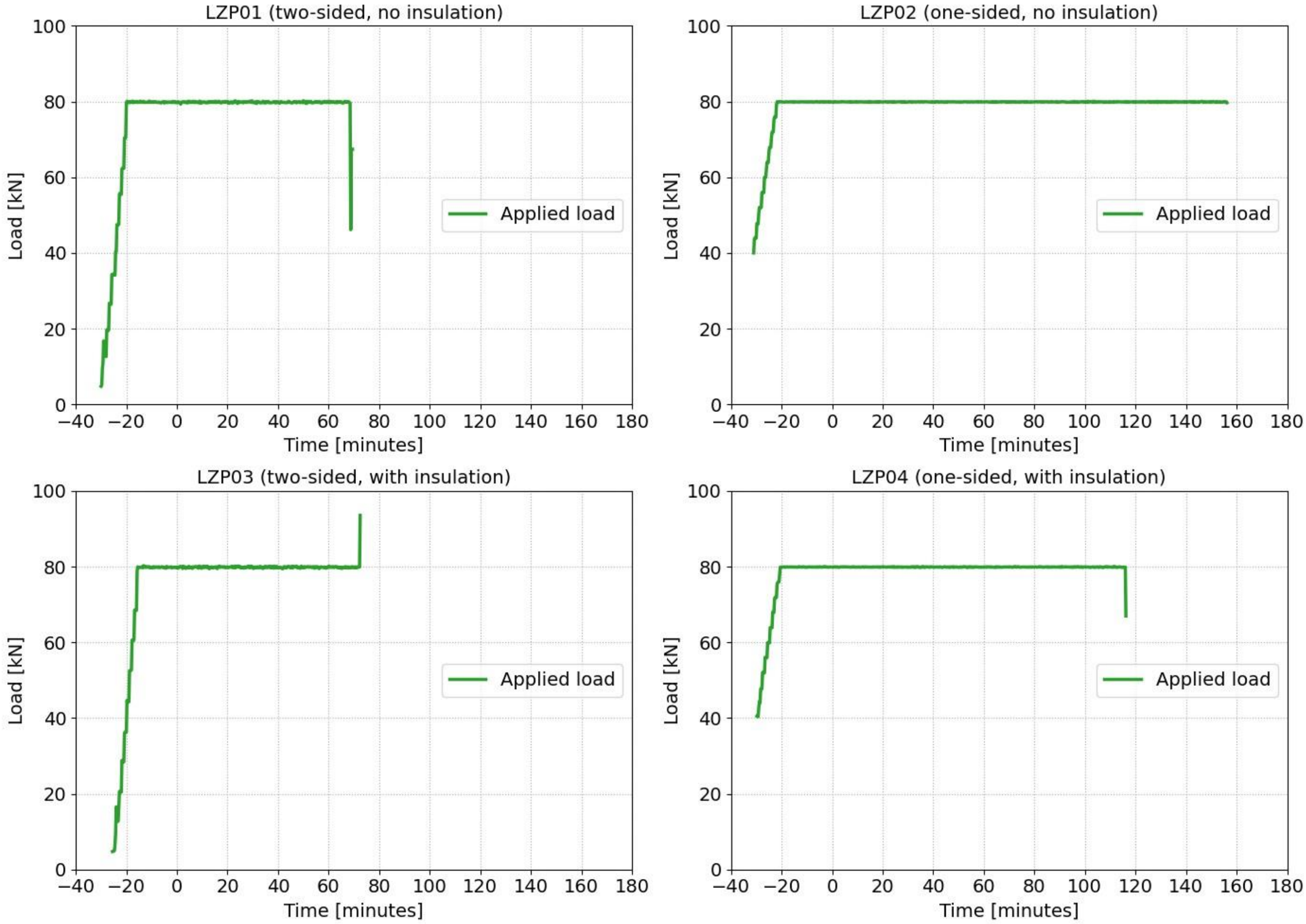

Figure 22. Applied load during test

Appendix B – ITB TEST REPORTS

Instytut Techniki Budowlanej

Nauka i wiedza ekspercka dla budownictwa przyszłości

Fire Research Department
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Tel.: 22 5664284
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Mazovian Branch – Laboratory
ul. Przemysłowa 2, 26-670 Pionki, Poland
Tel.: 48 3121600, fax: 48 3121601

Test Documentation LZP01-02520/23/Z00NZP

Client:	OFR Consultants Limited Sevendale House, Lever Street Manchester M1 1JA United Kingdom
Test Location:	ul. Przemysłowa 2, 26-670 Pionki, Poland
Date:	2023-10-19
Specimen:	Steel frame loadbearing wall with gypsum plasterboard cladding
Method:	EN 1365-4:1999
Comments:	two-sided fire exposure

Warszawa, 2023-12-27

1. Test specimen description

Single steel frame loadbearing wall with gypsum plasterboard cladding.

(D) – nominal/declared value, (M) – measured by laboratory

steel frame:	
– profiles:	
– – manufacturer:	Frame Factory Sp. z o.o.
– – type / trade name:	C89×1.2
– – material:	S350GD (D)
– – section:	
– – – height:	89 mm (D)
– – – width:	41 mm (D)
– – – thickness:	1.2 mm (D)
– – – area:	2.22 cm^2 (D)
– – – inertia:	28.28 cm^4 (D) / 5.13 cm^4 (D)
– – – specific mass:	1.75 kg/m (D)
– assembly:	
– – nodes:	pre-cut slots in beams for stud positioning
– – fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each beam/stud crossing, both flanges
– fixing:	
– – bottom edge (to plinth):	4pcs. (2 pcs. per side) steel angles fixed to bottom beam
– – top edge:	free (loaded)
cladding:	
– boards :	
– – amount:	two layers on both sides of test specimen; two layers on vertical edges
– – manufacturer:	Knauf
– – type / trade name:	F15-DF-15EN520
– – thickness:	15 mm (D); 14.88 mm (M)
– – size:	1200 × 2600 mm (D) (before assembly)
– – density:	12.6 kg/m^2 (M)
– – moisture content:	0.3% (M)
– assembly:	
– – layout:	
– – – horizontal:	in each layer 2 boards full-size (fixed to 3 studs) and a single border board half-width (fixed to 2 studs); overlapping joints between layers
– – – vertical:	full-width horizontal joint 40 cm (M) from one edge on all layers; alternating position of the joint relative to top/bottom edge through all 4 layers
– – masking tape:	
– – – manufacturer:	Knauf
– – – type / trade name:	Kurt CE 07T-EN13963
– – – location:	over board edges
– – filler:	gypsum filler
– – – manufacturer:	Knauf
– – – type / trade name:	Knauf G-K Start
– – – location:	over masking tapes and screw heads
– fixing (to steel frame):	
– – first layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)

– – second layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×55 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)

2. Test specimen preparation:

time registry:	
– assembly:	
– – start:	2023-10-16
– – end:	2023-10-17
– conditioning:	not required
laboratory involvement:	laboratory was involved in selection of the test specimen
manufacturer:	Knauf

3. Test

method:	EN 1365-4:1999
date:	2023-10-19
duration:	68 min 30 s
ambient conditions:	
– temperature:	19.6°C
– humidity:	35%
load:	
– total:	80 kN
– – beam:	0.5 kN
– – actuator:	79.5 kN
– location:	top edge of test specimen
furnace pressure:	
– reference value:	20 Pa
– – location:	distributed over top edge of the test specimen
– measurement location:	0.1 m below top edge of the test specimen
– set-point:	19.15 Pa
initial furnace temperature:	19.2°C

4. Measurement locations

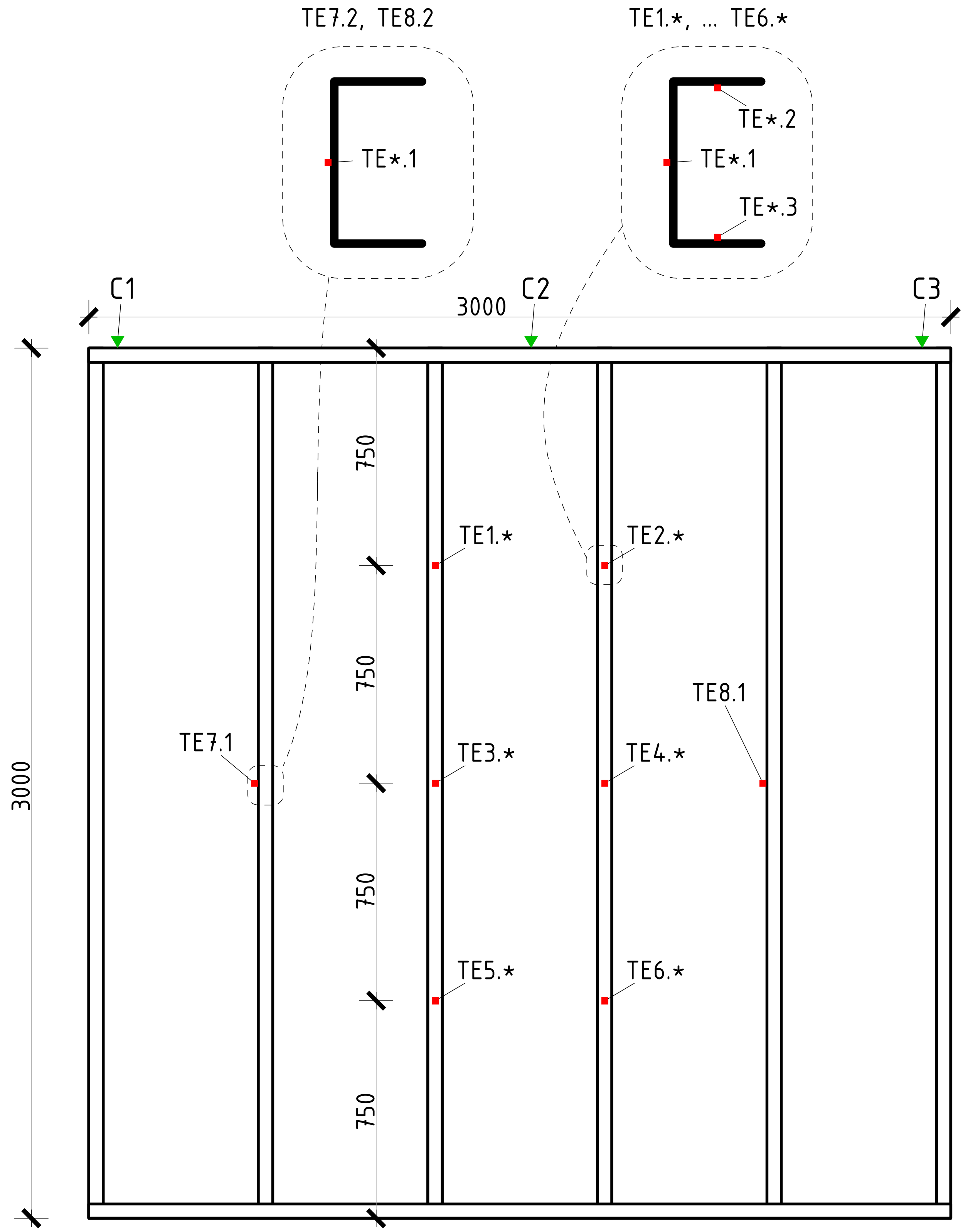

Fig. 1. Location of internal thermoelements and deflection gauges

5. Results summary

This part of documentation is for presentation purposes only. The properly labelled full data are included in data files.

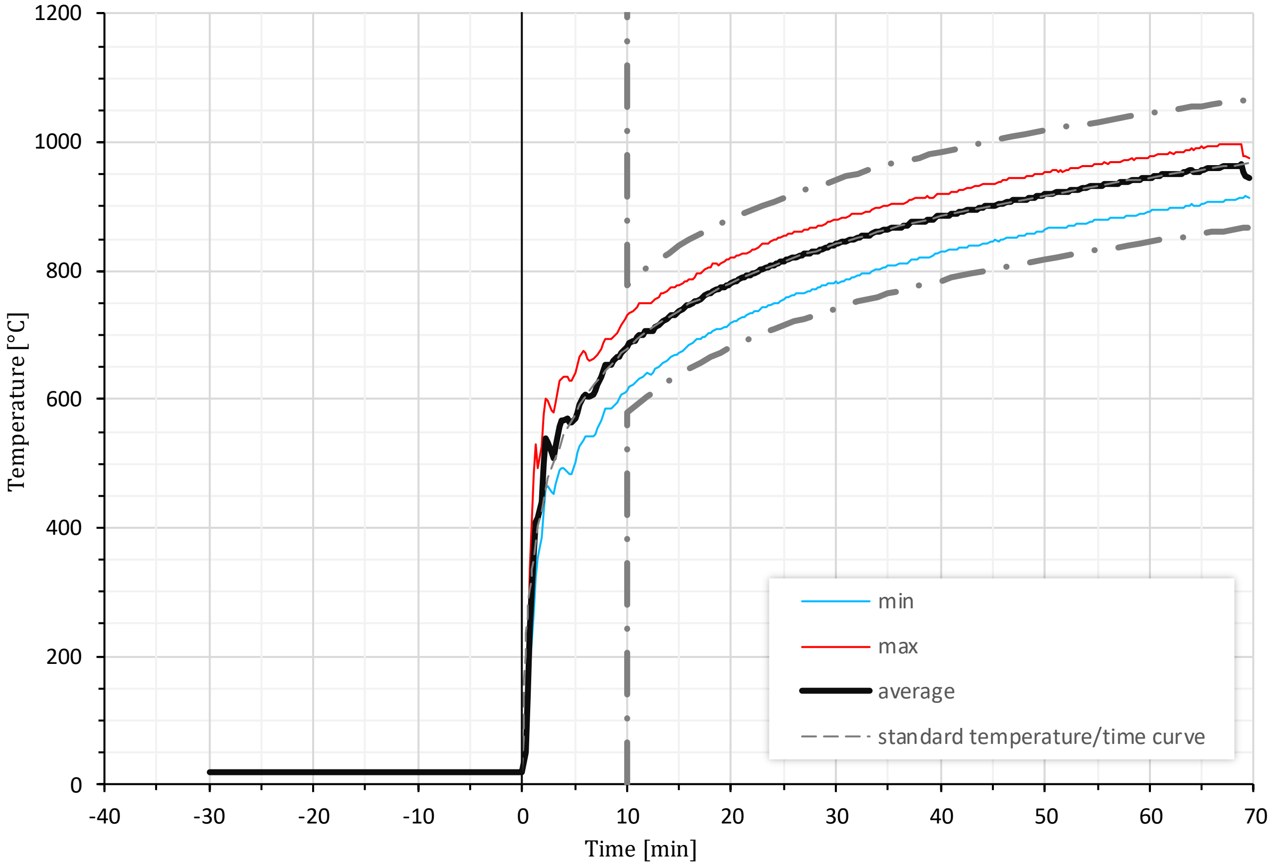

Fig. 2. Temperature of furnace heating conditions

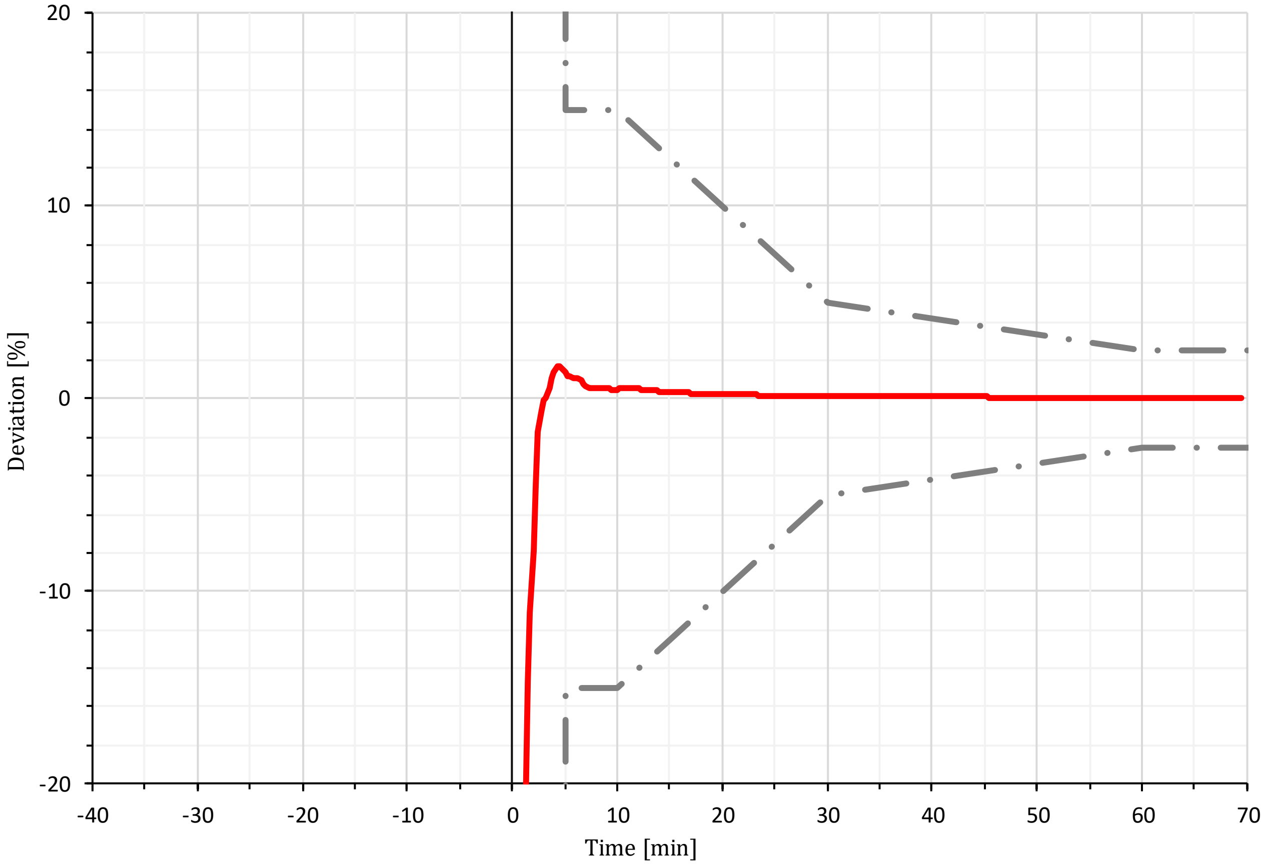

Fig. 3. Tolerance of the heating

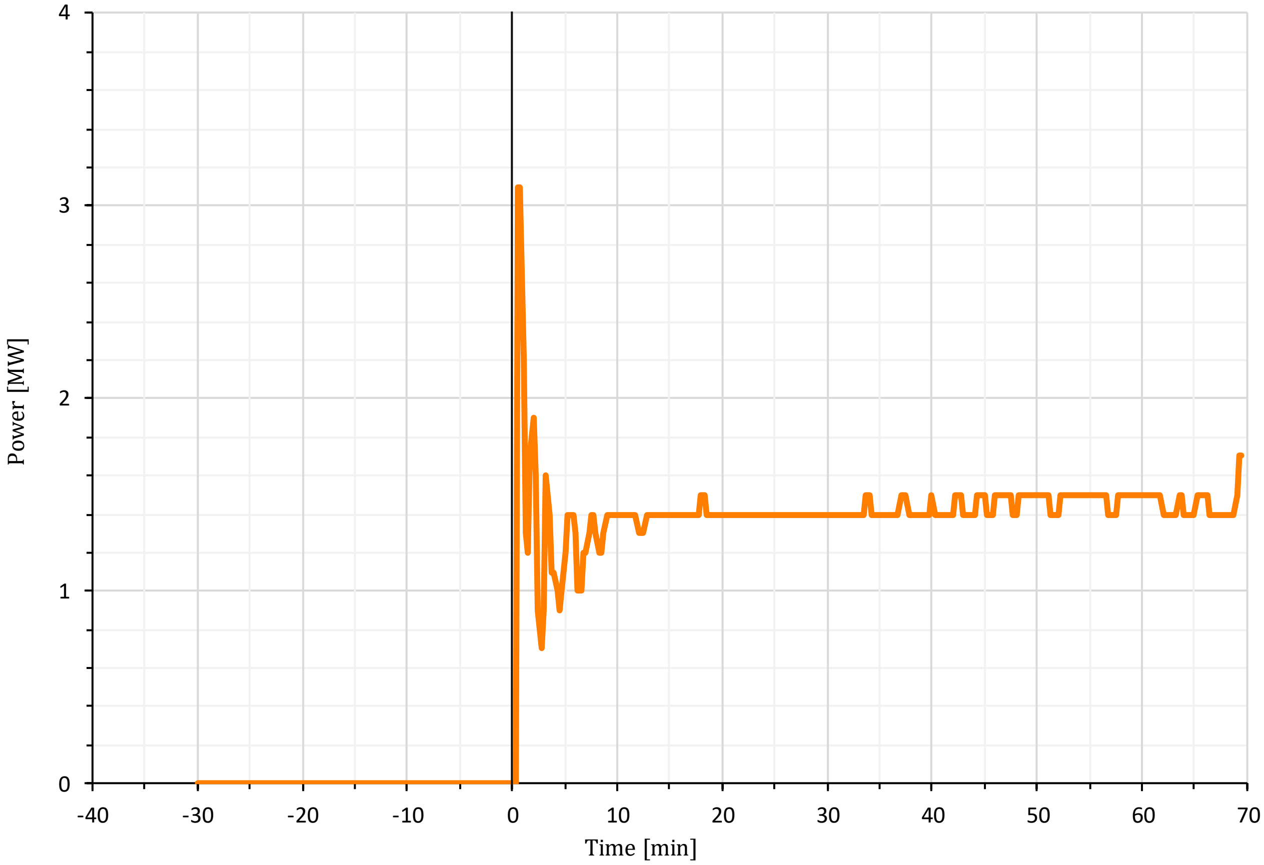

Fig. 4. Furnace power

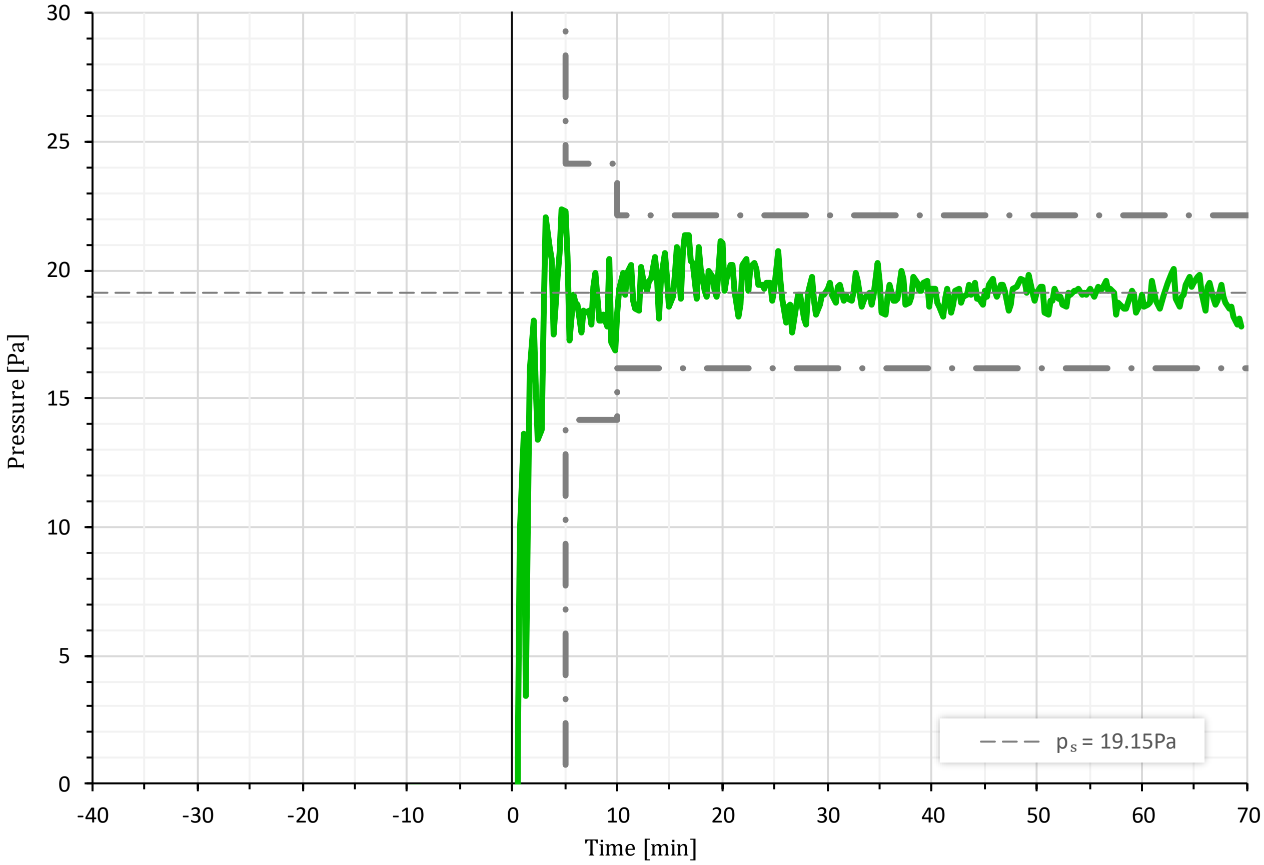

Fig. 5. Furnace pressure

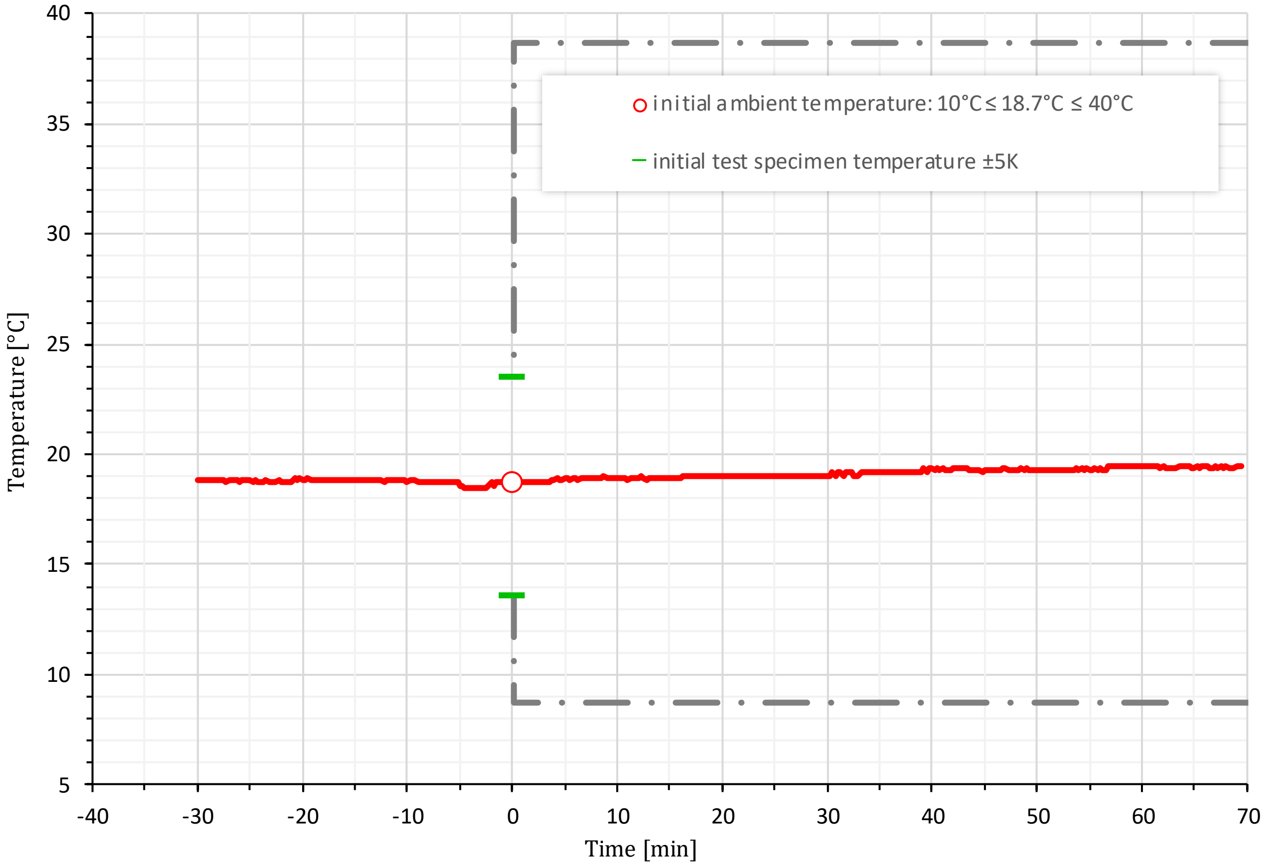

Fig. 6. Ambient temperature

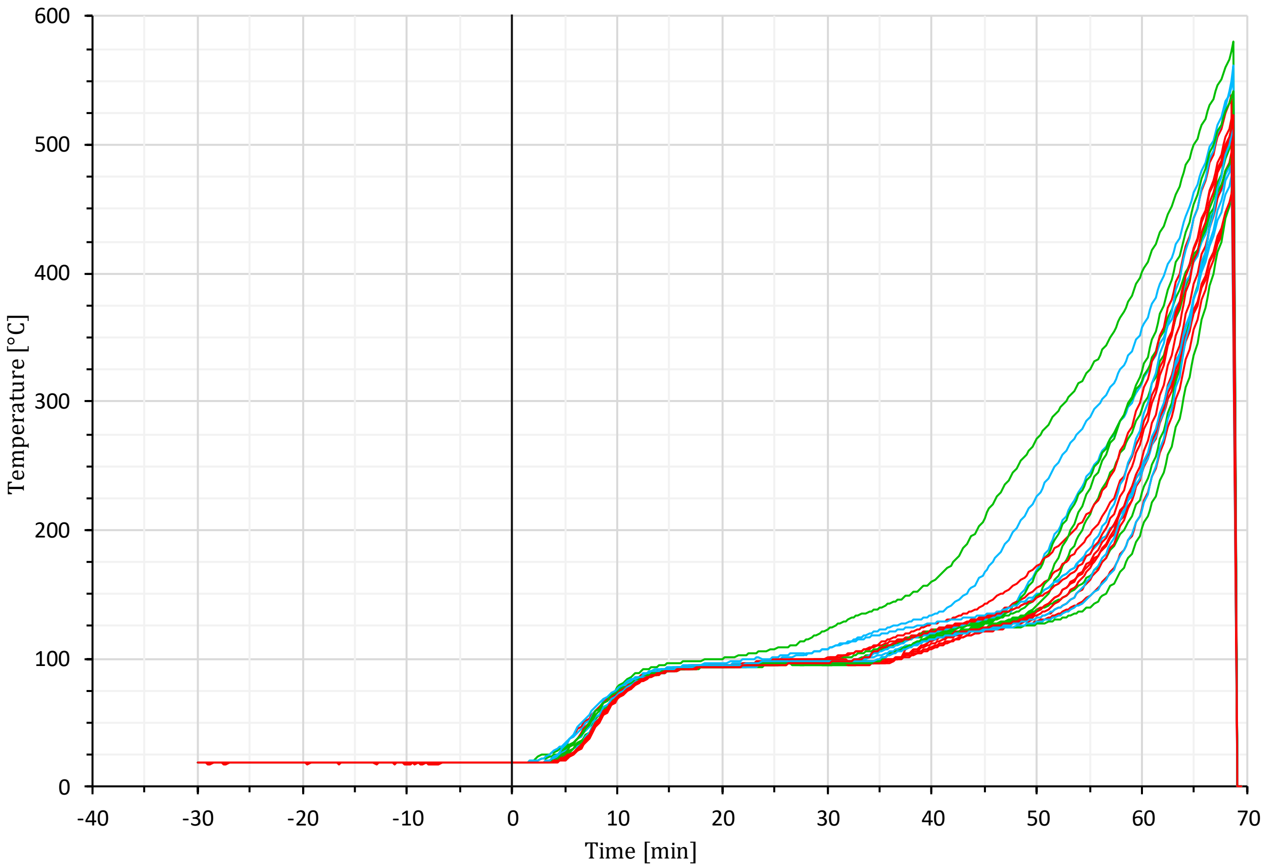

Fig. 7. Internal temperature thermoelements

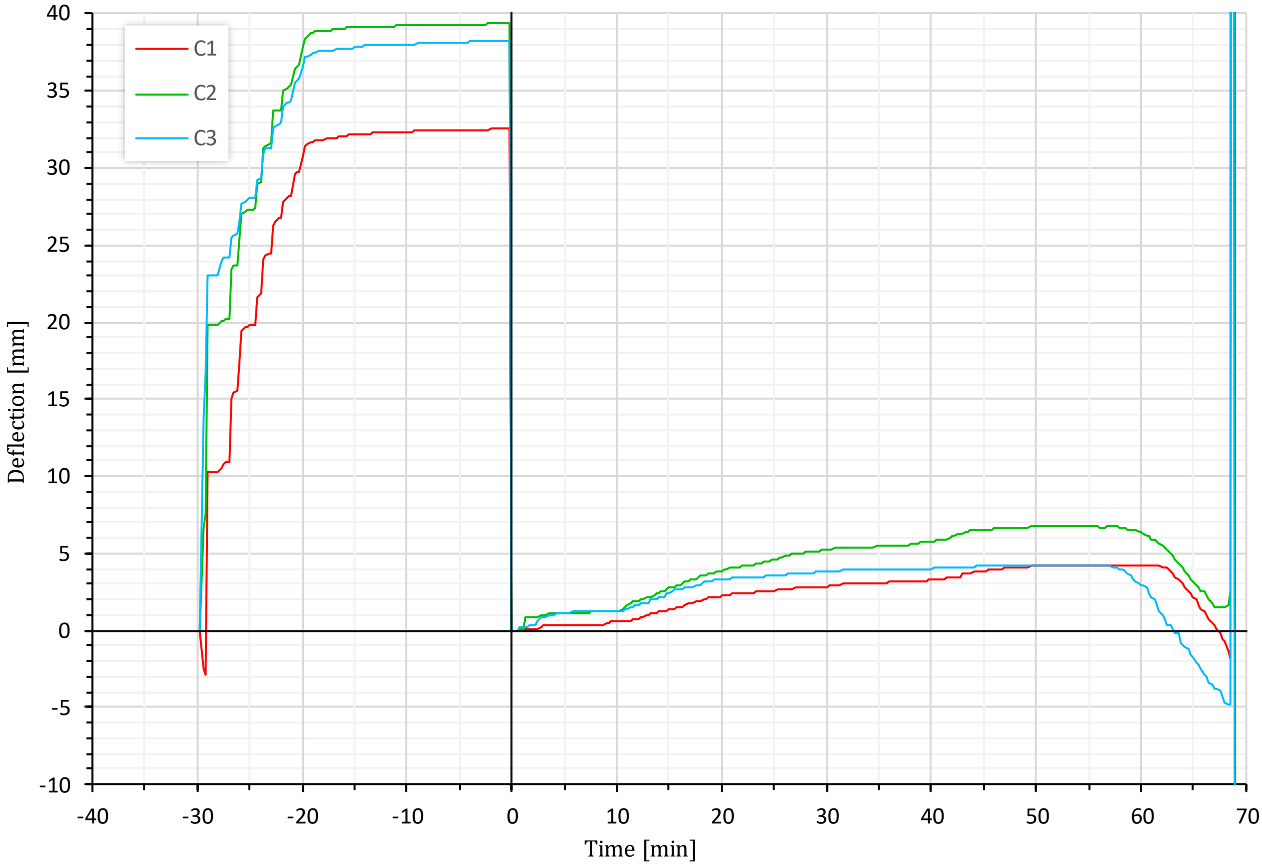

Fig. 8. Vertical deflection (contraction)

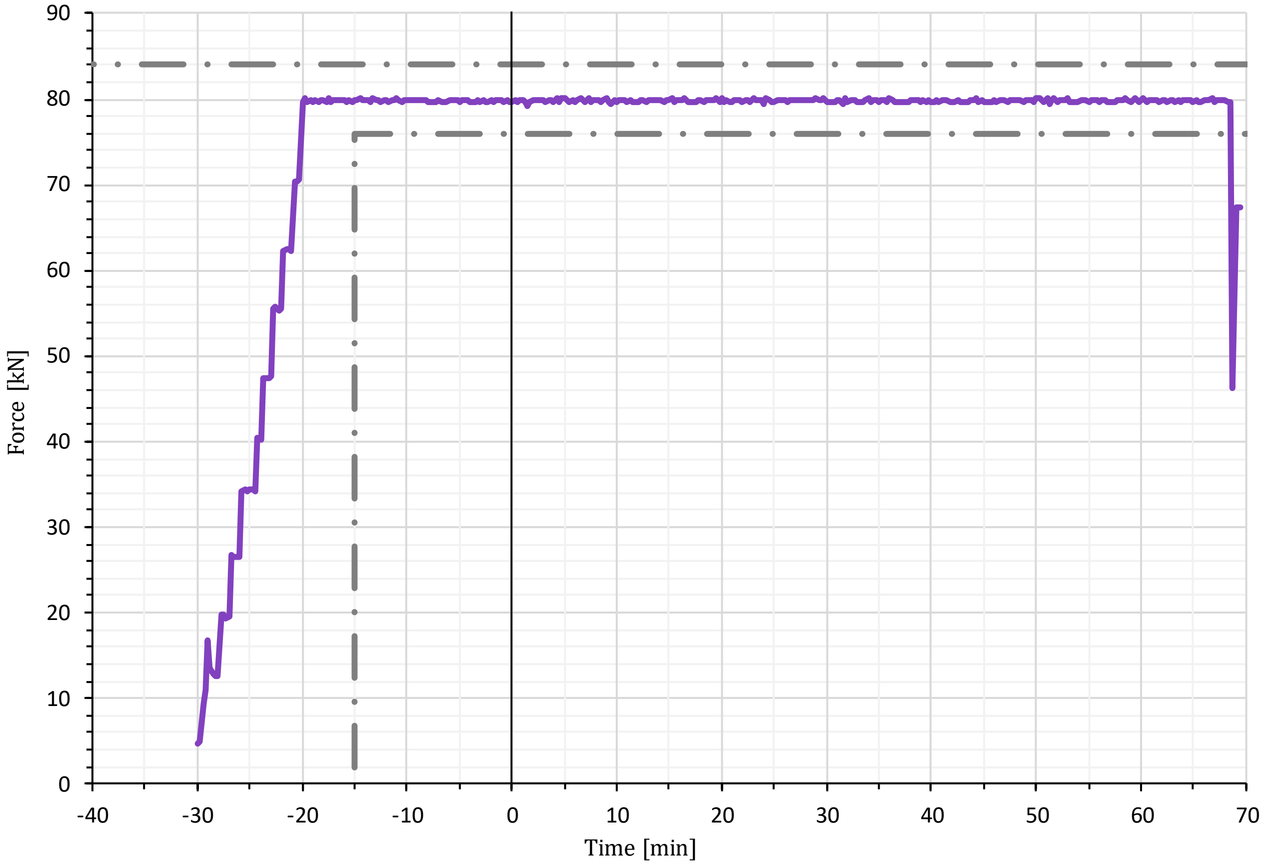

Fig. 9. Load force

6. Data files reference

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Frame Factory_Specyfikacja profili.pdf	c333caf04a05301b2e71bcf7cd35ac18

Instytut Techniki Budowlanej

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e-mail: fire@itb.pl

Mazovian Branch – Laboratory
ul. Przemysłowa 2, 26-670 Pionki, Poland
Tel.: 48 3121600, fax: 48 3121601

Test Documentation LZP02-02520/23/Z00NZP

Client:	OFR Consultants Limited Sevendale House, Lever Street Manchester M1 1JA United Kingdom
Test Location:	ul. Przemysłowa 2, 26-670 Pionki, Poland
Date:	2023-10-31
Specimen:	Steel frame loadbearing wall with gypsum plasterboard cladding
Method:	EN 1365-1:2012/AC:2013
Comments:	one-sided fire exposure

Warszawa, 2023-12-27

1. Test specimen description

Single steel frame loadbearing wall with gypsum plasterboard cladding.

(D) – nominal/declared value, (M) – measured by laboratory

steel frame:	
– profiles:	
– – manufacturer:	Frame Factory Sp. z o.o.
– – type / trade name:	C89×1.2
– – material:	S350GD (D)
– – section:	
– – – height:	89 mm (D)
– – – width:	41 mm (D)
– – – thickness:	1.2 mm (D)
– – – area:	2.22 cm^2 (D)
– – – inertia:	28.28 cm^4 (D) / 5.13 cm^4 (D)
– – – specific mass:	1.75 kg/m (D)
– assembly:	
– – nodes:	pre-cut slots in beams for stud positioning
– – fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each beam/stud crossing, both flanges
– fixing:	
– – bottom edge (to plinth):	4pcs. (2 pcs. per side) steel angles fixed to bottom beam
– – side edges:	free
– – top edge:	free (loaded)
cladding:	
– boards :	
– – amount:	two layers on both sides of test specimen
– – manufacturer:	Knauf
– – type / trade name:	F15-DF-15EN520
– – thickness:	15 mm (D); 14.88 mm (M)
– – size:	1200 × 2600 mm (D) (before assembly)
– – density:	12.6 kg/m^2 (M)
– – moisture content:	0.3% (M)
– assembly:	
– – layout:	
– – – horizontal:	in each layer 2 boards full-size (fixed to 3 studs) and a single border board half-width (fixed to 2 studs); overlapping joints between layers
– – – vertical:	full-width horizontal joint 40 cm (M) from one edge on all layers; alternating position of the joint relative to top/bottom edge through all 4 layers; horizontal joint close to top edge on unexposed side
– – masking tape:	
– – – manufacturer:	Knauf
– – – type / trade name:	Kurt CE 07T-EN13963
– – – location:	over board edges
– – filler:	gypsum filler
– – – manufacturer:	Knauf
– – – type / trade name:	Knauf G-K Start
– – – location:	over masking tapes and screw heads
– fixing (to steel frame):	
– – first layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)

– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)
– – second layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×55 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)

2. Test specimen preparation:

time registry:	
– assembly:	
– – start:	2023-10-26
– – end:	2023-10-27
– conditioning:	not required
laboratory involvement:	laboratory was involved in selection of the test specimen
manufacturer:	Knauf

3. Test

method:	EN 1365-1:2012/AC:2013
date:	2023-10-31
duration:	156 min 00 s
ambient conditions:	
– temperature:	19.5°C
– humidity:	53%
load:	
– total:	80 kN
– – beam:	40 kN
– – actuator:	40 kN
– location:	top edge of test specimen
furnace pressure:	
– reference value:	20 Pa
– – location:	distributed over top edge of the test specimen
– measurement location:	0.1 m below top edge of the test specimen
– set-point:	19.15 Pa
initial furnace temperature:	21.7°C

4. Measurement locations

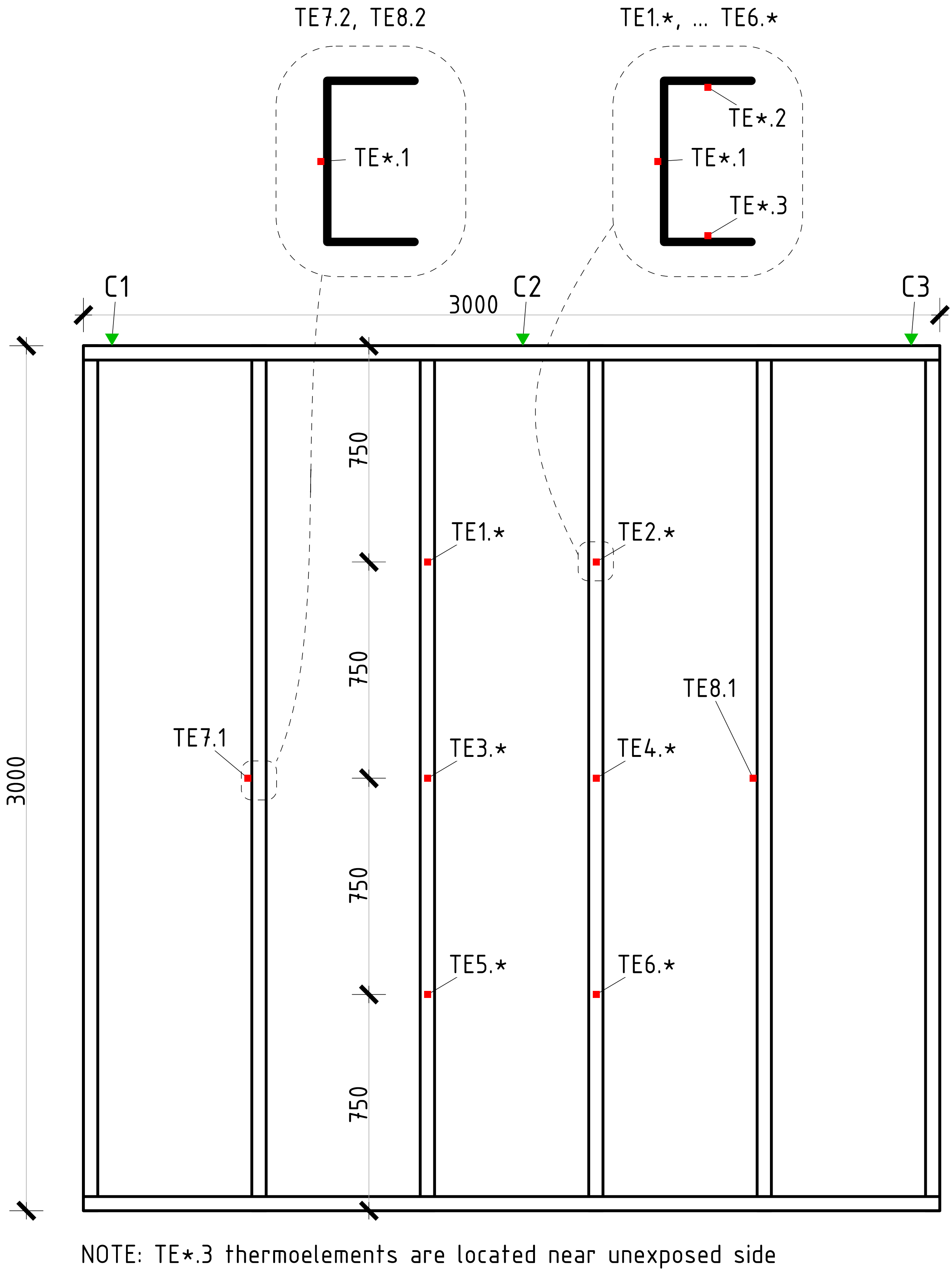

Fig. 1. Location of internal thermoelements and deflection gauges

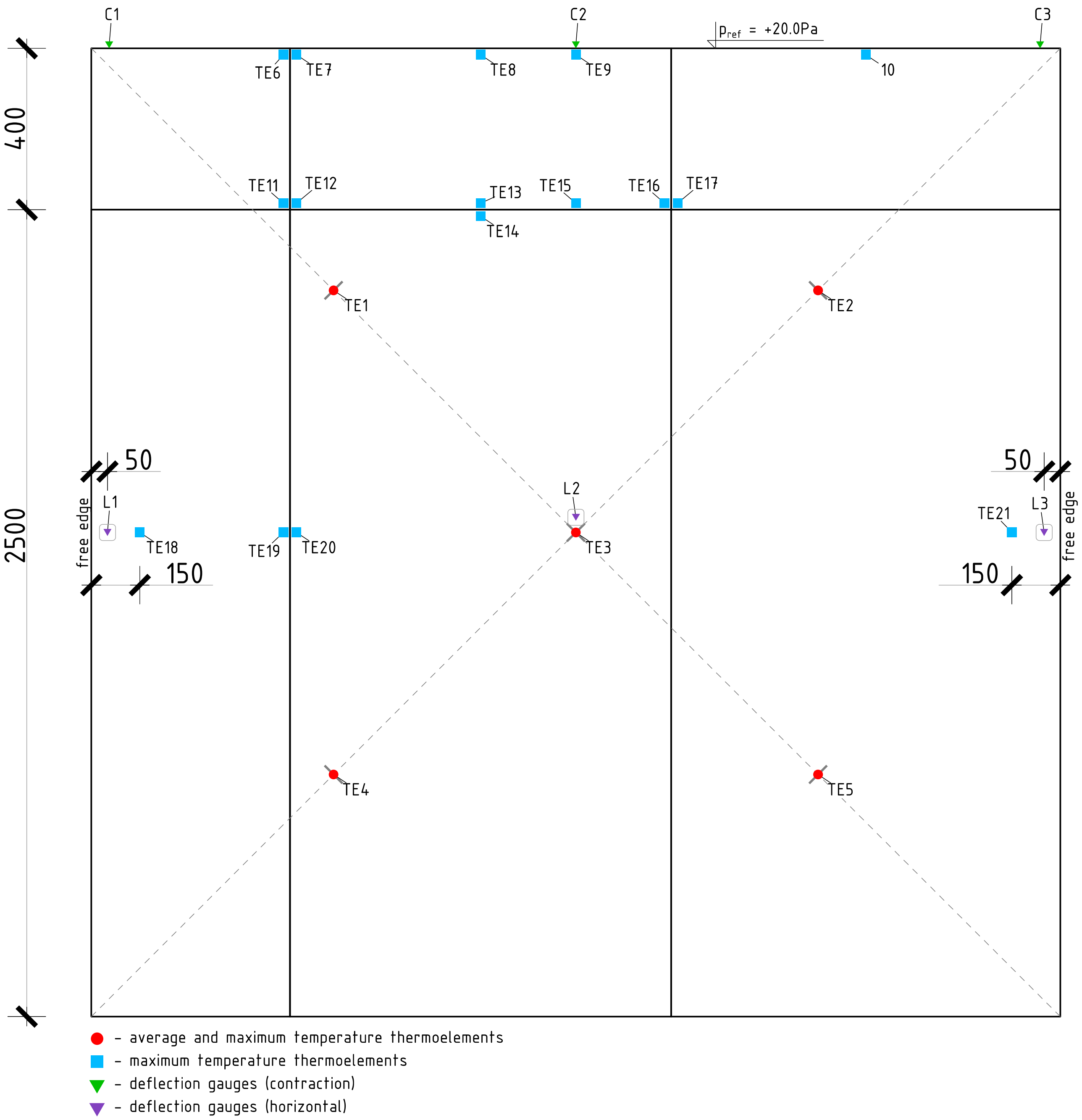

Fig. 2. Location of external thermoelements, deflection gauges and pressure reference

5. Results summary

This part of documentation is for presentation purposes only. The properly labelled full data are included in data files.

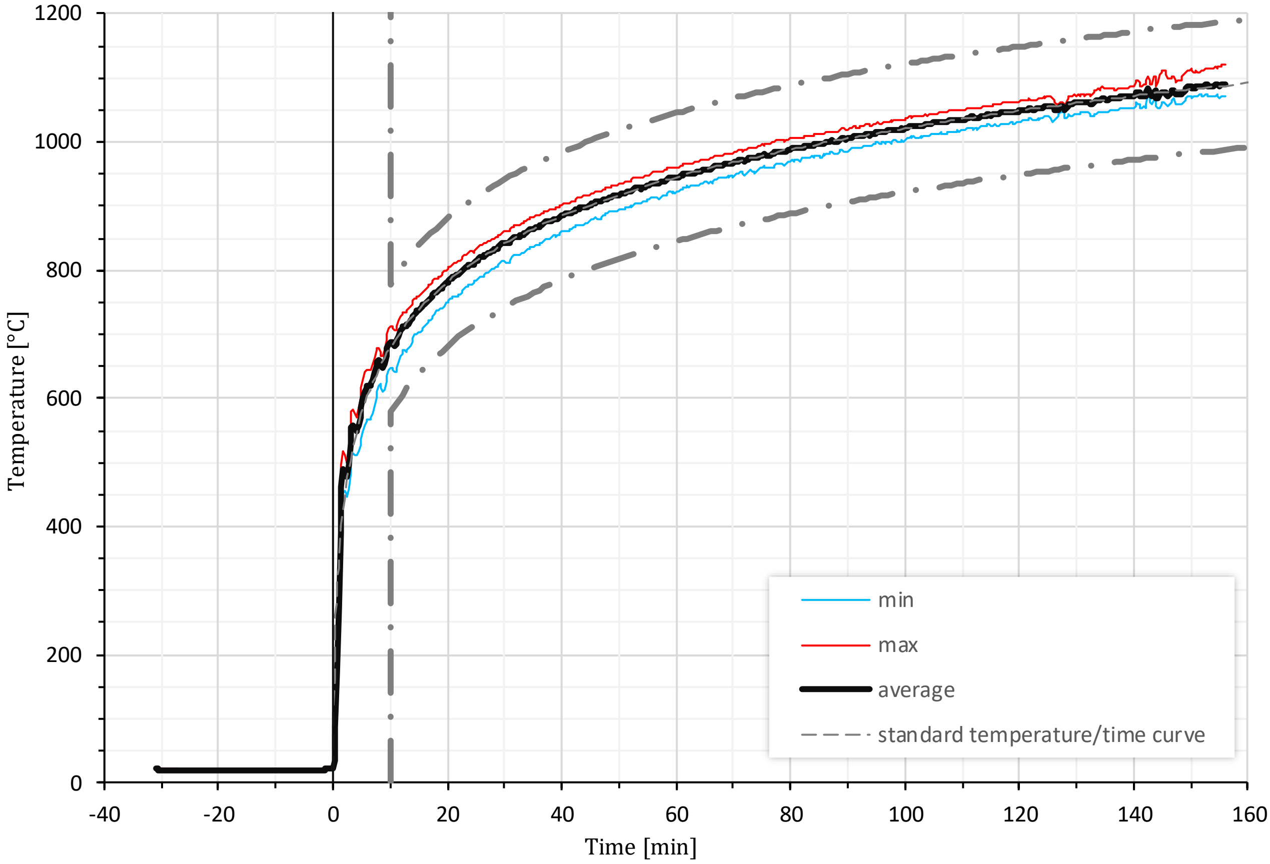

Fig. 3. Temperature of furnace heating conditions

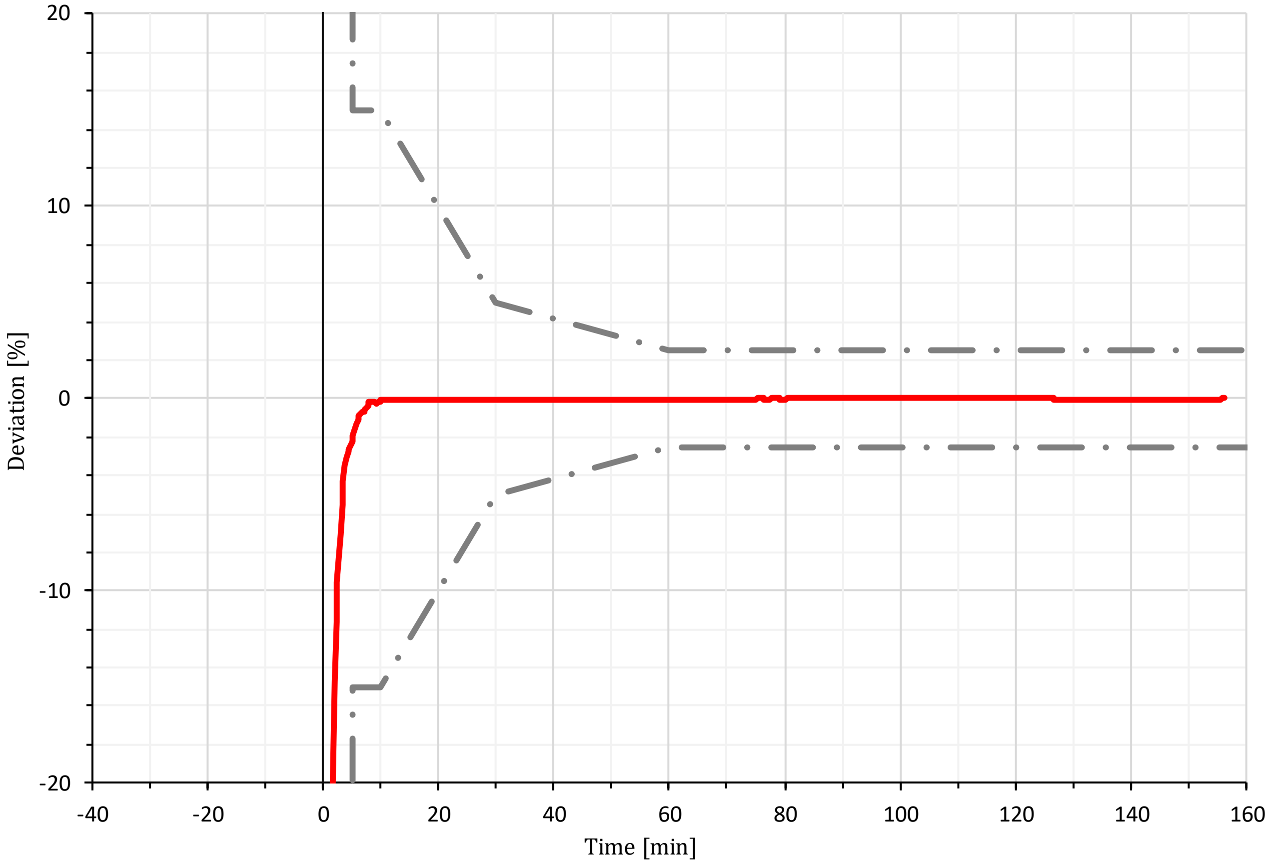

Fig. 4. Tolerance of the heating

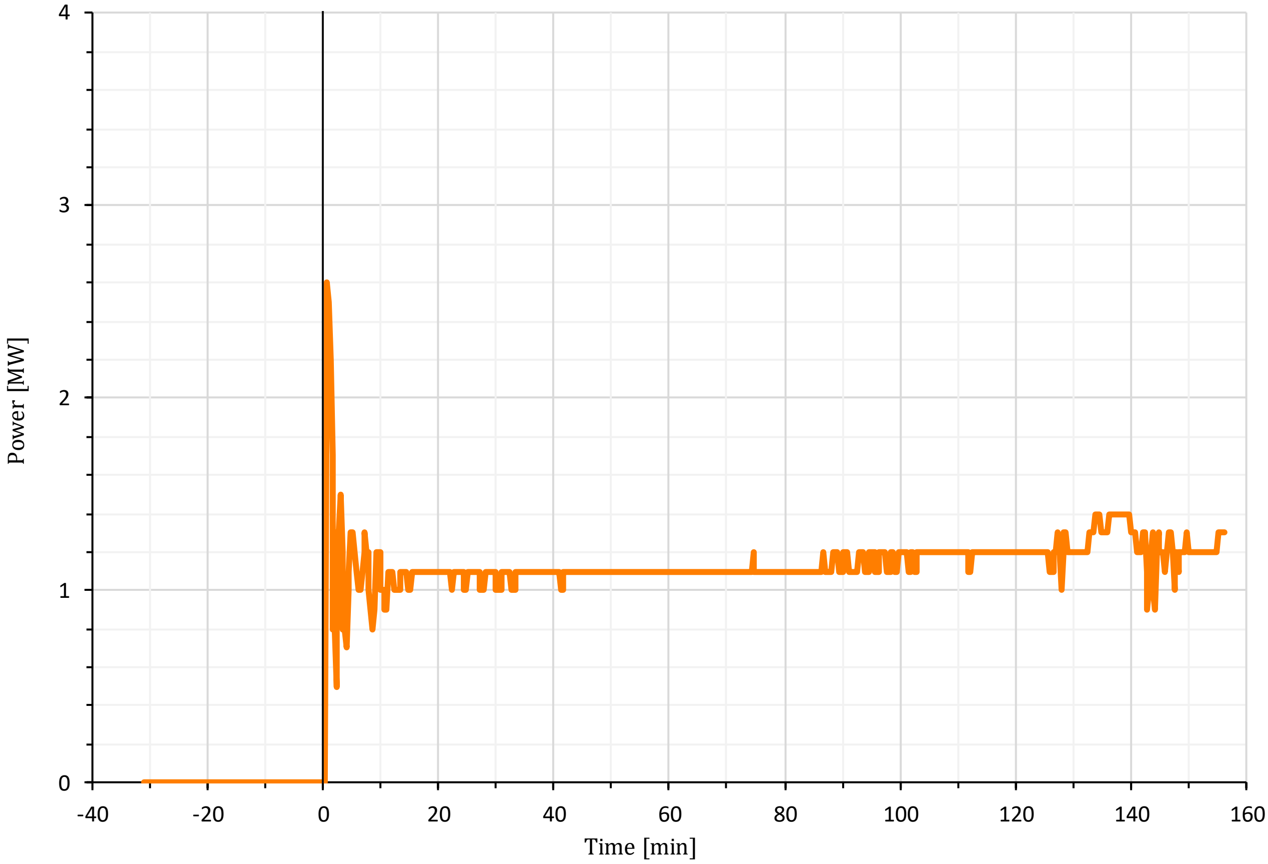

Fig. 5. Furnace power

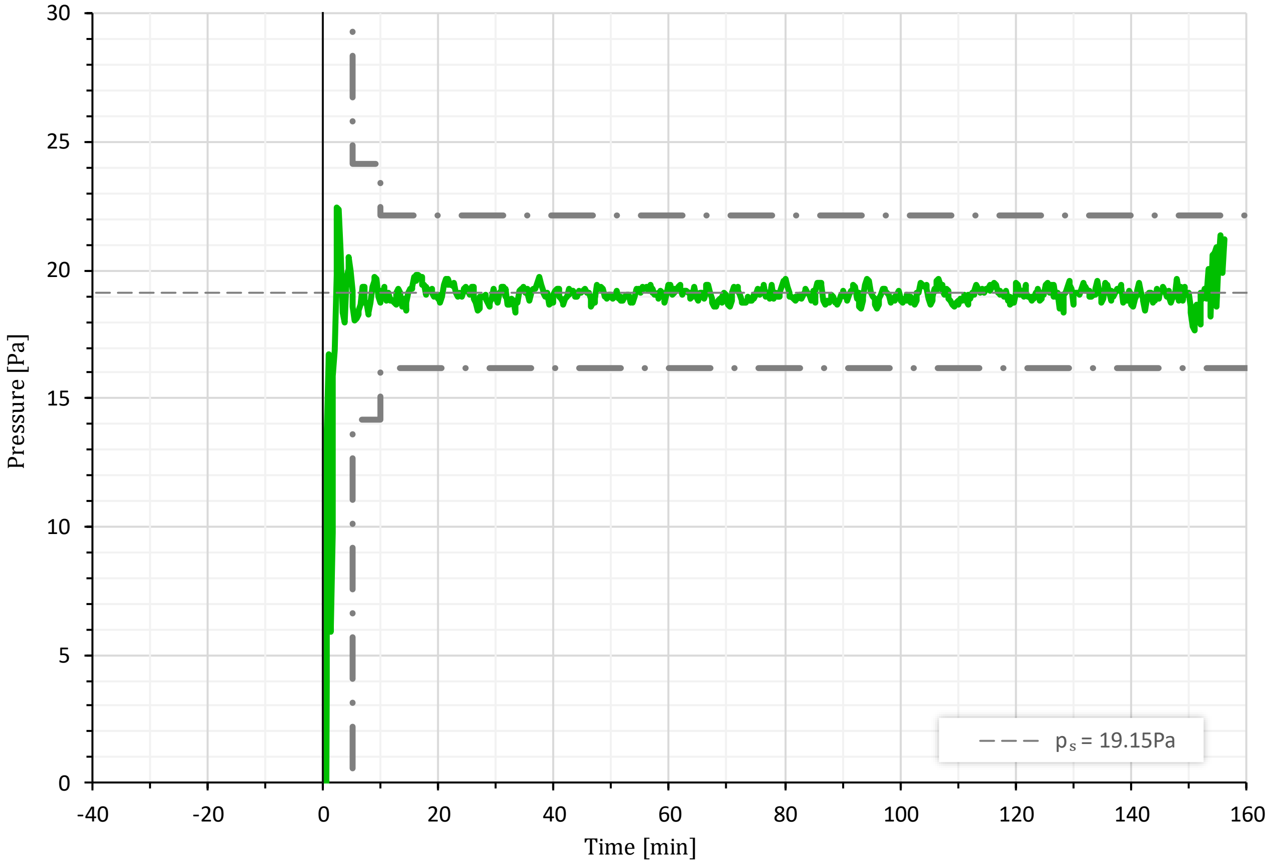

Fig. 6. Furnace pressure

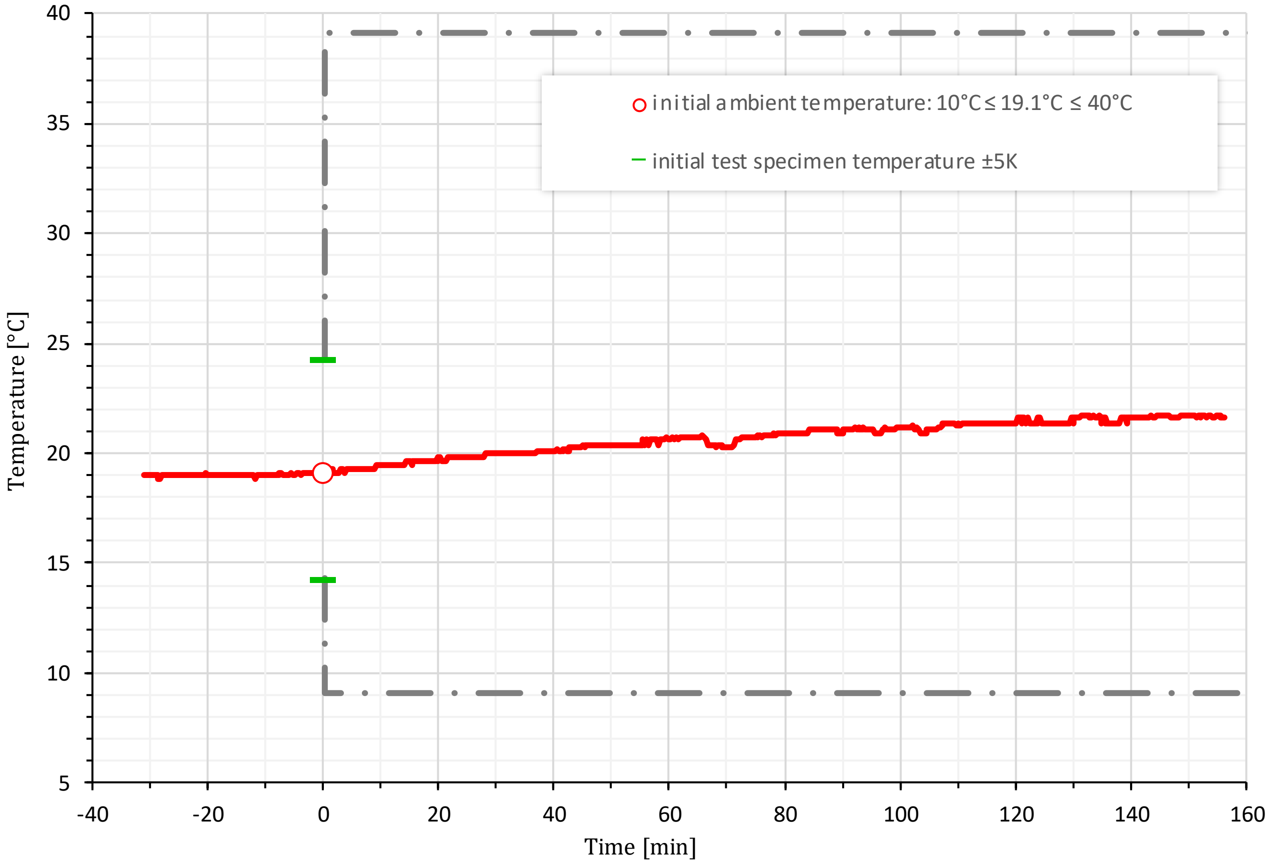

Fig. 7. Ambient temperature

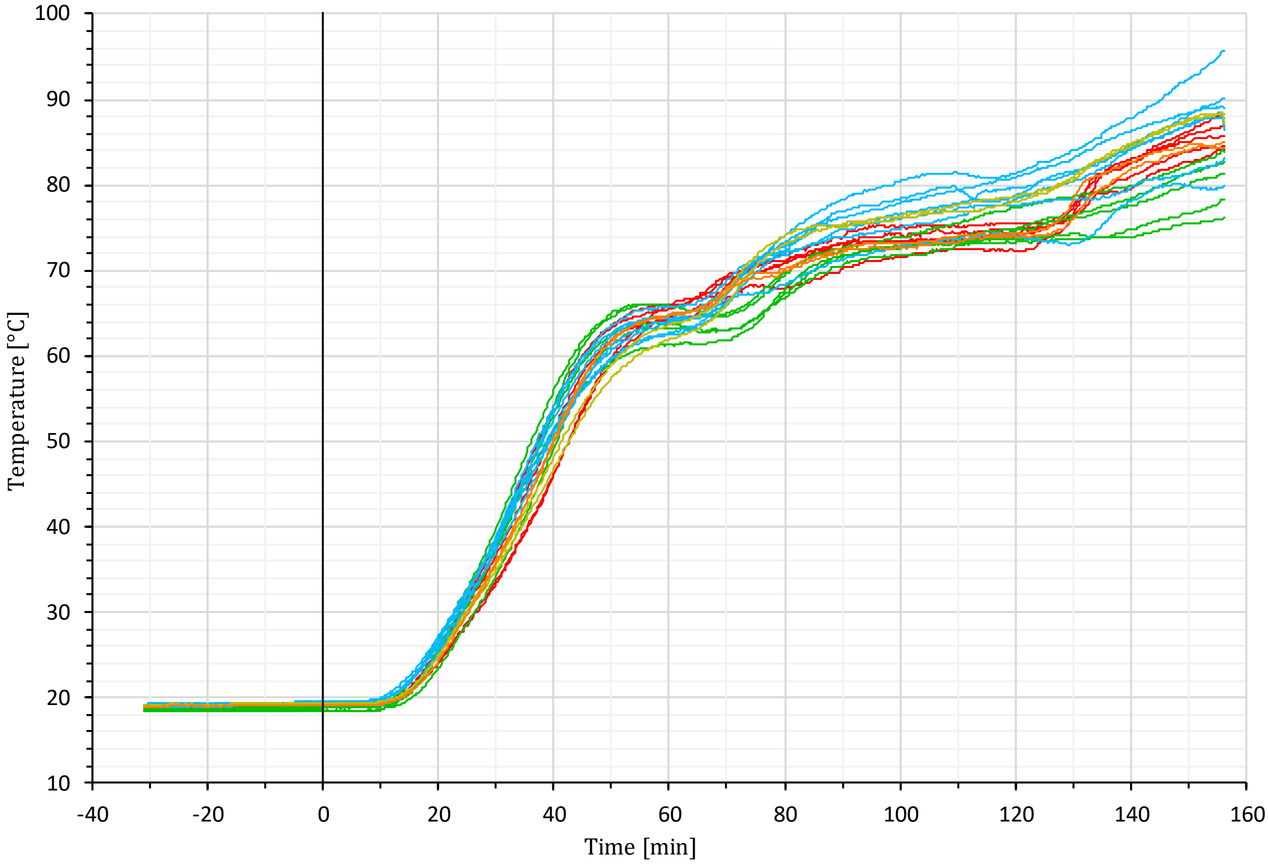

Fig. 8. External temperature thermoelements

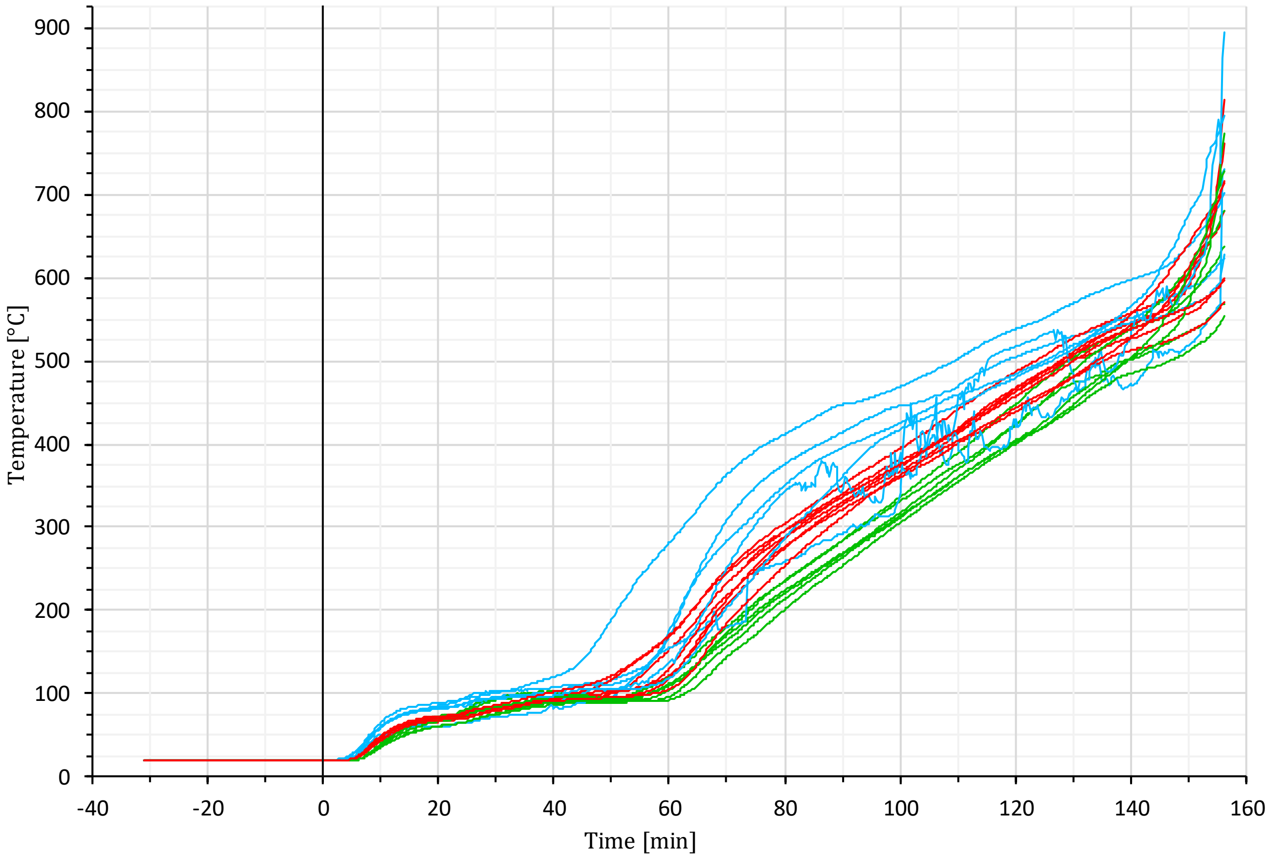

Fig. 9. Internal temperature thermoelements

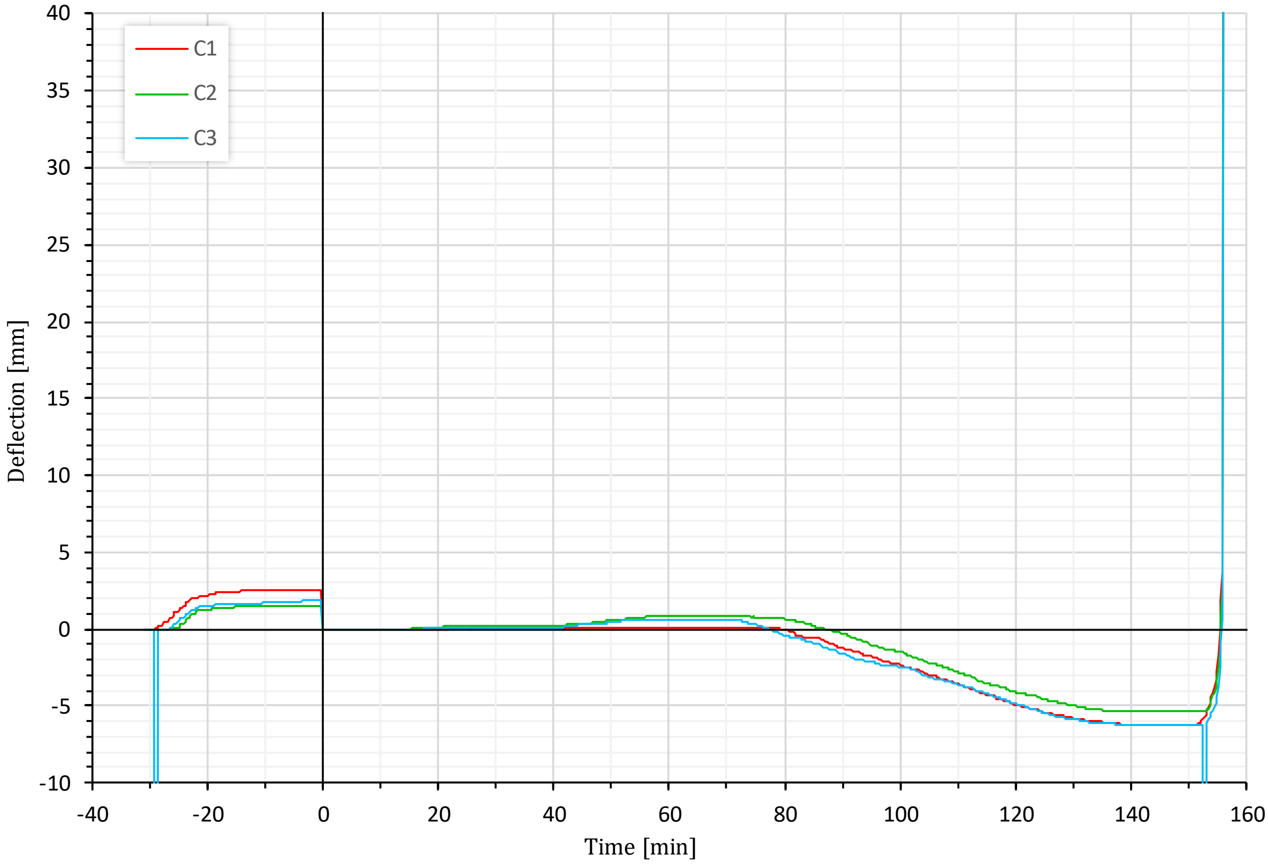

Fig. 10. Vertical deflection (contraction)

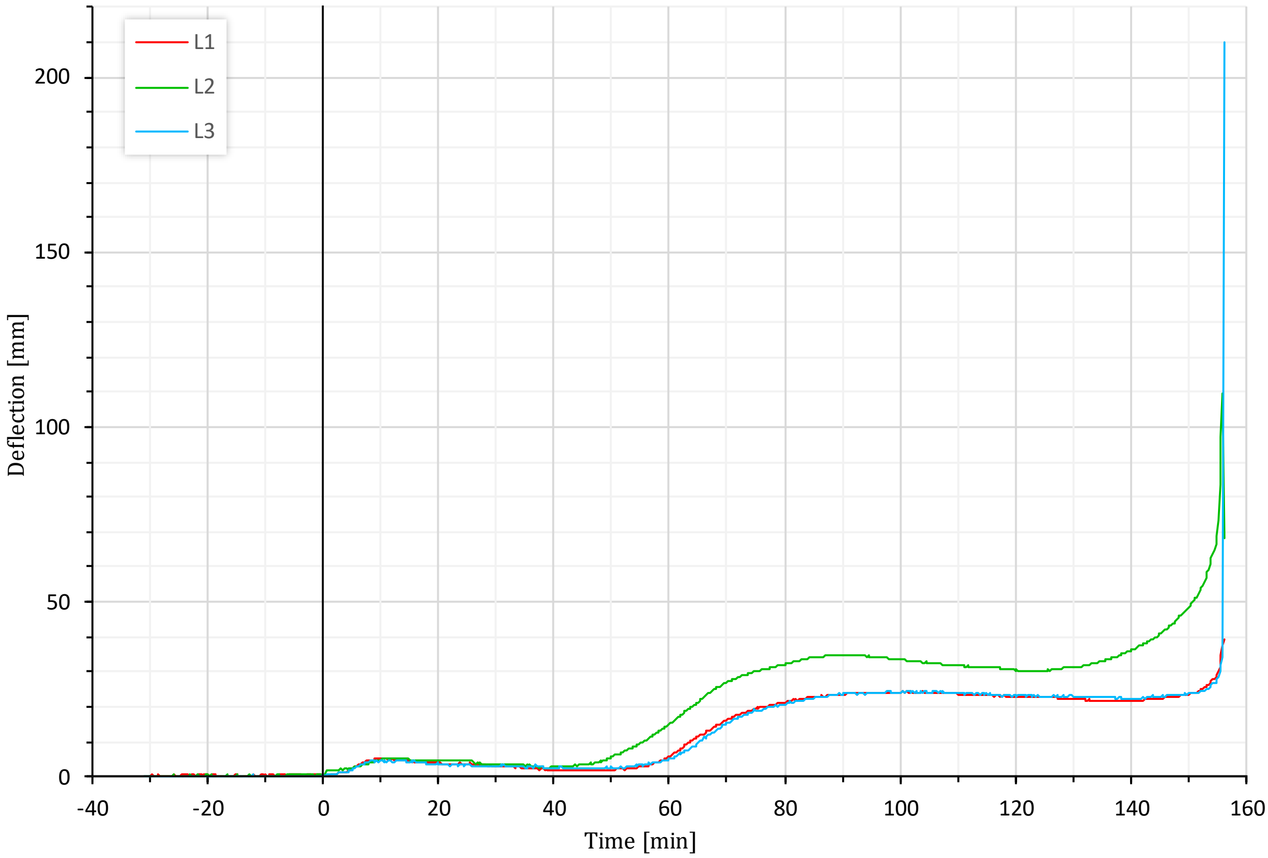

Fig. 11. Horizontal deflection (into the furnace)

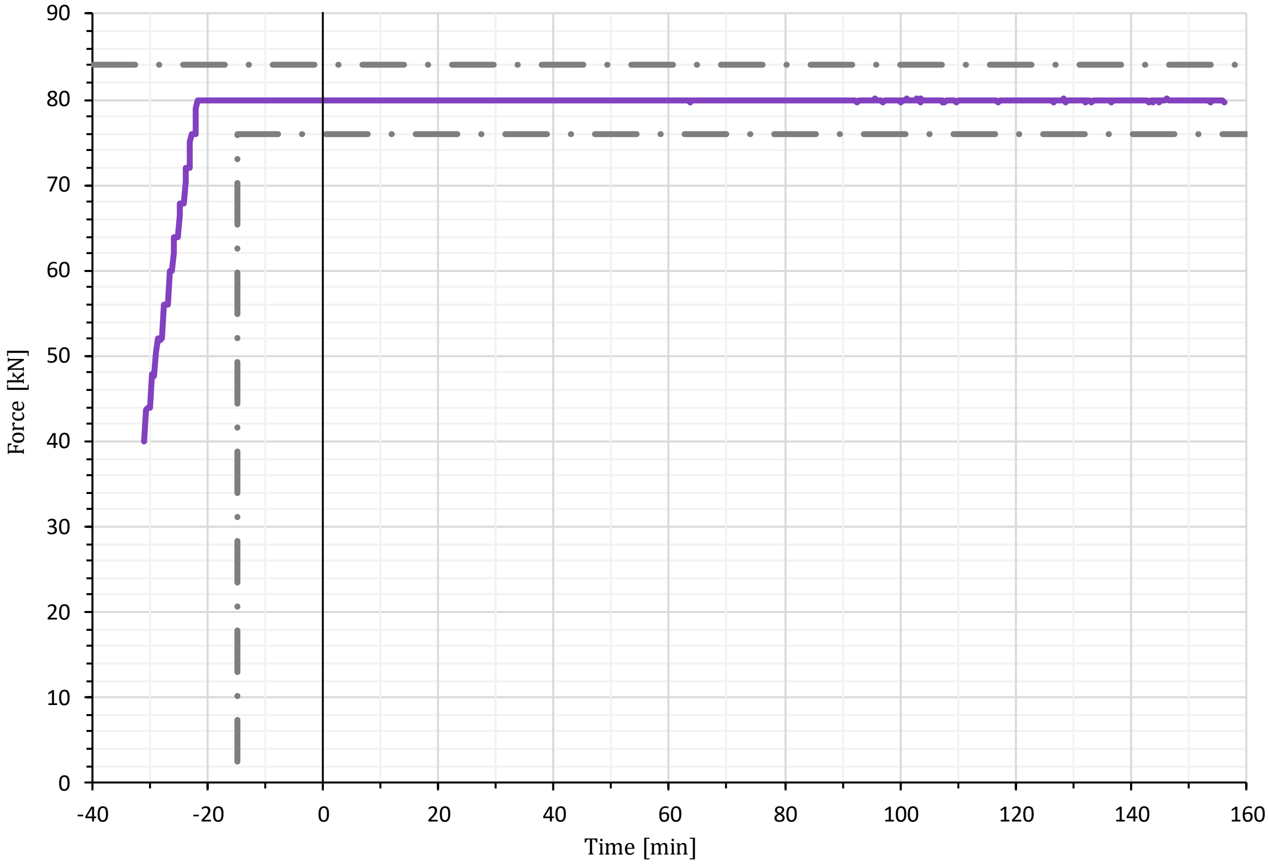

Fig. 12. Load force

6. Data files reference

This PDF file contains following attachment files (unless attachments were deliberately removed):

file name	MD5 hash
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Measurements 00-02520_23_Z00NZP.pdf	e5a62df30cb10d7aaea685cee8cdb242
Frame Factory_Specyfikacja profili.pdf	c333caf04a05301b2e71bcf7cd35ac18

Instytut Techniki Budowlanej

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Mazovian Branch – Laboratory
ul. Przemysłowa 2, 26-670 Pionki, Poland
Tel.: 48 3121600, fax: 48 3121601

Test Documentation LZP03-02520/23/Z00NZP

Client:	OFR Consultants Limited Sevendale House, Lever Street Manchester M1 1JA United Kingdom
Test Location:	ul. Przemysłowa 2, 26-670 Pionki, Poland
Date:	2023-11-09
Specimen:	Steel frame loadbearing wall with gypsum plasterboard cladding and mineral wool insulation
Method:	EN 1365-4:1999
Comments:	two-sided fire exposure

Warszawa, 2023-12-27

1. Test specimen description

Steel frame loadbearing wall with gypsum plasterboard cladding and mineral wool insulation.

(D) – nominal/declared value, (M) – measured by laboratory

steel frame:	
– profiles:	
– – manufacturer:	Frame Factory Sp. z o.o.
– – type / trade name:	C89×1.2
– – material:	S350GD (D)
– – section:	
– – – height:	89 mm (D)
– – – width:	41 mm (D)
– – – thickness:	1.2 mm (D)
– – – area:	2.22 cm^2 (D)
– – – inertia:	28.28 cm^4 (D) / 5.13 cm^4 (D)
– – – specific mass:	1.75 kg/m (D)
– assembly:	
– – nodes:	pre-cut slots in beams for stud positioning
– – fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each beam/stud crossing, both flanges
– fixing:	
– – bottom edge (to plinth):	4pcs. (2 pcs. per side) steel angles fixed to bottom beam
– – top edge:	free (loaded)
cladding:	
– boards :	
– – amount:	two layers on both sides of test specimen; two layers on vertical edges
– – manufacturer:	Knauf
– – type / trade name:	F15-DF-15EN520
– – thickness:	15 mm (D); 14.98 mm (M)
– – size:	1200 × 2600 mm (D) (before assembly)
– – density:	13.0 kg/m^2 (M)
– – moisture content:	0.3% (M)
– assembly:	
– – layout:	
– – – horizontal:	in each layer 2 boards full-size (fixed to 3 studs) and a single border board half-width (fixed to 2 studs); overlapping joints between layers
– – – vertical:	full-width horizontal joint 40 cm (M) from one edge on all layers; alternating position of the joint relative to top/bottom edge through all 4 layers
– – masking tape:	
– – – manufacturer:	Knauf
– – – type / trade name:	Kurt CE 07T-EN13963
– – – location:	over board edges
– – filler:	gypsum filler
– – – manufacturer:	Knauf
– – – type / trade name:	Knauf G-K Start
– – – location:	over masking tapes and screw heads
– fixing (to steel frame):	
– – first layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)

– – second layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×55 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)
insulation:	
– mineral wool:	
– – manufacturer:	Paroc
– – type / trade name:	Paroc Ultra MW-EN 13162-T2-DS(70,-)-WS-WL(P)-MU1
– – thickness:	100 mm (D); 98.8 mm (M)
– – size:	610 × 1220 mm (D)
– – density:	35.1 kg/m^3 (M)
– – moisture content:	0.8% (M)

2. Test specimen preparation:

time registry:	
– assembly:	
– – start:	2023-11-13
– – end:	2023-11-15
– conditioning:	not required
laboratory involvement:	laboratory was involved in selection of the test specimen
manufacturer:	Knauf

3. Test

method:	EN 1365-4:1999
date:	2023-11-09
duration:	72 min 22 s
ambient conditions:	
– temperature:	17.3°C
– humidity:	35%
load:	
– total:	80 kN
– – beam:	0.5 kN
– – actuator:	79.5 kN
– location:	top edge of test specimen
furnace pressure:	
– reference value:	20 Pa
– – location:	distributed over top edge of the test specimen
– measurement location:	0.1 m below top edge of the test specimen
– set-point:	19.15 Pa
initial furnace temperature:	21.2°C

4. Measurement locations

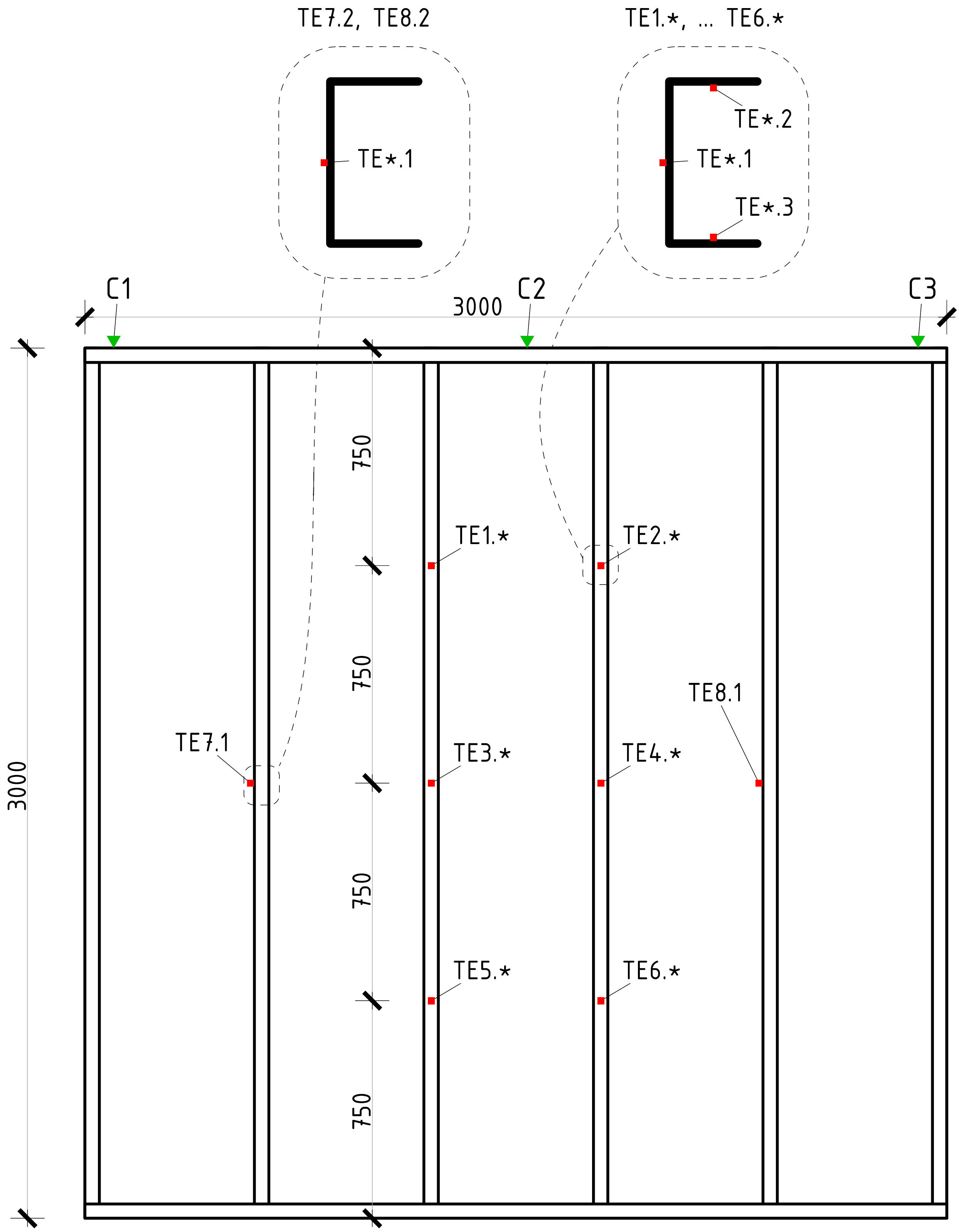

Fig. 1. Location of internal thermoelements and deflection gauges

5. Results summary

This part of documentation is for presentation purposes only. The properly labelled full data are included in data files.

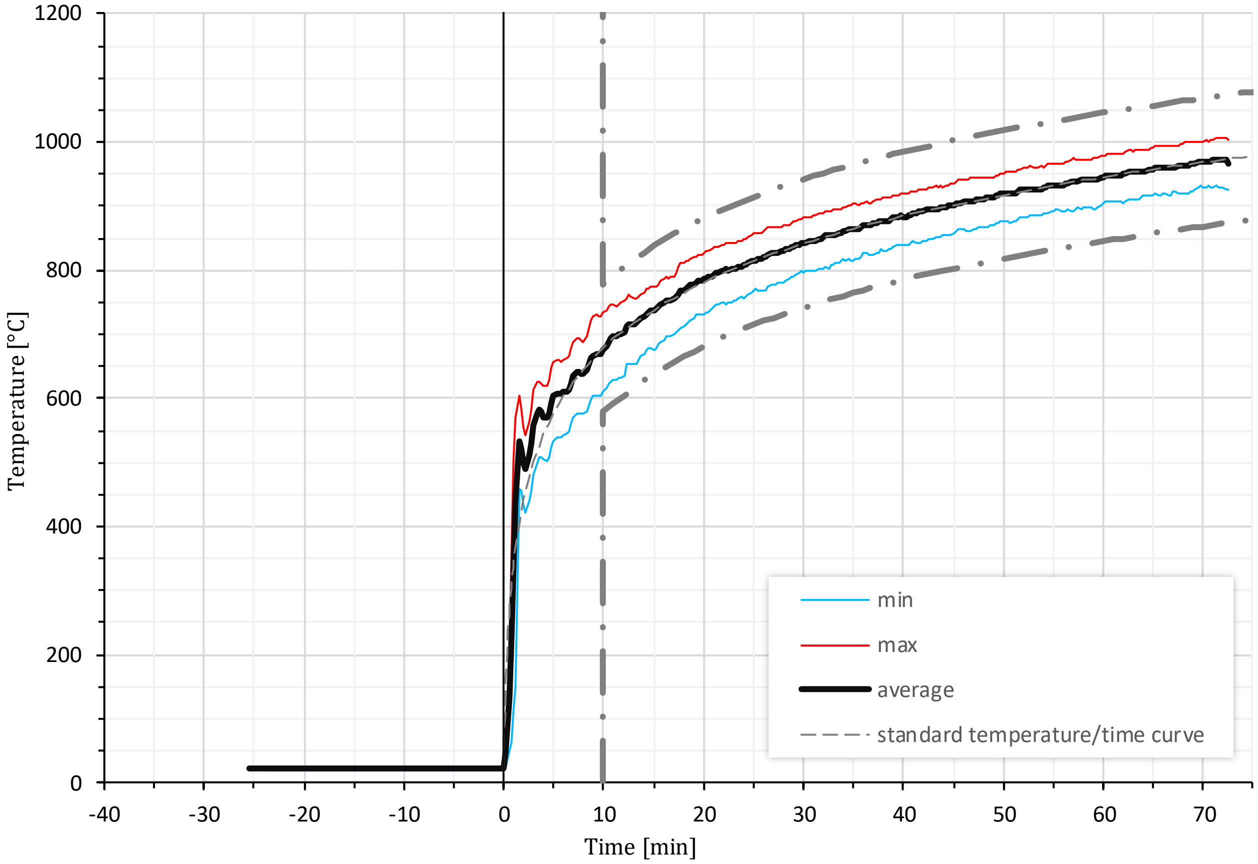

Fig. 1. Temperature of furnace heating conditions

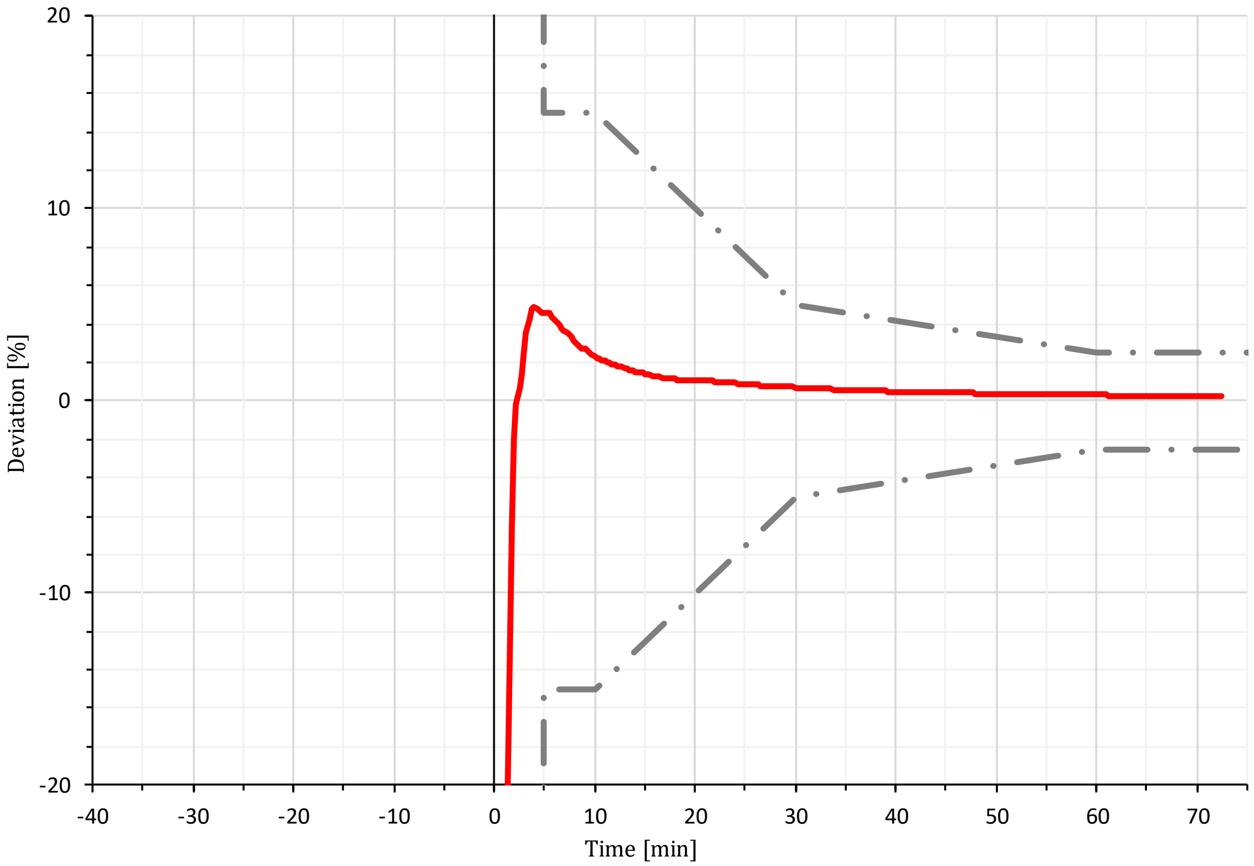

Fig. 2. Tolerance of the heating

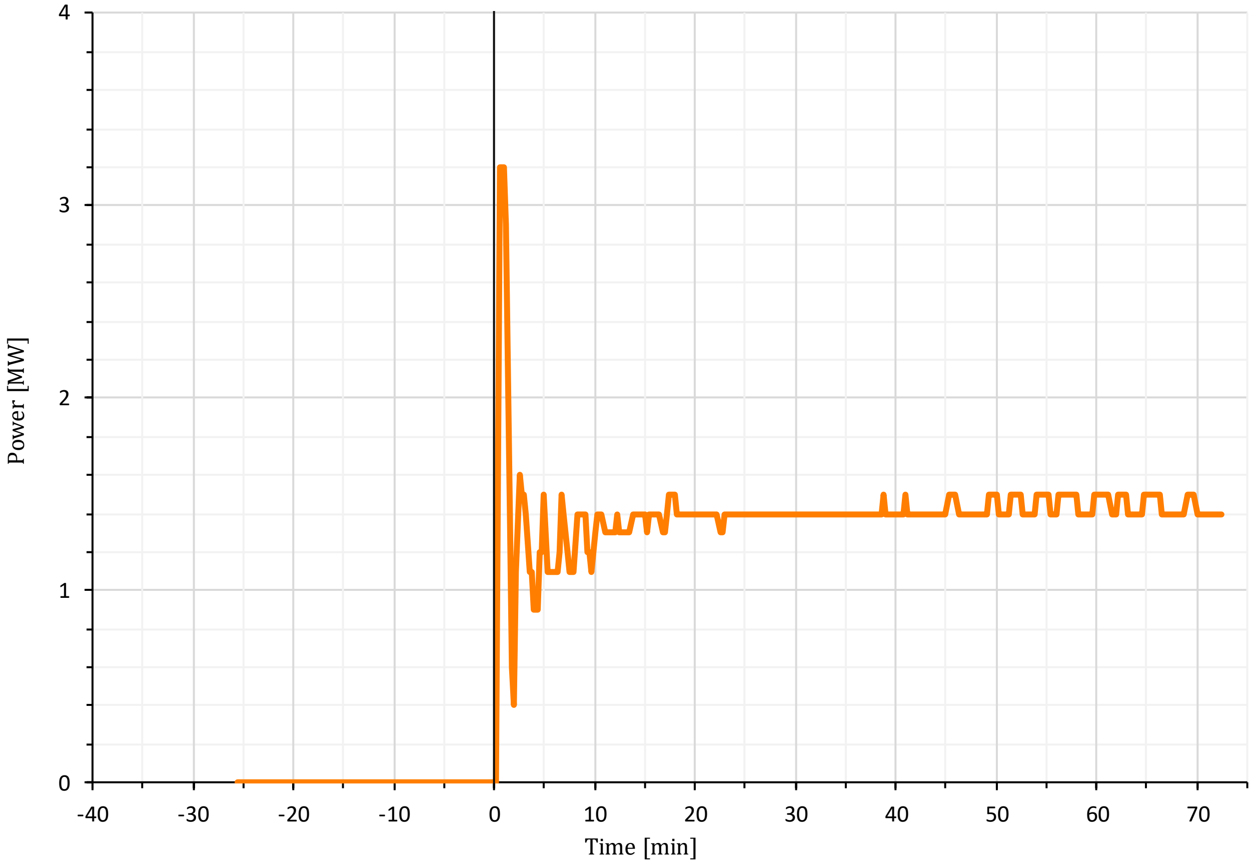

Fig. 3. Furnace power

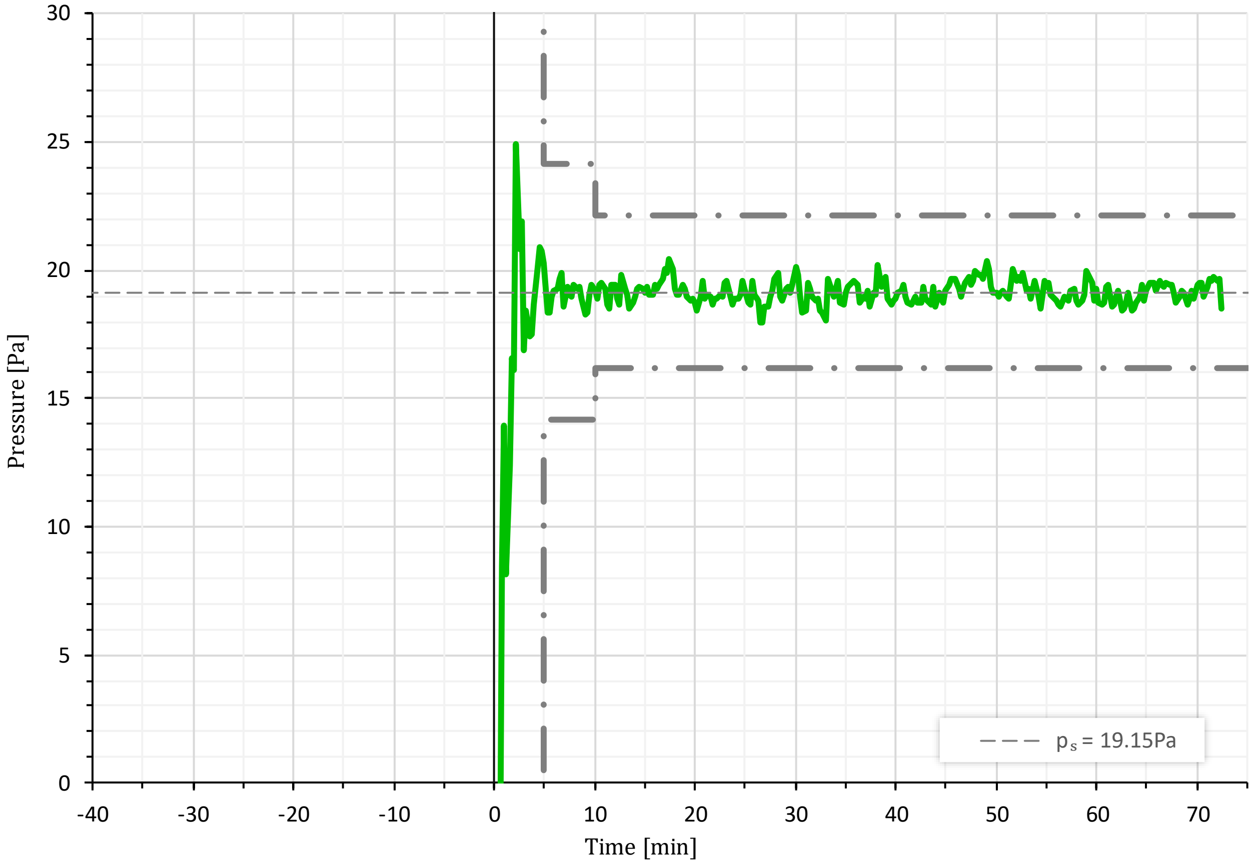

Fig. 4. Furnace pressure

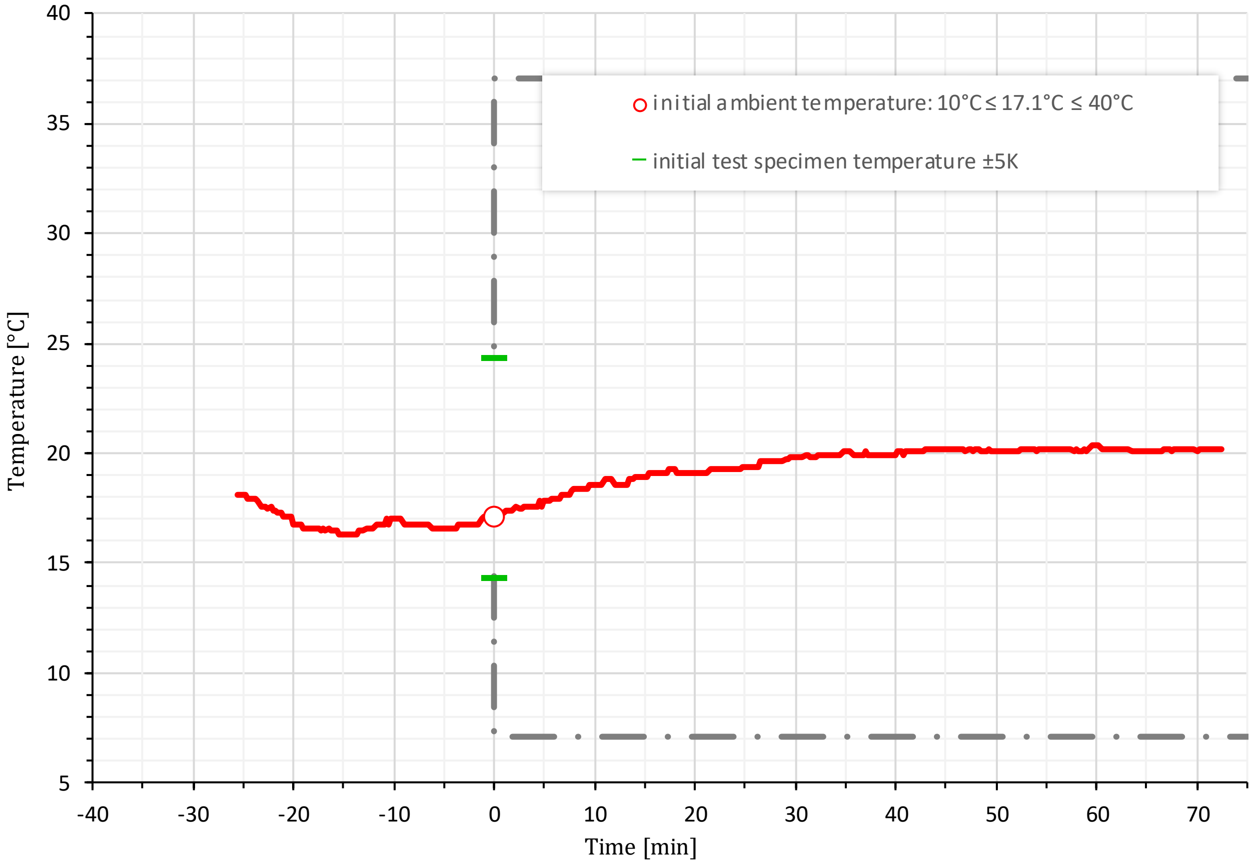

Fig. 5. Ambient temperature

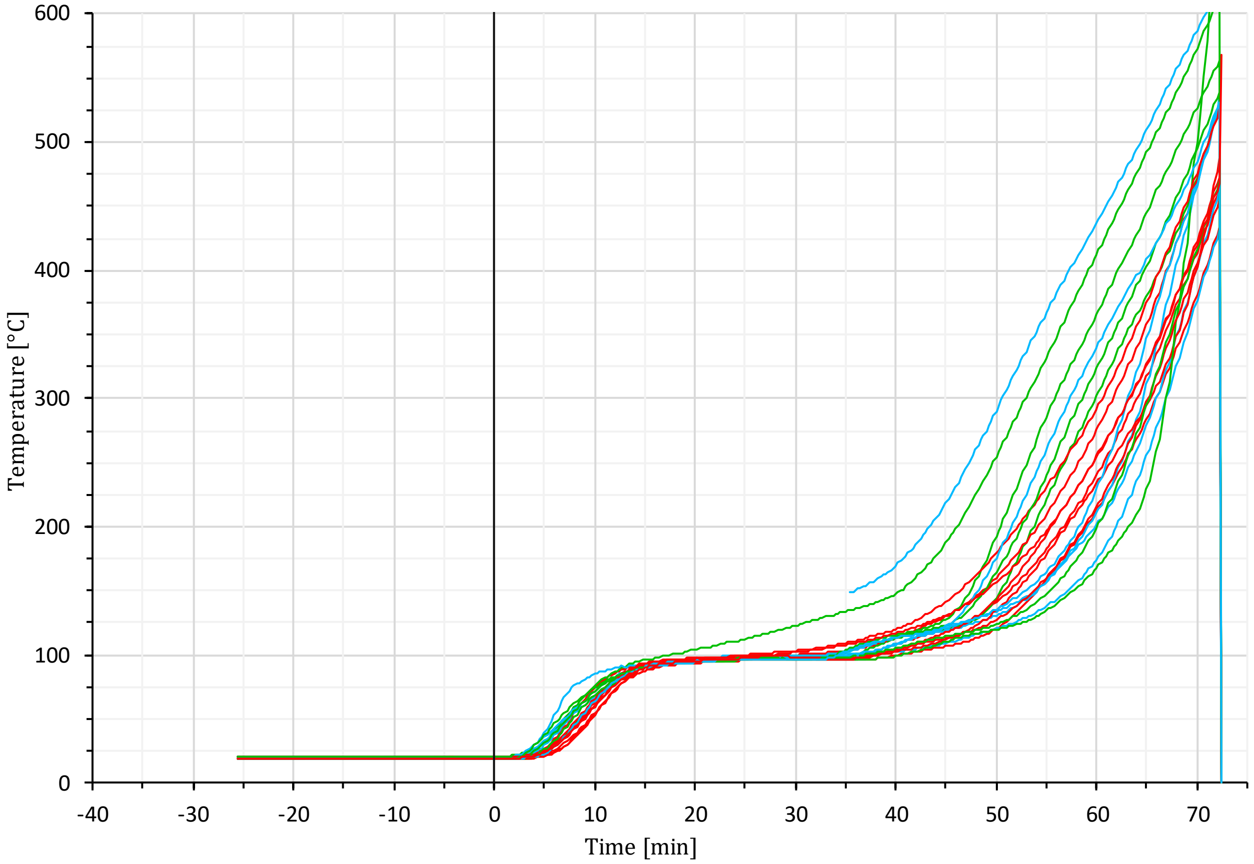

Fig. 6. Internal temperature thermoelements

Instytut Techniki Budowlanej

Nauka i wiedza ekspercka dla budownictwa przyszłości

Fire Research Department
ul. Ksawerów 21, 02-656 Warszawa, Poland
Tel.: 22 5664284
e-mail: fire@itb.pl

Mazovian Branch – Laboratory
ul. Przemysłowa 2, 26-670 Pionki, Poland
Tel.: 48 3121600, fax: 48 3121601

Test Documentation LZP04-02520/23/Z00NZP

Client:	OFR Consultants Limited Sevendale House, Lever Street Manchester M1 1JA United Kingdom
Test Location:	ul. Przemysłowa 2, 26-670 Pionki, Poland
Date:	2023-11-24
Specimen:	Steel frame loadbearing wall with gypsum plasterboard cladding and mineral wool insulation
Method:	EN 1365-1:2012/AC:2013
Comments:	one-sided fire exposure

Warszawa, 2023-12-27

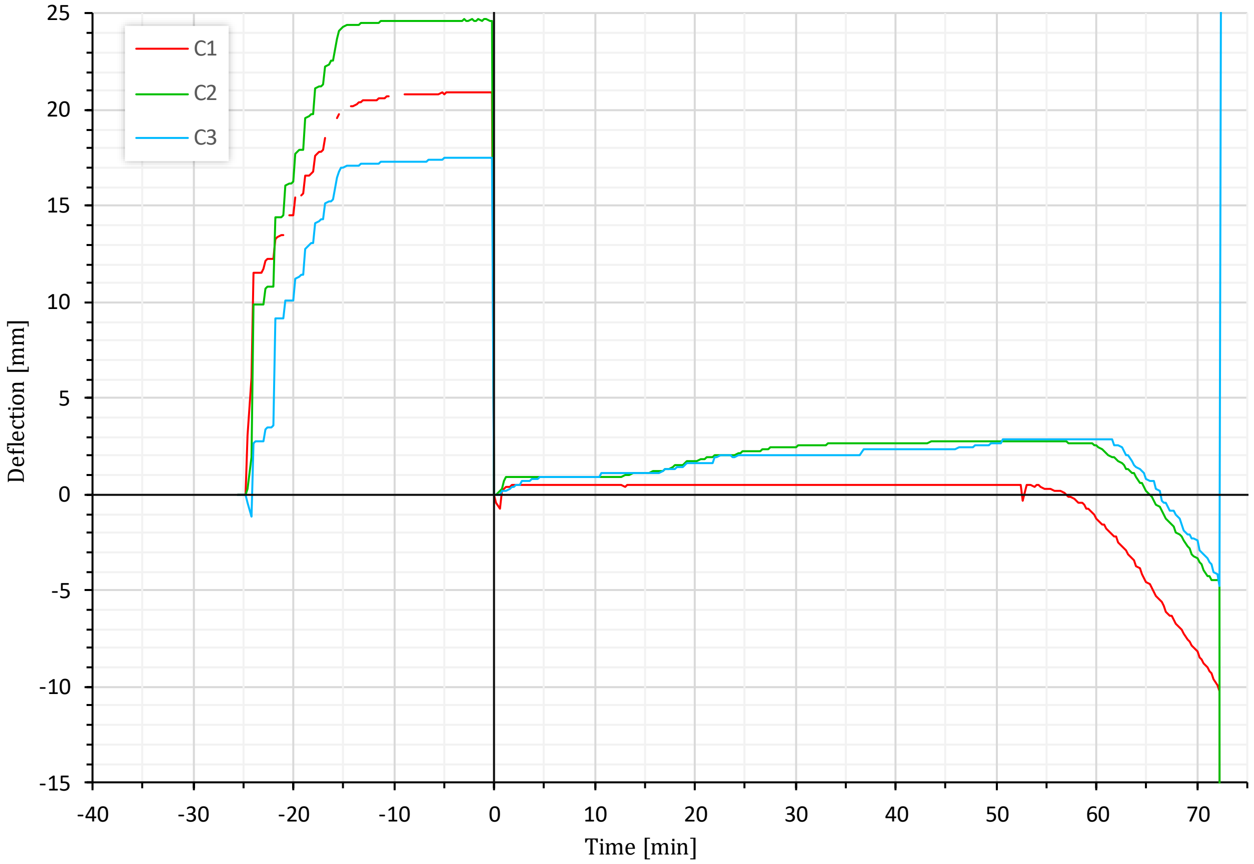

Fig. 7. Vertical deflection (contraction)

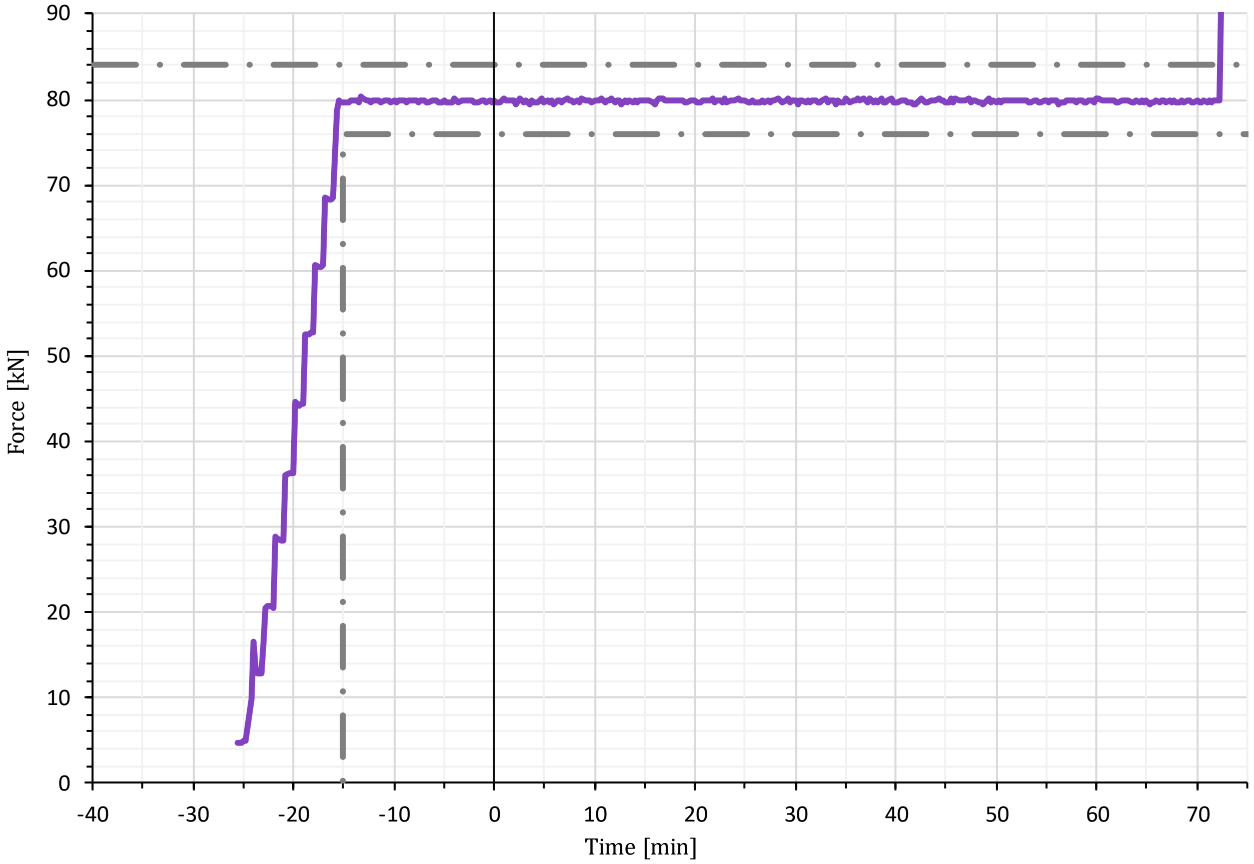

Fig. 8. Load force

6. Data files reference

This PDF file contains following attachment files (unless attachments were deliberately removed):

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Measurements 00-02520_23_Z00NZP.pdf	e5a62df30cb10d7aaea685cee8cdb242
Frame Factory_Specyfikacja profili.pdf	c333caf04a05301b2e71bcf7cd35ac18

1. Test specimen description

Single steel frame loadbearing wall with gypsum plasterboard cladding and mineral wool insulation.

(D) – nominal/declared value, (M) – measured by laboratory

steel frame:	
– profiles:	
– – manufacturer:	Frame Factory Sp. z o.o.
– – type / trade name:	C89×1.2
– – material:	S350GD (D)
– – section:	
– – – height:	89 mm (D)
– – – width:	41 mm (D)
– – – thickness:	1.2 mm (D)
– – – area:	2.22 cm^2 (D)
– – – inertia:	28.28 cm^4 (D) / 5.13 cm^4 (D)
– – – specific mass:	1.75 kg/m (D)
– assembly:	
– – nodes:	pre-cut slots in beams for stud positioning
– – fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)
– – – location:	each beam/stud crossing, both flanges
– fixing:	
– – bottom edge (to plinth):	4pcs. (2 pcs. per side) steel angles fixed to bottom beam
– – side edges:	free
– – top edge:	free (loaded)
cladding:	
– boards :	
– – amount:	two layers on both sides of test specimen
– – manufacturer:	Knauf
– – type / trade name:	F15-DF-15EN520
– – thickness:	15 mm (D); 14.87 mm (M)
– – size:	1200 × 2600 mm (D) (before assembly)
– – density:	12.9 kg/m^3 (M)
– – moisture content:	0.2% (M)
– assembly:	
– – layout:	
– – – horizontal:	in each layer 2 boards full-size (fixed to 3 studs) and a single border board half-width (fixed to 2 studs); overlapping joints between layers
– – – vertical:	full-width horizontal joint 40 cm (M) from one edge on all layers; alternating position of the joint relative to top/bottom edge through all 4 layers; horizontal joint close to top edge on unexposed side
– – masking tape:	
– – – manufacturer:	Knauf
– – – type / trade name:	Kurt CE 07T-EN13963
– – – location:	over board edges
– – filler:	gypsum filler
– – – manufacturer:	Knauf
– – – type / trade name:	Knauf G-K Start
– – – location:	over masking tapes and screw heads
– fixing (to steel frame):	
– – first layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×35 mm (D)

– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)
– – second layer fasteners:	screws
– – – manufacturer:	Knauf
– – – trade name/ size:	TB 3.5×55 mm (D)
– – – location:	each board edge + each board mid-width over a stud; c/c ~ 300 mm (D)
insulation:	
– mineral wool:	
– – manufacturer:	Paroc
– – type / trade name:	Paroc Ultra MW-EN 13162-T2-DS(70,-)-WS-WL(P)-MU1
– – thickness:	100 mm (D); 98.8 mm (M)
– – size:	610 × 1220 mm (D)
– – density:	35.1 kg/m^3 (M)
– – moisture content:	0.8% (M)

2. Test specimen preparation:

time registry:	
– assembly:	
– – start:	2023-11-13
– – end:	2023-11-15
– conditioning:	not required
laboratory involvement:	laboratory was involved in selection of the test specimen
manufacturer:	Knauf

3. Test

method:	EN 1365-1:2012/AC:2013
date:	2023-11-24
duration:	116 min 15 s
ambient conditions:	
– temperature:	19.1°C
– humidity:	31%
load:	
– total:	80 kN
– – beam:	40 kN
– – actuator:	40 kN
– location:	top edge of test specimen
furnace pressure:	
– reference value:	20 Pa
– – location:	distributed over top edge of the test specimen
– measurement location:	0.1 m below top edge of the test specimen
– set-point:	19.15 Pa
initial furnace temperature:	18.2°C

4. Measurement locations

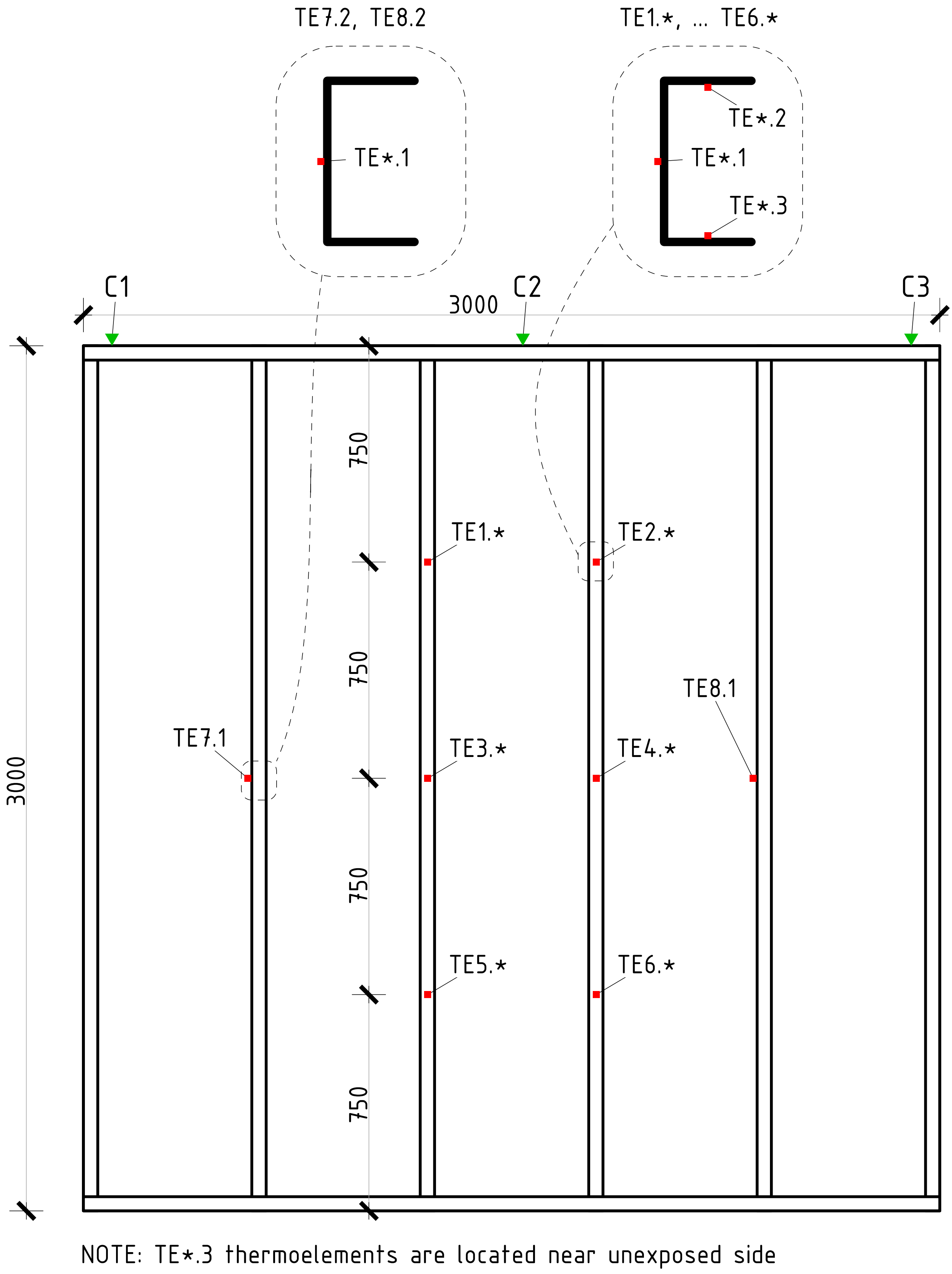

Fig. 1. Location of internal thermoelements and deflection gauges

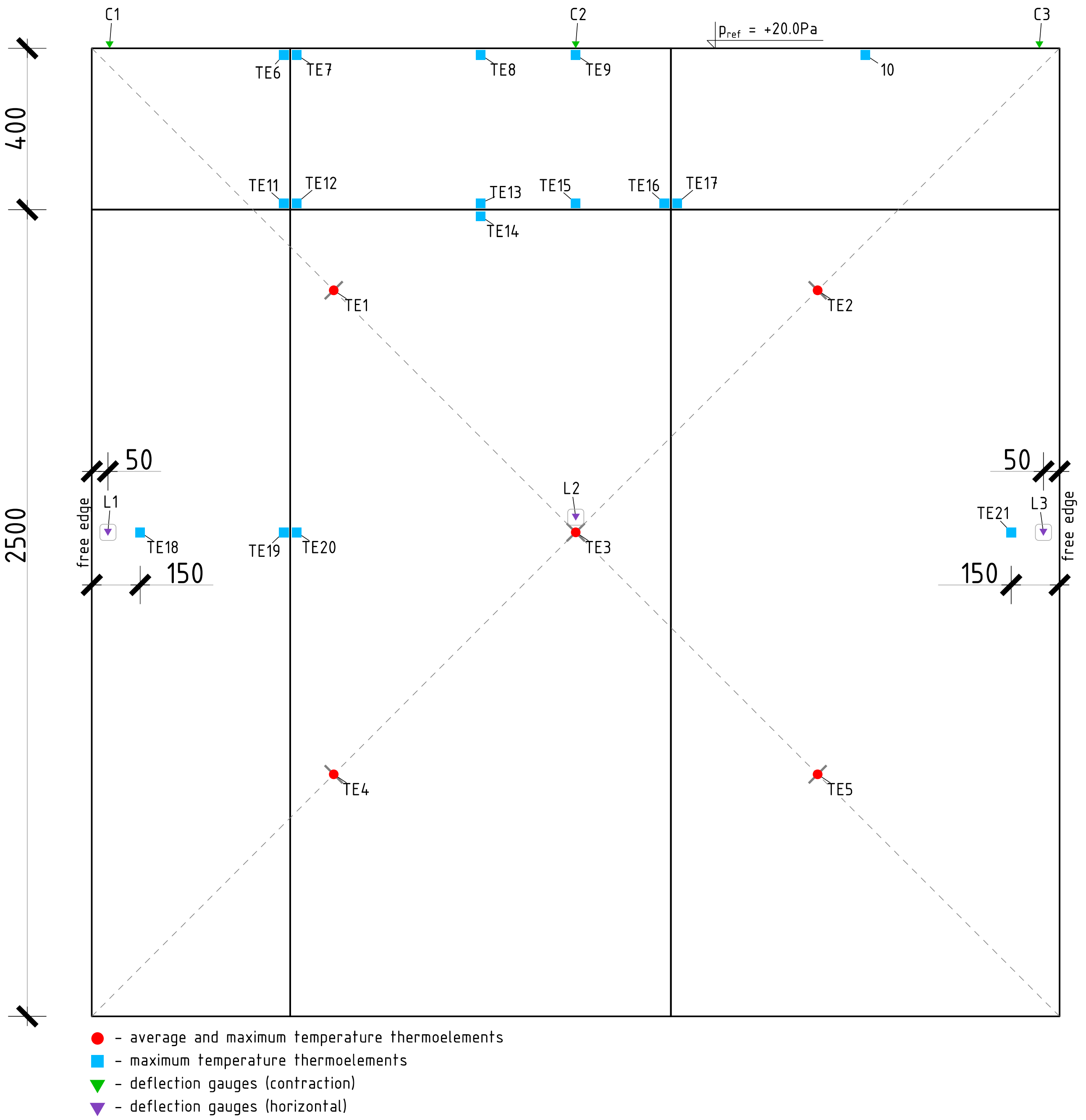

Fig. 2. Location of external thermoelements, deflection gauges and pressure reference

5. Results summary

This part of documentation is for presentation purposes only. The properly labelled full data are included in data files.

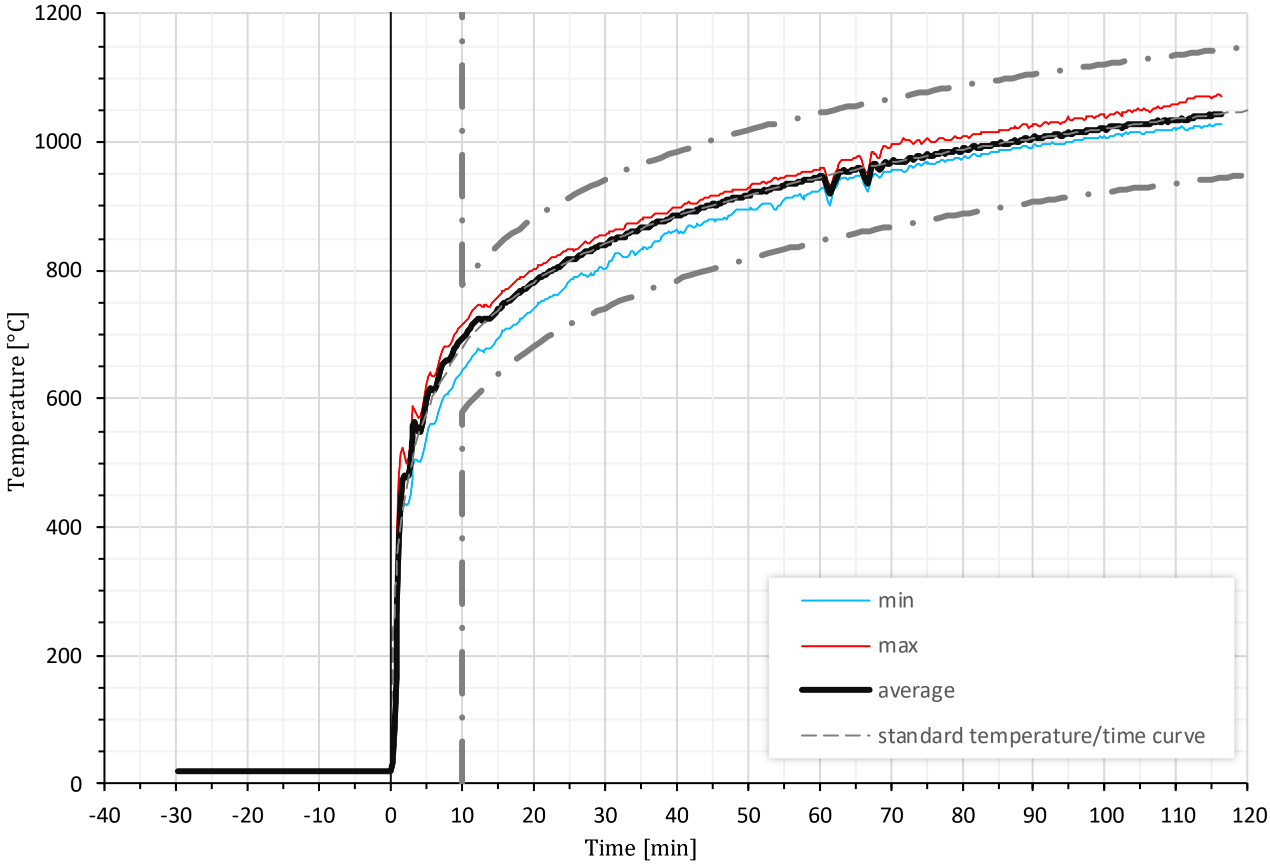

Fig. 3. Temperature of furnace heating conditions

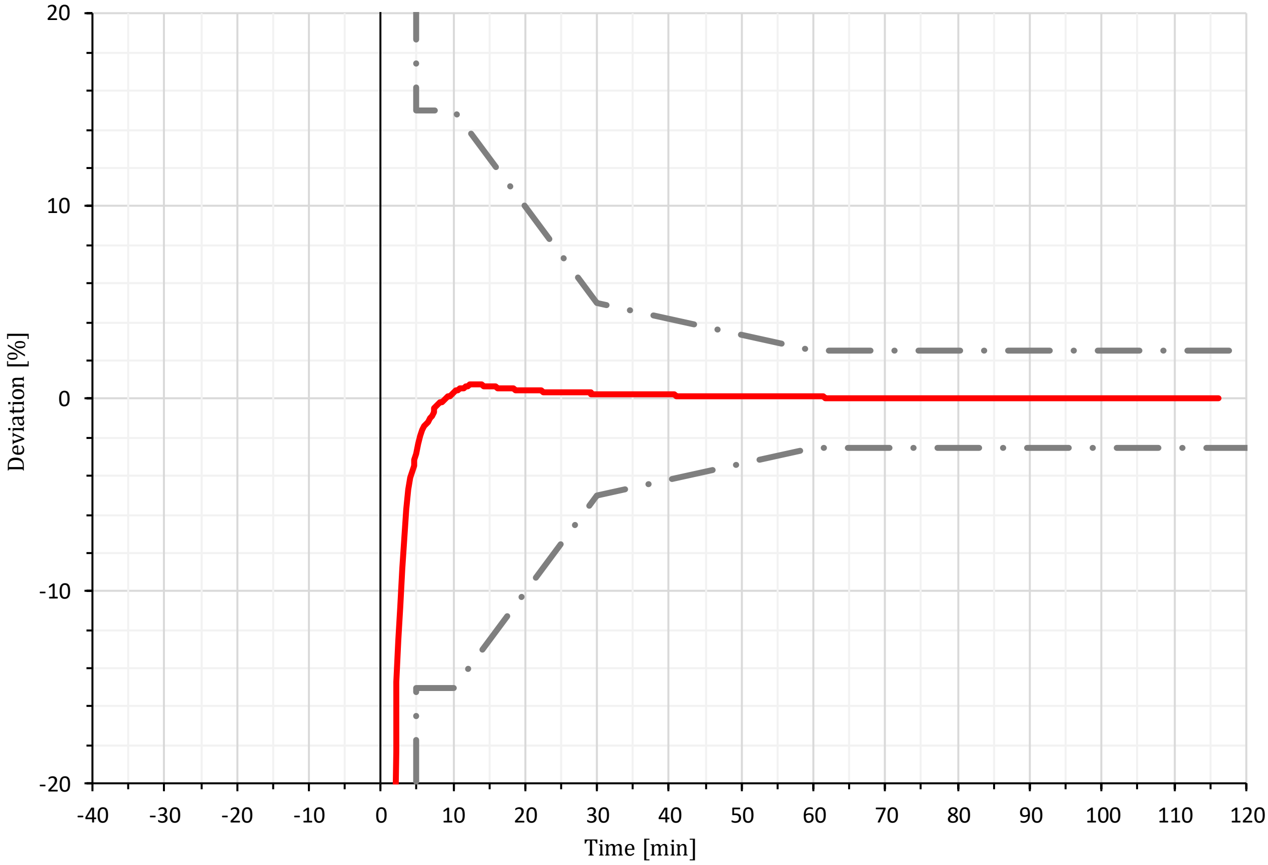

Fig. 4. Tolerance of the heating

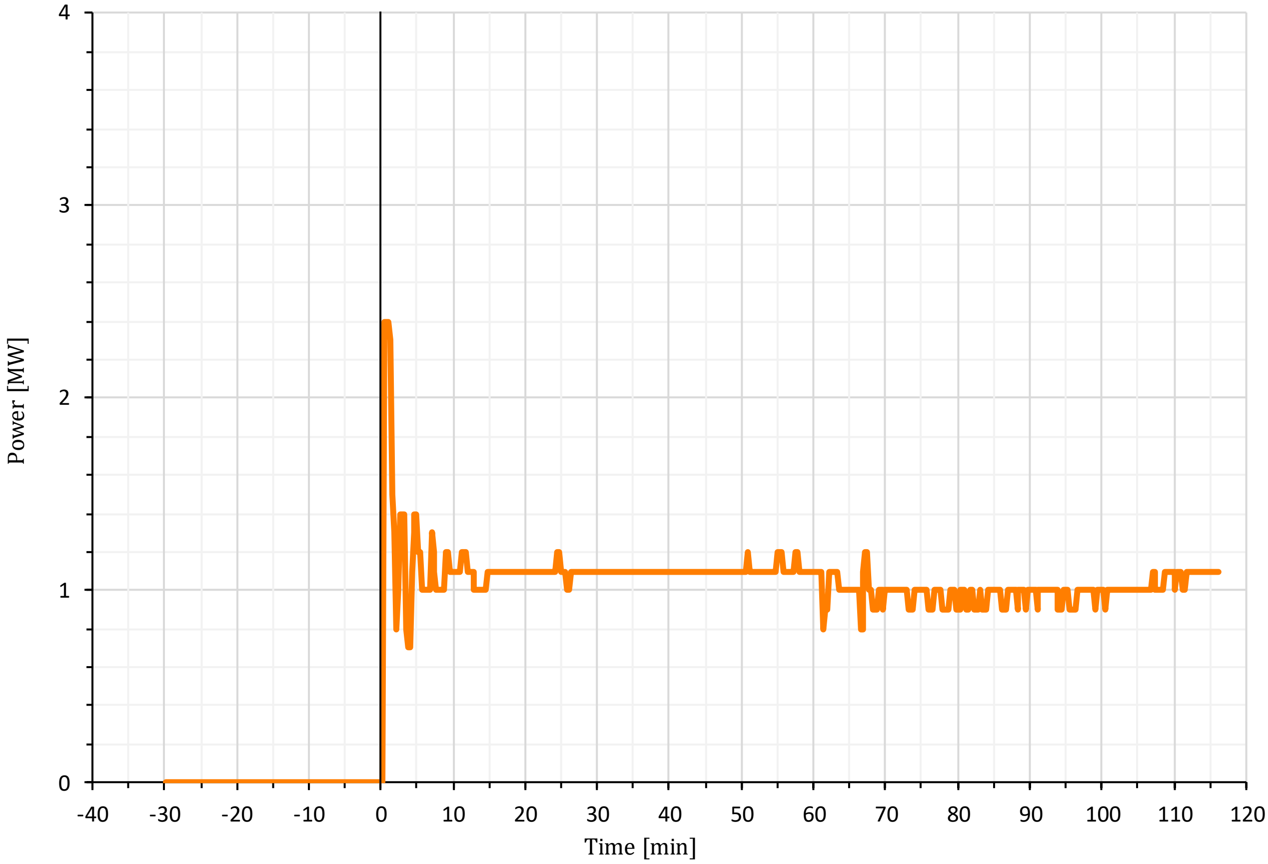

Fig. 5. Furnace power

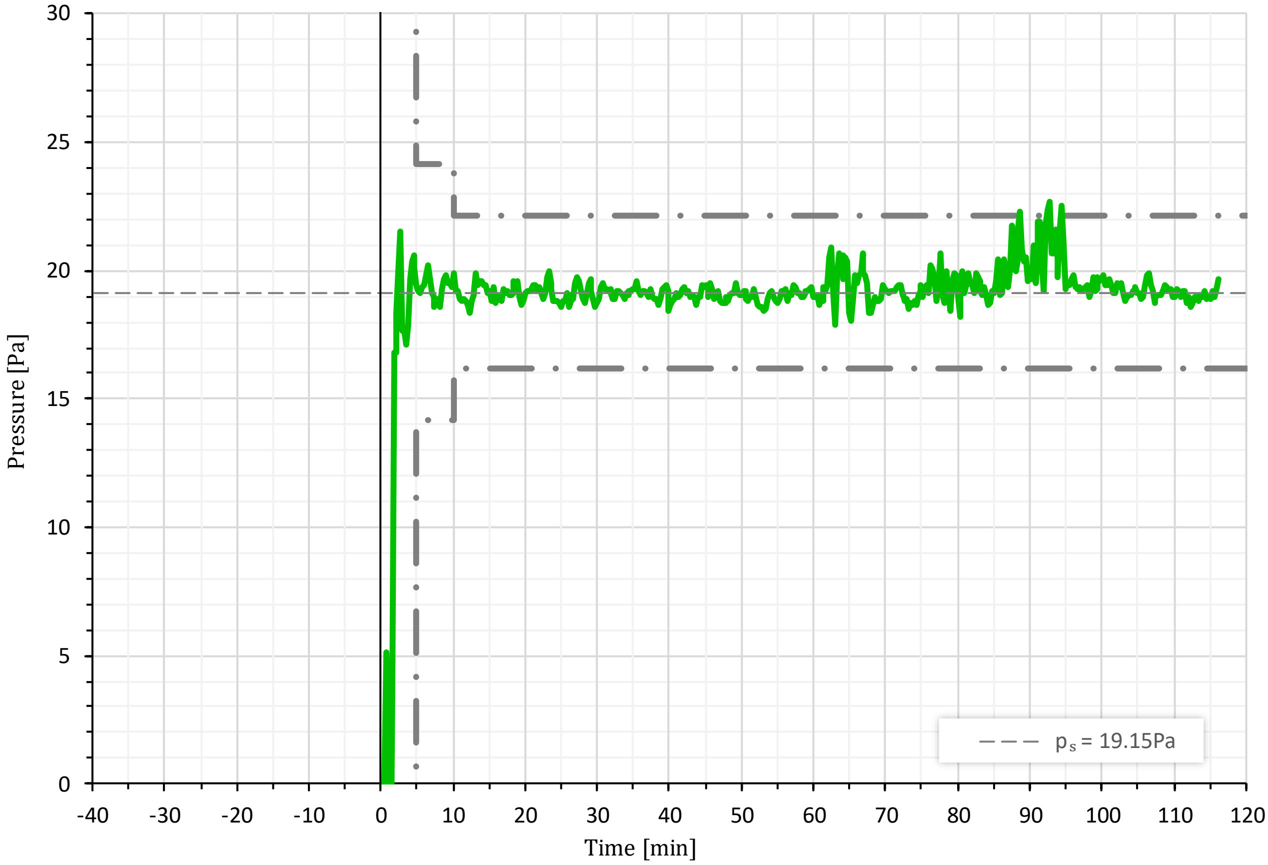

Fig. 6. Furnace pressure

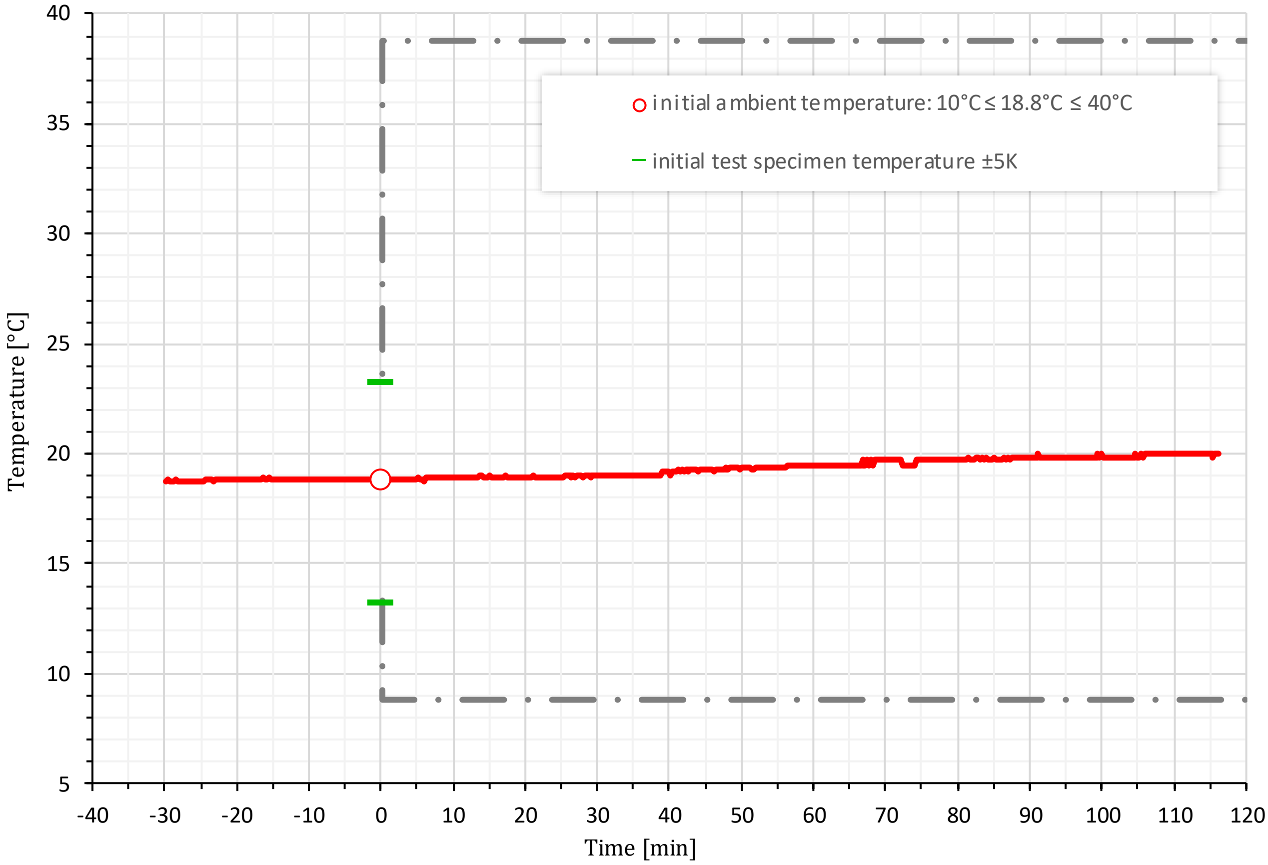

Fig. 7. Ambient temperature

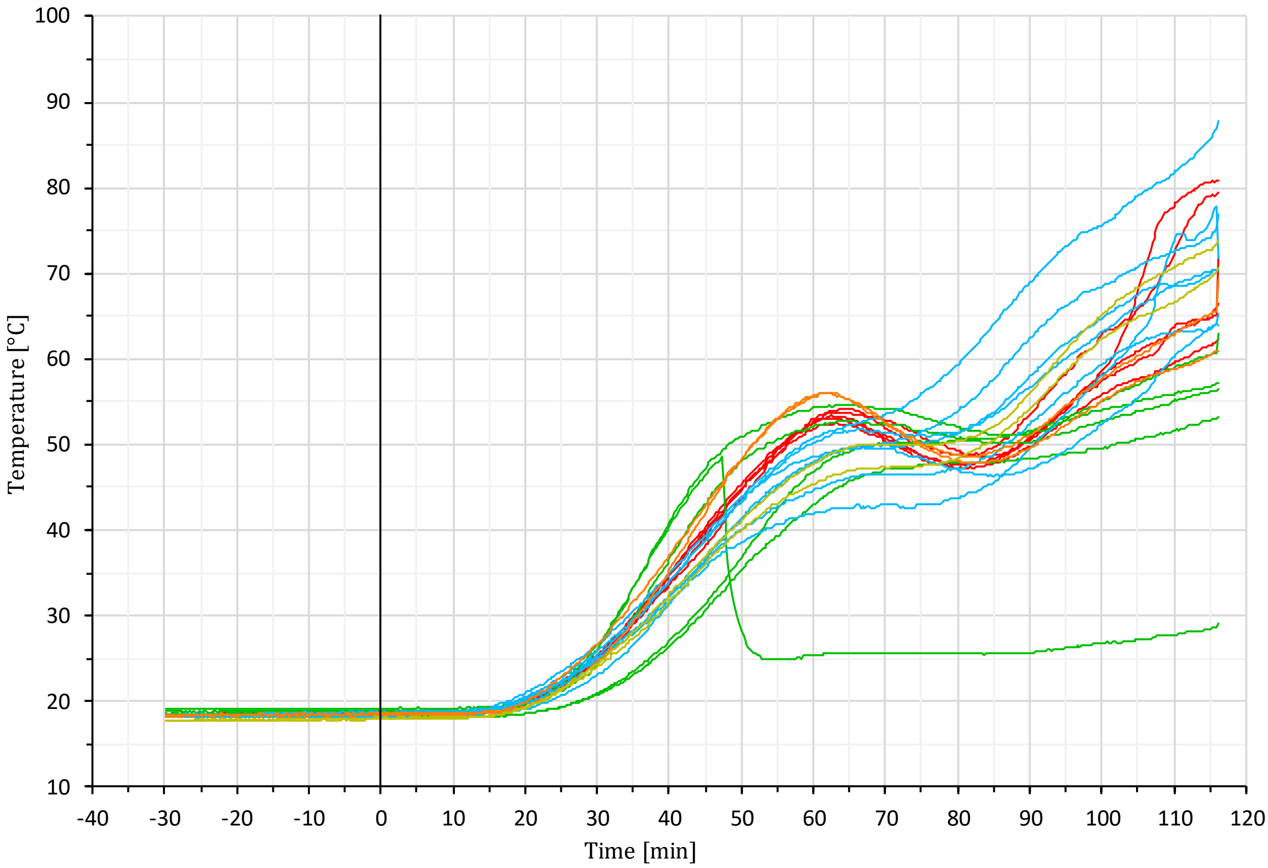

Fig. 8. External temperature thermoelements

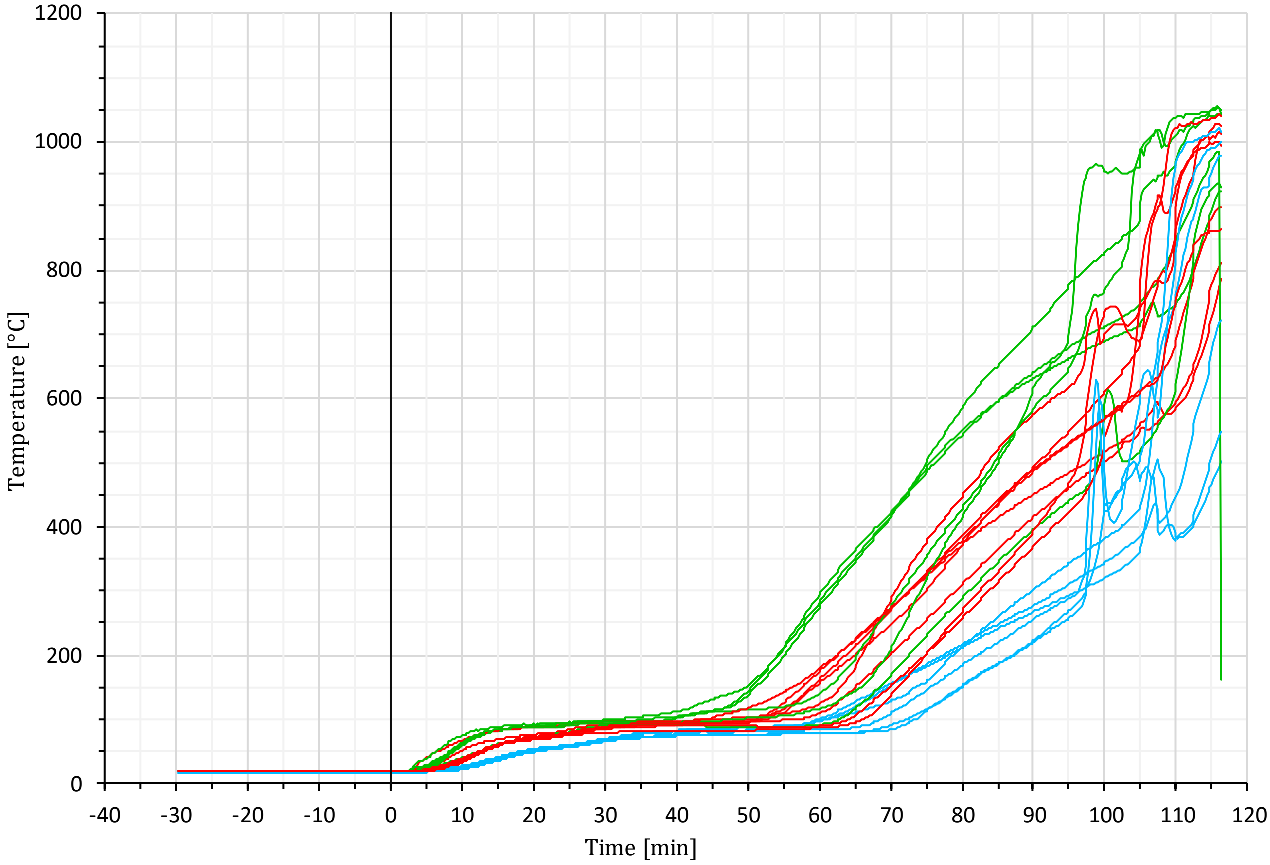

Fig. 9. Internal temperature thermoelements

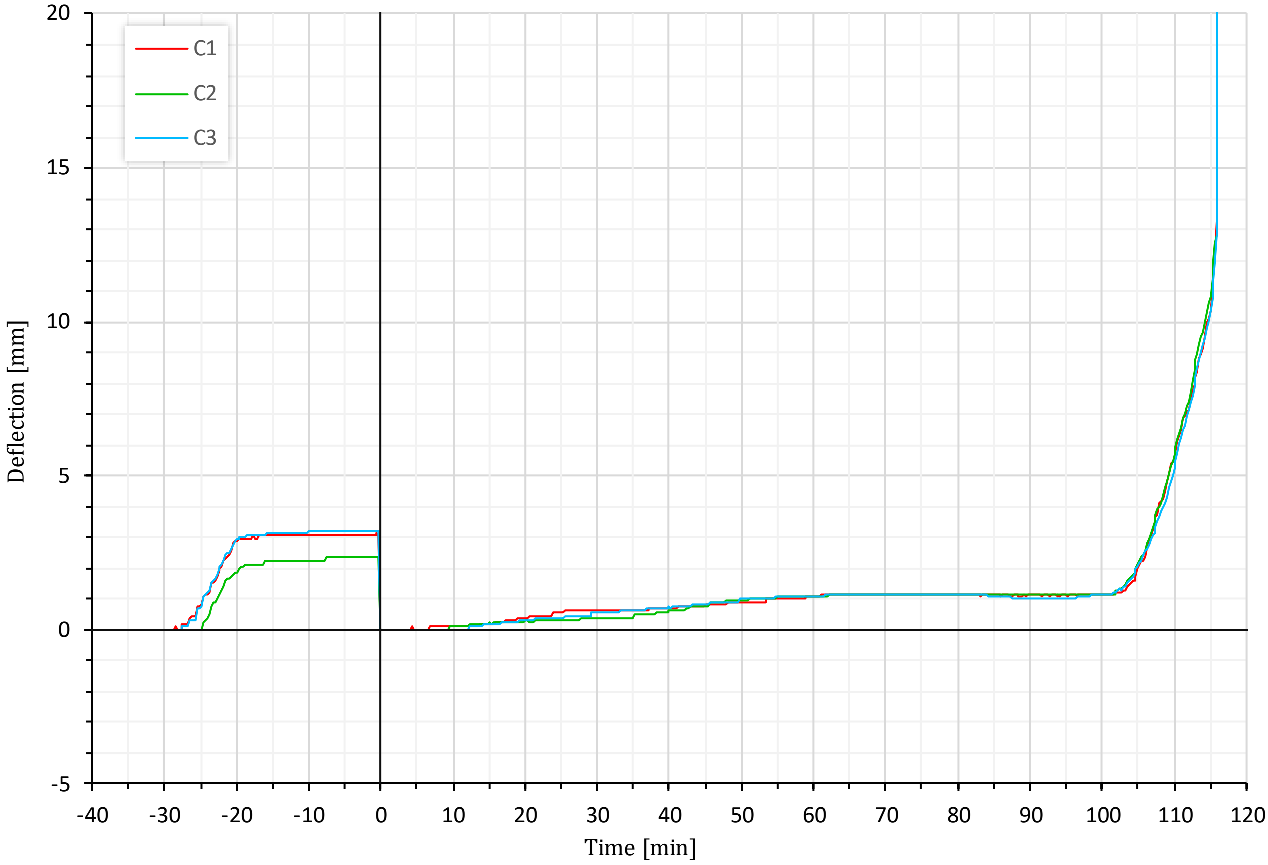

Fig. 10. Vertical deflection (contraction)

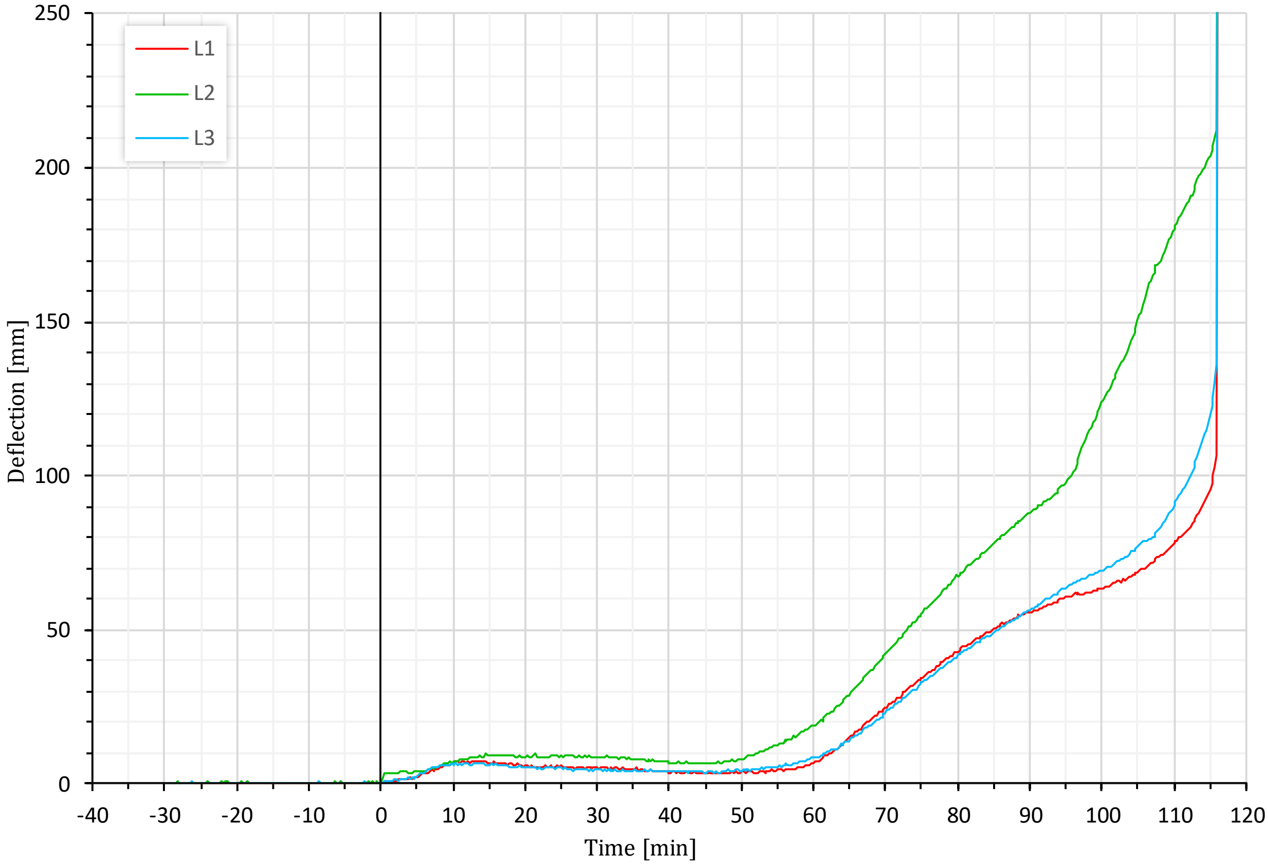

Fig. 11. Horizontal deflection (into the furnace)

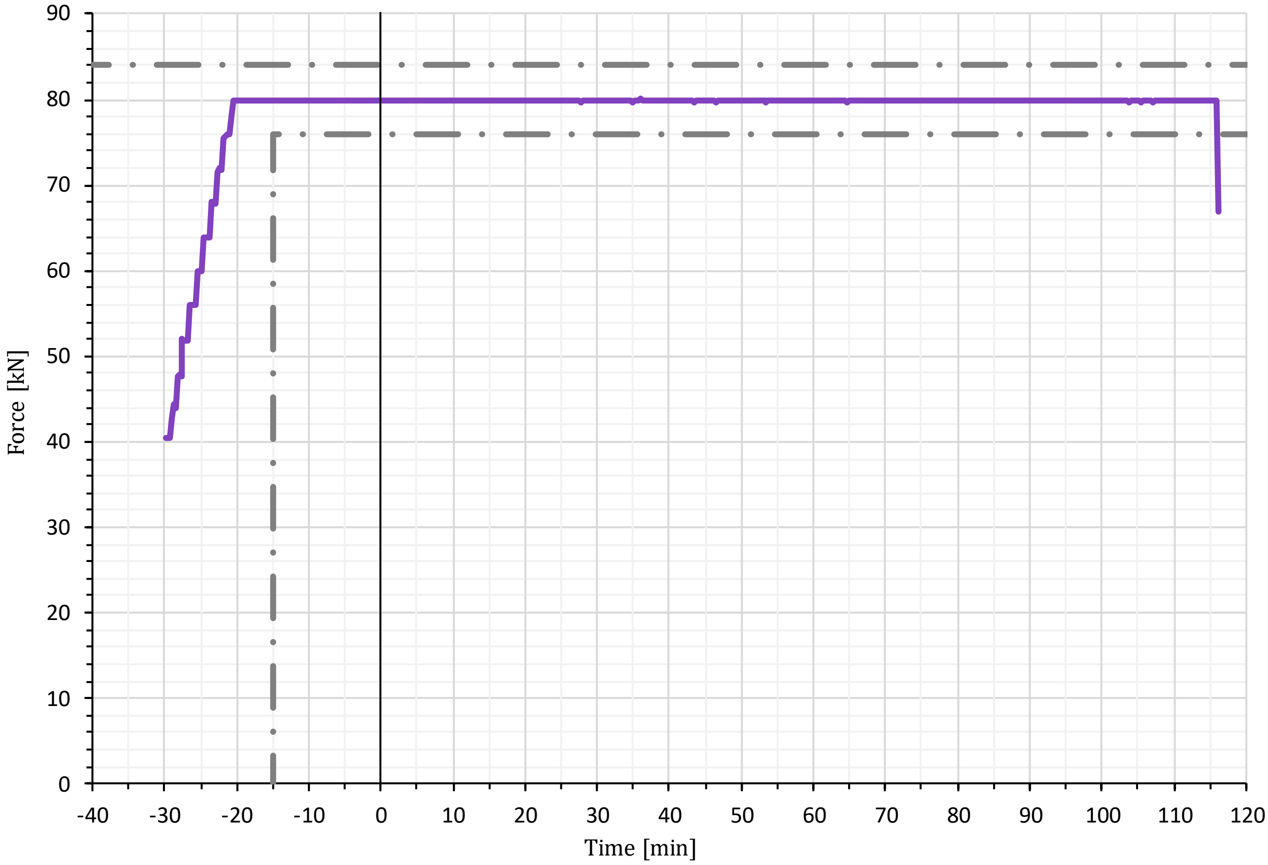

Fig. 12. Load force

6. Data files reference

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Measurements 00-02520_23_Z00NZP.pdf	e5a62df30cb10d7aaea685cee8cdb242
Frame Factory_Specyfikacja profili.pdf	c333caf04a05301b2e71bcf7cd35ac18

Appendix C – WP2b report: Numerical modelling and parametric study

Light gauge steel frame (LSF) walls exposed to fire: Parametric study report (WP2b)

Real fires project CPD/004/122/039

Revision: R00
Date: 07/10/2024
Project Number: OX21041

DOCUMENT REGISTER

Prepared for:	The Building Safety Regulator (BSR)
Prepared by:	OFR Consultants 44 South Bar Street Banbury OX16 9AB
Project No:	OX21041
Revision:	R00
Date:	07/10/2024

QUALITY MANAGEMENT

Revision	Date	Comment	Authors	Reviewer	Approver
D00	20/08/2024	Issued for BSR comments	Izzy Inerhunwa	Ian Fu	Danny Hopkin
R00	07/10/2024	Final issue after BSR comments	Izzy Inerhunwa	--	Danny Hopkin

TABLE OF CONTENTS

Executive summary

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR), who are part of the Government Agency, The Health and Safety Executive (HSE), to deliver the "Real Fires" project in support of fire safety technical policy. The Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC, formerly the Ministry for Housing Communities and Local Government, MHCLG, and now BSR), originally commissioned this project on the 22nd of October 2021. The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date for three years but has since been novated to the HSE. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake research on the fire performance of light gauge steel framing (LSF) walls.

LSF wall systems are characterised by three main components: cold-formed steel studs for load bearing, sheathing and insulation materials. Concerns have been raised by industry through Collaborative Reporting for Safer Structures UK (CROSS-UK) [1,2] regarding the expected fire performance of buildings that employ LSF as a solution for their structural loadbearing system. There is a level of uncertainty arising from the potential exposure of internal, loadbearing walls to heating conditions on both sides, with typical classification testing concerned with single sided exposure.

This research project investigates the performance of load bearing LSF walls exposed to fire on two sides and is split into two work packages. The first work package (WP1) involved conducting a comprehensive literature review focused on assessing the fire resistance performance of LSF walls when exposed to fire. The findings of this study have been issued to the BSR. The second work package (WP2) involved generating data and evidence concerning the fire resistance performance of LSF walls under one-sided and two-sided fire exposure. WP2 was arranged into two elements. The first (a) being concerned with fire resistance tests of LSF walls and the second (b) being a subsequent numerical parametric study. Results from (a) have been subject to a separate report and conference publication [3].

This report is the final deliverable of the research project and presents the results of a comprehensive parametric analysis conducted using validated Finite Element (FE) models to provide an understanding of how different factors influence the thermal behaviour of LSF walls and the potential implications for structural performance. The analysis covered a range of critical parameters, including the nature of insulation, the number of sheathing board layers, the type of fire model, and the time lag before the second face of the wall is exposed to fire (representative of fire spread). A total of 133 cases were investigated.

The analysis revealed that two-sided fire exposure leads to a uniform temperature distribution across the steel stud, irrespective of the insulation type, number of plasterboard layers, or fire model. In contrast, one-sided exposure results in a non-uniform temperature distribution.

Among the insulation types, external insulation proved to be the most effective in reducing temperature rise and delaying the attainment of critical temperatures, although its effectiveness was slightly reduced under two-sided exposure. The analysis also showed that while additional plasterboard layers significantly enhance thermal protection by delaying the onset of critical temperatures, their effectiveness diminishes at extended fire exposure durations, particularly under two-sided conditions. Furthermore, the type of fire exposure plays a crucial role in influencing the temperature profile, with standard ISO and long-cool parametric fires resulting in the highest temperatures. Two-sided fire exposure consistently presented a more severe scenario, especially when fewer plasterboard layers were used. Introducing a time lag between the exposure of the two faces reduced maximum temperatures; however, this benefit lessened with longer fire exposure durations.

Finally, the study postulates based on temperature profiles that two-sided fire exposure significantly reduces the loadbearing fire resistance of LSF walls compared to one-sided exposure. While cavity insulation reduces the load

bearing fire resistance under one-sided fire exposure compared to no insulation case, its impact is negligible under two-sided fire exposure. Whilst increasing the number of plasterboard layers can mitigate some reduction in loadbearing fire resistance, the overall structural performance is still notably compromised under two-sided fire conditions.

From a technical policy perspective, it is apparent that walls can be exposed to fire on two sides simultaneously in certain conditions and that this can bring about substantial reductions in structural fire resistance of lightweight wall construction. Therefore, the study recommends that consideration should be given to amending Approved Document B to include recommendations for such cases, including fire resistance classification under conditions where two sides of a wall are exposed simultaneously.

1 INTRODUCTION

1.1 Appointment

OFR Consultants, in collaboration with DCCH Experts LLP, have been engaged by the Building Safety Regulator (BSR) to deliver the "Real Fires" project in support of fire safety technical policy, which commenced on 22nd of October 2021, and will run for three years from this date. During the period of this engagement, the Technical Policy Division of the Department for Levelling Up, Housing and Communities (DLUHC) (formerly the Ministry for Housing Communities and Local Government), who originally commissioned this project has been novated to the Building Safety Regulator (BSR) who are part of the Government Agency, The Health and Safety Executive (HSE). The duration of the contract still stands from its initial award by DLUHC, running from the original commissioning date. As part of this project, the contract makes allowance for ad-hoc research to be undertaken to support fire safety technical policy on matters that emerge through dialogue with industry or through observations of real fires. Through this mechanism, OFR have been engaged to undertake a research project on the fire performance of light gauge steel framing (LSF) walls.

1.2 Work packages and deliverables

The research project is organised into two work packages (WP) described below:

- WP1: Literature review on the fire resistance performance of LSF walls exposed to fire.
- WP2: Generate data and evidence on the fire resistance performance between single-sided and double-sided exposure of LSF wall elements to support the BSR in understanding the risk to existing buildings and any future changes in fire safety guidance that may be necessary in the future. WP2 is split into two sub packages:
  - WP2a – benchmark furnace tests for LSF walls; and
  - WP2b – desktop / modelling appraisal of the implications of fire resistance specification of LSF walls for their ability to survive burn-out.

The literature review work package (WP1) and the benchmark furnace test work package (WP2a) has been completed, and reports issued to BSR on 13/07/2023[1] and 15/03/2024[2], respectively. Refer to the individual reports for full details. WP2a was also subject to a conference publication presented at the Structures in Fire conference[3].

This report is a culmination of WP2b and presents the results of thermal parametric studies of LSF walls exposed to fire via numerical modelling benchmarked against fire test results of WP2a. It involves development of a numerical representation (using the finite element method (FEM)) that can reproduce the thermal performance observed in tests undertaken during WP2a, followed by parametric studies investigating how sensitive or otherwise LSF walls exposed on two sides are to potential delays in thermal exposure associated with internal or external fire spread. Factors considered in the parametric studies were based on those identified in the literature review report as having impact on the performance of LSF walls exposed to fire.

As this report represents the final deliverable of this research project, it first covers a brief background to the research project and why it was commissioned, summary of the outcome of the literature review (WP1) and summary of results of the furnace testing (WP2a), used as a basis for the numerical modelling studies. The remainder of the report focusses on the work done in WP2b i.e., development, validation and results of the numerical modelling and parametric studies, and final design recommendations for LSF walls exposed to fire on two sides.

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[1] Report ref: 230713-R00-OX21041-Light gauge steel literature review-RR-CIC; Date of issue: 13/07/2023.

[2] Report Ref: 240315-D01-OX21041-Light gauge steel test report-RR-CIC; Date of issue: 15/03/2024

2 Research background, summary of literature review study and benchmark testing

2.1 Research background and motivation

LSF walls are commonly used in modern building construction [4]. They consist of three main components: cold-formed steel studs, sheathing material, and may include insulation [5]. LSF walls may be used as fire-separating walls to mitigate fire and smoke spread from one compartment to another and limit temperature increase on the unexposed surface for a specified period [6]. LSF walls also find application as both loadbearing and non-loadbearing walls which may not have a fire-separating function. A typical LSF wall system is shown in Figure 1. A more detailed review of the components of an LSF wall system, types of LSF wall systems, characteristics of LSF wall system, and use of LSF wall in construction has been carried out as part of WP1.

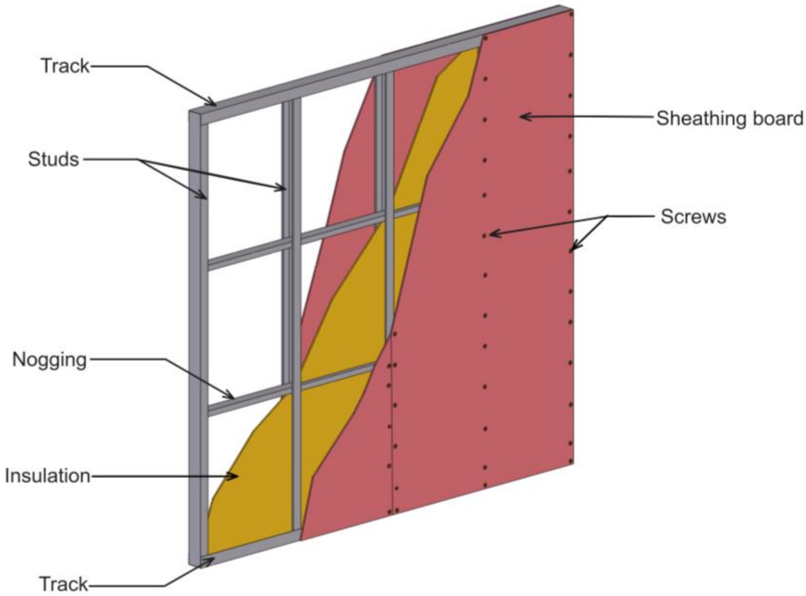


Figure 1. Typical LSF wall system

Concerns have been raised by industry (through CROSS-UK) regarding the expected fire performance of internal loadbearing LSF wall systems [1]. There is a level of uncertainty arising from the potential exposure of internal loadbearing walls to heating conditions on both sides. These walls may be architecturally separating elements, but not fire-separating elements, e.g., they do not form part of a compartment boundary. This means that where a compartment is fully involved in a fire, these walls will be exposed to fire on both sides and may not perform as expected in terms of loadbearing capacity compared to when heated from just one side. A similar concern has also been raised by industry [2] for external loadbearing walls afforded non-fire-resisting cladding, where flames emanating from an enclosure fire can heat the external surface of an LSF wall, with the internal face simultaneously heated by the internal fire.

It is understood that there is currently no design approach that is universally seen to be adequate available in industry to account for LSF walls exposed on two faces. FEM is one way designers may attempt to address the lack of a universally accepted design approach for LSF walls exposed to fire on two sides. Whilst this may be a valid means of evidencing performance, given a lack of experimental/test data, the assessment of such modelling remains a cause for concern as there is a limited basis for benchmarking under two-sided heating conditions.

Therefore, this research project was set out in three stages: literature review (WP1) to understand current knowledge on the performance of LSF walls exposed to fire; furnace testing (WP2a) to generate data for benchmarking; and numerical parametric studies using FEM (WP2b).

2.2 WP1: Summary of review of previous studies on LSF walls exposed

A detailed literature review has been undertaken and a review report issued (refer to WP1 report). A total of 521 articles were systematically screened and reviewed, leading to 92 studies being selected for detailed review. The review showed that there is currently a knowledge gap regarding the expected structural fire performance of LSF elements that are exposed to heating conditions on both sides. Key conclusions arising from the literature review study were:

i. Extensive experimental and numerical studies have been carried out to understand the performance of LSF walls exposed to fire on one side only (e.g., [7–16]); but there is lack of test data for two-sided exposure of LSF walls. This justifies the need for two-sided exposure testing.

ii. The one-sided exposure experimental and numerical modelling studies show that the insulation between the studs, number of sheathing board layers, and fire model, has a significant impact and, therefore, these are variables that should be considered.

iii. Evidence from other materials (i.e., masonry and concrete [17–19]) suggests that the difference between one-sided and two-sided exposure is more significant at higher fire resistance demands. Therefore, to observe the biggest difference between single- and two-sided fire exposure of LSF walls, investigation of high fire resistances is most likely to elucidate that difference.

iv. Furthermore, current design guidance in England (Table B3 of Approved Document B [20]) does not explicitly identify a need to test for two-sided exposure.

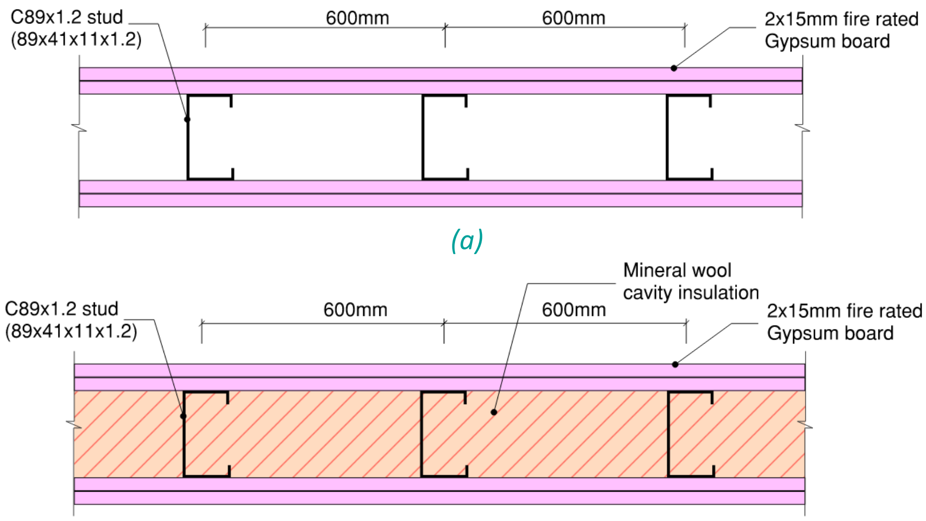
2.3 WP2a: Summary of benchmark furnace test results

To resolve the uncertainty that arises from the lack of data for the performance of LSF walls when exposed to fire on two sides as identified in the literature review studies, and to improve confidence in FEM studies, an experimental programme was conducted in WP2a. The aim was to carry out an experimental investigation of the loadbearing performance of LSF walls with both one- and two-sided fire exposure, to determine whether the loadbearing performance of LSF walls are likely affected by the number of faces simultaneously exposed to fire.

Based on the outcome of the literature review as highlighted in Section 2.2, a total of four wall specimens were tested, two each (with and without cavity insulation) for single- and two-sided fire exposure conditions (Figure 2 shows section details of the wall LSF types). The walls were designed to achieve a 'high' (minimum of 90-minute) fire resistance rating under single-sided fire exposure, when afforded cavity insulation. As summary of the test setup and results is provided in this section. For a detailed description of the test programme refer to the test report (WP2a report) and conference publication [3].

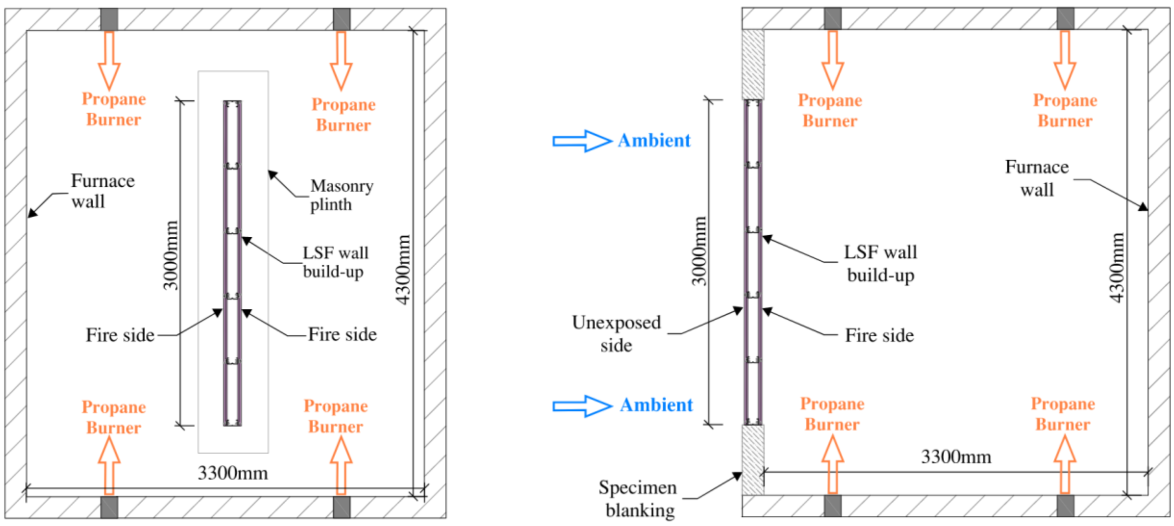
For the one-sided test, the wall was placed at the end of the furnace and heated on one side only. For the two-sided test, the wall was placed at the centre of the furnace along the longer side of the furnace (with approximately 650 mm of free space at both ends of the wall) and heated on both sides simultaneously. The free vertical side edges of the wall were covered with two layers of plasterboards, the same as the wall surfaces. In both cases, the wall was fixed to a 700 mm high masonry plinth at the bottom and loaded at the top. The furnace followed the ISO standard heating regime, which was achieved using propane gas burners. Figure 3 shows a sketch of the plan and elevation of the wall specimen inside the furnace for both exposure conditions. The load was applied axially to the wall specimen by means of a beam and actuator at the top edge of the wall. The total load applied to the wall was 80 kN i.e., 13.3 kN per stud. The load ratio of the LSF wall stud is the ratio of the load at the fire condition to the load carrying capacity of the stud under normal loading condition. The load capacity of the stud under normal condition is a function of its effective length, which typically varies from $0.5 \times L_0$ to $1.0 \times L_0$, where L_0 is the unrestrained length of the stud. Determining the exact normal load capacity is challenging because the effective length depends on the restraint provided by the plasterboard. The ambient load capacity is approximately 41 kN for an effective length of 1,500 mm and approximately

16 kN for an effective length of 3,000 mm. Therefore, the applied load ratio of the stud could vary between 32% to 83% depending on the actual in-situ support conditions during the test. Before the commencement of fire exposure, the load on the test specimen was increased gradually from 0 kN to 80 kN in 10 min and then sustained at the full test load (80 kN) for 20 min.



(b)

Figure 2. Section of tested LSF wall (a) without insulation (b) with cavity insulation

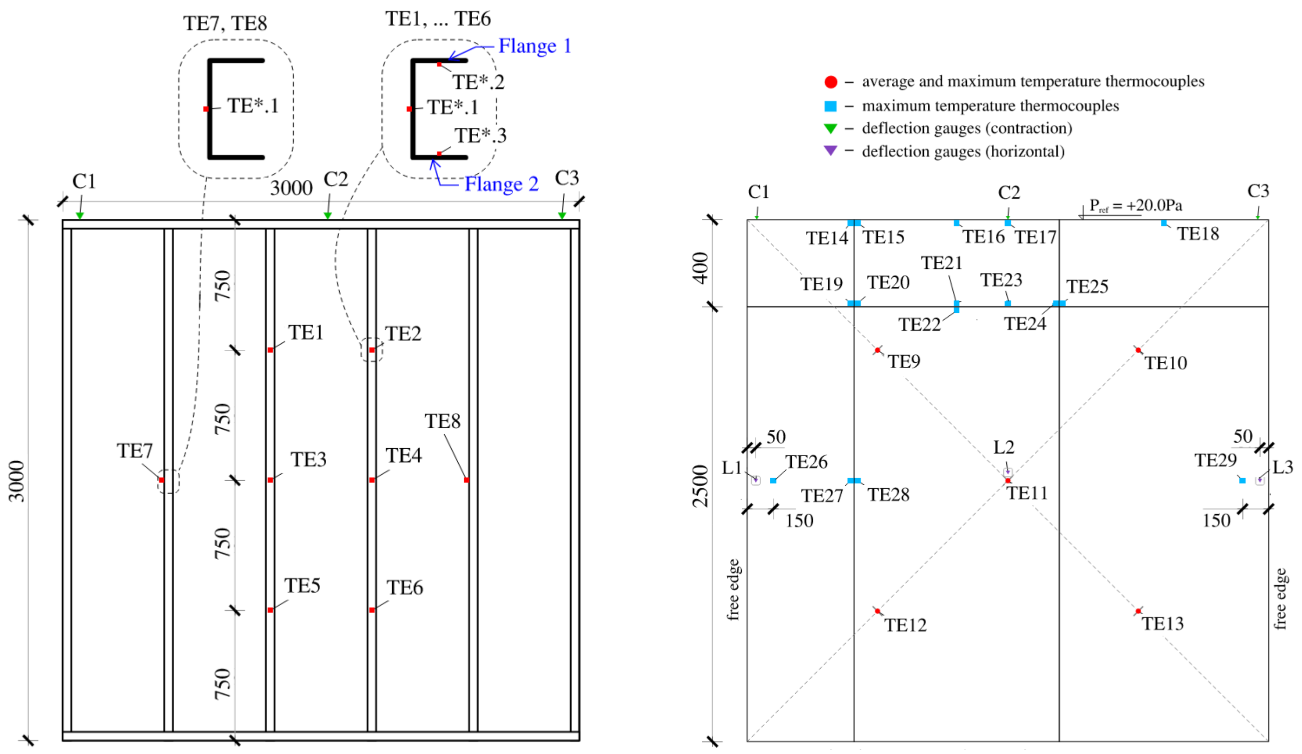


(a) *(b)*

Figure 3. Sketch plan of test setup for (a) two-sided exposure and (b) one-sided exposure

Each wall specimen was provided with internal thermocouples mounted on the flanges (Flange 1 and Flange 2) and web of the steel studs at different locations along the length and height of the wall to record the temperature rise of the steel. For the one-sided test, Flange 2 was the flange near the unexposed face of the wall. For the one-sided test, the unexposed wall surface temperature was also measured using external thermocouples attached to the unexposed face of the wall. The deflection of the wall was measured by gauges suitably arranged to measure the vertical deflection (contraction) and horizontal (lateral) deflection of the wall during the test. Horizontal deflection was only measured and recorded for the walls exposed to fire on one side. Figure 4 is a section drawing of the wall showing the location of the internal and external thermocouples.

The test was conducted until failure of the steel studs occurred, with failure defined as a loss in loadbearing capacity, indicated by runaway vertical / lateral deflection. All measurements (temperature, applied load, deflection, furnace pressure and furnace power) were recorded at 15 s intervals for the duration of the test. Table 1 summarises the recorded temperature at time of failure from the tests while Table 2 summarises time to failure.



(a) *(b)*

Figure 4. Section drawing showing location of (a) internal thermocouples and deflection gauges (b) external thermocouples and deflection gauges

Table 1. Summary of stud temperatures at failure at different locations of the wall

Location ref. (Figure 4)	Steel stud temperature at failure [°C]											
	Test ID: LZP01 (Two-sided, no insulation)			Test ID: LZP02 (One-sided, no insulation) *			Test ID: LZP03 (Two-sided, with insulation)			Test ID: LZP04 (One-sided, with insulation) *		
	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2	Flange 1	Web	Flange 2
TE1	487	459	502	622	597	569	432	433	526	924	786	501
TE2	476	461	491	615	569	550	537	488	673	994	931	548
TE3	546	521	515	697	675	635	535	529	614	985	900	723
TE4	550	539	573	864	790	758	620	528	538	1043	1014	1001
TE5	486	494	462	727	710	677	463	473	564	1045	1026	979
TE6	508	510	537	788	709	722	532	455	471	1050	1041	1017
TE7	--	460	--	--	741	--	--	465	--	--	812	--
TE8	--	512	--	--	595	--	--	468	--	--	865	--
Average†	548	530	544	781	733	697	578	529	576	1014	957	862
Section average§	541			737			561			944		

*Note: For the one-sided test, Flange 2 is the flange near the unexposed face of the wall.
† Average temperatures at mid-height of middle studs (i.e., TE3 and TE4, as these represent locations of maximum lateral displacements)
§ Average stud section temperature (i.e. flange 1, web and flange 2) at mid-height of middle stud (i.e., locations TE3 and TT4.

The main findings / conclusions from the tests were as follows:

i. Two-sided fire exposure results in a more severe heating condition on LSF walls than one-sided fire exposure, as indicated by higher temperatures and rates of temperature increase, particularly beyond 45 – 50 min of exposure.
ii. The loadbearing fire resistance of LSF walls decreased significantly when exposed to two-sided fire: down to 44% of the one-sided exposure capacity for non-insulated walls and 62% for insulated walls (Table 2).
iii. One-sided fire exposure leads to a significant thermal gradient within the stud section, especially when insulation is present, resulting in non-uniform heating. In contrast, two-sided exposure generally promotes a more even temperature distribution across the stud section. The temperature gradient due to presence of insulation for one-sided fire exposure typically results in reduced load-bearing fire resistance. However, the reduction due to two-sided heating is greater.
iv. Cavity insulation in one-sided fire exposure creates a significant temperature gradient, leading to thermal bowing and earlier structural failure compared to non-insulated walls. For two-sided fire exposure, the influence of cavity insulation on the performance was not significant versus non-insulated walls.
v. The cavity-insulated walls were designed to achieve at least 90 min fire resistance for one-sided exposure. Given walls exposed on two-sides failed to achieve this, fire resistance classifications for one-sided exposure should not be extrapolated to two-sided exposure.
vi. The temperature distribution along the height of the stud is largely uniform, regardless of whether the exposure is one-sided or two-sided, due to the uniform furnace temperatures. Temperature variations along the length of the wall are minimal for two-sided fire exposure but can be substantial for one-sided exposure with insulation, reaching variations of up to 150 °C.
vii. Vertical deflection of wall specimen is uniform across various top locations of the wall under all test scenarios, while the centre of the wall exhibits greater lateral deflection, particularly for insulated walls under one-sided exposure.

From the above findings, the following broader design implications were highlighted:

i. The test samples are considered to be representative of common LSF construction practices and, therefore, it is probable that the findings are broadly applicable to the technology.
ii. Where there is the potential for two-sided exposure, there is a sufficient reduction in load bearing performance that elements should be specifically designed to address such an exposure condition.
iii. In guidance, there is justification to explicitly request test evidence for two-sided exposure and the test programme conducted shows that testing such a configuration is achievable.

Table 2. Summary of time to failure from fire tests for one-sided vs two-sided fire exposure conditions

Test ID	Fire exposure condition	Cavity insulation	Time to failure [min]	Ratio of two-sided to one-sided
LZP01	Two-sided	No	68	0.44
LZP02	One-sided		156	NA
LZP03	Two-sided	Yes	72	0.62
LZP04	One-sided		116	NA

2.4 WP2b: Parametric Study

The WP2b work package covers the methodology and results of the parametric study on the fire performance of LSF walls subjected to fire on two sides via finite element analysis.

Details of how subsequent sections of this report are structured to deliver on the aim of the parametric studies is set out below:

- **FE model development and validation (Section 3):** This section describes the development of the FE model including the type of finite elements used, material properties, and boundary conditions applied. This study focusses on thermal analysis only. To assess the suitability of the developed FE models to model the behaviour of LSF walls exposed to fire on two sides, this section also present results of benchmarking of the FE analysis with the test results of WP2a (i.e., comparison of temperature-time plots of the FE model with the test results).
- **Parametric studies - Thermal response of LSF walls exposed to fire on two sides (Section 4):** This section covers parametric studies on the effect of different design parameters on the thermal response of LSF walls exposed to fire on two sides. Parameters investigated were based on the outcome of the literature review study and includes nature of insulation (no insulation, cavity insulation and external insulation), number of sheathing board layers, type of fire model (ISO 834 fire [21], Eurocode parametric fire model [22] and Eurocode external fire model [22]), and time lag to when the second face of the wall is exposed to fire after exposure of the first face. To assess and compare the performance of the cases studied, temperature distribution across the stud section and time to reach a defined critical temperature were analysed.
- **Discussion of results of LSF walls exposed to fire on two sides (Section 5):** This section presents discussion of the results of the parametric studies and how existing design methods for one-sided fire exposure can be applied for predicting the loadbearing performance of LSF walls when exposed to fire on two sides.
- **Conclusions (Section 6):** This section provides a synthesis of the key findings from the research project and suggests practical design implications.
- **Appendices:** This section contains supplementary results.

3 FINITE ELEMENT MODEL DEVELOPMENT AND VALIDATION

This section covers the development of the FE models. The developed models have configurations like the LSF wall configurations which were tested in the full-scale furnace test under the ISO standard fire [21]. These configurations are shown in Figure 5. A thermal model was developed to predict the temperature distribution of the LSF wall components. The FE models are then validated by comparing the results from the FE analysis with the test results.

The tool used for the finite element modelling (FEM) programme is SAFIR [23,24], developed by the University of Liege. SAFIR is a nonlinear finite element modelling computer program that models the behaviour of building structures in fire. The software has been validated through comparison with a series of cases in standards (e.g., Annex CC of DIN EN 1992-1-2 NA) [25] and fire experiments (e.g., by Maślak, et al. [26] and Reis et al. [27]). Previous studies on LSF walls have used SAFIR to model the performance of LSF walls exposed to fire (e.g. [28,29]). SAFIR can use various finite element types to simulate thermal and mechanical response of LSF walls exposed to fire.

The general purpose graphic pre-processor and post-processor software GiD [30] for FE programs was used in developing the SAFIR model. GiD provides a graphical user interface for creating an input file of the model geometry, material properties, thermal boundary conditions, and other model parameters for SAFIR analyses. Post-processing of the SAFIR output files (visualisation of temperature distribution and generation of time-temperature plots) was done using the graphic post-processor DIAMOND [31].

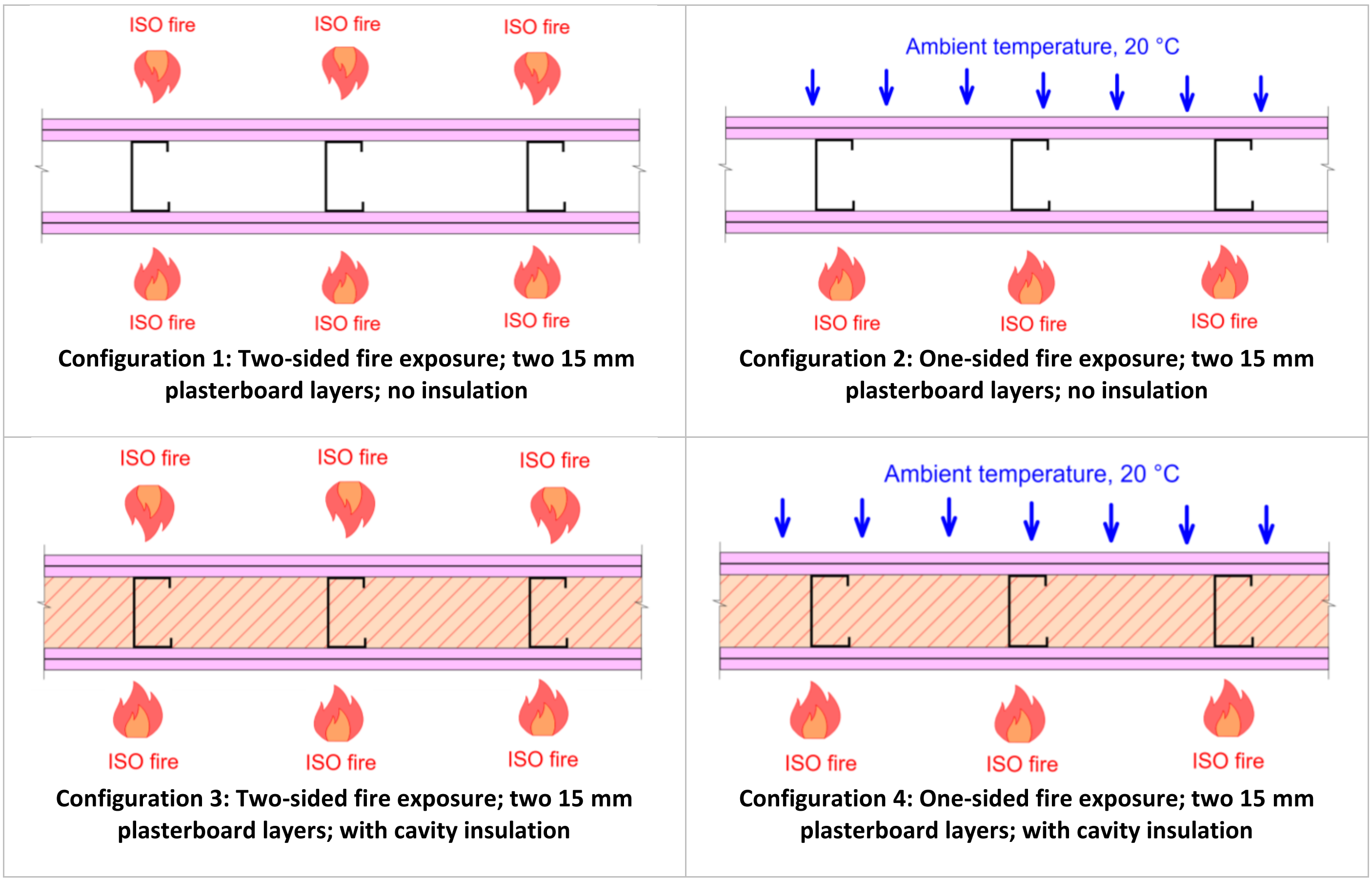


Figure 5. Modelled LSF wall configurations for benchmarking with full-scale furnace tests

3.1 FE model for the thermal analysis

From the tests, it was observed that the temperature distribution across an exposed face of the wall can be taken to be uniform for both one-sided and two-sided fire exposure condition. Therefore, 2D thermal FE models of the cross section were developed for the four LSF wall specimens tested in WP2a.

The modelled LSF wall system had the same geometry as the tested cases. It comprised of cold-formed steel studs and gypsum plasterboards, with the addition of insulation material within the cavity for the insulated LSF wall (Figure 5). The sheathing material was 2 layers (nominal thickness of 15 mm each) of fire rated (type F) gypsum board. The insulation material used (for the cavity insulated wall specimens) was stone mineral wool insulation completely filling the cavity between the studs and the plasterboards.

The thermal analysis was performed using 4-node solid conductive elements. Convective and radiative heat transfer at the boundaries on both sides of the wall were considered. For the non-insulated case, convective and radiative heat transfer within the cavities was also considered based on the following principles as detailed in [32]: heat transfer in the cavity by conduction in the gas is negligible, specific heat of the gas in the cavity is negligible, the gas within the cavity is assumed to be transparent, and the boundaries of the cavity are grey surfaces. The temporal integration of the thermal equilibrium equation of heat fluxes in the structure to obtain the evolution of the temperatures during the course of the fire was carried out using an implicit single step scheme of the generalised central point [32].

The tested wall build-up was 3 m long and 3 m high with 6 studs spaced at 600 mm centres. Therefore, to reduce computation time, only the middle portion of the wall with three studs was modelled. The test results support this simplification of the FE model as it showed that no major differences in temperature were observed along the length and height of the wall. Figure 6 and Figure 7 show the 2D FE model.

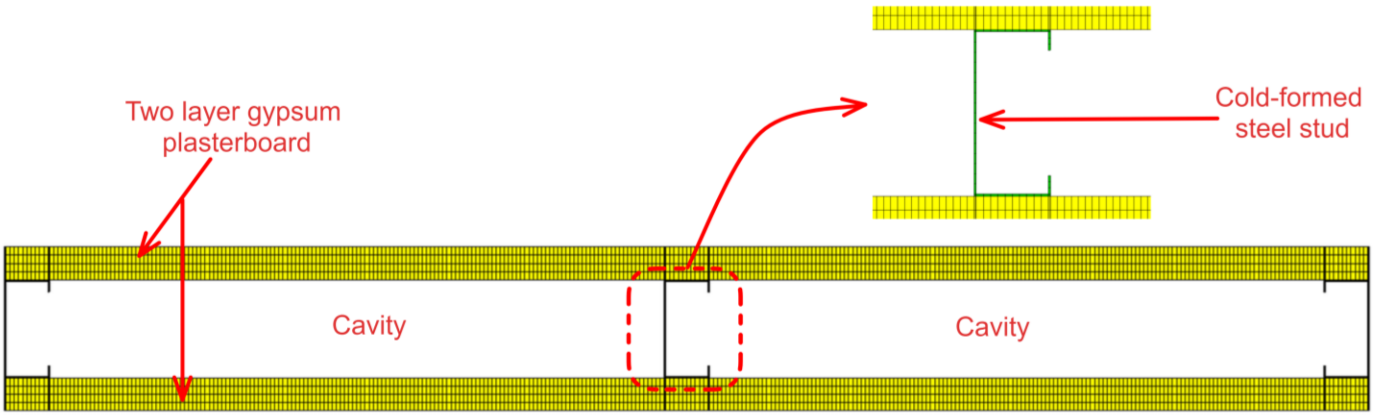


Figure 6. 2D thermal FE model of LSF wall section (no insulation)

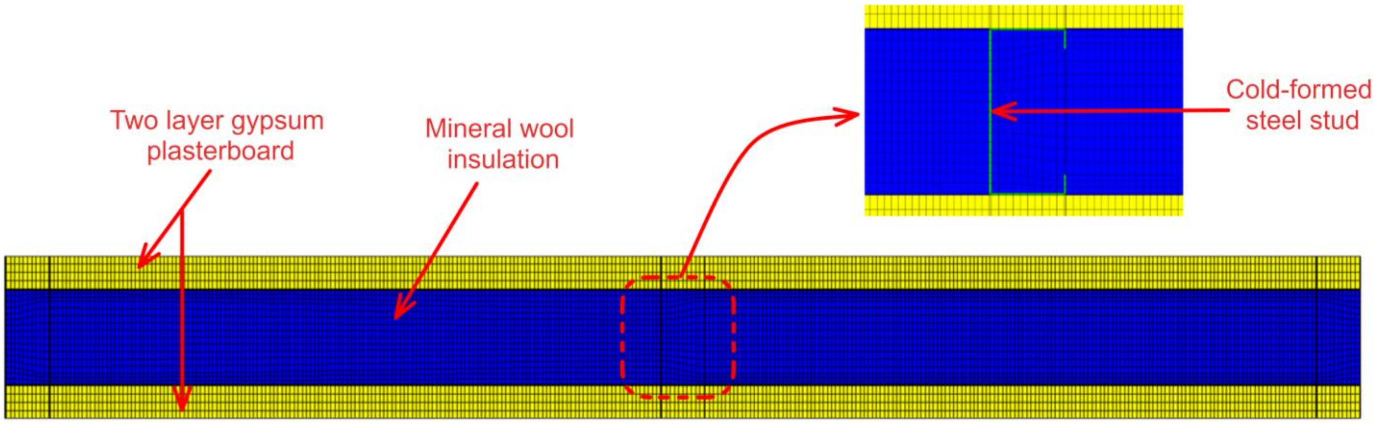


Figure 7. 2D thermal FE model of LSF wall section (with cavity insulation)

3.1.1 Temperature dependent thermal properties

In performing the 2D heat transfer FE analysis, temperature dependent thermal proprieties of the LSF wall components must be defined (i.e., thermal conductivity, specific heat capacity and density).

3.1.1.1 Cold-formed steel stud

The properties of steel follow recommendations in BS EN 1993-1-2 [33], with a temperature dependent thermal conductivity and specific heat capacity as shown in Figure 8 and Figure 9, and a constant density of 7850 kg/m³.

3.1.1.2 Gypsum plasterboard

The thermal properties of the gypsum plasterboard were based on values recommended in previous studies [34,35]. Due to modelling limitations, simulation of material fall-off, ablation, cracking, and moisture movement were indirectly accounted for by adjusting the thermal conductivity of the gypsum plasterboard at elevated temperatures. A similar approach has been used in the literature [11,12]. This means that the thermal conductivity is an apparent value to capture the influence of the thermal boundary condition on the front face and back face of the plasterboard. Adjustments were made to the thermal conductivity to get the best agreement between the time–temperature profiles from the FE analysis and those obtained the fire tests. Figure 10 shows the adopted apparent thermal conductivity curve for the FE analysis for the LSF wall with and without cavity insulation.

The temperature dependent specific heat capacity and density of the gypsum plasterboard are as per values recommended in Cooper [34]. For the density, the values at elevated temperatures are specified as a function of the density at ambient temperature (20 °C) taken as 867 kg/m³ (based on the test data: surface density of 13 kg/m² and plasterboard thickness of 15 mm). Figure 11 and Figure 12 show the specific heat capacity and density of the gypsum plasterboard, respectively. The applied moisture content of the gypsum plasterboard was 0.3% as measured during the tests.

3.1.1.3 Mineral wool insulation

While the density and specific heat of the insulation materials are often taken as constant values, the thermal conductivity is temperature dependent [36]. The thermal conductivity of the stone mineral wool insulation was based recommended values in Perera et al. [8]. Ablation results in reduction in the cross-section thickness of the insulation material and increase in heat transfer across it. Therefore, the effect of ablation and moisture movement within the insulation will be different for different fire exposure condition (one-sided vs two-sided). Like the gypsum plasterboard, to account for the effect of ablation, moisture movement and the difference in thermal boundary condition, apparent thermal conductivity values were adopted, by adjusting the thermal conductivity variation with temperature to get the best agreement between the time–temperature profiles from the FE analysis and those obtained from the fire tests. Figure 13 shows the adopted apparent thermal conductivity curve for the FE analysis for the LSF wall with and without cavity insulation.

The constant specific heat capacity of the mineral wool is 840 J/(kgK). The density is also specified as constant with a value of 35.1 kg/m³ as measured from the fire tests. The applied moisture content of the insulation was 0.8%, also measured from the tests.

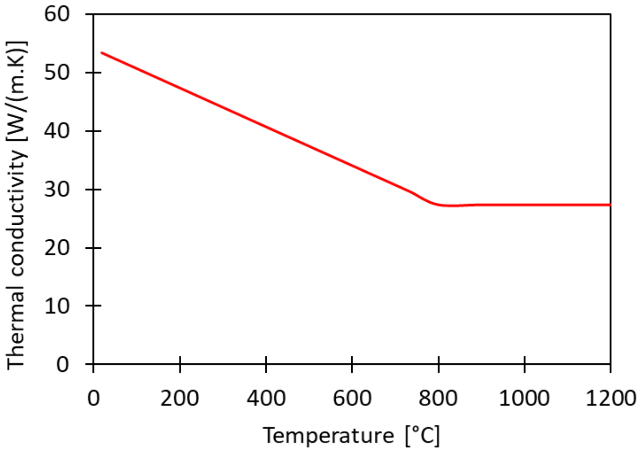


Figure 8. Thermal conductivity of steel [33]

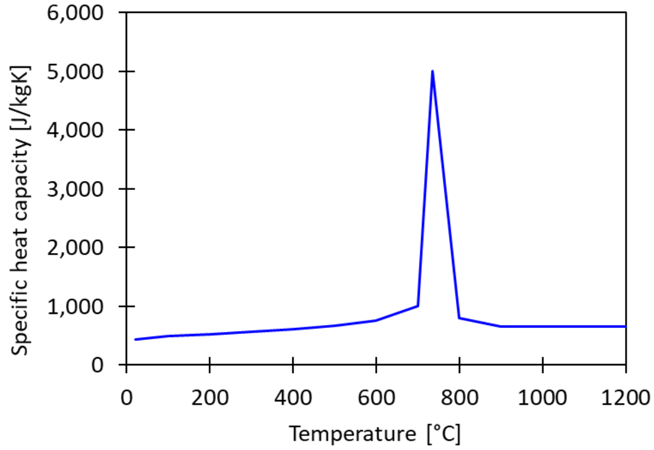


Figure 9. Specific heat capacity of steel [33]

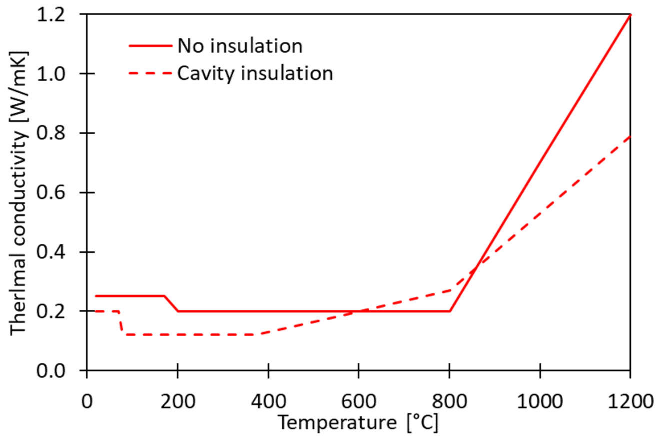


Figure 10. Thermal conductivity of gypsum plasterboard

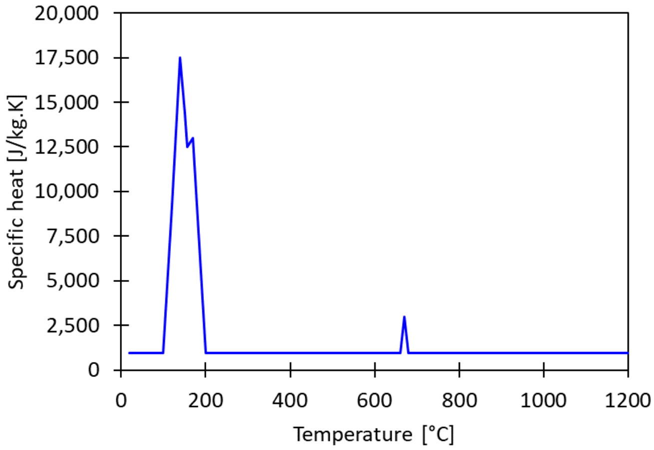


Figure 11. Specific heat capacity of gypsum plasterboard [34]

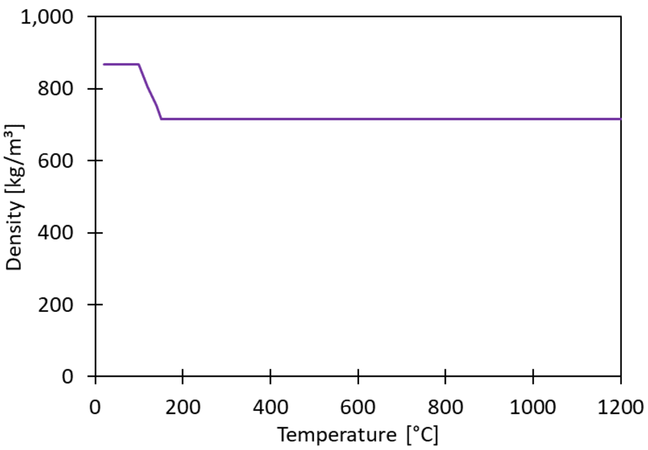


Figure 12. Density of gypsum plasterboard [34]

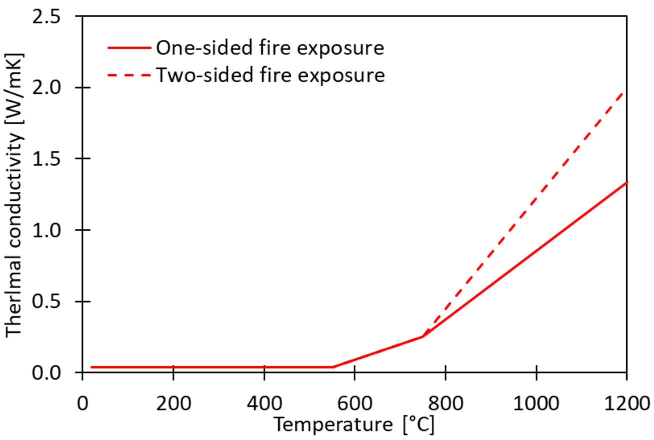


Figure 13. Thermal conductivity of stone mineral wool

3.1.2 Boundary conditions

On the fire exposed sides, the ISO standard fire [21] was applied as the evolution of temperature of hot gases surrounding the LSF wall section as in the test condition. Equation 1 shows the time-temperature relationship of the applied ISO standard fire, where T_g is the temperature in °C and t is time in min:

$$T_g = 20 + 345\log_{10}(8t + 1) \qquad \textit{Equation 1}$$

In SAFIR, the heat flux $\dot{q}$ exchanged between the boundary and the surrounding hot gas is computed from Equation 2 with a linear convective term and a radiation term. In Equation 2, h is the coefficient of heat transfer by convection in W/(m²K), T_g is the temperature of the hot gas in K, T_s is the temperature of the boundary in K, σ is the Stefan–Boltzman constant (5.67×10^{-8} W/(m²K⁴)), and ε is the relative emissivity of the material. The initial temperature applied to all elements of the model was ambient temperature (20 °C).

$$\dot{q} = h(T_g - T_s) + \sigma\varepsilon({T_g}^4 - {T_s}^4) \qquad \textit{Equation 2}$$

On the unexposed face of the wall, the ambient temperature condition (20 °C) was applied and radiation toward the environment was captured. A summary of the applied boundary condition parameters is provided in Table 3.

Table 3. Summary of boundary condition parameters

Parameters	FE model	Reference
Fire at the exposed LSF wall face	ISO standard fire	[21]
Temperature at unexposed face (one-sided exposure)	Ambient temperature (20 °C)	--
Convection coefficient (hot face)	25 W/m²/K	[22]
Convection coefficient (cold surface)	10 W/m²/K	[29]
Relative emissivity for steel	0.7	[33]
Relative emissivity for gypsum plasterboard	0.9	[29]

3.2 Validation of FE model

Validation of the suitability of the FE models to predict the thermal response of LSF walls exposed to fire on two sides was carried out by benchmarking against the WP2a test results. This was done by comparing the stud temperature profiles from the finite element thermal analysis with corresponding results from the full-scale furnace tests. The average stud temperatures obtained along the height of the two middles studs (at the top ¼ height, mid-height, and bottom ¼ height – see Figure 4a) were utilised in the validation studies. At each location, the temperature of the flanges (Flange 1 and Flange 2) and web of the lipped channel studs were compared. It is noted that for the one-sided test, Flange 2 is the flange near the unexposed face of the wall (also known as cold flange). Flange 1 may also be referred to as the hot flange, being the flange near the fire exposed face of the wall. For the two-sided test, both flanges are exposed to fire simultaneously. Figure 14 shows location within the 2D FE model where temperature measurements were extracted (based on location of thermocouples for recording stud temperatures during the test).

Figure 15 shows the comparison of the stud temperatures (Flange 1, Flange 2 and web) from the FE model with that recorded during the tests. The FE models exhibit good agreement with the test data for both one-sided and two-sided fire exposure (with and without cavity insulation), thereby validating the credibility of the finite element approach in accurately modelling the thermal behaviour of LSF walls during fire exposure. This also validates the thermal properties and boundary conditions used in developing the FE model. However, discrepancies are observed during the initial temperature rise, particularly up to approximately 100 °C. While the test data show a rapid temperature increase followed by a plateau, the FE models predict a more gradual rise. As noted by Ni et al. [37], this discrepancy may be attributed to the way moisture evaporation and transport are implicitly modelled through adjusted thermal properties. Despite this, the FE models catch up to the test data around 100 °C and follow the subsequent temperature profile of the test with good accuracy.

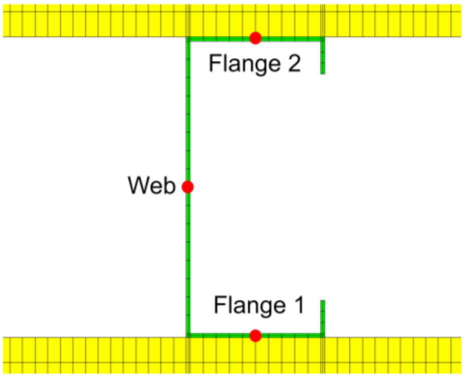
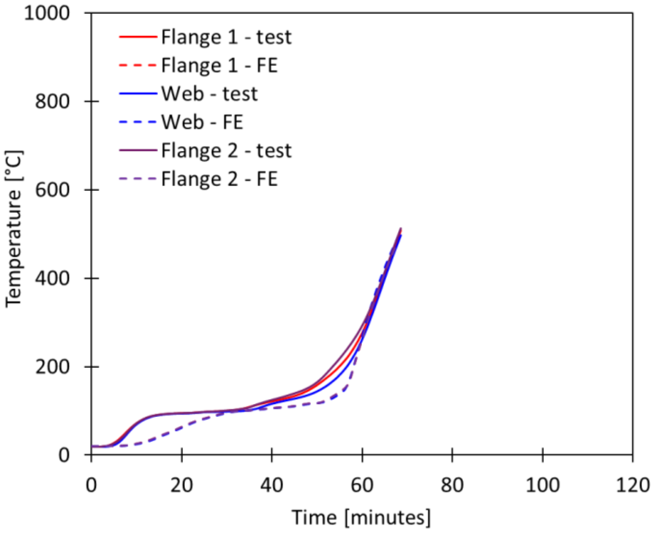
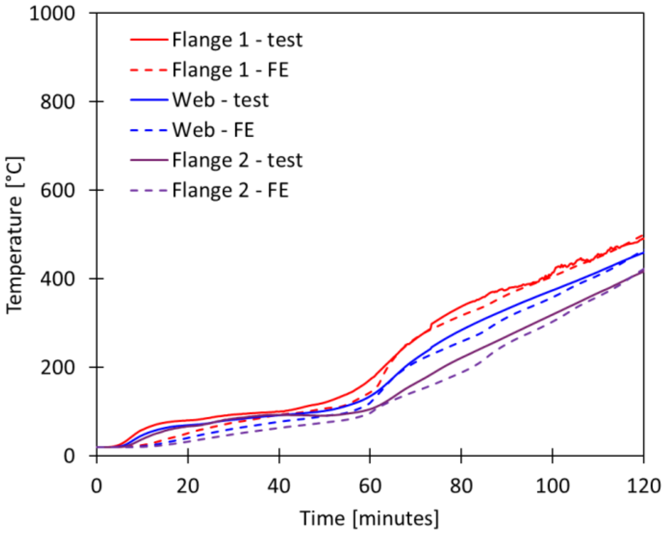


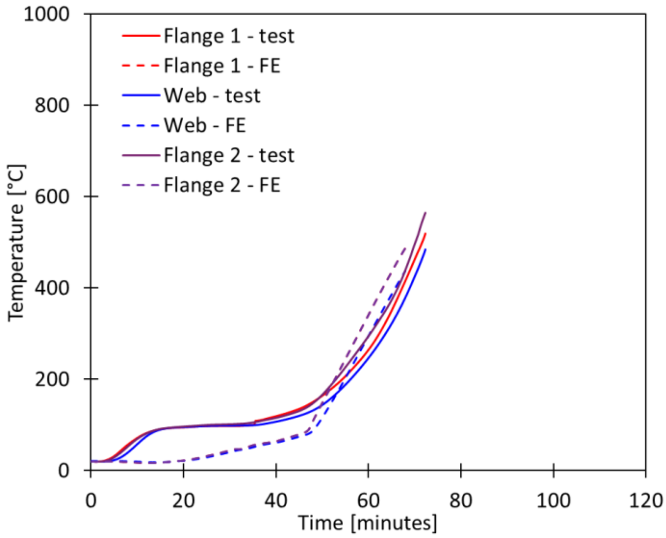
Figure 14. Location of temperature measurements in FE model



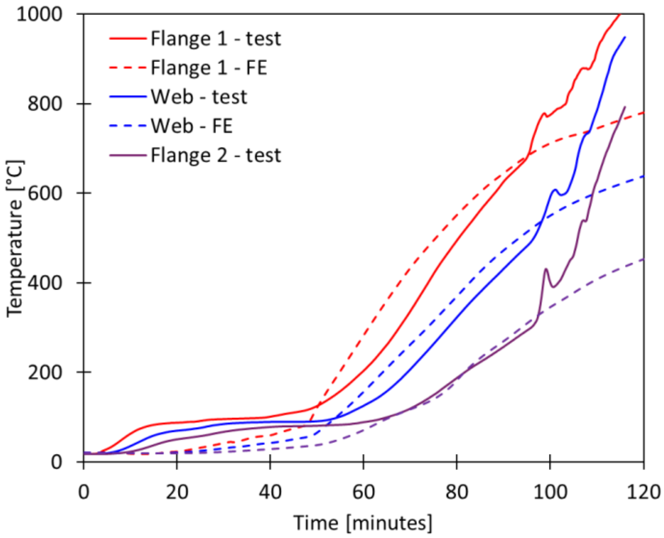
(a) Two-sided fire exposure, no insulation



(b) One-sided fire exposure, no insulation



(c) Two-sided fire exposure, with cavity insulation

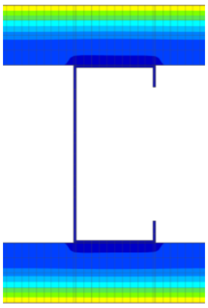
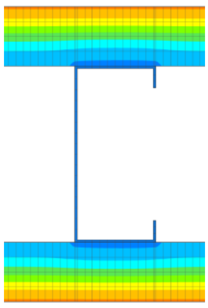
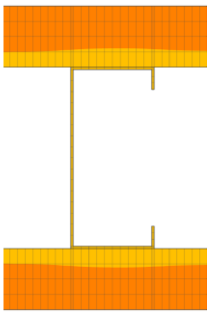
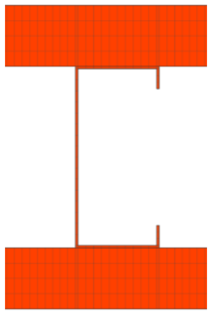
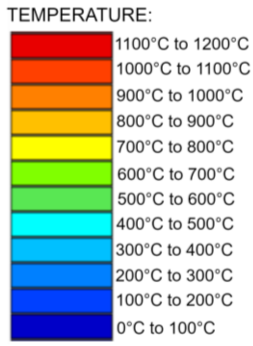
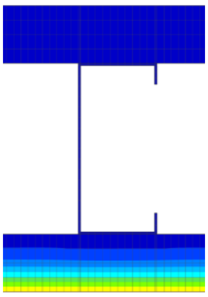
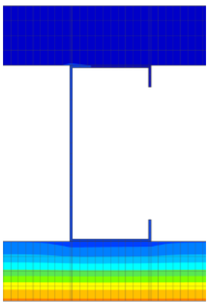
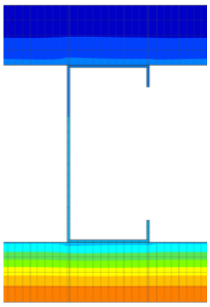
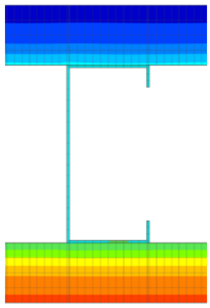
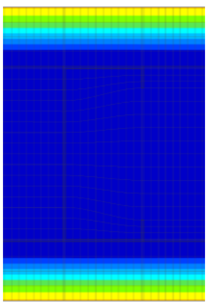
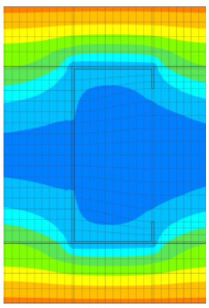
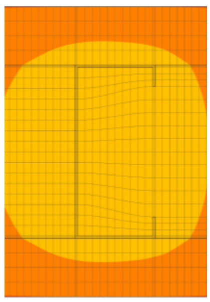
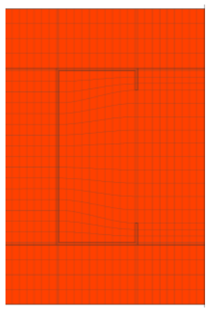
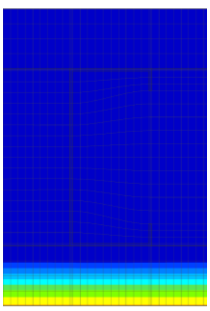
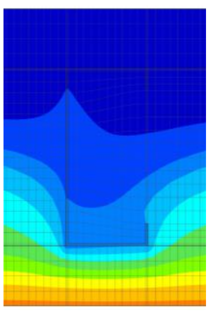
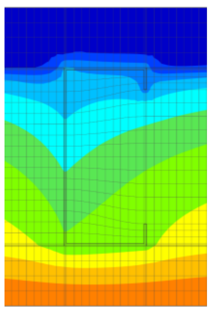
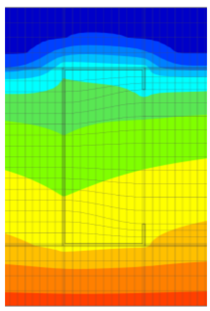


(d) One-sided fire exposure, with cavity insulation

Figure 15. Comparison of stud temperature profiles obtained from FE thermal analysis with test results

Table 4 shows the temperature distribution across the LSF wall cross-section after 30, 60, 90 and 120 min of exposure to the standard fire for all four LSF wall configurations modelled. The stud temperature distribution is uniform for two-sided fire exposure and non-uniform (have a temperature gradient across the section of the wall and stud) for the one-sided fire exposure, which aligns with observations from the tests.

Table 4. Temperature distribution in the LSF wall cross section from FE thermal analysis

LSF wall	30 min	60 min	90 min	120 min	Legend
Two-sided, no insulation					
One-sided, no insulation					
Two-sided, cavity insulation					
One-sided, cavity insulation					

4 Parametric analysis

As described in Section 2.4, this study aims to generate data on the thermal behaviour of LSF walls exposed to fire on two sides. Having validated the FE model and obtained good agreement between FE and test results, this section covers extensive parametric studies using the FE model to understand the influence of different design parameters on the thermal response of LSF walls exposed to fire on two sides. Parameters investigated were based on the outcome of the literature review study and includes nature of insulation (no insulation, cavity insulation and external insulation), number of sheathing board layers, type of fire model, and time lag before the second face of the wall is exposed to fire after exposure of the first face.

The parameters were selected based on possible realistic combinations of LSF wall design parameters as follows:

- For insulation, three types of insulation configuration were investigated i.e. no insulation, full cavity insulation and external insulation sandwiched between two sheathing board layers. The total thickness of external insulation was half of the full depth cavity insulation.
- For the number of sheathing board layers, 1 – 3 sheathing board layers of 15 mm each were investigated as this represents the typical number of layers and thickness of sheathing board used in practice [38].
- For the type of fire model, two compartment fire models (nominal fire curve - ISO standard fire; and natural fire curve - Eurocode parametric fire) and one nominal external fire model were investigated. The external fire model was studied so as to cover the scenario where flames emanating from an enclosure fire can heat the external surface of an LSF wall, with the internal face simultaneously heated by the internal compartment fire (standard fire was used as the internal fire in this study). To explore the influence of ventilation conditions on the fire development within a compartment, two types of parametric fires based on ventilation condition were investigated – short duration and hot fire (short-hot) representing compartments with larger opening factors; and long duration with relatively cool fire (long-cool) representing compartments with smaller opening factors [39,40]. The fire curves are shown in Figure 16. In the thermal model, the applied hot surface convective heat transfer coefficient for the standard fire curve and external fire curve is 25 W/m²/K, while that for parametric fires is 35 W/m²/K [22].
- For time lag before second face of wall is exposed to fire, the following times**:** 0, 5, 10, and 20 min were investigated. These were chosen to represent different delay times in fire spread from one side of a wall to another. Plots of the fire curves with time lags are presented in Appendix B.

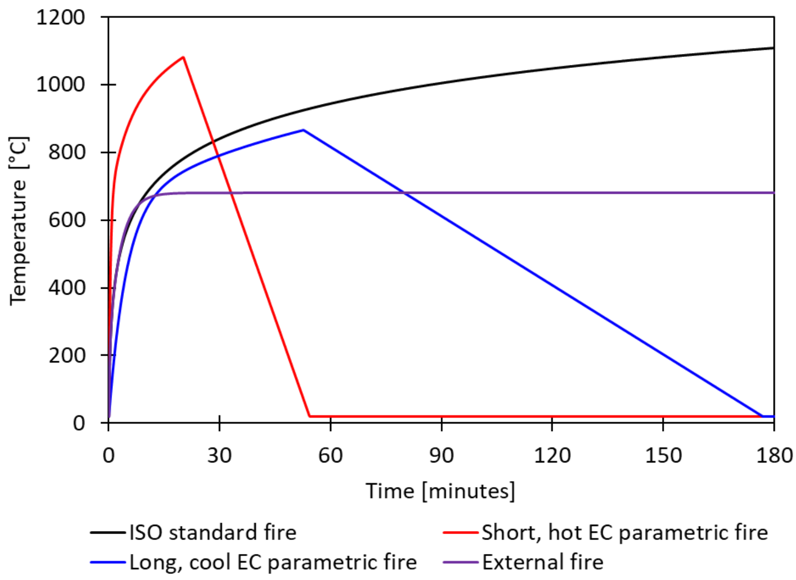
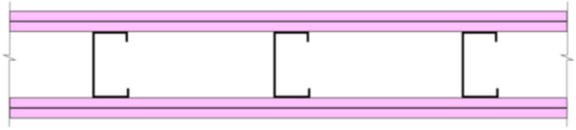
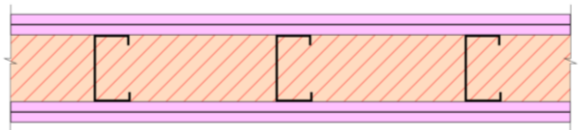
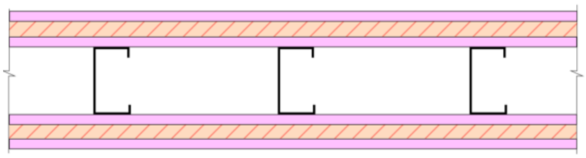
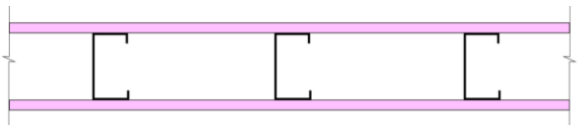
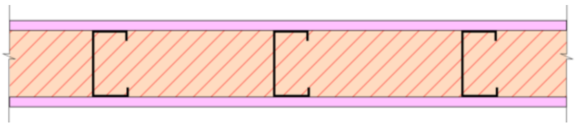
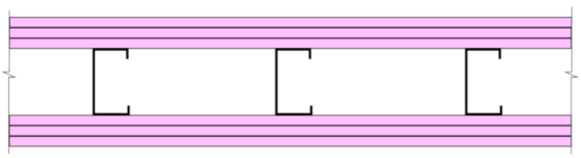
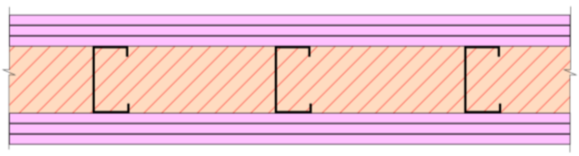


Figure 16. Fire models considered in the parametric studies

The parametric studies also considered one-sided fire exposure condition, with each of the fire models on one side and ambient temperature on the other side of the wall.

Based on the above, the parametric studies involved a total of 133 different FE models to cover all the design parameters as shown in Table 5.

Table 5. Parametric study cases

<table>
<tr><th rowspan="2">LSF wall configuration</th><th rowspan="2">Number of faces exposed</th><th colspan="2">Fire exposure condition</th><th rowspan="2">Time lag [min]</th></tr>
<tr><th>Face 1 (near flange 1)</th><th>Face 2 (near flange 2)</th></tr>
<tr><td rowspan="5">
Type 1: 2 plasterboard layers, no insulation

Type 2: 2 plasterboard layers, cavity insulation

Type 3: 2 plasterboard layers, external insulation

Type 4: 1 plasterboard layer, no insulation

Type 5: 1 plasterboard layer, cavity insulation

Type 6: 3 plasterboard layers, no insulation

Type 7: 3 plasterboard layers, cavity insulation</td><td>Two-sided</td><td>ISO fire</td><td>ISO fire</td><td>0, 5, 10 and 20</td></tr>
<tr><td>Two-sided</td><td>Short-hot parametric fire</td><td>Short-hot parametric fire</td><td>0, 5, 10 and 20</td></tr>
<tr><td>Two-sided</td><td>Long-cool parametric fire</td><td>Long-cool parametric fire</td><td>0, 5, 10 and 20</td></tr>
<tr><td>Two-sided</td><td>ISO fire</td><td>External fire</td><td>0, 5, 10 and 20</td></tr>
<tr><td>One-sided</td><td>All fire models</td><td>Ambient temperature</td><td>N/A</td></tr>
</table>

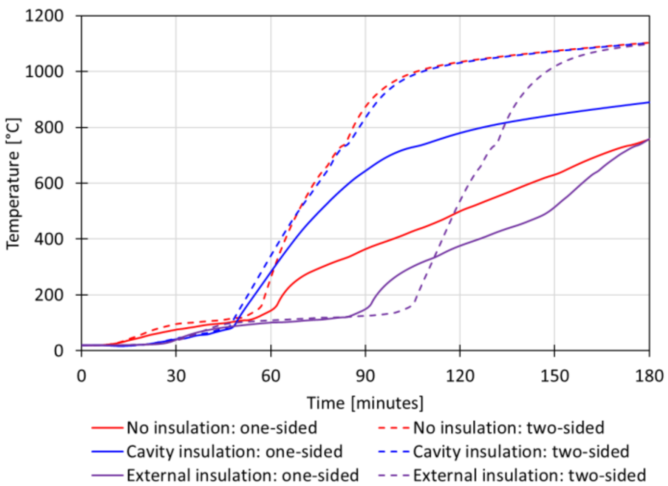
4.1 Effects of insulation type

Figure 17 shows the temperature profiles for the flanges and web of the stud, subjected to ISO fire exposure for various insulation conditions – no insulation, cavity insulation and external insulation. Both one-sided and simultaneous two-sided fire exposure scenarios are compared. Appendix A compares the stud temperature distribution across the stud cross-section for both one-sided and two-sided fire exposure conditions.

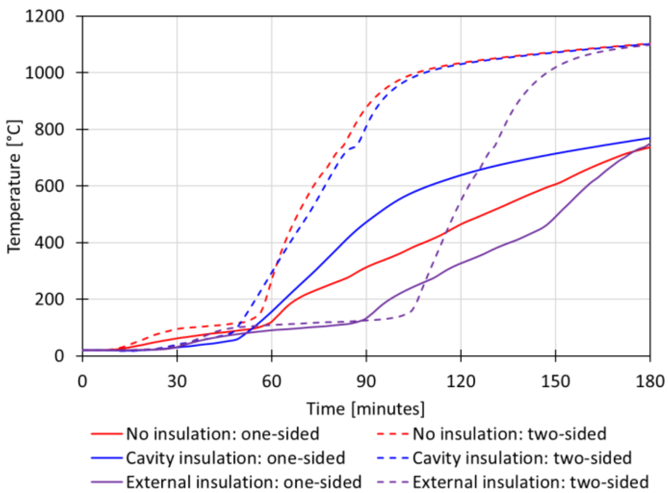
The analyses show that:

- Under one-sided fire exposure, cavity insulation led to the highest temperature rise, while external insulation resulted in the lowest temperatures across the flanges and web of the stud.
- Under two-sided fire exposure, external insulation generally resulted in the lowest temperatures across the stud section. Temperatures in the no insulation and cavity insulation cases were comparable, both significantly lower than those observed with external insulation.
- External insulation provided the greatest fire resistance, maintaining temperatures below 200 °C for 90 - 100 min of standard fire exposure, compared to 45 - 50 min for the no insulation and cavity insulation cases.
- Temperature distribution was non-uniform under one-sided exposure for all insulation types, with the temperature gradient more pronounced in the cavity insulation case. In two-sided exposure, a uniform temperature distribution was observed across all insulation conditions.

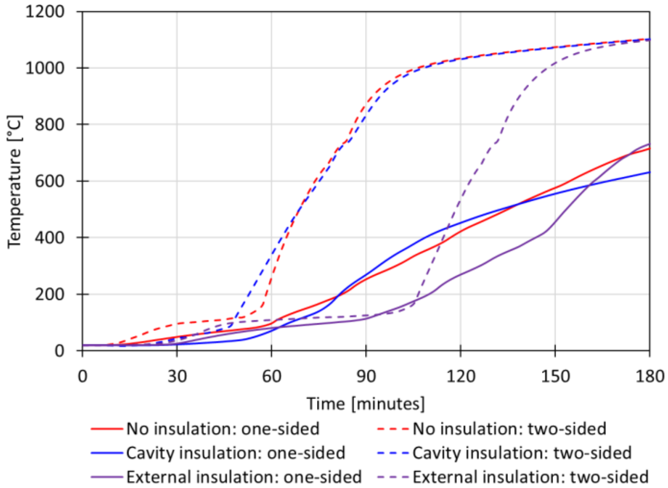
Table 6 presents the stud temperatures recorded at various time intervals (30, 60, 90, and 120 min) under ISO fire exposure for both one-sided and simultaneous two-sided fire exposures across the three insulation types considered. The table elucidates the findings from the temperature profiles (Figure 17) that two-sided fire exposure results in substantially higher temperatures and faster rates of heating across all insulation types.



(a) Flange 1



(b) Web



(c) Flange 2

Figure 17. Stud temperature profile for different insulation types (one-sided vs two-sided ISO fire exposure)

Table 6. Stud temperature at different times of ISO fire exposure for different insulation types

Stud location	Time [min]	Stud temperature [°C] - One-sided			Stud temperature [°C] - Two-sided		
		No insulation	Cavity insulation	External insulation	No insulation	Cavity insulation	External insulation
Flange 1	30	76	42	40	96	44	37
	60	144	282	101	262	340	109
	90	364	644	149	874	834	125
	120	500	780	376	1034	1031	537
Web	30	62	30	31	95	40	36
	60	121	156	91	268	294	109
	90	313	472	133	878	811	125
	120	465	638	327	1035	1030	548
Flange 2	30	49	23	26	96	44	37
	60	98	71	81	262	340	109
	90	254	270	114	874	834	125
	120	423	453	270	1034	1031	537

Note: Colour coding is based on a critical steel temperature of 430 °C specified in SCI P424 [41] for a limiting load ratio of 0.5 and a modification factor k_1 of 0.8.

< 200 °C — > 430 °C

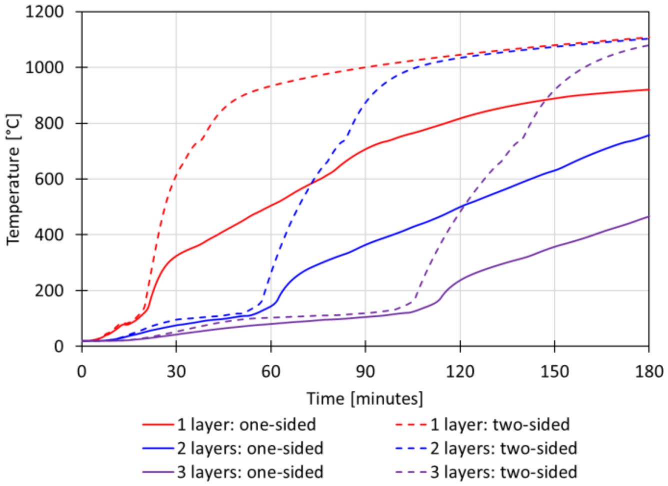
4.2 Effects of number of plasterboard layers

Figure 18 shows the temperature profiles of the steel stud subjected to ISO fire exposure. It compares the performance of the steel stud when protected by 1, 2, and 3 layers of plasterboard (with no insulation provided), under both one-sided and simultaneous two-sided fire exposure conditions. Table 7 provides detailed temperature data for the stud over varying time intervals (30, 60, 90, and 120 min) of standard fire exposure.

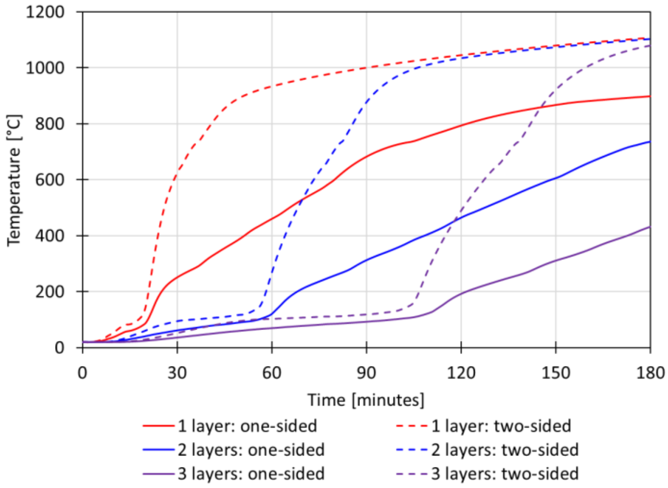
The analyses show that:

- The time of standard fire exposure at which rapid temperature rise and beyond which significant difference is observed in the stud temperatures for one-sided and two-sided fire exposure conditions varies depending on the number of plasterboard layers. (i.e., c. 20 min for 1 plasterboard layer, c. 50 min for 2 plasterboard layers and c. 100 min for 3 plasterboard layers).

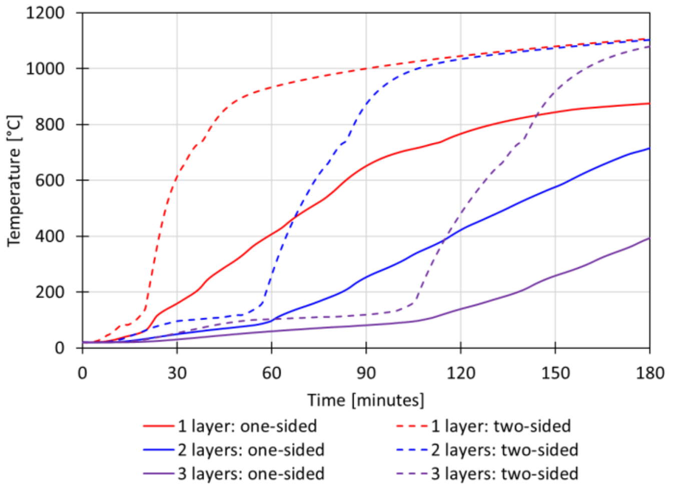
- At higher fire exposure durations under two-sided conditions, the number of plasterboard layers has negligible influence on the stud temperatures. Beyond 100 minutes, there is no significant difference between one and two layers, and after 180 minutes, there is no difference between one, two, and three layers.



(a) Flange 1



(b) Web



(c) Flange 2

Figure 18. Stud temperature profile for 1, 2 and 3 plasterboard layers (no insulation) (one-sided vs two-sided ISO fire exposure)

Table 7. Stud temperature at different times of ISO fire exposure for 1, 2 and 3 plasterboard layers (no insulation)

Stud location	Time [min]	Stud temperature [°C] - One-sided			Stud temperature [°C] - Two-sided		
		1 plasterboard layer	2 plasterboard layers	3 plasterboard layers	1 plasterboard layer	2 plasterboard layers	3 plasterboard layers
Flange 1	30	324	76	43	614	96	53
	60	505	144	81	934	262	103
	90	707	364	105	1000	874	119
	120	817	500	237	1045	1034	482
Web	30	251	62	36	625	95	52
	60	461	121	70	934	268	103
	90	683	313	93	1001	878	119
	120	794	465	193	1046	1035	490
Flange 2	30	159	49	30	614	96	53
	60	408	98	60	934	262	103
	90	652	254	81	1000	874	119
	120	767	423	140	1045	1034	482

Note: Colour coding is based on a critical steel temperature of 430 °C specified in SCI P424 [41] for a limiting load ratio of 0.5 and a modification k_1 of 0.8.

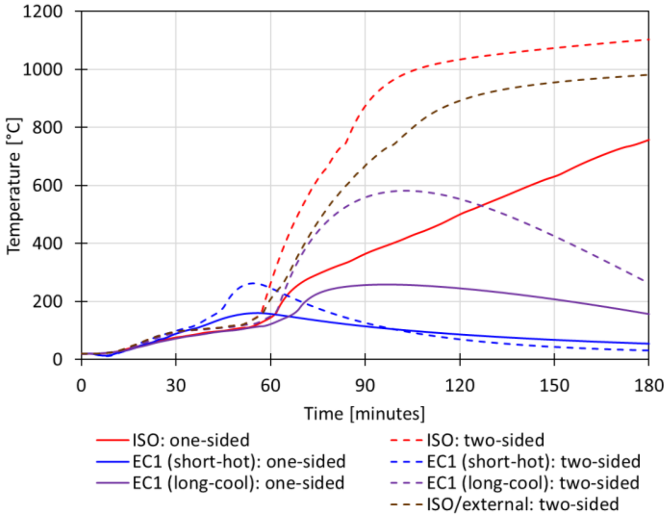
< 200 °C > 430 °C

4.3 Effect of fire type

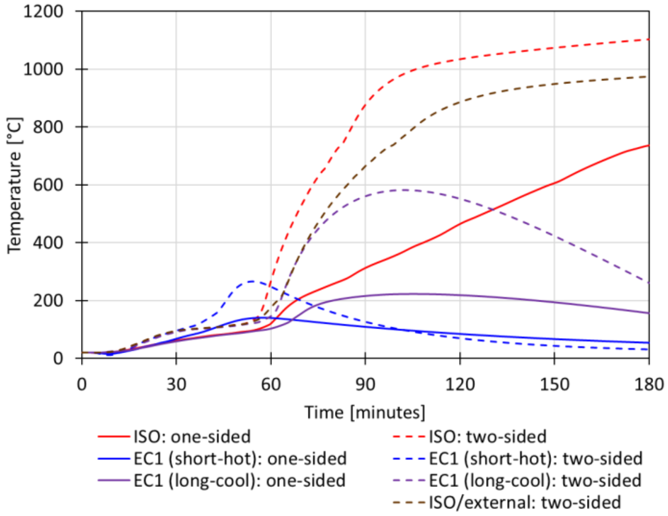
Figure 19 shows the temperature profiles of the steel stud section, subjected to different fire types. The fire scenarios considered include the standard ISO fire, two Eurocode parametric fires - EC1 (short-hot) and EC1 (long-cool) - and an external fire curve. The 'ISO/external' fire scenario is the condition where the ISO fire is applied to one face and the external fire to the opposite face.

For each fire scenario, one-sided exposure results in a slower and lower temperature rise compared to two-sided exposure. The most significant differences are observed in the ISO and EC1 (long-cool) fires, where two-sided exposure leads to much higher temperatures. The EC1 (short-hot) fire scenario shows the least difference between one-sided and two-sided exposure. This is because for this fire type, the peak fire temperature occurs early in the fire at the region where there is less difference in the thermal response between one- and two-sided fire exposure conditions as noted in Section 4.2.

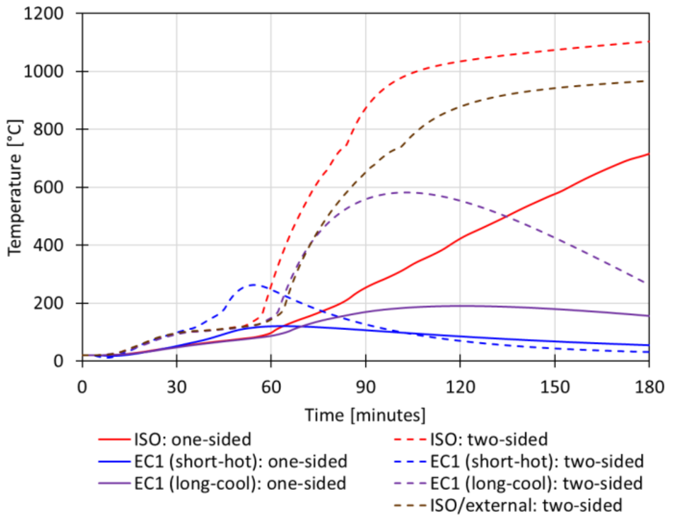
The ISO/external fire scenario under two-sided exposure also shows a significant temperature increase, though less severe than the case of ISO fire on both sides of the wall, indicating the combined effect of different fire types from opposing sides.



(a) Flange 1



(b) Web



(c) Flange 2

Figure 19. Stud temperature profile for different fire models (one-sided vs two-sided)

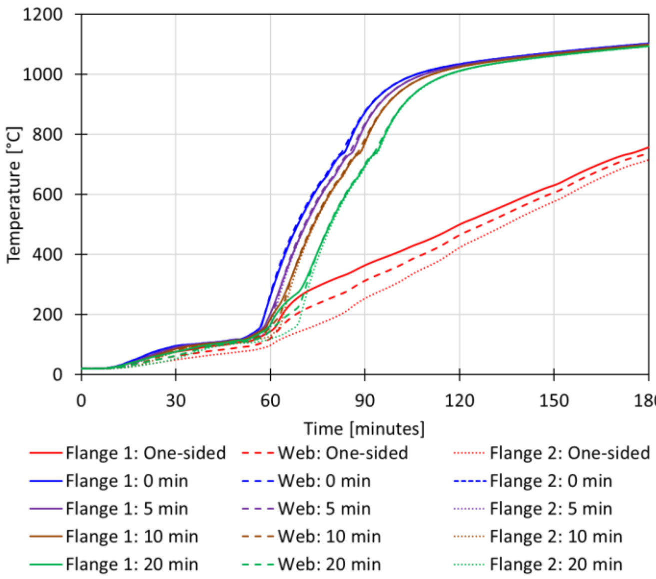
4.4 Effect of time lag

Figure 20 shows the temperature profiles of the steel stud, subjected to ISO standard fire exposure under different scenarios involving time lags before the second face of the wall is exposed to fire. The graph compares these scenarios for three insulation conditions – no insulation, cavity insulation and external insulation, to explore whether the effect of time lag is amplified or diminished by the insulation condition. Figure 21 shows the same comparison under exposure to a natural fire curve. The natural fire curve used was the EC1 long-cool parametric fire model as it has been shown in Section 4.3 that this is the natural fire model for which the number of faces exposed to fire has the most impact on the thermal behaviour of the LSF wall.

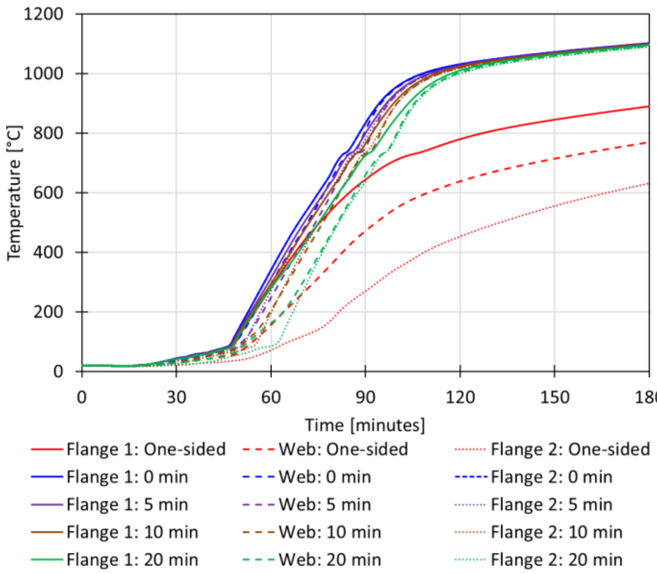
The analyses show that:

- Under ISO standard fire, the effect of time lag is noticeable between 45 and 60 minutes for no insulation and cavity insulation, and between 100 and 145 minutes for external insulation. Outside these periods, the time lag has no significant impact on the temperature profile.

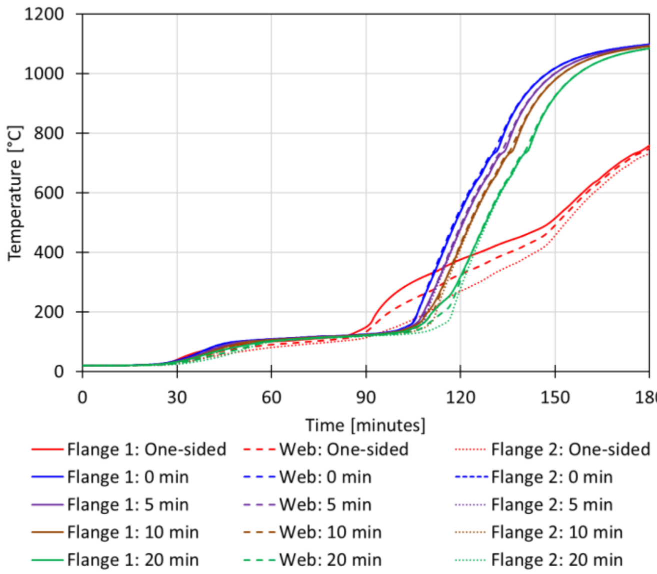
- Under the natural fire curve (EC1 long-cool parametric fire model), the effect of time lag remains consistent throughout the fire duration, albeit with the time to peak temperature largely insensitive to the delay time.



(a) No insulation

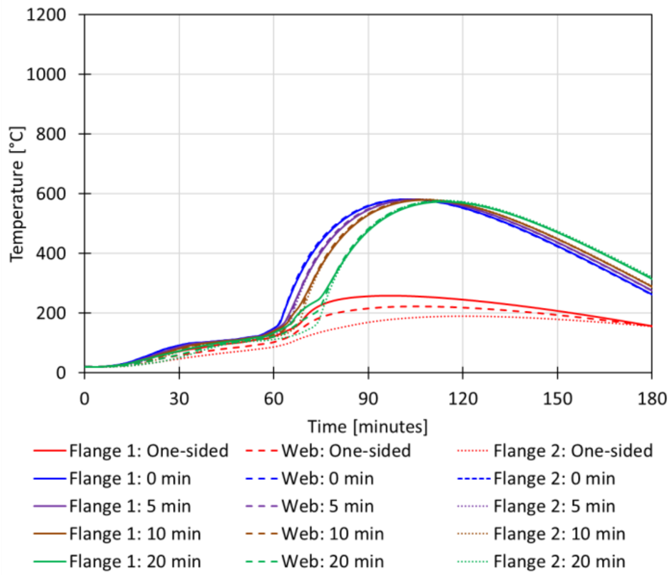


(b) Cavity insulation

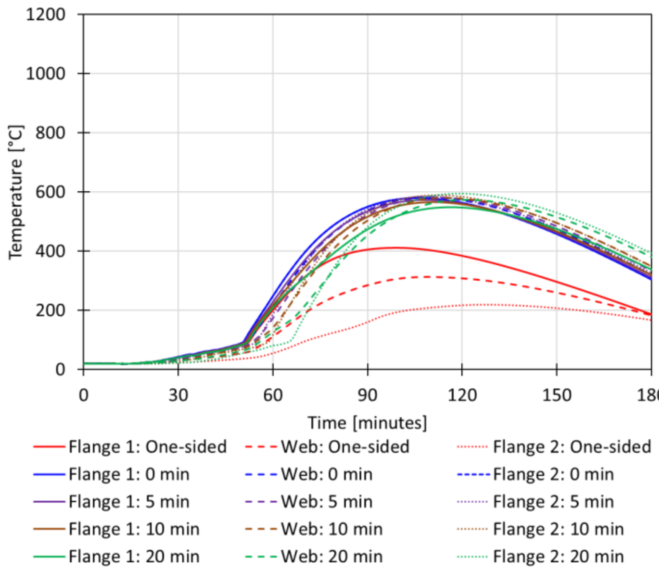


(c) External insulation

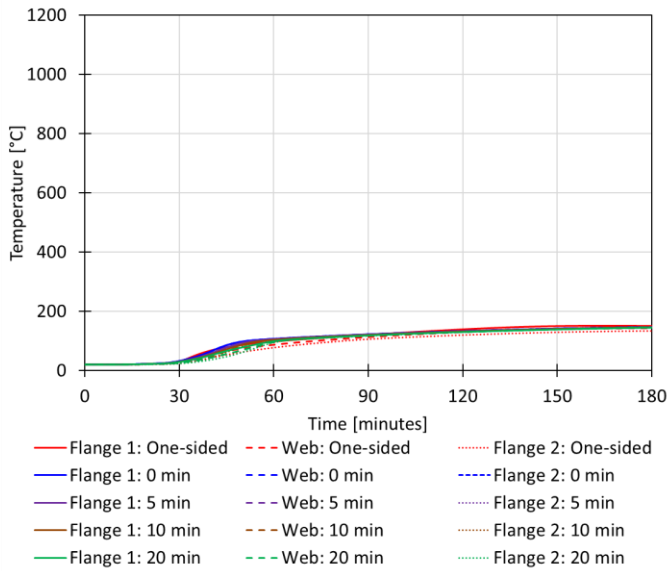
Figure 20. Stud temperature profile for varying time lags before exposure of second face of wall for different insulation types – standard fire



(a) No insulation



(b) Cavity insulation



(c) External insulation

Figure 21. Stud temperature profile for varying time lags before exposure of second face of wall for different insulation types – EC1 long-cool parametric fire

5 Discussion

5.1 Temperature distribution under two-sided fire exposure

The parametric analysis presented in section 4 assesses the impact of different parameters on the thermal behaviour of LSF walls exposed to fire on both sides. The analysis showed that irrespective of the insulation condition (no insulation, cavity insulation or external insulation), number of insulation layers, and fire type (nominal or natural fire curves), two-sided fire exposure of LSF walls results in uniform temperature distribution across the stud section throughout the duration of the fire. For one-sided fire exposure, the temperature distribution is non-uniform.

For all configurations studied, at early stage of the fire, the temperature rise is gradual. The temperatures are very low and there is no significant difference between temperature values and temperature distribution between one-and two-sided fire exposure. This is because the temperature profile is dominated by the moisture plateau of the plasterboard layers, which begins to dehydrate.

As the fire exposure duration increases, the difference between one- and two-sided fire exposure become significant marked by rapid temperature rise across the stud section. The exposure time before rapid temperature increase in the stud is experienced depends on the number of plasterboard layers and insulation configuration. For external insulation with two plasterboard layers, rapid temperature rise due to two-sided fire exposure was observed at 90 – 100 min of standard fire exposure, compared to 45 - 50 min for the no insulation and cavity insulation cases. For different number of plasterboard layers with no insulation, the time at which rapid temperature rise due to two-sided fire exposure occurred was c. 20 min for 1 plasterboard layer, c. 50 min for 2 plasterboard layers and c. 100 min for 3 plasterboard layers.

For two-sided fire exposure subject to a lag indicative of fire spread, the delay marginally affects the time taken to reach peak temperatures under natural fire exposure. Under standard fire exposure, the delay marginally affects the time taken to reach temperatures typically associated with structural failure, i.e., in the range 400 to 600°C. It is generally observed that simultaneous heating of both sides of a wall without a delay is the most onerous. A delay in heating is likely to marginally improve the potential time to structural failure. Similar observations were also reported in a previous research study [42].

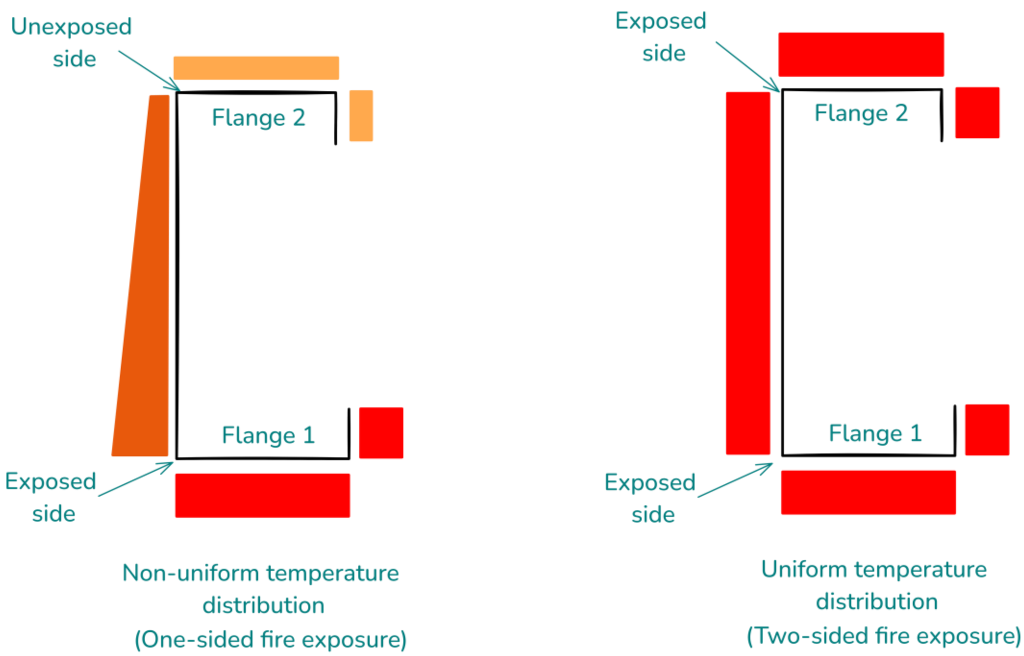


Figure 22. Sketch of temperature distribution of LSF wall stud under one-sided and two-sided exposure conditions

5.2 Influence of various design parameters on thermal behaviour of LSF walls exposed to fire on two sides

5.2.1 Influence of insulation

The study considered three insulation configurations: no insulation, cavity insulation, and external insulation positioned between plasterboard layers. The results indicate that external insulation is the most effective in reducing temperature rise, delaying the rise in temperature and maintaining lower temperatures for extended periods under both one-sided and two-sided fire exposures. However, its effectiveness is diminished under two-sided exposure compared to one-sided exposure, although it still outperforms the other insulation types. Under two-sided fire exposure, both no insulation case and cavity insulation have comparable performance in terms of stud temperature distribution and magnitude, exhibiting higher temperatures across the steel stud sections compared to the external insulation scenario. Similar observations were reported in the one-sided fire exposure study by Kesawan and Mahendran [43], where it was noted that, for the same number of plasterboard layers, the externally insulated LSF walls had a better fire performance than the uninsulated and cavity insulated LSF walls under one-sided fire exposure. Cavity insulated LSF walls performed poorly due to the insulation acting retaining more heat in the stud locally, thereby causing a rapid increase in the hot flange temperatures and increased bending due to the large difference between the hot and cold flange temperatures.

External insulation configuration delays the onset of rapid temperature increases and maintaining lower overall temperatures during the early stages of fire exposure. The ability of external insulation to sustain lower temperatures for extended periods before a sharp rise is particularly advantageous in enhancing the fire resistance of loadbearing LSF walls, delaying structural failure and providing additional time for evacuation and fire-fighting efforts.

5.2.2 Influence of plasterboard layers

The number of plasterboard layers has a substantial impact on the thermal protection of the steel stud. Each additional layer delays the time at which critical temperatures are reached and lowers the overall maximum temperature. it is shown that the combined thickness of the plasterboard layers and where provided, external insulation between the plasterboard layers, impacts the time at which significant difference is observed in the stud temperatures of one- vs two-sided fire exposure conditions. (i.e., c. 20 min for 1 plasterboard layer, c. 50 min for 2 plasterboard layers and c. 100 min for three plasterboard layers.). Therefore, as more layers are added, the maximum temperature decreases significantly. A single plasterboard layer offers limited protection, particularly under two-sided exposure, while two and three layers significantly improve thermal response for both one- and two-sided fire exposure. However, at higher fire exposure durations under two-sided fire exposure, the number of plasterboard layers has negligible to no influence on the stud temperatures. Overall, the analysis showed that increasing the number of plasterboard layers significantly enhances the fire performance of LSF walls by delaying the onset of critical temperatures.

5.2.3 Type of fire exposure

The type of fire to which an LSF wall is exposed plays a crucial role in determining its thermal behaviour. The study considered the ISO standard fire, two Eurocode parametric fires (short-hot and long-cool), and an external fire scenario. The maximum temperatures recorded under the ISO and EC1 (long-cool) parametric fires, particularly under two-sided exposure, are near or exceed critical levels for steel, underscoring the severity of these fire scenarios. In contrast, the EC1 (short-hot) parametric fire scenario results in much lower maximum temperatures, indicating the ability of the LSF wall to withstand the full duration of these types of fire in terms of load bearing function. The ISO/external fire scenario under two-sided exposure (where the ISO fire is applied to one face and the external fire to the opposite face) also shows a significant temperature increase, though less severe than the case where both faces of the wall are subjected to ISO fire.

Simultaneous exposure of both faces to fire (0 min lag) resulted in the highest temperatures. Introducing a time lag between the exposure of the first and second faces moderated the temperature rise to some extent. The longer the time lag, the lower the maximum temperatures, although the difference became less significant at higher fire exposure durations. Even with a 20-minute lag, the temperatures remained high, indicating that while a delay in fire exposure provides some benefit, it is not sufficient to prevent the steel stud from reaching critical temperatures. Time lags exceeding 20 min were not investigated in this study, in which case the time lag might have a more significant effect.

5.3 Loadbearing fire resistance of LSF walls exposed to fire on two sides

Review of methods for assessing the loadbearing fire resistance of LSF walls under one-sided ISO fire exposure have shown that the load bearing fire resistance is a function of the stud critical temperature.

The SCI (The Steel Construction Institute) Publication P424 'Fire Resistance of Light Steel Framing' [41] provides critical (limiting) temperature of the cold-formed steel stud section for different load ratios (Figure 23). In Figure 23, k_1 is a modification factor to allow for buckling and thermal bowing effects in the fire design case. Load ratio is the ratio of load on the LSF wall stud at the fire condition to the load carrying capacity of the stud under normal loading condition. For a given load ratio, the steel reference temperature is calculated and compared with the critical temperature. Steel reference temperature is calculated from [41]:

$$T_{ref} = \left(2T_{flange\ 1} + T_{flange\ 2}\right)/3$$ *Equation 3*

The above can be applied to two-sided fire exposure, with the difference between one- and two-sided exposure being time to reach this critical temperature.

Load ratio of C section in wall $N_{b,Rd,fi}$ / $N_{b,Rd}$	Critical temperature of C section in a single leaf loaded wall (°C) with modification factor:			Default value in BS EN 1993-1-2 UK NA for Class 1 to 3 sections in compression
	k_1 = 0.8	k_1 = 0.9	k_1 = 1.0	
0.2	630	645	660	665
0.3	560	580	600	610
0.4	510	530	560	570
0.5	430	470	510	535
0.6	330	390	430	500
0.7	220	320	360	410

Figure 23. Critical temperatures for C sections in single leaf walls in fire [41]

Another approach is to use the polynomial relationship between load ratio versus exposed flange (flange 1) temperatures at structural failure given in Perera et al. [14] based on results of previous research studies. See Figure 24.

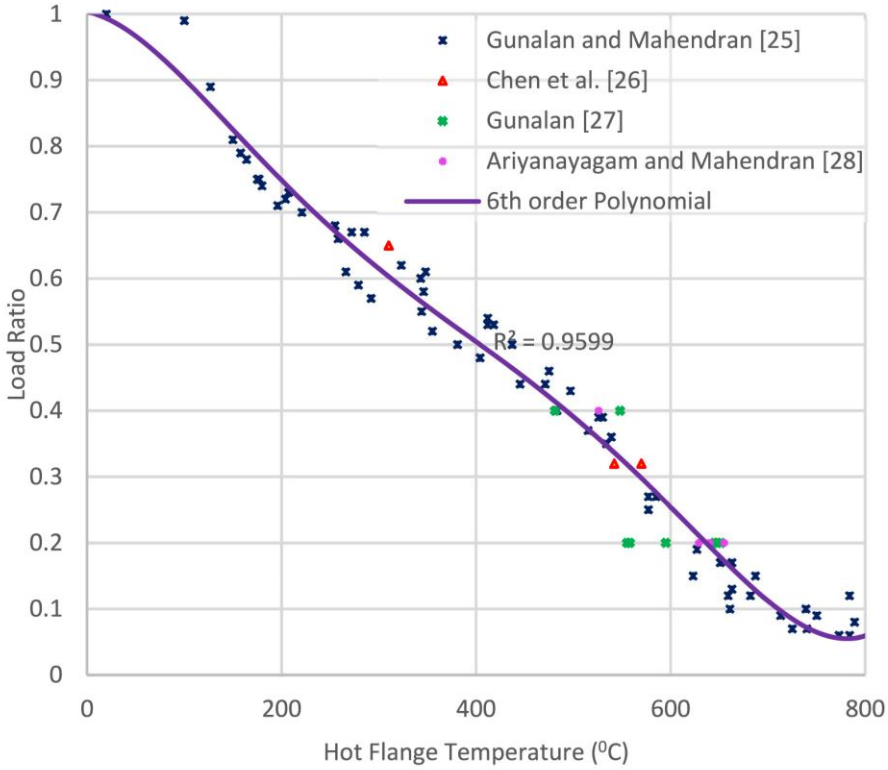


Figure 24. Load ratio versus exposed flange temperature at the structural failure of LSF wall, based on previous studies [14]

Using the SCI critical temperature tables (k_1 = 0.8) and the Perera et al. polynomial relationship, Table 8 and Table 9 summarises the limiting load ratio derived using stud temperatures from the FE models analysed in Section 4 of LSF walls under one- and two-sided fire exposure conditions for different insulation configurations, and different number of plasterboard layers, respectively.

Table 8 illustrates that the load ratio of LSF walls decreases under two-sided fire exposure compared to one-sided fire exposure across different insulation types. For instance, with no insulation at 90 minutes fire resistance (FR), the load ratio drops from 0.60 under one-sided exposure to 0.37 under two-sided exposure. Similarly, for cavity insulation at 90 minutes FR, the load ratio falls from 0.60 under one-sided exposure to less than 0.2 under two-sided exposure. External insulation shows a relatively better performance, but still exhibits a decrease in load ratio from 0.70 under one-sided exposure to 0.59 under two-sided exposure for 60 minutes FR. This demonstrates that two-sided fire exposure significantly reduces the load-bearing capacity of LSF walls, consistent with the testing undertaken. As observed during the test, while cavity insulation reduces the load bearing fire resistance under one-sided fire exposure compared to no insulation case, its impact is negligible under two-sided fire exposure.

Table 9 shows that the load ratio of LSF walls decreases with two-sided fire exposure compared to one-sided exposure, and the impact varies depending on the number of plasterboard layers. For example, with one plasterboard layer at 60 min FR, the load ratio drops from 0.43 under one-sided exposure to less than 0.2 under two-sided exposure using the SCI method. Similarly, with three plasterboard layers at 120 min FR, the load ratio decreases from 0.72 under one-sided exposure to 0.43 under two-sided exposure using the Perera et al. relationship. The trend is consistent across both methods, with the load ratio generally being lower for two-sided exposure, especially when fewer plasterboard layers are used. This indicates that increasing the number of plasterboard layers can somewhat mitigate the reduction in load-bearing capacity, but two-sided fire exposure still significantly impacts the structural performance of LSF walls.

Overall, the results show that, for the same LSF wall configuration, the load ratio the stud can sustain is less for two-sided fire exposure compared to one-sided fire exposure.

Table 8. Limiting load ratio of LSF walls exposed to ISO fire for various fire resistance periods and insulation types (2 plasterboard layers)

Method	FR [min]	Load ratio - One-sided			Load ratio - Two-sided		
		No insulation	Cavity insulation	External insulation	No insulation	Cavity insulation	External insulation
SCI [41]	30	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7	> 0.7
	60	> 0.7	0.68	> 0.7	0.59	> 0.7	> 0.7
	90	0.60	< 0.2	0.37	< 0.2	> 0.7	> 0.7
	120	0.43	< 0.2	< 0.2	< 0.2	0.59	0.35
Perera et al. [14]	30	0.91	0.96	0.96	0.89	0.95	0.96
	60	0.83	0.67	0.88	0.69	0.60	0.87
	90	0.57	0.23	0.83	<0.05	<0.05	0.86
	120	0.41	0.07	0.55	<0.05	<0.05	0.36

Table 9. Limiting load ratio of LSF walls exposed to ISO fire for various fire resistance periods and number of plasterboard layers (no insulation)

Method	FR [min]	Load ratio - One-sided			Load ratio - Two-sided		
		1 plasterboard layer	2 plasterboard layers	3 plasterboard layers	1 plasterboard layer	2 plasterboard layers	3 plasterboard layers
SCI [41]	30	0.67	> 0.7	> 0.7	0.26	> 0.7	> 0.7
	60	0.43	> 0.7	> 0.7	< 0.2	0.68	> 0.7
	90	< 0.2	0.60	> 0.7	< 0.2	< 0.2	> 0.7
	120	< 0.2	0.43	> 0.7	< 0.2	< 0.2	0.42
Perera et al. [14]	30	0.62	0.91	0.95	0.27	0.89	0.94
	60	0.40	0.83	0.91	<0.05	0.69	0.88
	90	0.16	0.57	0.88	<0.05	<0.05	0.86
	120	0.05	0.41	0.72	<0.05	<0.05	0.43

6 CONCLUSIONS

This report has presented the results of the WP2b study to investigate the thermal behaviour of LSF walls exposed to fire on two sides. To achieve this, a comprehensive parametric analysis was conducted using a validated FE model to provide an understanding of how different factors influence the thermal behaviour of LSF walls.

The parametric analysis conducted in this study provided comprehensive insights into the influence of various design parameters on the thermal behaviour of LSF walls subjected to fire exposure on two sides. The analysis covered a range of critical parameters, including the nature of insulation, the number of sheathing board layers, the type of fire model, and the time lag before the second face of the wall is exposed to fire. A total of 133 cases were investigated.

The main findings/conclusions from the parametric study are:

- **Temperature distribution:**
  - Two-sided fire exposure of LSF walls results in uniform temperature distribution across the stud section. For one-sided fire exposure, the temperature distribution is non-uniform, regardless of the insulation type, number of plasterboard layers, fire model, or time lag before the second face of the wall is exposed to fire (within the time frame investigated i.e., up to 20 minutes).
- **Insulation type/configuration:**
  - External insulation was found to be the most effective in reducing temperature rise and delaying the onset of critical temperatures under both one-sided and two-sided fire exposures. However, its effectiveness was somewhat reduced under two-sided exposure compared to one-sided exposure, although it still outperformed the other insulation types.
  - Overall, temperature distribution for all insulation types, showed non-uniform distribution under one-sided fire exposure. However, the temperature gradient is more pronounced in the cavity insulation case, with the no-insulation and external insulation conditions having comparable temperature gradients. For the two-sided exposure, uniform temperature distribution was observed for all the insulation conditions.
- **Number of plasterboard layers:**
  - The number of plasterboard layers has a substantial impact on the thermal protection of the steel stud. Each additional layer delays the time at which rapid increase in temperatures are experienced and beyond which significant difference is observed between one- and two-sided fire exposure conditions(i.e., c. 20 min for 1 plasterboard layer, c. 50 min for 2 plasterboard layers and c. 100 min for three plasterboard layers) under standard fire exposure.
  - For a given number of plasterboard layers, two-sided fire exposure remains a more severe scenario, significantly compromising the effectiveness of the plasterboard layers, particularly when fewer layers are used.
  - At extended fire exposure durations under two-sided fire conditions, the number of plasterboard layers has little to no effect on stud temperatures. Specifically, beyond 100 minutes for standard fire exposure, there is no significant difference in temperatures between 1 and 2 plasterboard layers, and after 180 minutes, there is no difference among 1, 2, and 3 layers. This may be because they have, in-effect, failed and fallen off.
- **Fire model/type:**
  - The fire type significantly influences the temperature profile, with standard and long-cool parametric fires presenting the highest temperatures due to their intense and prolonged heating. The short-hot parametric fire is less severe in terms of peak temperatures.

- The combined ISO/external fire scenario showed a significant temperature increase under two-sided exposure relative to one-sided, though it was less severe than when both faces were exposed to the ISO fire.

- **Time Lag:**
  - Simultaneous exposure of both faces to fire resulted in the highest temperatures. Introducing a time lag between the exposure of the first and second faces reduced the maximum temperatures, but this effect diminished with longer fire exposure durations.
  - Even with a 20-minute time lag, the temperatures remained high, indicating that while a delay in exposure offers some benefit, it is still more onerous than one-sided exposure. Further investigation into longer time lags may reveal more significant effects.
- **Loadbearing fire resistance:**
  - Two-sided fire exposure significantly reduces the loadbearing fire resistance of LSF walls compared to one-sided exposure across various insulation types, with the limiting load ratio dropping more drastically for walls with no insulation or cavity insulation compared to external insulation.
  - Increasing the number of plasterboard layers can mitigate some reduction in loadbearing fire resistance under two-sided fire exposure.
  - For the same LSF wall configuration, the load-bearing capacity of the stud is significantly reduced under two-sided fire exposure compared to one-sided exposure. For instance, with no insulation and a load ratio of 0.6, the load-bearing resistance decreases from 90 minutes under one-sided exposure to 60 minutes under two-sided exposure.
- **Technical policy implications:**
  - From a technical policy perspective, it is apparent that walls can be exposed to fire on two sides simultaneously in certain conditions and that this can bring about substantial reductions in structural fire resistance of lightweight wall construction.
  - ISO 834 heating under two sides simultaneously has been shown to be conservative when considering stud temperatures under a range of heating and time lag conditions.
  - The current ADB (Table B3) recommends that, for fire resistance classification, structural elements as part of a structural frame should be tested and designed for fire exposure on all exposed faces, but it does not specifically include walls. Therefore, based on the outcome of this study, consideration should be given to amending Approved Document B to include more explicit recommendations for fire resistance classification under conditions where two sides of a wall are exposed simultaneously. This is currently implied through recommendations for the structural frame, with separate recommendations then following for load-bearing and external walls.

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APPENDICES

Appendix A – Comparison of stud temperature distribution for different insulation types

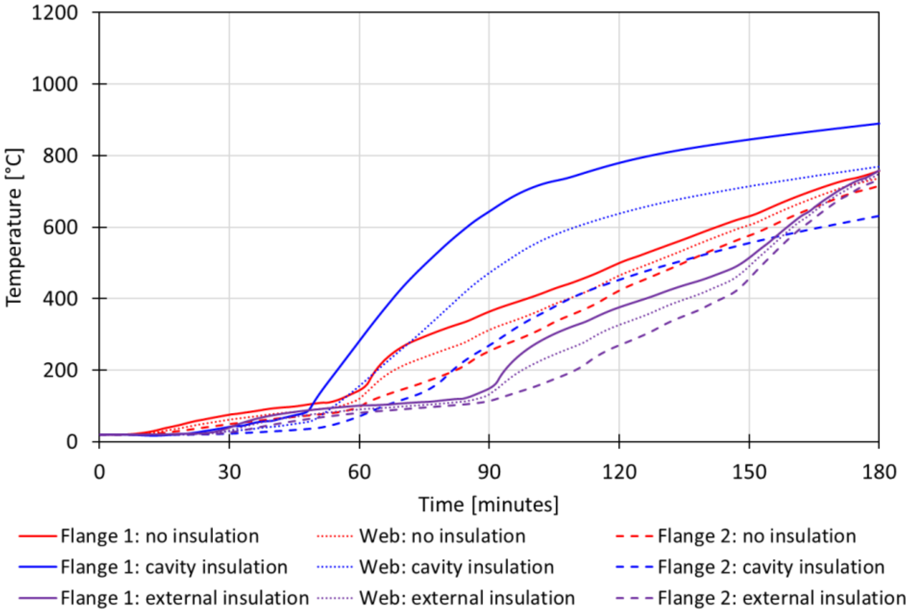

Figure 25. Comparison of stud temperature distribution for different insulation types (one-sided fire exposure)

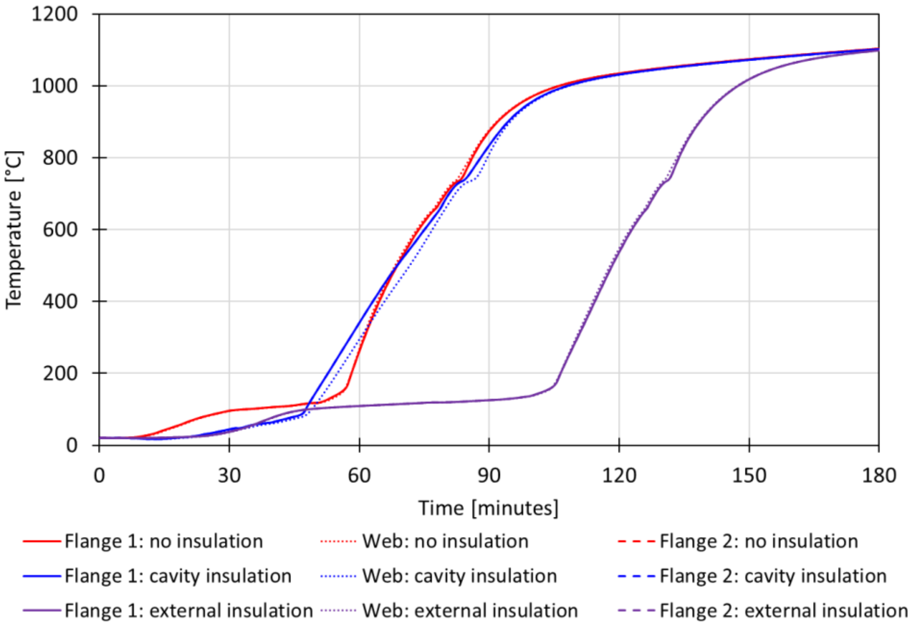

Figure 26. Comparison of stud temperature distribution for different insulation types (one-sided fire exposure)

Appendix B – Plot of fire curves with time lags

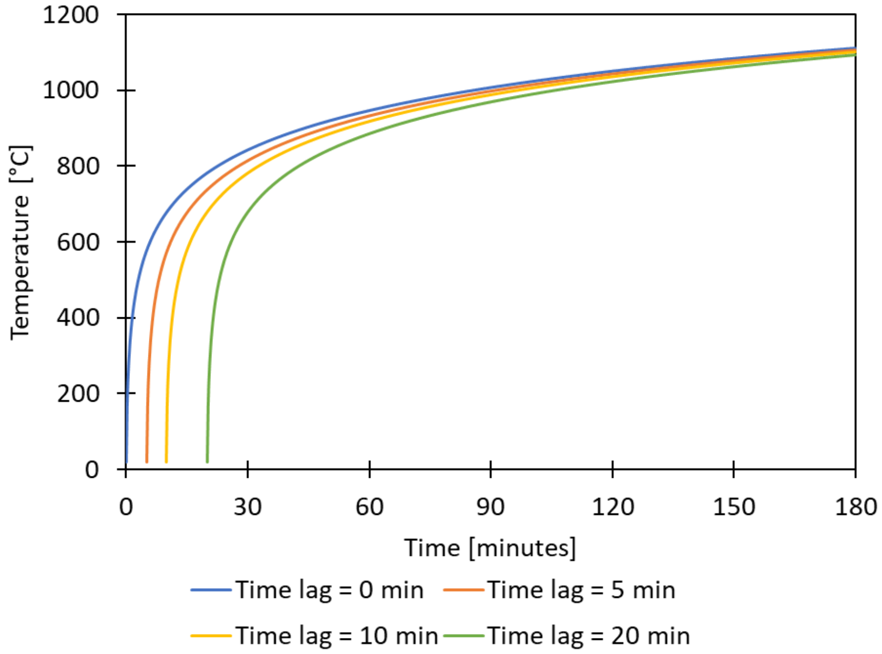

Figure 27. ISO fire curves with varying time lags

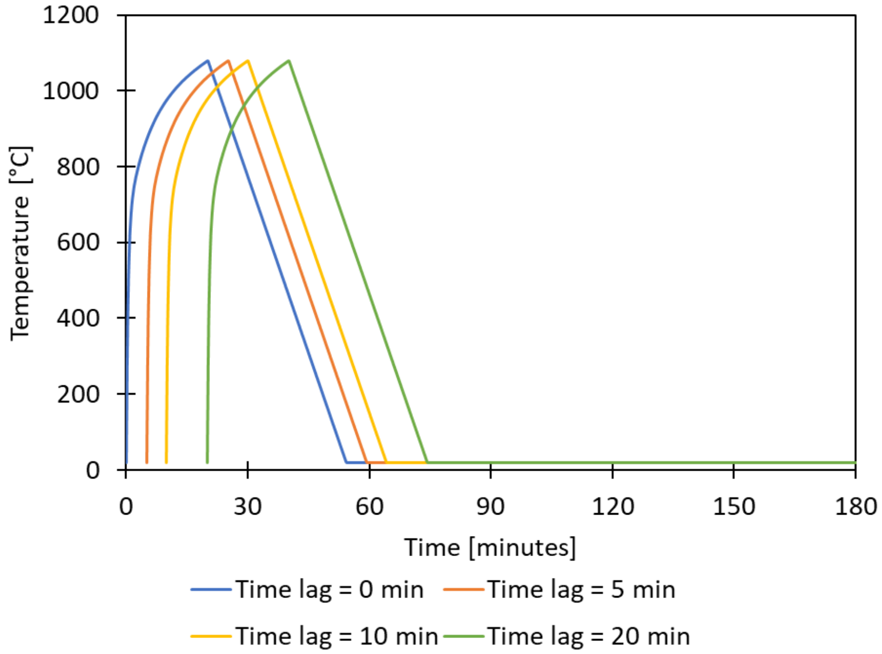

Figure 28. EC1 short-hot parametric fire curves with varying time lags

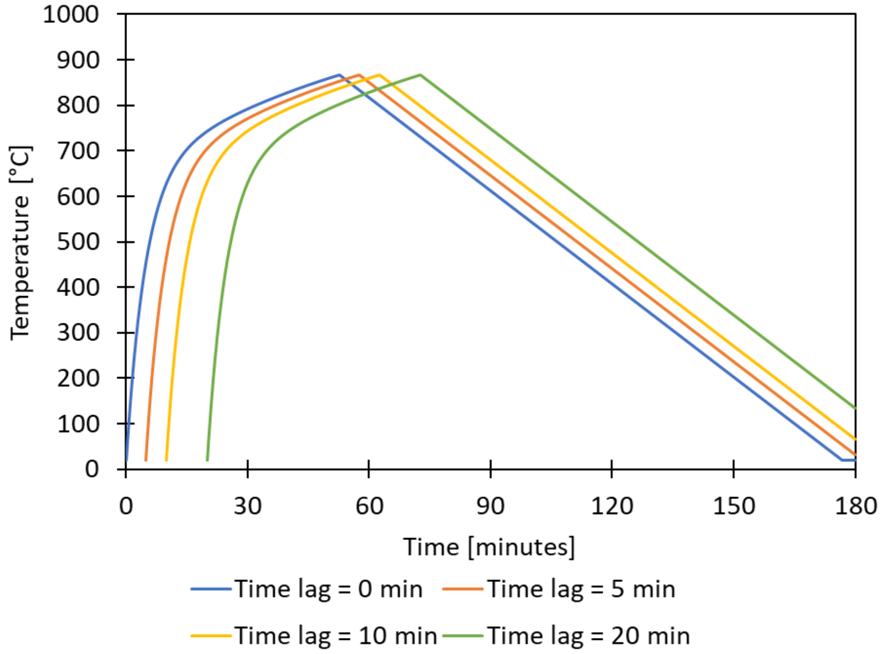

Figure 29. EC1 long-cool parametric fire curves with varying time lags

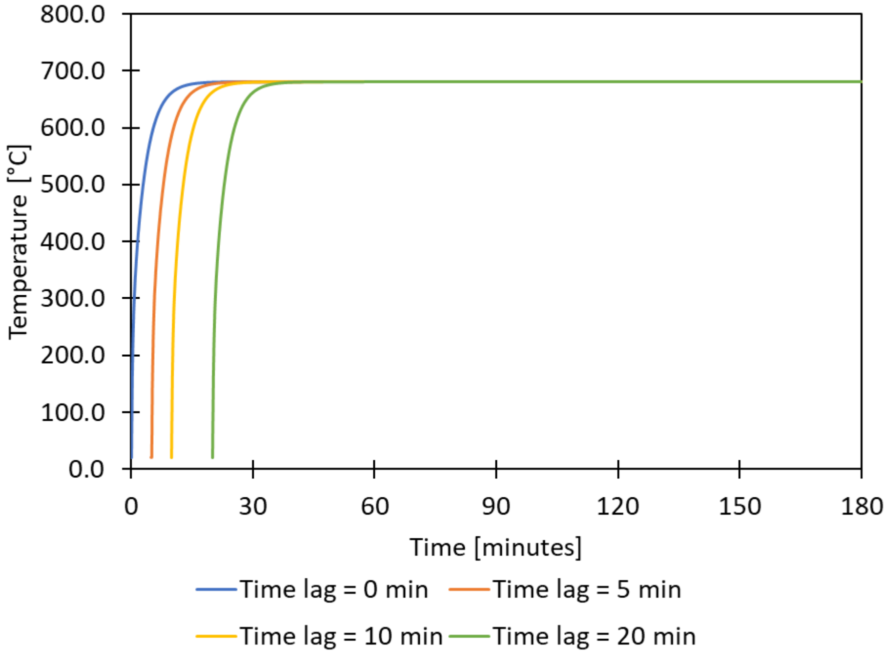

Figure 30. EC1 external fire curves with varying time lags