DTLR - GUIDANCE ON ROBUSTNESS AND PROVISION AGAINST ACCIDENTAL ACTIONS

The Current Application of Requirements A3 of the building Regulations 1991

Final Report Including background Documentation

CONTENTS

1.0 INTRODUCTION

The DETR has commissioned Allott & Lomax under Contract Reference No. CI/21/2/66 to undertake consultancy work on the subject of "Guidance on Robustness and Provision against Accidental Actions". The work scope is to carry out research and studies in support of the DETR/BR Robustness Committee in preparing submissions to the Building Regulations Advisory Committee (BRAC) on the subject of robustness of buildings and provision against accidental actions.

Specific objectives are,

1. Carry out and report on research required in support of the DETR/BR Robustness Committee.

2. Develop alternatives for revisions to the existing Requirement A3 of the Building Regulations 1991 and associated guidance.

3. Produce feedback from the studies and DETR/BR proposals as input into the National Application Document for Eurocode EC1 Part 2.7 "Accidental Actions due to Impact and Explosions".

The studies are to concentrate on buildings. Bridges and special structures, including grandstands, are not considered.

The current Requirement A3 specifically provides for safeguarding buildings greater than 4 storeys in height against disproportionate collapse in the event of an accident. The Department has concluded that, having monitored building collapses over many years, the A3 requirement and its associated authoritative guidance material has generally fulfilled its intended purpose. However, there is opinion that the fundamental property of resistance to disproportionate collapse should be required by regulations for all building structures. In addition, there is the view that the time is ripe to take stock of this whole area of design requirements and solutions, to bring best practice up to date by setting acceptable levels of risk, and to take advantage of recent work in Europe to improve our approach to this important issue.

A study was carried out and a report was prepared which,

a) summarised the initial study carried out into the current application of Building Regulation Requirement A3 together with trends in building construction and any comments on perceived short comings. The results of this work were qualitative and are intended to help the DETR/BR Robustness Committee guide the main thrust of the later studies.

b) presented a categorisation based upon ENV1991-2-7 using simple numerical values of coefficients to define the level of design and protection required.

The report was discussed with DETR staff and was the subject of a seminar held at DETR's offices on 17th May 1999. Following this, the contract was extended to include the following additional work:

1. Carry out calibration to validate the "Categorisation of Buildings" to ensure that,

   - the proposal gives satisfactory categorisation for all common buildings, with clearly established limitation on its application,

   - it does not bring significantly more buildings under control, and

   - it does not have any unduly adverse effect on the cost of building construction.

2. Prepare an addendum report to form a comprehensive background information document for use of the Working Party reporting to the Building Regulation Advisory Committee on "Review of Part A (Structure)".

The previous report has been extended to meet the requirements of the additional work, and as such, this document forms the final report on the contract and also includes all the background documentation required for the Working Party.

2.0 METHODOLOGY

The current limits on Requirement A3 are recognised as arbitrary, being without reference to building size (except the number of storeys), occupancy, use or sensitivity of structural form or structural materials to progressive collapse. An initial study was undertaken to establish,

a) the broad statistics of building construction to identify in an approximate way the proportion of buildings to which Requirement A3 applies.

b) trends in construction in which the limitation, which applies to A3, may not provide an adequate level of security.

c) where the current provisions may provide inadequate levels of reliability.

This was undertaken as follows,

a) Industry databases were reviewed to provide an insight into the application of Requirement A3.

b) A "straw poll" was conducted with a small number of engineers, architects and Building Control officers to establish trends in construction and the procurement of construction which give rise to concerns about erosion of safety margins.

The aim was not to produce a definitive position, but to provide insight into this area of structural design.

An alternative categorisation was developed using as a basis the concepts in ENV 1991-2-7 "Accidental Actions due to Impact and Explosions and long established principles in CIRIA Report 63. This allowed a simple numerical classification to be established, which was developed in discussion with DETR staff. The way in which the current Regulation A3 and its associated guidance would be amended was also developed.

The proposals were calibrated by determining the categorisation of 80 different structural types. This work was carried out by an Engineer who had not been involved in the development of the proposals or the discussions.

3.0 CURRENT APPLICATION OF REQUIREMENT A3

Published statistics have been reviewed to gauge the scope of the current application of Requirement A3. Not surprisingly, no single data source provides an answer to this question, and indeed conclusions may only be drawn by inference. This in itself is not seen as denying the objective of this part of the study, and should encourage a healthy reaction to the thoughts presented.

The Digest of Data for the Construction Industry (1995) provides data on the "typical" number of storeys of different types of construction as follows,

Residential	**Typical No. of Storeys**
High Rise Apartments	8
Capital City Hotel	10
Provincial Hotel	4
Retail	
Shopping Centres	2
Offices	
Heated Offices	4
Air Conditioned offices	8
Industrial	
Factories, Warehouses	1
High Technology/Research	2

These figures are for the UK but are typical of Europe in general.

Thus we may anticipate that the building types currently subject to Regulation A3 are generally limited to quite specific uses, namely,

Residential
Offices

i.e. places where people live and work. The inference is, that as currently applied, Regulation A3 provides protection to people, as opposed to protection of industrial and commercial assets.

Housing statistics have been used to establish, in an approximate way, proportions of the population who are exposed to risk from buildings falling within the current Regulation A3. These suggest that approximately 2.5% of all households in England are accommodated in buildings having more than 5 floors. Using the estimated number of households in England as 20,000,000 and the average number of people per household as 2.2 indicates that, approximately 1 million people are protected by Regulation A3.

Similar calculations for offices are more tenuous and subjective. However, again using statistics from the Digest of Data for the Construction Industry and making broad assumptions suggests that 500,000 people are protected by Regulation A3 in their work place.

Using a Fatality Accident Rate of 0.002 for death by building collapse would lead to the conclusion that Regulation A3 leads to the prevention of 1-2 deaths/year.

In a recent paper Ellis and Currie provided estimates of the costs of repairs to dwellings following significant (=structurally damaging) explosions. Their estimate at 1990 prices is an annual cost of £3.2M. This figure relates only to the proportion of the costs of structural failure associated with explosions; the total figure will be higher - but probably less than £10M pa at 1990 prices.

4.0 CURRENT TRENDS IN CONSTRUCTION

There is sparse data on collapses, and statistical analysis is not possible. Comments in the literature must also be treated with caution. However, progressive collapse is seen to be a very important feature in collapses.

Failure analyses do not indicate one type of structure is more badly designed than another. Predominantly failures appear to relate to gross errors.

A "straw poll" of engineers, architects and Building Control officers produced a mixed response to concerns on current trends in construction. These are summarised below.

Precast Construction

There is concern that prefabricated structures of the precast or system build type, although now less widely used, continue to provide the main potential for progressive collapse. The sensitivity of these types of structures to deficiencies in workmanship, particularly with respect to tolerances and potential loss of bearing was commented on.

Lightweight Non-Structural Partitions

The use of lightweight non-structural partitions is recognised to reduce overall robustness. However, concerns expressed related more to fire situations rather than structural stability and collapse.

Use of Computer Design Aids

There was a mixed reaction to this issue. Most current computer design aids disregard robustness considerations. An inexperienced user of some of the design packages could inadvertently overlook the overall stability of the building. This was not, however, considered to be a major cause of concern with respect to robustness.

Design and Build Contracts

Answers to the question on the effect of increased use of Design and Build contracts on building robustness brought a response which focused on the commercial and time pressures perceived to exist under this form of contract. However, this was considered manageable provided an experienced team was appointed. The concern is therefore to do with experience rather than contract form.

Interestingly the discussions held resulted in unsolicited comments on the effectiveness of the current Regulation A3, which support tentative conclusions drawn during early studies of building collapses, namely

a) Problems arise due to either

i) not applying the regulation, or

ii) not applying the regulation correctly rather than in the Regulation itself.

b) Problems do not arise in projects where the right team is appointed.

c) Division of responsibilities, particularly under design and build contracts can lead to errors, and disregard for robustness considerations. That is, no one has responsibility for the overall stability of the structure and robustness relies on two or more separately designed elements interacting.

There was also recognition that there is an argument for consideration of robustness to be included for any structure and that robustness is a design issue for structures of four storeys or less depending upon the sensitivity of the structure to progressive collapse. The method of construction is also recognised as having a bearing on this issue.

Also, unsolicited, a number of comments were received on the lack of sensitivity of framed structures to progressive collapse due to their inherent robustness.

5.0 ALTERNATIVE CATEGORISATION

There is the general opinion that Requirement A3 has served its purpose in that the public are relatively well protected from building collapse. By implication, the major effect of structural collapse due to lack of robustness is not loss of life but losses of a financial and commercial nature. As noted previously, industrial and commercial assets are largely unprotected by Regulation A3.

Suggestions for the wider application of Regulation A3, are generally founded in the concerns of erosions in safety. However, robustness is also seen as a way to safeguard buildings against actions not explicitly accounted for in design, e.g. effects of constructional inaccuracy.

These are therefore a number of issues which need to be taken into account in the development of alternatives to Requirement A3. Further consideration will need to be given to -

A. Primary Concern
1) Safety
2) Economy

B. Structural Form
1) Sensitivity to collapse
2) Redundant

C. Structural Materials
1) Brittle
2) Ductile

D. Construction Methods

before appropriate reliability levels can be established.

Building regulations will generally concern buildings which have an engineering input, structures commonly referred to as "engineered structures".

ENV 1991-2-7 provides guidance on accidental actions due to impact and explosions but excludes:

external explosions
warfare
sabotage
natural phenomena, e.g. tornadoes

and provides procedures to identify extreme events, their causes and consequences. The safety precautions required to maintain a level of safety which complies with acceptance criteria are described and include measures to reduce the probability or consequence of the extreme events.

Accidental design situations are categorised by,

low probability of occurrence
severe consequences
short duration

with the advice that severe consequences will require consideration of extensive hazard scenarios whilst less severe consequences allow less extensive consideration of hazard scenarios.

The consequences to be considered are,

injury to humans
death to humans
environmental consequence
economic consequence to society.

ENV 1991-2-7 suggests that the representative value of an accidental action should be chosen in such a way that there is an assessed probability of less than P = 10^{-4} per year for one structure that this or a higher impact energy will occur. It is noted however, that in practice design values are often nominal values.

The basic question in the approach suggested within ENV 1991-2-7 is what is the level of acceptable risk? The Eurocode approaches this question by a categorisation based upon a qualitative description of the consequences.

However, the background document to the Eurocode gives a quantitative background in terms of both risk to the individual and societal risk.

The figures presented in previous sections suggest that risks to the individuals are small and acceptable. A numerical categorisation has therefore been developed on the basis of societable risk. An acceptable target risk has been taken from CIRIA report 63 in the form of equation 39.

$$P_{ft} = \frac{10^{-4}}{n_r} K_s n_d$$

In this equation the main factors are

K_S a social criteria factor
n_r the average number of people within or near to the structure during the period of the risk.
n_d design life in years

As an hypothesis a numerical classification based upon the powers of (10) and this equation has been developed using 5 basic parameters. The derivation is summarised in Appendix 1.

The method proposed consists of establishing;

the Risk (or likelihood) of failure, and

the Consequences of failure.

The Risk is calculated from,

$$Risk = 2.3 - C - D$$

Where C is defined as a Load Parameter,

D is defined as a Structural Parameter

which take the values below, and the value 2.3 is chosen to give a graphical presentation in the upper quadrant.

Load Parameter (C)

This parameter is related to the type of load and the likelihood that the load will occur at the same time as a large number of people will be present within or near the structure.

The load type is broadly classified as either Accidental Load or Other, the distinction being on the rate of build up of the load. The Accidental Load category is based upon structures having piped gas, and no protection against impact accidents. If structures have no piped gas (and this can be guaranteed) or have protection against impact, then values in the Table for Accident Load should be increased by 0.3.

The number of people within or near the structure at the time of the load is categorised as either Full, Normal or None.

Suggested values of the load parameter are given in Table 5.1.

Structural Parameter (D)

This parameter is related to the structural type and the nature of the material.

The structural type is classified by the redundancy of the system. Structural types which depend upon single elements are considered to have higher risk.

The nature of the material is classified as either brittle, normal or ductile and is presently independent of the material type.

Suggested values of the structural parameter are given in Table 5.2.

Values in Table 5.2 under the heading "With Redundancy" should be reduced by 0.3 if any parts of the structure are not clearly visible and major structural elements requiring maintenance cannot be easily inspected.

The Consequence is calculated from

Consequence = N+E+S-2

Where N is related to the number of people at risk,

E is defined as an Environmental Parameter,

S is related to societal risk,

and the value 2 is chosen to give a graphical presentation in the upper quadrant.

These parameters take the values given below.

People at Risk (N)

This parameter is related to the number of people at risk as shown below.

N	=	0	for domestic situations
		1	for office and flat
		2	for public assembly

Environmental Parameter (E)

This parameter is related to the location of the structure and its height.

The location of the structure defines the number of people who may be in proximity with the structure. The height of the structure is a broad indication of the area adjacent to the structure which may be subject to collateral damage.

Suggested values of the environmental parameter are given in Table 5.3.

Societal Criteria (S)

A parameter related to the societal risk is given below.

S	=	1.6	for single family dwellings less than 3 storeys
		2	for all other domestic dwellings with less than 3 storeys, offices, trade and industry
		3	for public assembly

To determine the categorisation the graph in Figure 5.1 is used. The lines on the graph defining the boundaries between the categories have been chosen to provide as close a match to present requirements as possible. The formulation is subjective, but it has the merit that its simplicity allows an understanding of the major factors affecting the required performance of the structure. The straight lines delineating the categories have been curved close to the axes to avoid step changes in category. Also, small adjustments have been made to the equations for Risk to ensure that all possible values of Risk and Consequence lie wholly within one category or another, i.e. no values actually lie on the lines. This is achieved by redefining the equation for Risk to -

Risk = 2.25 - C - D

In addition to the Eurocode categories, a new category marked "Exempt" has been introduced.

As, in principle, the lines differentiating the categories are straight lines; the categorisation rule can be presented as a combination of Risk and Consequence in a single factor. This Risk Factor is

Risk Factor = N+E+S-C-D

This factor has been used to categorise the present guidance, as shown in Appendix 2.

TABLE 5.1 PARAMETER -C

LOAD PARAMETER -C	**LOAD TYPE**	
HUMAN LIVE LOAD	**ACCIDENT**	**OTHER**
FULL	0	0.5
NORMAL	1	1.5
NONE	2	2.5

If the structure does not have piped gas or is protected against impact, the values of C for Accident Load Type may be increased by 0.3.

TABLE 5.2 STRUCTURAL PARAMETER -D

STRUCTURAL PARAMETER -D	**STRUCTURAL TYPE**	
	SINGLE ELEMENT	**WITH REDUNDANCY***
MATERIAL TYPE		
BRITTLE	0	0.3
NORMAL	0	0.5

DUCTILE	0.3	1

* These values should be reduced by 0.3 if any parts of the structures are not clearly visible and major structural elements requiring maintenance cannot be easily inspected.

TABLE 5.3 ENVIRONMENTAL STRUCTURAL PARAMETER -E

ENVIRONMENTAL PARAMETER - E	LOCATION		
	DOMESTIC	**SUBURBAN**	**CITY CENTRE**
HEIGHT			
<10m	0	0	0.3
10 to 30m	0	0.3	0.5
>30m	0.3	0.5	1

PROPOSED CATEGORISATION

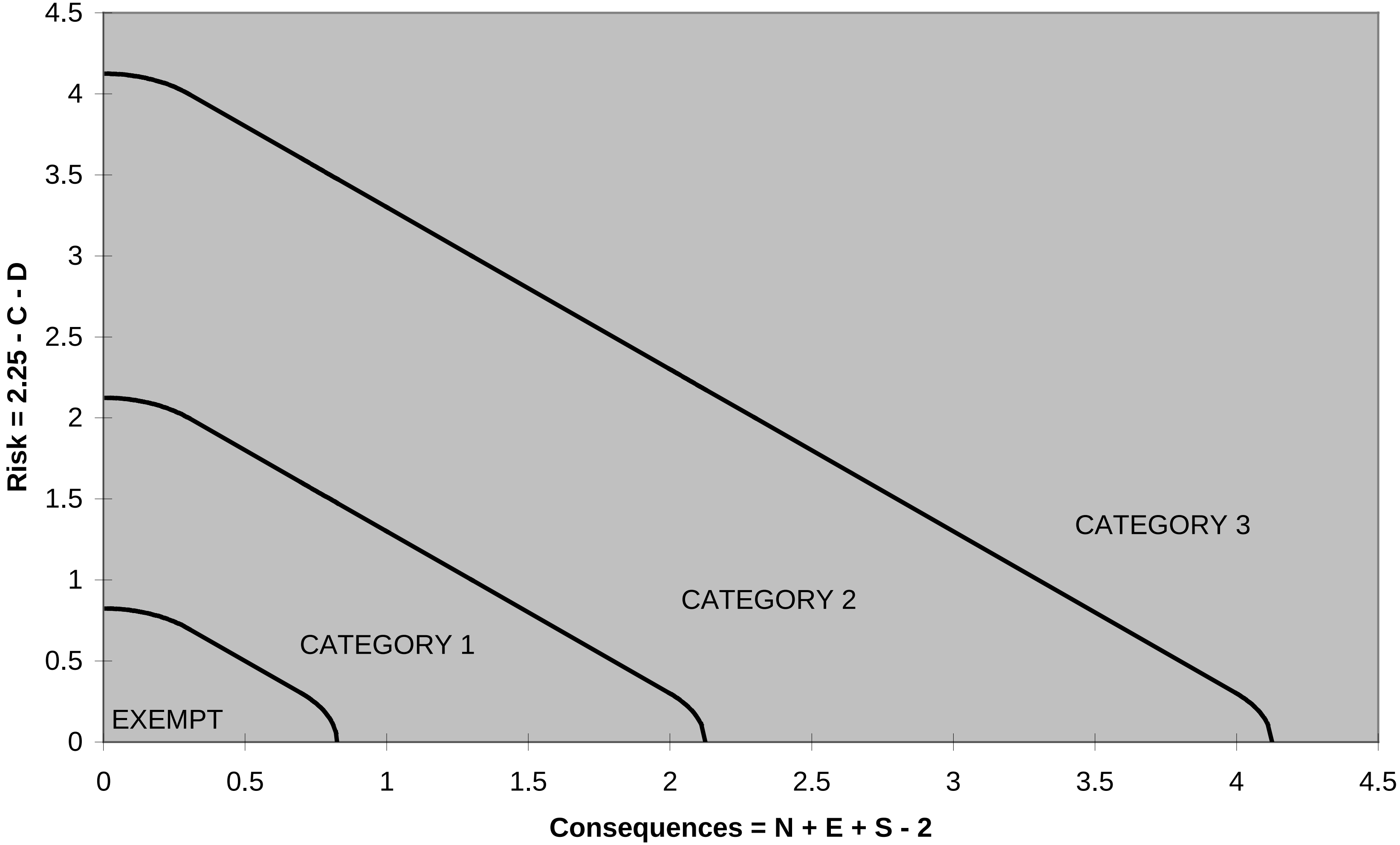

FIGURE 5.1 PROPOSED CATEGORISATION

6.0 SEMINAR ON DEVELOPMENTS IN DESIGN OF ROBUST BUILDINGS

DETR, BRE and BSI arranged a seminar on 17th May 1999 to present to, and discuss, with invited representatives of the professions, the provision of safety and robustness in all buildings, including measures for avoiding disproportionate collapse.

The work described in the previous sections of this report was presented at the seminar. In particular, development of alternatives was discussed and the proposed categorisation was explained.

The detailed notes of the meeting are given in Appendix 3, with correspondence received after the event being given in Appendix 4.

Generally, the proposed categorisation received an encouraging measure of support. Whilst there were concerns about understanding the basis of the figures for the 5 basic parameters, the attempt at categorisation was welcomed. Particular issues which the Working Party may consider appropriate to examine in more detail are,

1. Is the categorisation integral to the design and does it take account of structural form, continuity etc?

2. Change of use of structures, particularly the introduction of piped gas.

3. Whether the parameter N will be accepted by Building Control Officers.

4. The cost of moving from one category to another.

5. The continuity of design rules moving from one category to another.

The last two items relate to the desire for there to be no significant step change between categories.

The correspondence received supports the proposed categorisation. Dr. Pope has used the proposed method to categorise four structures,

- Sports Arena
- Department Store
- Warehouse
- Large office Block

and concludes the resulting categorisations for these structure are sensible.

Professor MacLeod welcomes the classification and notes the parallel with risk assessment methods used by BAA. He intends to involve students in studying robustness and comparing methods.

As a result of the comments made at the seminar, it was agreed that a calibration of the categorisation be carried out, and this is described in Section 7.

7.0 CALIBRATION OF PROPOSED CATEGORISATION

The categorisation procedure developed in Section 5 is based on established principles. The proposed values of the parameters are also based on established thinking, but simplifications and approximations have been introduced to produce a workable procedure. To check that the resulting categorisation is sensible a calibration exercise has been carried out. This has been done by a member of staff who has not been involved in the development of the proposals or the subsequent discussions.

A list of 80 buildings has been categorised as summarised below:

	Total	Exempt	Cat 1	Cat 2	Cat 3
Industrial	5	1	4	-	-
Agricultural	3	2	1	-	-
Commercial	22	-	5	16	1
Community	14	-	3	6	5
Museums & Art Galleries	6	-	-	-	6
Residential	12	3	6	3	-
Education	4	-	-	1	3
Recreation	6	-	1	5	-
Medical/Social Services	8	-	-	6	2
TOTAL	80	6	20	37	17

In the following sections a review of the categorisation is provided. Full results of the calibration exercise are given in Appendix 5.

(In the following figures, a number of points are plotted over each other.)

Industrial Buildings

	Category			
	Exempt	Cat 1	Cat 2	Cat 3
Storage Sheds	✓			
Speculative factories and warehouses		✓		
Assembly and machine workshops		✓		
Transport Garages		✓		
Purpose built factories and warehouses		✓		

See Figure 7.1. The categorisation seems appropriate.

Agricultural Buildings

	Category			
	Exempt	Cat 1	Cat 2	Cat 3

Barns and sheds	✓			
Stables	✓			
Animal Breeding Units		✓		

See Figure 7.2. This categorisation appears appropriate.

Commercial Buildings

	Category			
	Exempt	Cat 1	Cat 2	Cat 3
Speculative shops			✓	
Surface Car Parks		✓		
Multi-storey car parks			✓	
Underground Car Parks			✓	
Supermarkets			✓	
Banks			✓	
Purpose Built Shops			✓	
Office Developments			✓	
Retail Warehouses		✓		
Garages/showrooms		✓		
Department Stores			✓	
Shopping Centres				✓
Food processing Units		✓		
Breweries			✓	
Telecommunications and Computer Buildings		✓		
Restaurants			✓	
Restaurants			✓	
Public Houses			✓	
Public Houses			✓	
High Risk research and production buildings			✓	
Research and development labs			✓	
Radio, TV and recording studios			✓	

See Figure 7.3. This categorisation seems appropriate.

Community Buildings

	Category			
	Exempt	Cat 1	Cat 2	Cat 3
Community halls				✓
Community centres				✓
Branch libraries		✓		
Ambulance and Fire Stations			✓	
Bus stations			✓	
Railway Stations			✓	
Airports				✓
Police Stations		✓		
Prisons				✓

Postal buildings			✓		
Broadcasting				✓	
Civic Centres					✓
Churches and Crematoria				✓✓	
Specialist Libraries				✓	

See Figure 7.4. A sensible mix of categories. There are a high number of Category 3 buildings due to the societal risk value associated with buildings for public assembly.

Museums and Art Galleries

	Category			
	Exempt	Cat 1	Cat 2	Cat 3
Magistrate/county court				✓
Theatres				✓
Opera Houses				✓
Concert Halls				✓
Cinemas				✓
Crown Courts				✓

See Figure 7.5. The categorisations recognise these buildings as public meeting places.

Residential Buildings

	Category			
	Exempt	Cat 1	Cat 2	Cat 3
Dormitory hostels			✓	
Estates housing and flats		✓		
Barracks			✓	
Sheltered housing		✓		
Housing for single parents		✓		
Student housing		✓		
Parsonages/manses	✓			
Apartment blocks		✓		
Hotels			✓	
Housing for the handicapped	✓			
Housing for the frail and elderly	✓			
Houses and flats for individual clients		✓		

See Figure 7.6. Negative values of consequence occur in the proposed classification. This needs to be reviewed.

Education Building

	Category			
	Exempt	Cat 1	Cat 2	Cat 3

Primary/nursery/first schools				✓
Other schools including middle and secondary				✓
University complexes				✓
University laboratories			✓	

See Figures 7.7. The categorisation of most buildings as Category 3 is due to the high number of people who may be at risk, and the use of these buildings for public assembly. This should be reviewed.

Recreation Buildings

	Category			
	Exemp t	Cat 1	Cat 2	Cat 3
Sports halls			✓	
Squash Courts		✓		
Swimming Pools			✓	
Leisure complexes			✓	
Leisure Pools			✓	
Specialised complexes			✓	

See Figure 7.8. The categorisation is generally satisfactory.

Medical/Social Services

	Category			
	Exemp t	Cat 1	Cat 2	Cat 3
Clinics			✓	
Health Centres			✓	
General Hospitals				✓
Nursing Homes			✓	
Surgeries			✓	
Teaching Hospitals				✓
Hospital Laboratories			✓	
Dental Surgeries			✓	

See Figure 7.9. Generally appropriate.

This calibration exercise shows that, with the possible exception of educational buildings the categorisation is sensible. Also, detailed examination of the calculations in Appendix 5 shows that the structural parameter D can be used to reduce classification by one category by the use of redundant, ductile designs. This would positively promote good design.

Generally, therefore, it is concluded that the procedure proposed will give satisfactory categorisation for all common buildings with clearly established limitation on its application. With some minor adjustments, it is expected that the procedure would have a neutral effect on the buildings under control and hence the cost of building construction.

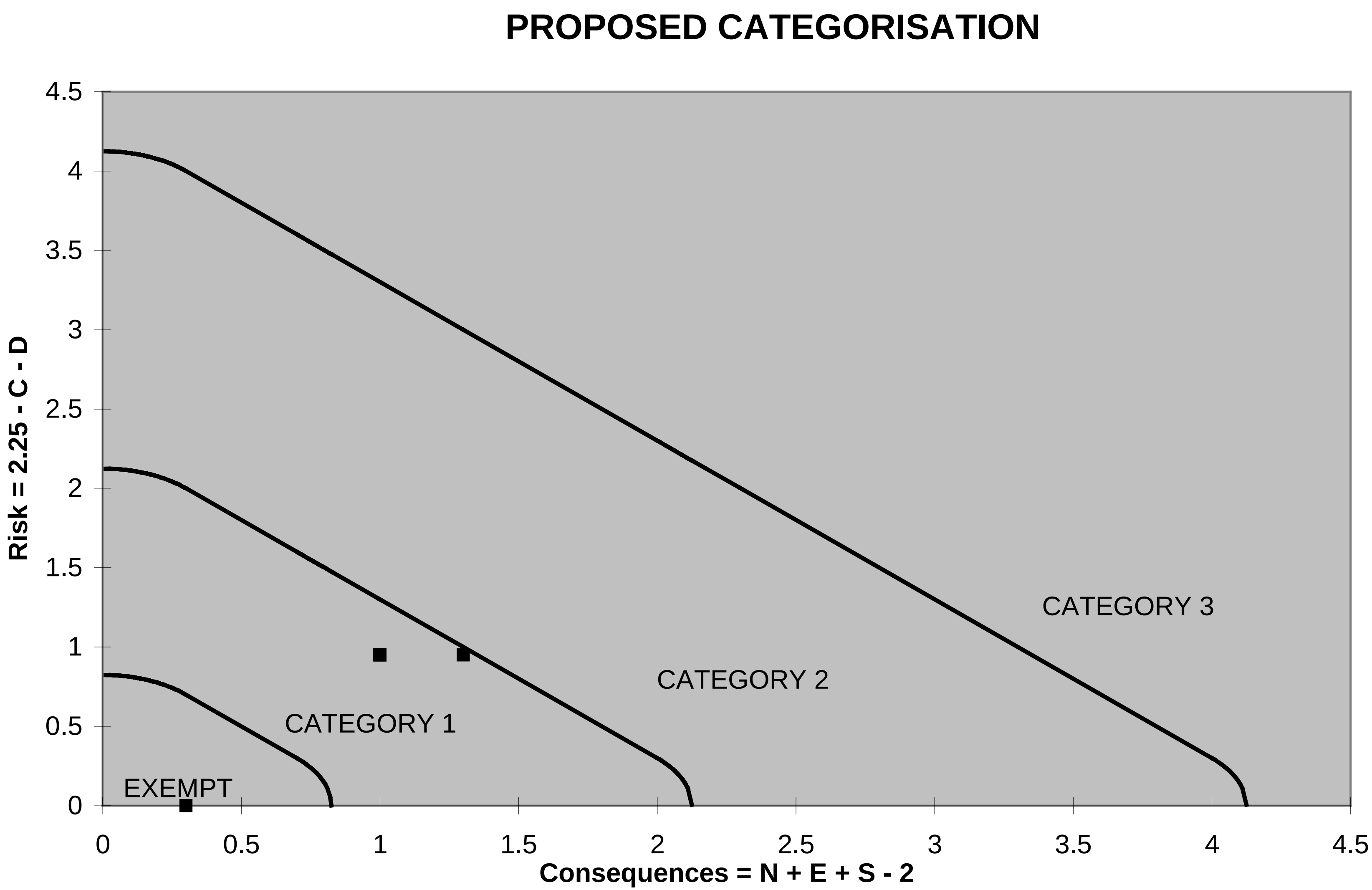

FIGURE 7.1 INDUSTRIAL CATEGORISATION

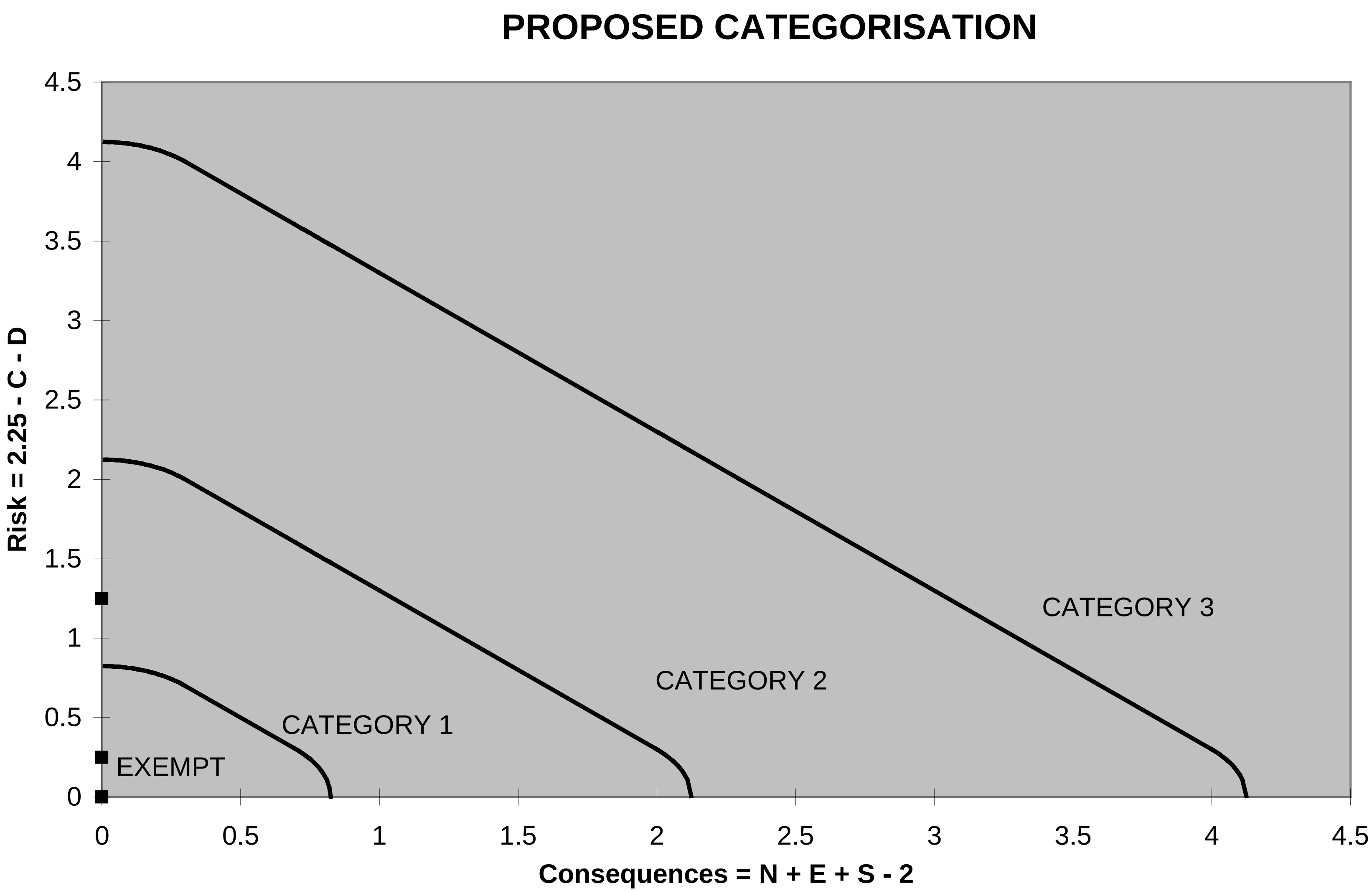

FIGURE 7.2 AGRICULTURAL CATEGORISATION

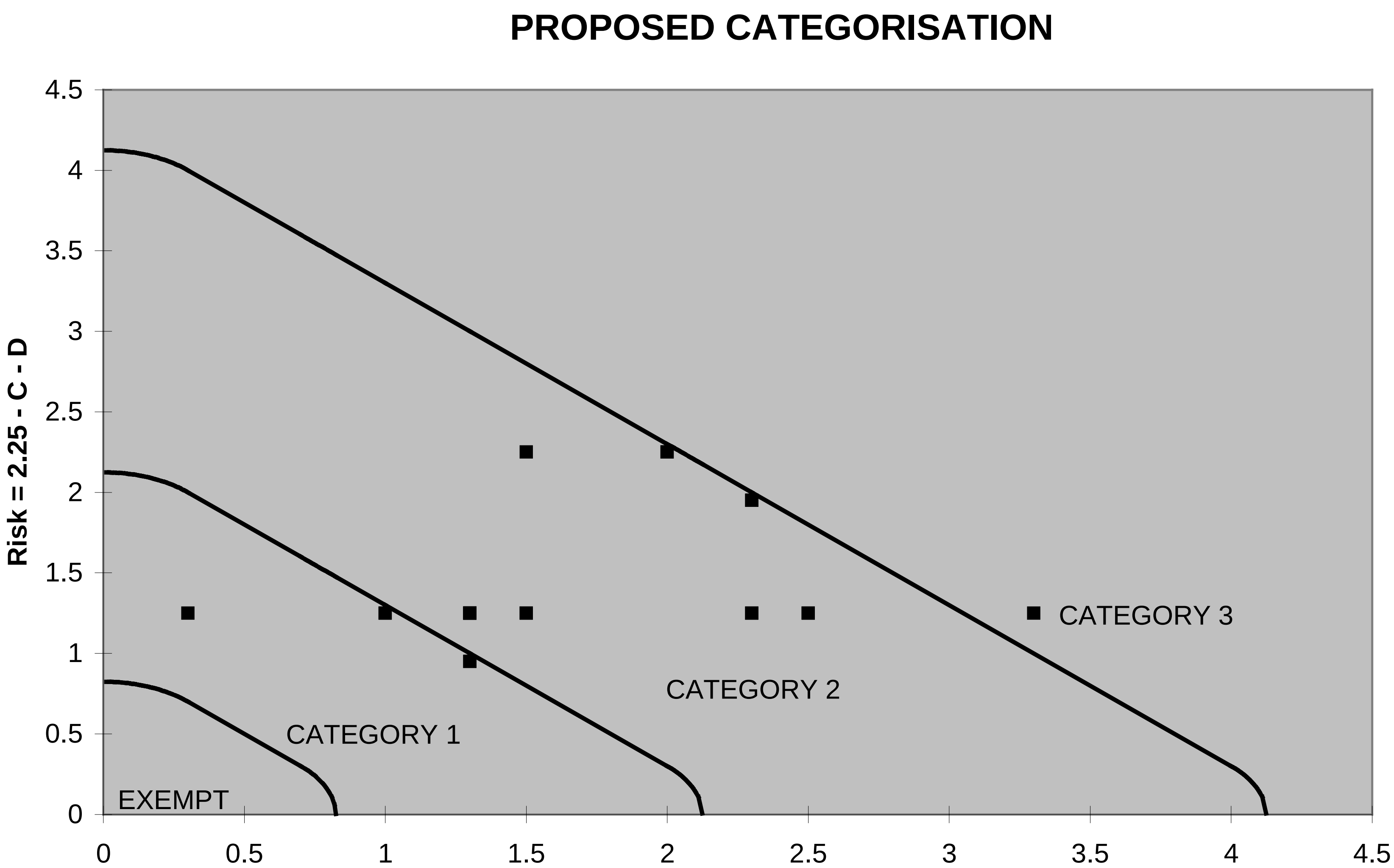

FIGURE 7.3 COMMERCIAL CATEGORISATION

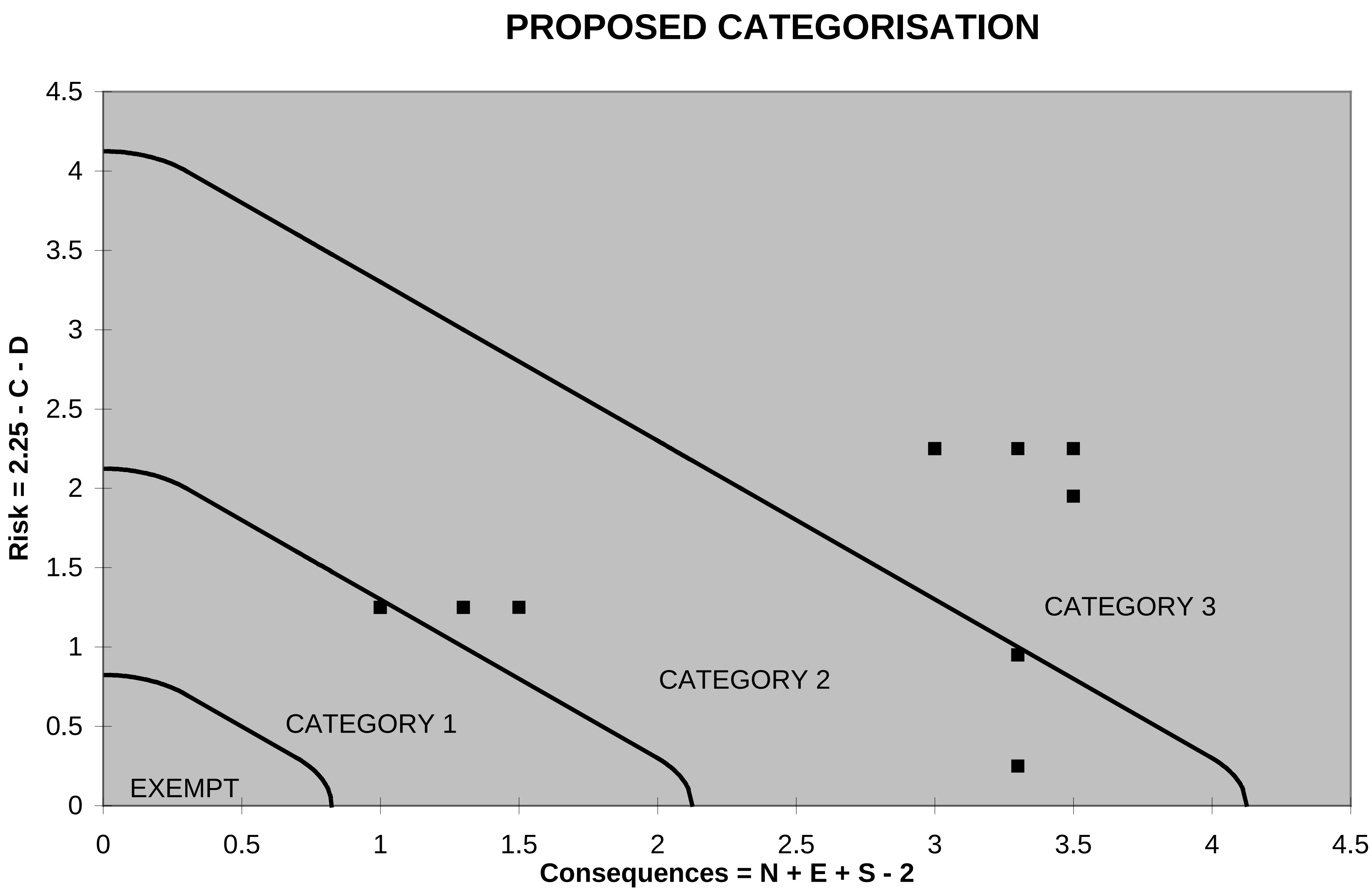

FIGURE 7.4 COMMUNITY CATEGORISATION

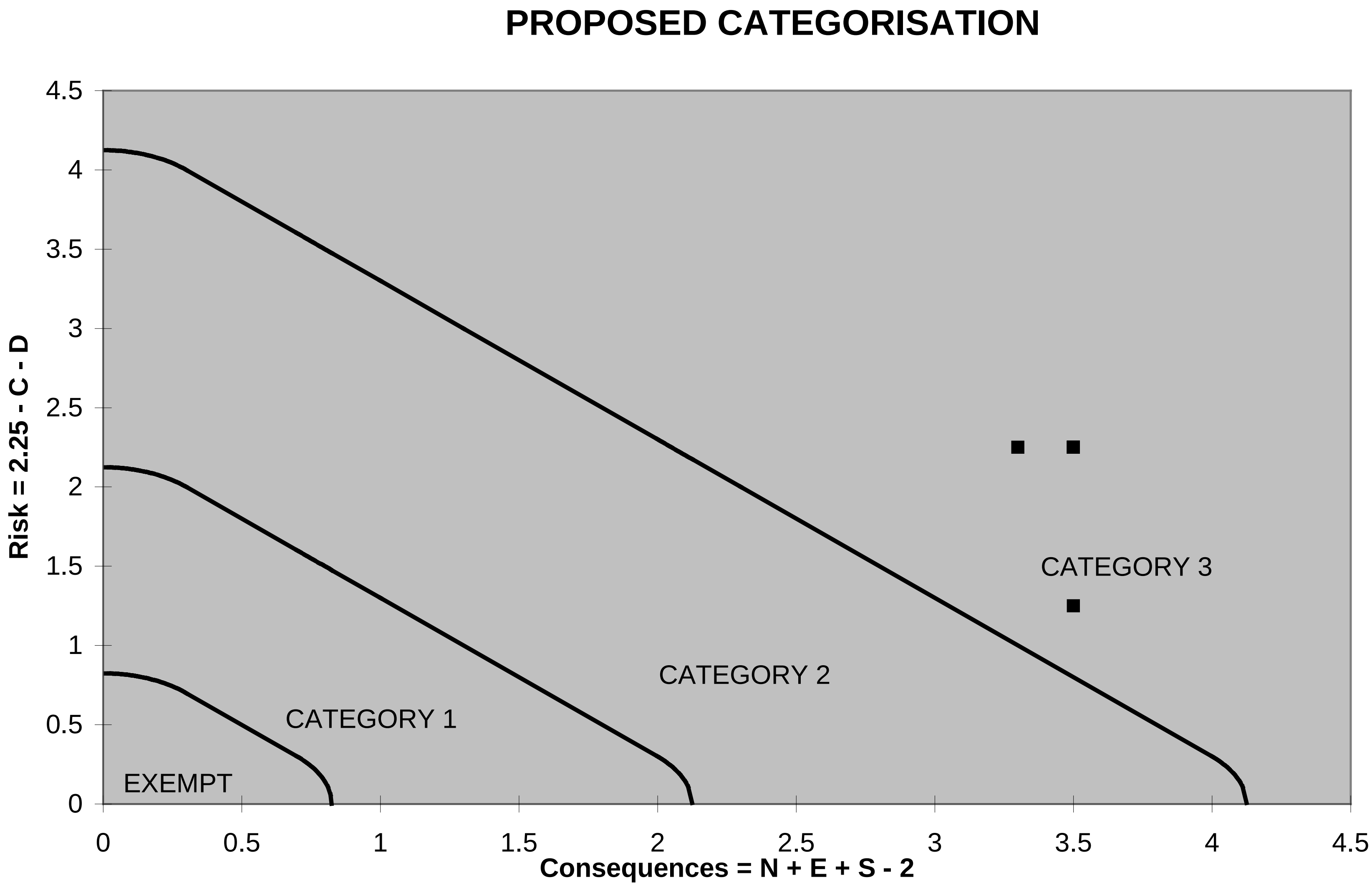

FIGURE 7.5 MUSEUMS AND ART GALLERIES CATEGORISATION

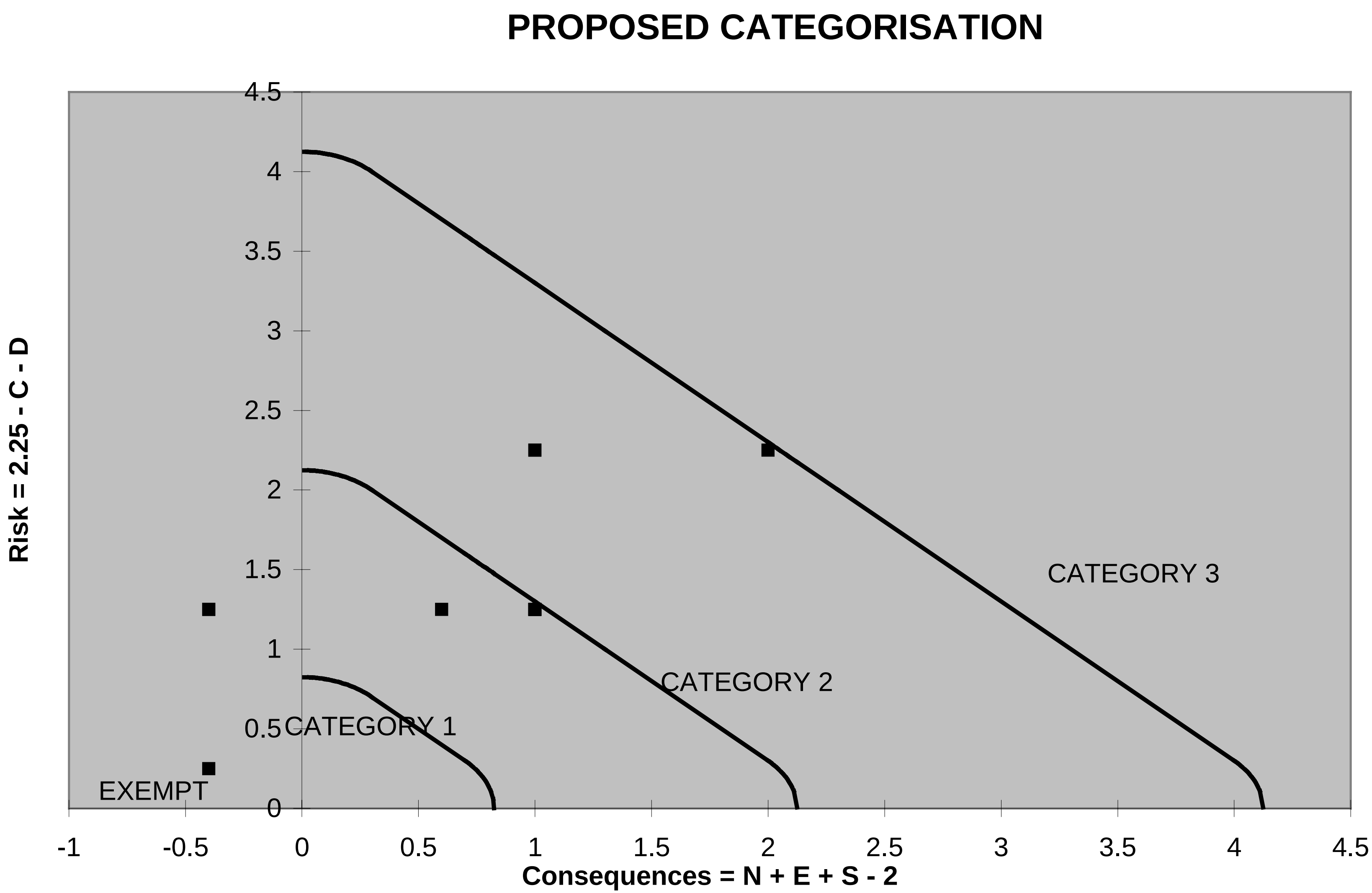

FIGURE 7.6 RESIDENTIAL CATEGORISATION

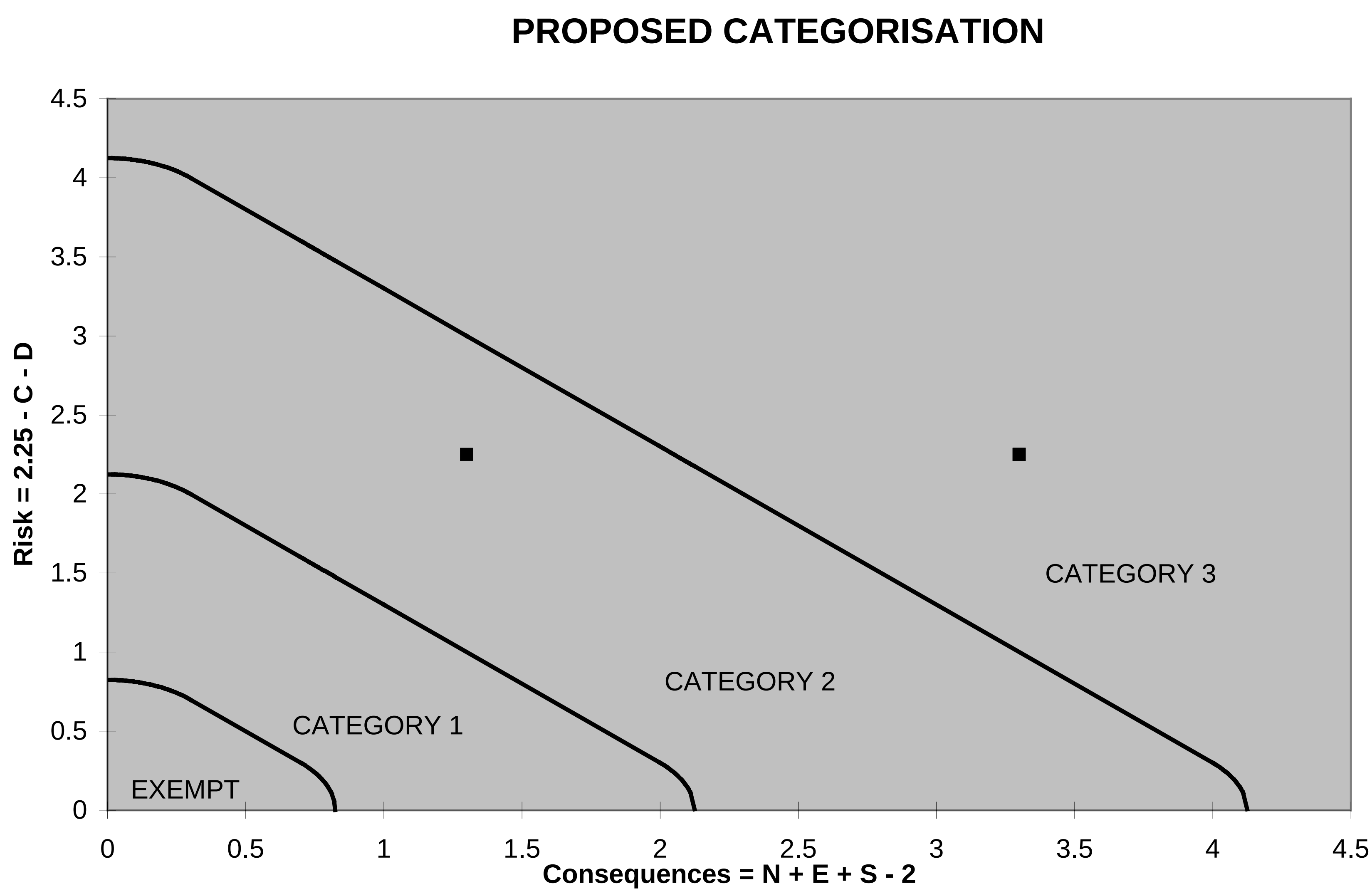

FIGURE 7.7 EDUCATION CATEGORISATION

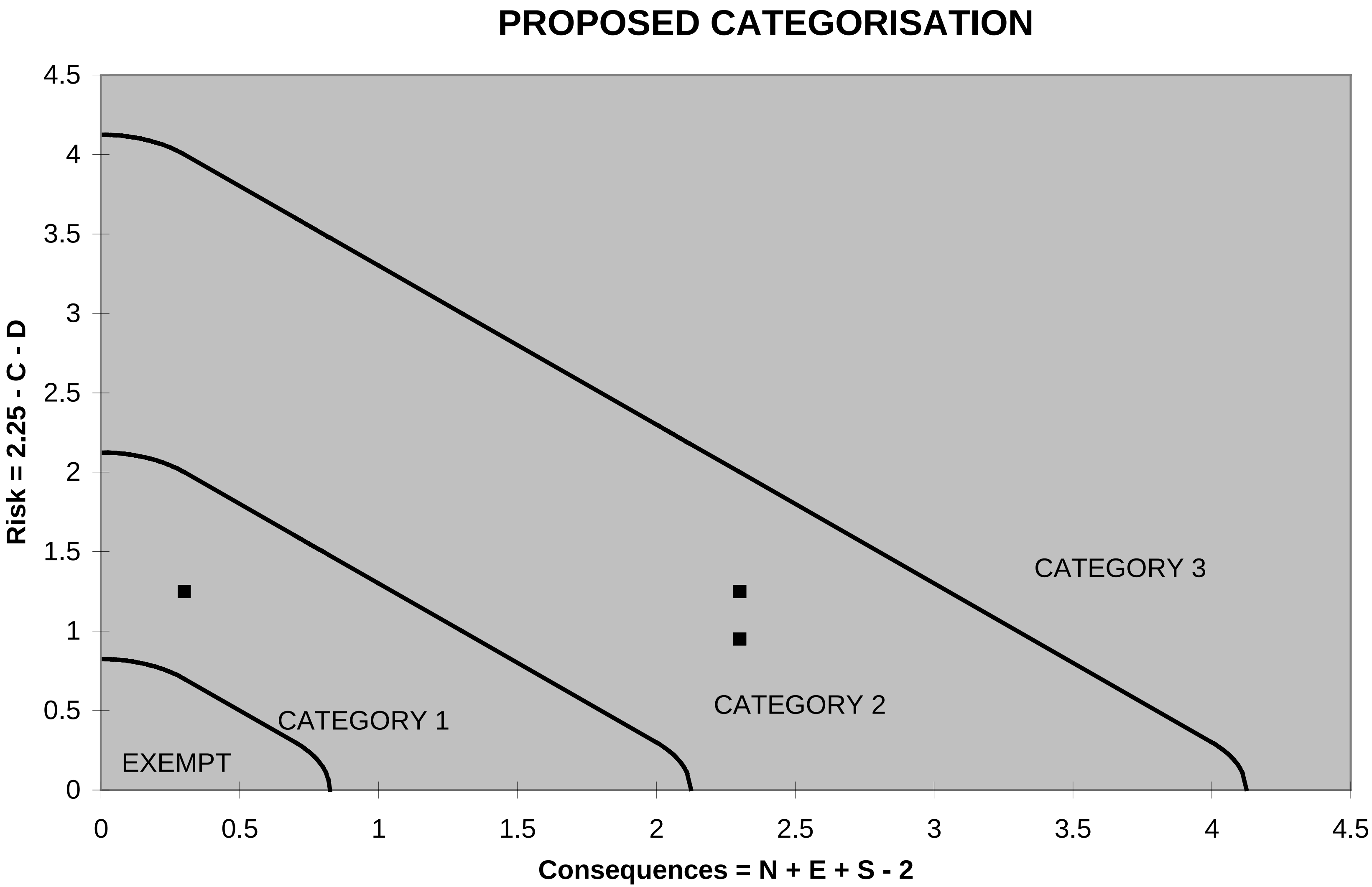

FIGURE 7.8 RECREATION CATEGORISATION

PROPOSED CATEGORISATION

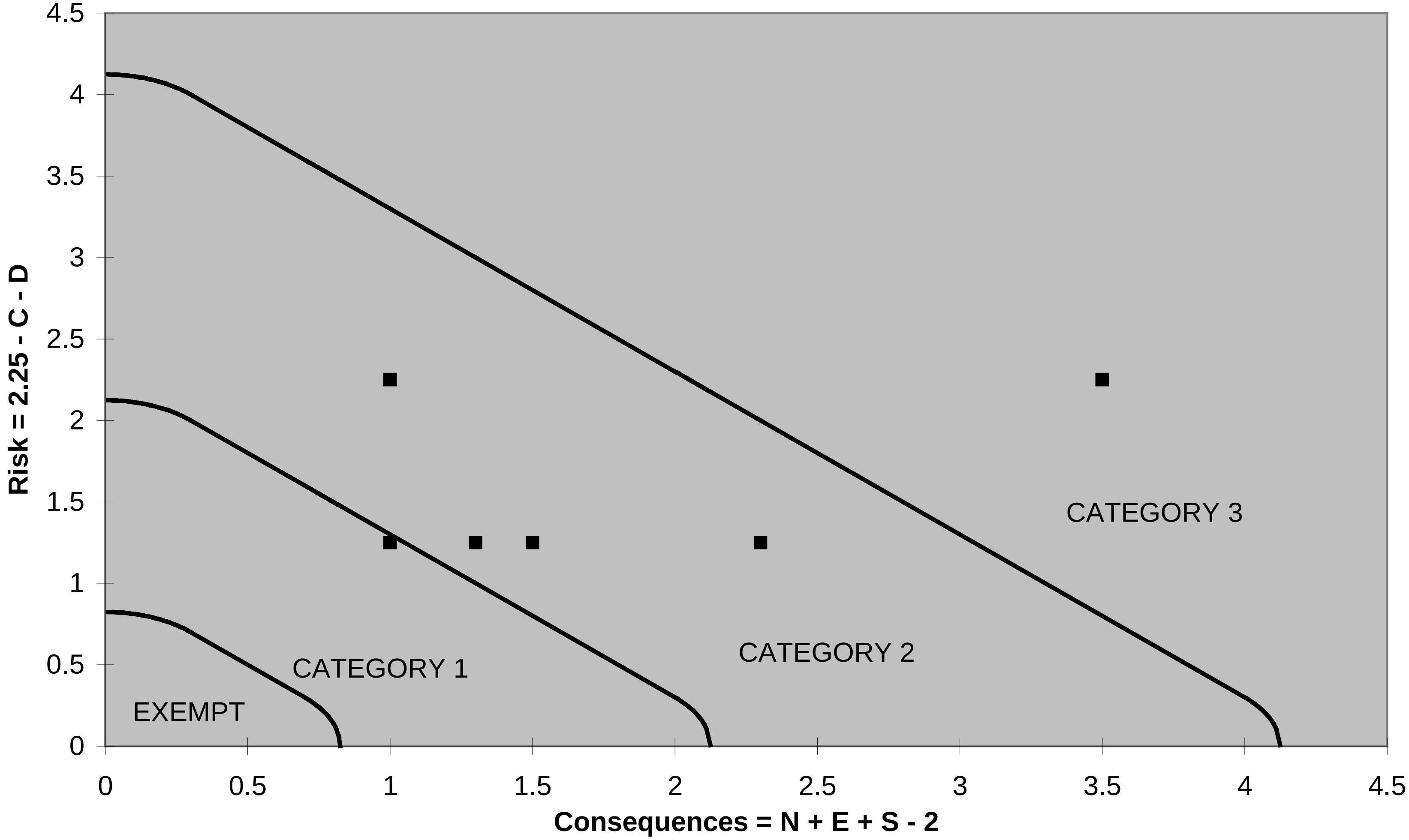

FIGURE 7.9 MEDICAL/SOCIAL SERVICES CATEGORISATION

8.0 REFERENCES

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APPENDIX 1 Derivation of Categorisation

$$P_{ft} = \frac{10^{-4} K_s n_d}{n_r}$$

For a standard design life

P_{ft} is proportional to $\frac{K_s}{n_r}$

CIRIA 63, Table 3 Defines K_S as a value between 0.005 for places of public assembly and 0.5 for bridges.

This can be expressed as

$K_S = 5 \times 10^{-S}$

with S = 2 for domestic, offices and industry
= 3 for public assembly

A value of S = 1.6 for single family dwellings has been selected for trial use.

$n_r = n_m + n_2$

n_o = number of people supported by the element or structure

n_1 = additional number at risk in the event of failure

n_m = Sum ($n_o + n_1$), which depends on
i) the number of people at risk)
ii) the correlation of the loading with the)
C
number at risk)

iii) the rate of build up of load)
iv) the failure type) D
v) the material type)

n_2 = the additional number at risk in the environment)
of the structure, which depends on its location
) E
and height)

An approximation of the values given in CIRIA 63 is

$n_o = 10^N$

$n_m = n_o \times 10^{-C} \times 10^{-D}$

$= 10^N \times 10^{-C} \times 10^{-D}$

$n_r = n_m + n_2 \approx 10^N \times 10^{-C} \times 10^{-D} \times 10^E$

So $P_{ft} \approx \dfrac{5 \times 10^{-S}}{10^N \times 10^{-C} \times 10^{-D} \times 10^E}$

$\approx [C + D - N - S - E]$

From which we can define the Risk Factor as

Risk Factor = [C + D - N - S - E]

This factor can be divided into two parts as follows:

A Risk Factor relating to parameters C & D

A consequence relating to parameters N, E and S.

APPENDIX 2 Proposals for Revisions to Building Regulation A3 and its Associated Guidance

The following pages show the proposed revisions to Building Regulation A3 and its associated guidance. It should be noted that the actual Requirement A3 is unaltered, being a fundamental principle of design.

Requirement	*Limits on Application*
Disproportionate Collapse A3. The building shall be constructed so that in the event of an accident the building will not suffer collapse to an extent disproportionate to the cause.	

Performance

In the Secretary of State's view, the requirement of A3 will be met by an appropriate choice of measures:

a. preventing the action from occurring or reducing to a reasonable level the probability and/or magnitude of the action.

b. protecting the structure against the effects of an action by reducing the actual loads on the structure (e.g. protective bollards)

c reducing the sensitivity of the building to disproportionate collapse should an accident occur.

Introduction

0.3 The guidance is divided into the following Sections:

a. Section 5 deals with the means of reducing the sensitivity of the building to disproportionate collapse in the event of an accident. (relating to requirement A3)

Section 5

REDUCING THE SENSITIVITY OF THE BUILDING TO DISPROPORTIONATE COLLAPSE IN THE EVENT OF AN ACCIDENT.

Category 1 - Risk Factor 0.7< > 2

5.1 The requirement will be met by adopting the following approach:

Provide effective horizontal ties in accordance with the recommendations given in the Codes and Standards listed under paragraph 5.2 below.

Category 2 - Risk Factor 2 < > 4

If effective horizontal tying is provided and it is not feasible to provide effective vertical tying of any of the vertical loadbearing members, then each such untied member should be considered to be notionally removed, one at a time in each storey in turn, to check that its removal would allow the rest of the structure to bridge over the missing member albeit in a substantially deformed condition.

In considering this option, it should be recognised that certain areas of the structure (e.g. cantilevers or simply supported floor panels etc.) will remain vulnerable to collapse. In these instances, the area at risk of collapse of the structure should be limited to that given under paragraph a below.

If it is not possible to bridge over the missing member, that member should be designed as a protected member (see paragraph b below)

a. If it is not feasible to provide effective horizontal and vertical tying of any of the loadbearing members, then each support member should be considered to be notionally removed, one at a time in each storey in turn, to check that, on its removal the area at risk of collapse of the structure within the storey and the immediately adjacent storeys is limited to

i. 15% of the area of the storey or

ii. $70m^2$

whichever is the less (see Diagram 25). It should be noted that the area at risk is the area of the floor at risk of collapse on the removal of the member and not necessarily the entire area supported by the member in conjunction with other members.

b. **Design of protected members**: The protected members (sometimes called 'key' elements) should be designed in accordance with the recommendations given in the appropriate Codes and Standards listed in paragraph 5.2

Alternative approach

5.2 The performance can also be met by following the relevant recommendations given in the clauses of the Codes and Standards listed below:

Structural work of masonry: Clause 37 of BS 5628: *Code of practice for use of* *masonry Part 1: 1978 Structural use of unreinforced masonry.*

Structural work of steel: Clause 2.4.5.3 of BS5950: *Structural use of steelwork in building Part 1: 1990 Code of Practice for design in simple and continuous construction: hot rolled Sections.* (The accidental loading referred to in clause 2.4.5.5 should be chosen having particular regard to the importance of the key element and the consequences of failure, and the key element should always be capable of withstanding a load of at least $34kN/m^2$ applied from any direction).

Structural work of reinforced, presstressed or plain concrete: Clause 2.2.2.2 of BS8110 *Structural use of concrete*. Part 1: 1985 *Code of practice for design and construction,* and Clause 2.6 of Part 2: 1985 *Code of practice for special circumstances.*

Category 3 - Risk Factor > 4.0

For buildings in this category the use of dynamic analysis as descibed in Appendix B of ENV 1991-2-7

APPENDIX 3 Notes of DETR/BRE/BSI Seminar on Developments In Design Of Robust Buildings

STATUS REVIEW ON ACCIDENTAL ACTIONS

1. Current Position - ENV 1991-2-7 'Accidental Actions'

When draft ENV 1991-2-7 'Accidental Actions' was presented for formal vote for acceptance as a European Prestandard, the UK was not satisfied with its technical content and consequently cast a negative vote. The draft was, however, generally acceptable to the other CEN Members and approval to publish was gained on majority voting. Therefore the Prestandard has to be made available for trial use in all the Members States prior to a vote on whether the document is suitable for conversion to Euronorm status.

The ENV includes a more detailed approach to design than current UK practice, in that it provides guidance for specific hazards, rather than providing a general level of robustness. The specific hazards considered include gas explosions and vehicle impact.

To ensure that safe use of the Prestandards during its trial (or ENV) period, it can only be used in conjunction with a National Application Document (NAD) which specifies additional requirements, clarifications and technical variations to make the Prestandard acceptable in the particular country of use. The UK NAD has yet to be drafted for this Prestandard and therefore ENV 1991-2-7 is not yet available for trial use in the UK.

It should be noted that as part of the publication procedure, the draft ENV underwent a final phase of technical editing. This significantly improved the text that was submitted for the vote. However, concerns on the technical content remain and it is important that the content of the UK NAD addresses these difficulties. This will ensure that the document can be trialled safely and effectively in the UK during the ENV period and the NAD will also provide a comment on the changes the UK consider either desirable or essential before the document could be considered acceptable to the UK as a Euronorm.

The ENV proposes three approaches to design for accidental actions, each assigned to an accidental design situation.

Category 1, defined as having 'limited consequences', requires no specific considerations for accidental actions.

Category 2, with ‘medium consequences’ requires either a simplified analysis by static equivalent models or the application of prescriptive design/detailing rules, depending on the specific circumstances of the structure in question.

Category 3 which relates to ‘large consequences’ recommends a more extensive study, using dynamic analyses, non-linear models and load-structure interaction if considered appropriate.

The application of these requirements will be a matter for the relevant National regulatory authorities and the actual categorisation may follow national traditions and preferences. The development of the European Prestandard and the national responsibility for categorisation provides an opportunity for the UK to review our current National practice on this subject and examine how the Eurocode may reflect the position that the UK wishes to adopt in relation to disproportionate collapse procedures.

2. Review of UK Position

2.1 Seminar on ‘Developments in design of Robust Buildings.

An initial stage of this review process was to gather and prevent data on the risks and consequences of accidental actions on buildings in the UK and present potential methods of building categorisation for peer review. A seminar on ‘Developments in the design of robust buildings’ was held at the DETR on 17 May 1999.

Representatives from the following BSI technical committees and bodies were invited to attend.

BSI committee B/525 Building and Civil Engineering Design Codes
BSI committee B/525/1 Loading and basis of design (including members of working groups)
Building Control Liaison Group
Institution of Civil Engineers
Institution of Structural Engineers
NHBC
BCA
SCI
Trada
BRE

A number of people from industry and academia also received personal invitations.

The seminar was chaired by Dr John Roberts, Allott & Lomax, President elect of the Institution of Structural Engineers.

Dr Desai (DETR) introduced the technical presentations, explaining the background to the proposed review of Building Regulations requirement A3 on disproportionate collapse and the establishment of a Part A Working Party to review the current Approved Document A (Structure) of the Building Regulations.

The initial guidance on disproportionate collapse was based on data available to the Ronan Point Inquiry. Since 1971, survey data on accidental damage to buildings have been compiled and the results of the BRE research on the probability and consequences of gas explosions based on these data were then presented by Mrs Currie (BRE). Indicative results (previously unpublished) from the vehicle impact survey data were also presented although further analysis of these data is required.

A presentation by Dr Ellis (BRE) then described the mechanisms involved in gas explosions and related the experimental data available to the survey data. Following an examination of the accuracy of design calculations for this situation, further developments in relation to design for accidental actions were considered in the light of the results of the survey data on frequency, cause and severity of gas explosions in buildings.

Dr Mills (Allott & Lomax) presented tentative proposals for changes to the Building Regulations Requirement A3 particularly related to the classification of buildings. The papers presented by all speakers at the seminar were distributed at, or before, the seminar.

2.2 Initial comment and discussion

Following these presentations, the audience was asked for initial reaction and comment.

1. Professor Beeby questioned whether there was any data on the probability of occurrence of significant damage due to overload, so that this could be compared with those for the specific occurrence of gas explosion and vehicle impact damage. Mrs Currie responded that BRE did not have such information available.

2. Dr Menzies commented on perceptions of acceptable risk. He discussed the limits of risk generally used as a basis for risk assessment describing the usual assumption that an involuntary risk to an individual is negligible (i.e. unconditionally acceptable) if it is similar to the risk due to natural hazards (approximately 10^{-6} per annum). He also noted that it is assumed to be excessive (i.e. unconditionally unacceptable) if it is similar to the risk due to disease (approximately 10^{-3} per annum for a 30 year old). It was suggested that it would

be helpful to compare the probabilities quoted for the different severities of explosion with these figures. It may be considered that 10^{-6} per annum is a reasonable limit for a single death in an incident and possibly 10^{-8} per annum for multiple deaths. Tall buildings have to be very safe in terms of disproportionate collapse and we should probably be considering the 10^{-8} per annum limit when designing buildings against disproportionate collapse.

Dr Menzies suggested that the approach being proposed essentially may be an 'add on' to design. It is difficult to identify an approach integral to the design which takes account of the form of the structure, continuity etc. He was not sure the answer to this problem could be provided by a simple 'add-on'.

3. The Chairman raised the question of risk vs occurrence. Dr Mills reiterated that hazard x consequence = risk and suggested that the division of risk and consequence was both important and helpful in considering the categorisation of buildings. He pointed out that getting the numbers into perspective is difficult. Risks of 10^{-6} per annum are not considered acceptable by the people who are killed! Significant damage in the UK due to earthquake is estimated at 10^{-4} per annum. It is difficult to explain risk to the public. In general the public aren't always prepared to accept any risk. For example, with the BSE crisis, no risk was acceptable to half the UK public, and this also raises the issue of voluntary vs involuntary risk. Dr Mills explained that in the approach being proposed, the form of the structure could be taken into account, as could redundancy.

4. The Chairman questioned the background to the limit of 10^{-6} per annum being acceptable and Dr Menzies explained its origins were in the Health and Safety at Work Act and in the broadly acceptable region.

5. Dr Walley regretted there had not been more detailed discussion on the actual design of robust buildings. He recommended that wartime bulletins on strengthening buildings and designing for explosions. He noted that there may never have been a Ronan Point incident had the windows been of a different type and size, as that explosion had not vented.

Dr Walley also discussed the background to the five-storey limit, recalling that five storeys and above generally had lift shafts. He suggested that the origins of this limit should be re-examined in relation to the form of construction as this was not set in tablets of stone.

6. Mr Snell returned to the subject of relative risks and compared the figures quoted to those considered in the offshore industry. Originating from the UK HSE, 10^{-3} per annum is the risk for anyone to be injured on an oil platform. However, there is a large investment in safety with approximately £6million spent per life saved. Although there is no requirement in law to achieve the following limit, 10^{-5} is considered to be the level of 'acceptable risk' on an oil platform.

Mr Snell also suggested that accidental damage and risk to people should be looked at on a holistic basis. He noted that bottled gas is more difficult and dangerous to transport than piped gas. If the results of the survey steered the public towards increased use of bottle gas, that would be a disservice to society.

On the subject of venting, he doubted the success of being able to design a building, particularly a large public building, based on adequate venting occurring. He noted that CFD codes were used in the offshore industry with + 30% accuracy on overpressures.

7. Dr Somerville returned to the subject of the 5-storey limit and suggested a more logical limit may be appropriate. The graph presented by Dr Mills was considered. Whereas single residence dwellings were seen to be exempt and large public buildings to be category 3, it was questioned where supermarkets and car parks would appear. He also raised the issue of change of use and how this would be taken account of.

Dr Somerville noted that a numerical approach was attractive but questioned the basis of these figures. He also stressed that it was the quality of design which was critical and asked what design methods would be appropriate given the large difference in, for example, static test strengths and yield line analysis as quoted by Dr Ellis.

8. Dr Desai emphasised that the exempt class in the graph would be for single to 3-storey buildings and it would be wrong to include such domestic properties into a category requiring horizontal ties. Dr Somerville asked where you draw the line between categories, but Dr Desai responded that there would no longer be 'a line' such as the 5-storey limit, but a matrix. The approach being proposed is a tool to get away from the crude 5-storey limit. The proposals from Dr Mills describe generalised requirements which try to rationalise the process without departing too far from current

practice. It is a more logical, less rigid approach which is intended to overcome current difficulties.

9. Dr Mills emphasised that these were tentative proposals and he would welcome feedback from the audience and encouraged those present to try to classify structures such as supermarkets and car parks and review the results.

   The Eurocode format, which requires different methods of analysis for different categories, was questioned. In general, it was more usual to carry through the rules or approach from the category below.

10. Mr Cox related his accidental damage experiences in Building Control which were mostly caused by vehicular impacts. He noted the occupation figures possible in the model and asked how Building Control could accept anything other than full occupation. He also noted the possible change in occupancy with time and that if the Ronan Point explosion had occurred at 8 pm, or breakfast time, many more people would have died.

    On a historical note, Mr Cox agreed that the 5-storey limit was related to the provision of lifts. Buildings over 4-storeys therefore generally have a core structure. He also recalled the “circle of ignorance” and how incidents tended to have a twenty-year cycle as a result.

    Mr Cox also agreed that it can be difficult to make a building 'ventable'.

11. Prof Narayanan considered Dr Mills’ contribution to be very useful. He noted that the current provisions are simple to determine and felt that every designer should not have to use such a graph as presented for every building design, and that prescriptive rules or simple tables would be welcome. He said that of course there should be provisions for detailed analysis in any structure, but in general felt we should not exclusively go down that route too far. After all, alternative prescriptive rules had served us well in the past.

12. Prof McLeod noted that following the withdrawal of A4, the profession was left to sort out the issue with insufficient research and guidance. The subject requires research then guidelines to be issued.

13. Mr Tietz presented further information on the risk of death (FAR scale which takes into account the time subjected to the risk). Buildings falling down was shown to be a risk at the very bottom of the

scale, and he appealed to people to consider the risk in perspective. To add complexity to design consideration and extra strength to building may not be cost effective. A sophisticated approach is fine as long as the engineer has the choice of using it. Prescription can be a dangerous area. It must also be questioned whether the aim is to save property or life, and it may be appropriate to consult insurance companies on their assessments of risk.

Mr Tietz recalled Egan proposals for 30-50% savings on construction costs and stated it was important to cost the options proposed. In particular, how much it costs to move up a category? He also questioned whether such proposals would apply to new build only (in which case it would take 30 years to filter through into the building population) or is there would be a requirement to upgrade any existing buildings, (which could pose serious problems).

He concluded that $34kN/m^2$ was excessive and that it should be reduced to a more realistic figure. Why waste money?

14. Mr Wakeman introduced his experience in robustness of bridges. He described this subject as more straightforward (1 owner, 1 usage) but noted he had used a similar risk approach supported by a matrix for the problem (but without figures). There were therefore parallels with these tentative proposals. Mr Wakeman noted the interesting results quoted and discussed from the tests on concrete panels and said this indicates that we should be looking at the strength side of the design equation as well as the loading requirements.

15. Dr Desai returned to the points made by Mr Tietz. He noted that there would have to be a strong reason to increase the number of buildings to which regulations applied, due to the economic implications of such a change. If engineers think the current system is illogical, this is the opportunity to do something about it. Some consider we have put off reviewing these requirements for too long. It was acknowledged that engineers don't generally design for $34kN/m^2$, but choose alternative means of compliance. Dr Desai said that in the light of that, there may be a case to review the actual pressure specified. He then added a final historical note that the 5-storey limit did not include the larger Victorian dwellings.

16. Mr Snell commented that in the offshore industry the $34kN/m^2$ was not considered to be a high structural load, unlike the opinions generally being expressed in this discussion. He noted there was probably more risk to life from fixtures and fittings than

building collapse. Dr Mills noted that there was a difference in materials used (i.e. no masonry). Mr Snell acknowledged this difference but noted that some design techniques could be applied to buildings.

17. Mr Hammersley concluded the discussion by thanking the Chairman and speakers.

After the seminar, Mrs Colwell submitted the following written comment:

CFD has been used extensively by the offshore industry to model the characteristics and subsequent effects of explosions in steel structures. Unfortunately, these techniques cannot be used successfully in the 'real building' environment due to the complex response of materials such as brickwork and concrete that do not behave in an homogenous manner. Significant work is on going in this area but the current level of technology precludes this type of analysis for 'real building' applications.

The pressure limits proposed by Ellis and Currie in their paper are based on extensive research undertaken by BRE in vented steel chambers designed to replicate traditional building stock; single rooms; double rooms and corridors. This research (reference PD 58/99) fully characterised the behaviour of domestic gas explosions in these symmetries. Although, it has not been rigorously assessed in 'real buildings' to confirm the potential interaction of the structure and general furnishings on the course and subsequent consequences of an explosion in this type of property.

All those attending the seminar have been asked to consider the issues further and send additional written discussion to BRE by the end of July 99.

A seminar supported by BSI Technical Sub-committee *Loading and Basis of Design.* DETR and BRE

Developments in Design of Robust Buildings
17 May 1999 2pm

Room 66, DETR Eland House, Bressenden Place, London SWIE 5DU

Thank you for registering to attend. The purpose of the seminar is to present current issues. and receive views of the invited representatives of the profession on the provision of safety and robustness in all buildings. including measures for avoiding disproportionate collapse.

The current UK provisions were developed following the partial collapse at Ronan Point in 1968. with consideration of internal explosion as the representative accidental action. However, research and development in the UK during the past thirty years have provided substantial information on internal explosions and vehicle impact. These could now be accounted for as accidental actions in design of buildings to provide robustness measures appropriate to the intended use of the building. The programme of presentations and discussion is as follows:

PROGRAMME

Chairman: **Dr J. Roberts**, Director of Allott and Lomax (Manchester)
& President-Elect of the Institution of Structural Engineers

2pm	*Reception*		
2.15	*Introduction*	Dr S B Desai OBE	Building Regulations Division, DETR.
	The current picture	Dr J H Mills Director, Allott & Lomax	UK Technical Co-ordinator. ECI,
	Statistics on building damage	Mrs D M Currie	Centre for Structural Performance, BRE
	Alechairisnis of gas explosious and design options	Dr B R Ellis	Technical Director, Centre for Structural Performance, BRE
	Building categorisation and alternative regulatory approaches	Dr J H Mills	
4pm	Coffee		
4.15	*The way forward*	Dr W W L Chan	Chairman. BSI Technical sub-committee B1525/l Loading and basis of design

This will be followed by a general discussion of issues relevant to the design of robust buildings to which delegates will be invited to contribute.

Please find enclosed:

B R Ellis and D M Currie — *Gas explosions in buildings in the UK: regulation arid risk.* Reprint from The Structural Engineer.

J H Mills — *Developments in design of robust buildings - Building Regulations Requirement A3* - seminar paper abstract.

Should you require any further information before the seminar, please contact Richard Beattie, Construction Division. BRE. Telephone: 01923 664569.

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received on 25 MAY 1999

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file no			

May 24, 1999

Dear John,

Developments in the Design of Robust Buildings

I attach some ramblings that I have assembled in relation to the presentation that you gave at DETR last week. I have been in liaison with Geoff Harding at DETR about the requirements for steel, especially those for light steel framing (a PII project run by SCI) and in case of fire (a BCSA/British Steel project). I have also been involved in attempting to unravel the target reliability index in an ECSC project or fire safety engineering for steel that BCSA were involved with over the last few years. I am also the UK NTC for conversion of EC3 Part 1.1.

All these threads are difficult to knit together, as the background is not fully defined – despite the ECCS 94 Background Document presented at Delft where we first met. I have found EC1-2-7 and its Background Document most informative, as it is relatively clear advice. I also personally prefer ISO 2394 to EC1-1 in terms of clarity. You will see that my conclusions support your formula for defining the categories, but I should like to understand the calculation basis for the indices that related your formula to the 10^{-4} pa criterion. Could you please send me that information (perhaps by email may be easiest).

When I am giving the presentations on robustness that I take part in for the SCI/IStructE [Manchester this Wednesday!], designers appreciate the relationship between the rules and the "normative NGD event", both in terms of scale of event and what are "proportionate" consequences. It helps to start from there and then allow them to decide whether other scenarios need be considered as well, and whether the straightforward application of the code rules is sufficient.

Yours sincerely,

Dr Roger Pope

Risk Analysis and Accidental Actions

1. The basis of any quantified use of risk analysis to establish benchmarks of acceptable risk (target failure probabilities or target reliability indices) is a database of recorded incidents. Unfortunately a suitable database does not exist, but nevertheless some targets have been mooted in the development of the Eurocodes.

2. It is suggested that the central benchmark for ultimate failures is β = 3.8 per (design) life. This gives a reliability of 7 x 10^{-5} per life or 1 x 10 $^{-6}$ pa based on a 70 year design life or 1.3 x 10^{-6} based on a 50 year design life. This is say β = 4.7 pa. What failure scenario this relates to is not specified in the Eurocodes, but the ECCS 94 Background Document indicates that it relates to the design reliability of a building element with a moderate expected consequence of failure. Alternative values are suggested for less and more important elements, ie lesser and greater consequences by implication.

3. I have made an attempt to interpret the suggested figures for steelwork, and have derived the following indicative figures:

Expected consequences of failure		
Minor	Moderate	Large
Secondary/tertiary	Primary beam	Column
0.7 x 10^{-5} pa	1 x 10^{-6} pa	1.5 x 10^{-7} pa
β = 4.3 pa or	β = 4.7 pa or	β = 5.1 pa or
β = 3.3 per life	β = 3.8 per life	β = 4.3 per life

   However, there are no application rules that seem to distinguish the different required levels of reliability for, say, beams cf columns. This would be difficult for designers in practice, and may well be justified by the fact that the contribution to the overall β factor from the variability is relatively low for steel.

4. The key concern with achieving the required level of reliability in design for non-accidental loads is to determine the loading, and thence to apply a sensible partial safety factor. The Eurocodes assume, as does ISO 2394, in the absence of other data, that the influence coefficient for the actions is α = 0.7 – irrespective of how reliable or otherwise the materials are that determine the influence coefficient for resistance. Ignoring this anomaly that is presumably based on the fact that no better data exists, $\alpha\beta$ for actions is 0.7 x 3.8 $\cong$ 2.7 per life or a probability of exceedance of 0.6 x 10^{-4} pa.

5. Setting the basic return period for variable actions at 50 years, the basic design load has a probability of exceedance of 0.02 pa ie 2 x 10^{-2} pa. However in design this load is then factored (by 1.35 say) such that the expected exceedance probability is reduced to Φ(0.7 x 3.8) – ie β = 2.7 per life or 0.6 x 10^{-4} pa as noted above. Reconciliation of the 1.35 partial safety factor with another assumption that the coefficient of variability of actions is about 0.4 is only possible if a value for $\gamma_D \cong$ 1.15 (ie design uncertainties) is also assumed to be included in the 1.35 factor.

6. The case of an abnormal or extreme variable action that exceeds the design action (ie the **factored** 50 year return load) may be viewed as equivalent to an accidental action. In broad terms this

means the "abnormal" variable action should occur as frequently as the 10^{-4} pa figure cited in Eurocodes for accidental actions. The principle is that abnormal variable actions that cause "elements" to fail should not cause the "system" to fail – ie no progressive/disproportionate damage/collapse/failure.

7. Again, the Eurocode does not define the benchmark scenario for accidental actions. Typically it is suggested that such actions would occur for each "structure" with a likelihood of 10^{-4} pa (ie 5 x 10^{-3} or 0.5% per lifetime of 50 years) which would mean only 1 in 200 structures would be subjected to such loads. Note that the "test" is applied to a "unit" that is the structure. A dwelling unit that is free-standing is easy to identify, but the block of flats may be many dwellings in one "structure". Also some very large buildings are essentially more than one structure.

8. What appears clear is that, whilst the β = 3.8 per life benchmark for normal design is focussed on the single element, the concern is with accidental actions that threaten the whole structure, ie much more than a single element. Relating back to the equivalence with abnormal/extreme overload beyond the normal design case, it can be seen that an extreme wind could be of this nature and threaten the whole structure simultaneously, but an abnormal snow drift might only threaten one frame/bent of a steel-framed shed.

9. A link is now needed between the chosen benchmark failure scenario and the consequences to establish what is "proportionate". Starting from the abnormal load case, it might be acceptable for the beam, what it directly supports, and nothing else to collapse if the beam was overloaded by say 50% [ie to 1.5 x 1.35 = 2.0 times the 50 year return base load]. Making assumptions about the probability distribution function for imposed loads that are consistent with γ_G = 1.35 (including γ_D = 1.15) indicates that at the 2.0 times factor the probability of exceedance is less than 10^{-7} pa.

10. In considering the consequences of abnormal overload, it is necessary to consider what happens if such a beam fails. The following table gives an indication:

Target failure probability for normal design		
Secondary/tertiary	Primary beam	Column
0.7 x 10^{-5} pa	1 x 10^{-6} pa	1.5 x 10^{-7} pa
Area supported		
2 m^2	20 m^2	200 m^2
Persons supported		
None	2	20

As an order of magnitude, there is some rationale to these figures in that the current UK regulations set a limit of 70 m^2 per floor supported, and columns often support up to three floors.

11. The alternative load paths available to redistribute the loads should a lower column fail are obviously important to maintaining both the structural integrity and equilibrium of tall buildings against overturning in such cases. Here it is important also to make the link between the reliability of complete systems (ie structures) as opposed to individual elements. The literature indicates that it is common for overall structures to achieve higher β factors [eg 3.0 for "worst element becomes 3.9 for an assembly] as added reliability from redundancy usually more than makes up for the greater number of possible paths in the failure event tree. This may be used to justify observing the ISO 2394

recommendation to base the analysis on discrete events. [Very extreme actions that threaten a whole structure simultaneously (eg a tsunami), or key elements with no alternative load paths (eg the Sungsoo Bridge collapse) are obviously exceptions to this.]

12. The redundancy is conferred by alternative load paths (hyperstaticity), post-“failure” behaviour that limits the amount of load that needs to be redistributed and statistical independence of actions such that the probability of occurrence of certain failure related events is independent of others. One might add to this “over-design” in that many elements that surround a failed element may not have been designed close to the unity factor, and the code rules followed would tend to have been formulated on the safe side.

13. Next, the failure of an element in abnormal overload of say 2.0 times the unfactored 50 year return load may or may not lead to any fatalities. It is at this stage that the question of acceptable individual risk (and its relation to societal risk) needs to be addressed. Consider the following in relation to the HSE guidance that indicates that a target reliability index for individual risk from fatality caused by structural collapse of 10^{-6} pa is on the safe side:

- As some failure is anticipated $p(f|e)$, the conditional probability of failure given the event, is effectively 1.0. Taking the probability of the overload scenario as 10^{-7} pa gives the probability of failure as 10^{-7} pa too. It is the scale of the failure that matters.
- A measure of the “acceptable individual risk” is 10^{-6} pa for a single fatality incident. Thus if $p(d|f)$ is the conditional probability of a person being killed given failure then the “target failure probability” is $< 10^{-6}/ N \times p(d|f)$ pa where N is the number of persons. Note this is affected by occupancy factors such as the time a person spend in or around a certain building.
- These figures imply that the “base case” is $N < 10/p(d|f)$ or $N < 10$ for the limiting case of $p(d|f) = 1.0$. This leads to the design criterion of a 10-fatality incident for abnormal overload failure of a say a steel member supporting O[20 m^2] and < O[200 m^2].
- Given the societal aversion to multi-fatality incidents that seems to follow an N^2 weighting, perhaps $\sqrt{10}$ not 10 fatalities might be a more appropriate limit for this benchmark case. This figure of < 3 accords with the conjecture that such a steel member supports around O[2] persons.
- Finally if the failure is at just over normal factored load (ie a factor of 1.35 not 2.0) then the probability of the initiating event is O[10^{-6} pa] and the fatality limit becomes $N < 1/p(d|f)$, which indicates that were such a steel member supporting N = 2 persons at the time $p(d|f) <$ 1/2, ie 1 person needs to survive participation in the event.

14. This then raises the question of the relative weighting of injuries (major and minor) to fatalities, and the value of each fatality prevented [VFP]. By that means other consequent losses can also be compared as well as loss of life of life. Documents from HSE, DETR, Highways Agency and the Railways Inspectorate indicate the following: VFP ≅ £800,000 ≅ 10 Major Injuries ≅ 200 Minor Injuries.

15. It is then possible to make a link with the economic cost of safety measures, and this is suggested by the ECCS 94 Background Document. Adapting the table from β factors per life to failure probabilities pa gives the following table (with rounded numbers):

Relative cost of safety measures	Serviceability limit states (irreversible)	Ultimate limit states		
		Expected consequences of failure		
		Minor	Moderate	Large
High	3×10^{-3}	0.35×10^{-4}	0.7×10^{-5}	1×10^{-6}
Moderate	1×10^{-3}	0.7×10^{-5}	1×10^{-6}	1.5×10^{-7}
Low	0.35×10^{-3}	1×10^{-6}	1.5×10^{-7}	1.5×10^{-8}

No guidance is given in the Background Document on the interpretation of the terms used in the table, but the terms could be interpreted as follows in failure probability pa:

Relative cost of safety measures	Excessive deflection leading to loss of compartmen-tation in fire	Collapse		
		Examples of component that fails and area of floor/roof or tonnage of steelwork that collapses		
		Secondary beam	Primary beam	Key column
		2 m^2	20 m^2	200 m^2
		0.1 tonnes	1 tonnes	10 tonnes
Additional bracing system to stabilise component	3×10^{-3}	0.35×10^{-4}	0.7×10^{-5}	1×10^{-6}
Doubling the amount of welding on component	1×10^{-3}	0.7×10^{-5}	1×10^{-6}	1.5×10^{-7}
Increasing serial size of component profile by one step	0.35×10^{-3}	1×10^{-6}	1.5×10^{-7}	1.5×10^{-8}

16. One further step now needs to be taken, which is to check the framework of criteria derived from normal design and abnormal overload as a “proxy” for accidental actions against the experience of accidental events themselves. Again the question arises as to how extreme an accidental event should be considered and then how extensive the post-failure consequences might be and still be considered by society as not disproportionate.

17. Conveniently, the BRE data provide both in that a Natural Gas Deflagration may be considered as the “normative accidental event”, and the statistical record of the consequences reviewed. From the statistical data in the survey of Ellis and Currie, existing design practice already achieves a rate of failure around 10^{-6} pa for “significant” (= severe and very severe) incidents. This is considerably better than the suggested target criterion of 10^{-4} pa. Also the incidence of “very severe” to “severe” incidents is less than 10% and hence severe incidents are around 10^{-7} pa. This is not as much as the desired factor of 100 better than that for significant incidents, but still seems to be on the safe side of an adjusted target for such incidents of $10^{-4} \times 10^{-2}$ pa.

18. Remember that these rates are per “dwelling” not per “structure”, and the question of multi-dwelling structures such as apartment blocks needs addressing. In structural terms, we may take advantage of two points in ignoring the need to multiply the figures by the average number of dwellings per structure:

- The scale of the NGD normative event is unlikely to threaten more than one dwelling at a time as an initiating event. [Note that the

disproportionate consequences at Ronan Point were not due to the scale of the initiating event but due to the inability of the details to cope with the debris loading that ensued.]
- The ISO 2394 rationale argues that analysis should be based on discrete events, as in suitably redundant structures β for the assembly exceeds β for the single elements (due to redundancy etc).

19. It seems that existing construction is more reliable than the benchmark in accidental events. This is consistent with other data that indicates that the same is true for normal design, especially when the stock of old and unmaintained structures is separated from structures designed and executed to “modern” codes (say post 1945). Such data also points to two other conclusions that are relevant:

    - The incidence of gross error in design accounts for a large proportion of failures, and this is not always countered by $\gamma_D = 1.15$.
    - Another major contribution to failure is “change of use” type overload, again not formally allowed in γ_Q. [In the accidental case of fire this has been recognised by the emphasis on fire safety management in Fire Precautions (Workplace) Regulations and other health and safety legislation.]

20. From Eurocode sources, what constitutes “proportionate” collapse is a function of the number of persons at risk (or value of economic loss or scale of environmental damage) and the scale of the initiating event. We have noted that current UK Regulations are based on the scale of the initiating event, but not in a formally explicit way. The classification of use does have an informal connection with the likely number of persons at risk. Economic loss is likely to remain a business/insurance concern.

21. If the wider consequences are to be considered, the VFP type figure noted above is needed. It is illustrative to consider four design examples used in the drafting of DD 240 for fire safety engineering:

Case study	Occupants	Total VFP	Area [m^2]	Value
Sports Arena	20,050	£16 billion	14,000	£10 million
Dept Store	6,500	£5.2 billion	35,000	£50 million incl business
Warehouse	< 20	< £16 million	13,300	£110 million incl contents
Office Block	1,000	£800 million	2,500	£12 million

Such figures help establish the design scenarios that should be considered, and accepting that the occupants can escape whereas the structure and contents are fixed, the table clearly enables designers to focus on what accidental events are most likely to occasion losses – of life or economic. Only in the warehouse with high value pharmaceutical contents are economic consequences of a higher value than the threats to life.

22. The same type of illustration can be made using figures from Ellis and Currie paper.

Values per annum	Gales	Explosions	Fire
Fatalities pa	5.8	38.5	707
VFP figure[1]	4.6 M£pa	30.8 M£pa	567 M£pa

Damage	44 M£pa[2]	3.2 M£pa	863 M£pa[3]
Total	49 M£pa	34 M£pa	1429 M£pa
Notes: 1. Value per fatality prevented as £800,000 2. Based on 1987 or 1990 gales occurring once every 5 years [approx] 3. Includes businesses losses and business interruption			

Here gales emerge as an insurance issue whereas explosions are relatively life threatening. That argues strongly that the NGD event is a sensible regulatory norm.

23. However, for a stock of 20 million dwellings, say 2 million are 5 stories or more. Say new build costs are £40,000 per unit and 40,000 units are built annually in multi-storey constructions. Allow 100,000 new units pa including non-domestic. Hence costs are £4000 million pa. To eliminate all effects (fatalities and damage) from gas explosions in such structures it would not justify spending more than about 1% more on new build costs. [These numbers are guesses that would need adjusting to accord with those deduced by John Mills, but the overall order of magnitude is about right.]

24. Taking the NGD event as the normative initiating event, it seems that damage to the enclosure of origin and some structural damage to the surrounding enclosures and the enclosures above and below is anticipated. Thus three levels of a multi-storey structure may be damaged, but collapse of the whole building/structure should not occur. The guidance in the approved document sets limits at failure of the floor and “roof” of the affected enclosure. This comprises two levels at $70m^2$ each with a third loaded with the consequent debris. This is failure of $140m^2$ and severe damage to another $70m^2$, ie $210m^2$ in total. [It should be noted that the regulation covers life safety and persons in the debris loaded level will be in immediate and direct danger.]

25. In percentage terms the $70m^2$ is reduced to 15% of each storey for floor plates of less than about $467m^2$, that is 6-storey buildings of, say, $2800m^2$. An NGD event would be limited to damaging 7.5% of such a building. The 8-storey Cardington frame has floor plates of $945m^2$, that is $7560m^2$ or 2.7 times larger than $2800m^2$. An NGD event would be limited to damaging just less than 3% of the Cardington frame. It is possible to characterise the NGD event as a $200m^2$ and 5% type event.

26. Significantly worse events, such as terrorist bomb detonations [TBD], will cause much more damage, but should still not cause total collapse of buildings of a size covered by the Building Regulations. No limit is set but it would be <100%, and $<2800m^2$ and $<<7560m^2$. A general measure of scale might be the “decimal coinage scale”, ie events that damage: 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, 20%, 50% and 100%. As the NGD event is around 5% [between 2 and 10%], then the TBD might be around 20% [between 10 and 50%].

27. The bottom end of the scale for accidental events might be set by considering what the $\beta = 3.8$ event represents for the “basic design case” [BDC] under the Eurocodes. In the Cardington frame, the primary beams generally support $54m^2$ (some support $81m^2$ and secondaries $27m^2$). This is less than 1% of the Cardington frame but would be nearly 2% of a $2800m^2$ frame. It should be remembered

that the Eurocodes imply higher levels of reliability should be set for columns supporting several floors.

28. To complete the table, and in comparison with the accidental limit state of fire, this produces the following “proportionate collapse measures”:

Code	Event	Area	Percentage
BDC	Basic design case	50	0.5 < 1 > 2
NGD	Natural gas deflagration [cf Fully engulfed enclosure of origin]	200	2 < 5 > 10
TBD	Terrorist bomb detonation [cf Established burning throughout fire compartment]	1000	10 < 20 > 50

29. The NGD event is seen as a sensible normative event to apply to structures to establish their general robustness. The existing provisions seem to provide the necessary level of structural integrity such that they also serve to limit damage to a “proportionate” amount even in much larger scale events such as the TBD event. [Current proposals are to extend the application of the rules to the interpretation of the response of the Cardington frame to an accidental fire event of a similar scale to the NGD event.]

30. The NGD event can be applied directly as a scenario. Using the advice in EC1-2-7, and assessing the likely venting pressure produces a range of scenarios to evaluate from the initial stage of the deflagration when there is a generalised over pressure of 7 kN/m^2 to all surfaces, to the later stages when the blast pressure may be assumed to be 20 kN/m^2 applied to structural elements only. [The 34 kN/m^2 is on the conservative side for assessing the NGD scenario.]

31. Alternatively codified design rules (to BS 5950-1 properly applied) can be used to check whether the steel structure is robust in terms of tying/continuity, column removal or key elements. [Currently the extension of this approach to BS 5950-5 for light steel frames is being undertaken.]

32. Using the background above, it seems that the criteria are consistent generally, and may be used to evaluate John Mills’ new proposals. Firstly, if A3 only prevents 1-2 fatalities and £10 million pa, then it does not justify any significant increase in construction costs. This is not a significant problem currently as the tying rules for steel are generally economic to apply (as beam connections serve to provide the tying forces).

33. Secondly, using the guidance given by John Mills, we can categorise the four case studies used to develop DD 240 as follows:

Case study	C	D	**Risk**	E	N	S	**Conseq**	Factor	**Category**
Sports Arena	2	0.3	**0**	0.3	2	3	**3.3**	3	**2**
Dept Store	0	1	**1.3**	0.5	2	3	**3.5**	4.5	**3**
Warehouse	2	0.3	**0**	0	1	2	**1**	0.7	**1**
Office Block	1	1	**0.3**	1	1	2	**2**	2	**1 or 2**

The assessments were done assuming the following:

- Accident scenario for load parameter.
- All frames in steel, ie ductile.
- Sports arena and warehouse single storey with no human live load on roof, and ductile material but no redundancy in large span roof trusses considered as single elements.
- Department store and office block with full human live load, and composite steel and concrete frames with redundancy.
- Warehouse was < 10 m, sports arena and department store were > 10 m < 30 m, and office block > 30 m.
- N and S read off table with warehouse classified with offices/flats.

34. The verbal presentation given by John Mills included a link with the 10^{-4} pa criterion, but the paper handed out does not contain this. It is therefore not possible to extend the numerical risk analysis further.

35. The classifications seem sensible with the office block being perhaps category 2 rather than 1. The high classification for the department store is influenced by having a multi-storey structure used by the public who constitute a large human live load. How one would apply the “dynamic analysis” of EC1-2-7 to such a case is problematic. The procedures established by DD 240 are analogous, and the qualitative design review [QDR] stage is an essential precursor to any analysis.

Dr Roger Pope
23 May 1999
ha0523paprob

APPENDIX 5 SUMMARY OF CALIBRATION CALCULATIONS

BUILDING TYPE	LOAD PARAMETER 'C'		STRUCTURAL PARAMETER		PEOPLE AT RISK	SOCIETAL CRITERIA	RISK		RISK FACTOR
	Accidental	Other	D	E	N	S	2.25-C-D	N+E+S-2	N+E+S-C-D
Industrial	^^	^^	^^	^^	^^	^^	^^	^^	^^
Storage sheds	2	2.5	0.3	0.3	1	1	-0.05	0.3	0
Speculative factories and warehouses	1	1.5	0.3	0	1	2	0.95	1	1.7
Assembly and machine workshops	1	1.5	0.3	0	1	2	0.95	1	1.7
Transport garages	1	1.5	0.3	0	1	2	0.95	1	1.7
Purpose built factories and warehouses	1	1.5	0.3	0.3	1	2	0.95	1.3	2
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Agricultural	^^	^^	^^	^^	^^	^^	^^	^^	^^
Barns and sheds	2	2.5	0.3	0	1	1	-0.05	0	-0.3
Stables	2	2.5	0	0	1	1	0.25	0	0
Animal breeding units	1	1.5	0	0	1	1	1.25	0	1
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Commercial	^^	^^	^^	^^	^^	^^	^^	^^	^^
Speculative shops	1	1.5	0	0.5	2	2	1.25	2.5	3.5
Surface car parks	1	1.5	0	0.3	1	1	1.25	0.3	1.3
Multi-storey car parks	1	1.5	0	0.5	1	2	1.25	1.5	2.5
Underground car parks	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Supermarkets	0	0.5	1	0.3	2	2	1.25	2.3	3.3
Banks	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Purpose built shops	1	1.5	0	0.3	2	2	1.25	2.3	3.3
Office developments	0	0.5	0	0.5	1	2	2.25	1.5	3.5
Retail warehouses	1	1.5	0.3	0.3	1	2	0.95	1.3	2
Garages / showrooms	1	1.5	0	0	1	2	1.25	1	2
Department stores	0	0.5	1	0.5	2	2	1.25	2.5	3.5
Shopping centres	0	0.5	1	0.3	2	3	1.25	3.3	4.3
Food processing units	1	1.5	0.3	0.3	1	2	0.95	1.3	2
Breweries	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Telecommunications and computer buildings	1	1.5	0	0	1	2	1.25	1	2
Restaurants	0	0.5	0	0	2	2	2.25	2	4
Restaurants	0	0.5	0.3	0.3	2	2	1.95	2.3	4
Public houses	0	0.5	0	0	2	2	2.25	2	4
Public houses	0	0.5	0.3	0.3	2	2	1.95	2.3	4
High risk research and production buildings	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Research and development labs	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Radio, TV and recording studios	1	1.5	0	0.5	1	2	1.25	1.5	2.5
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Community	^^	^^	^^	^^	^^	^^	^^	^^	^^
Community halls	0	0.5	0	0	2	3	2.25	3	5
Community centres	0	0.5	0	0	2	3	2.25	3	5
Branch libraries	1	1.5	0	0	1	2	1.25	1	2
Ambulance and fire stations	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Bus stations	1	1.5	0.3	0.3	2	3	0.95	3.3	4
Railway stations	1	1.5	0.3	0.3	2	3	0.95	3.3	4
Airports	0	0.5	0.3	0.5	2	3	1.95	3.5	5.2
Police stations	1	1.5	0	0	1	2	1.25	1	2
Prisons	0	0.5	0	0.3	2	3	2.25	3.3	5.3
Postal buildings	1	1.5	0	0	1	2	1.25	1	2
Broadcasting	1	1.5	0	0.5	1	2	1.25	1.5	2.5
Civic centres	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Churches and crematoria	2	2.5	0	0.3	2	3	0.25	3.3	3.3
Specialist libraries	1	1.5	0	0.3	1	2	1.25	1.3	2.3
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Museums and art galleries ^^		^^	^^	^^	^^	^^	^^	^^	^^
Magistrates / county courts	0	0.5	0	0.3	2	3	2.25	3.3	5.3
Theatres	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Opera houses	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Concert halls	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Cinemas	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Crown Courts	1	1.5	0	0.5	2	3	1.25	3.5	4.5
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Residential	^^	^^	^^	^^	^^	^^	^^	^^	^^
Dormitory hostels	0	0.5	0	0	1	2	2.25	1	3
Estates housing and flats	1	1.5	0	0	1	2	1.25	1	2
Barracks	0	0.5	0	0	1	2	2.25	1	3
Sheltered housing	1	1.5	0	0	1	1.6	1.25	0.6	1.6
Housing for single people	1	1.5	0	0	1	2	1.25	1	2
Student housing	1	1.5	0	0	1	2	1.25	1	2
Parsonages / manses	2	2.5	0	0	0	1.6	0.25	-0.4	-0.4
Apartment blocks	1	1.5	0	0	1	2	1.25	1	2
Hotels	0	0.5	0	0	2	2	2.25	2	4
Housing for the handicapped	1	1.5	0	0	0	1.6	1.25	-0.4	0.6
Housing for the frail & elderly	1	1.5	0	0	0	1.6	1.25	-0.4	0.6
Houses and flats for individual clients	1	1.5	0	0	1	2	1.25	1	2
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Education	^^	^^	^^	^^	^^	^^	^^	^^	^^
Primary / nursery / first schools	0	0.5	0	0.3	2	3	2.25	3.3	5.3
Other schools including middle and secndary	0	0.5	0	0.3	2	3	2.25	3.3	5.3
University complexes	0	0.5	0	0.3	2	3	2.25	3.3	5.3
University laboratories	0	0.5	0	0.3	1	2	2.25	1.3	3.3

	^^	^^	^^	^^	^^	^^	^^	^^	^^
Recreation	^^	^^	^^	^^	^^	^^	^^	^^	^^
Sports halls	1	1.5	0.3	0.3	2	2	0.95	2.3	3
Squash courts	1	1.5	0	0.3	0	2	1.25	0.3	1.3
Swimming pools	1	1.5	0.3	0.3	2	2	0.95	2.3	3
Leisure complexes	1	1.5	0	0.3	2	2	1.25	2.3	3.3
Leisure pools	1	1.5	0	0.3	2	2	1.25	2.3	3.3
Specialised complexes	1	1.5	0	0.3	2	2	1.25	2.3	3.3
	^^	^^	^^	^^	^^	^^	^^	^^	^^
Medical/Social Services	^^	^^	^^	^^	^^	^^	^^	^^	^^
Clinics	1	1.5	0	0.3	1	2	1.25	1.3	2.3
Health Centres	1	1.5	0	0.3	2	2	1.25	2.3	3.3
General hospitals	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Nursing homes	0	0.5	0	0	1	2	2.25	1	3
Surgeries	1	1.5	0	0	1	2	1.25	1	2
Teaching hospitals	0	0.5	0	0.5	2	3	2.25	3.5	5.5
Hospital laboratories	1	1.5	0	0.5	1	2	1.25	1.5	2.5
Dental surgeries	0	0.5	0	0	1	2	2.25	1	3