Rail Accident Investigation Branch

Rail Accident Report

Partial failure of a structure inside Balcombe Tunnel, West Sussex 23 September 2011

Report 13/2013
August 2013

This investigation was carried out in accordance with:

- the Railway Safety Directive 2004/49/EC;
- the Railways and Transport Safety Act 2003; and
- the Railways (Accident Investigation and Reporting) Regulations 2005.

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Partial failure of a structure inside Balcombe Tunnel, West Sussex, 23 September 2011

Contents

Summary

Early on the morning of Friday 23 September 2011, the crew of an engineering train passing through Balcombe tunnel observed that part of a large steel structure mounted in the roof of the tunnel, spanning over both railway tracks, was sagging down. An emergency inspection found that on one side of the structure, three supports had become detached from the tunnel lining leaving a 12 metre length partially supported.

The structure, one of six within the tunnel, was intended to catch water dripping from the tunnel roof. It was supported by anchor studs fixed with polyester resin into holes drilled in the tunnel's brick lining. Within the tunnel, 18 studs (5%) were found to be missing and a further five studs were loose. The RAIB's investigation has found that this connection was inadequate because the resin was not compatible with the tunnel brickwork and may have been adversely affected by shrinkage and the damp conditions in the tunnel. It is probable that the resin was selected using inadequate technical data and probable that insufficient resin was placed around some studs. Although some railway staff were aware that studs had fallen from the structure on more than one occasion since 2008, this did not result in appropriate risk mitigation. This was because of inadequacies in the reporting of these events and because there was insufficient support for a member of railway staff who was managing some aspects of the tunnel maintenance but had limited experience. Inadequate access for tunnel examinations due to conflicting demands on the limited available access is considered to be an underlying factor.

The RAIB has identified three learning points from this incident: the need to consider the adequacy of information contained in manufacturer's data sheets; the need to maintain awareness of published information; and the benefit of marking significant tunnel defects such that they are visible from track level.

The RAIB has made nine recommendations addressed to Network Rail that focus on managing existing polyester resin connections and controlling the future use of this material; confirming the compatibility of materials during design work; effective responses to defects and abnormal events; competency of staff managing structures; access for examining structures; the examination process for structures in tunnels; and retention of records relating to structures.

Introduction

Preface

1 The purpose of a Rail Accident Investigation Branch (RAIB) investigation is to improve railway safety by preventing future railway accidents or by mitigating their consequences. It is not the purpose of such an investigation to establish blame or liability.

2 Accordingly, it is inappropriate that RAIB reports should be used to assign fault or blame, or determine liability, since neither the investigation nor the reporting process has been undertaken for that purpose.

3 The RAIB's investigation is independent of all other investigations, including those carried out by the safety authority, police or railway industry.

4 This report supersedes the RAIB's interim report about this incident, IR1/2013, published on 24 January 2013.

Key definitions

5 All dimensions in this report are given in metric units, except speed and locations which are given in imperial units, in accordance with normal railway practice. Where appropriate the equivalent metric value is also given.

6 Locations within the tunnel are referenced in this report using tunnel chainage (ie the distance from a datum point at the north end of the tunnel).

7 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B.

The incident

Summary of the incident

8 At 05:24 hrs on Friday 23 September 2011 the crew of an engineering train[1], which had just passed through Balcombe Tunnel in West Sussex, advised Three Bridges Area Signalling Centre that a girder within the tunnel was "not connected". The signaller blocked the route with immediate effect to allow an emergency inspection of the tunnel.

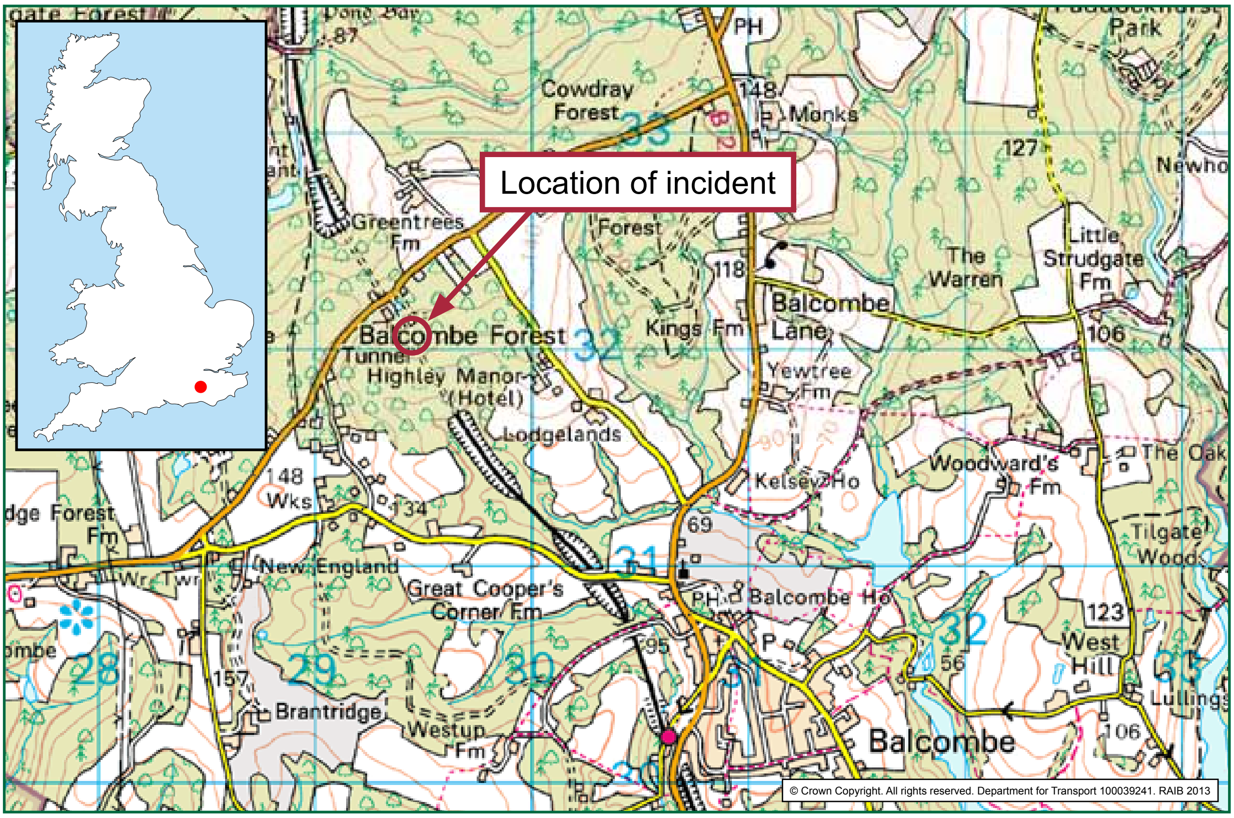

Figure 1: Ordnance survey map showing location of incident

9 This inspection showed that the ends of three beams supporting a *water catchment tray* in the roof of the tunnel had become detached from the tunnel lining. This resulted in the beams sagging until the intended 0.87 m clearance between the structure and train roofs was reduced to approximately 0.3 m.

Context

Location

10 Balcombe tunnel is located 1 mile 10 chains[2] (1810 metres) north of Balcombe station on the route from London Victoria to Brighton. The tunnel is 1131 yards (1034 metres) long, with the north portal located at 32 miles 02 chains and the south portal at 32 miles 54 chains from London Victoria.

[1] A train used for maintenance of the track or other railway infrastructure.

[2] One chain is equal to 22 yards (approximately 20 metres).

11 The tunnel is located on a double track section of the Brighton main line between Three Bridges and Haywards Heath. The *up* and *down lines* are bi-directionally signalled with a speed limit of 90 mph for trains travelling in the normal direction (eg up direction trains on the up line), and 75 mph for trains running in the wrong direction (eg down direction trains on the up line). Both lines are equipped with the 750 V DC *third rail* electrification system to provide power for electric trains.

12 The tunnel was constructed between 1838 and 1841 prior to the opening of the line in 1841 (figure 2). The tunnel was driven through Grinstead clay, overlain by sandstone and clay, and has five open ventilation shafts[3]. The tunnel is lined throughout in brickwork in the form an elliptical arch. During 1906 the original soft red brick lining was found to be in poor condition. Between 1907 and 1909[4], the inner ring of brickwork was removed to a height of 3.3 m, and the tunnel was relined with blue *engineering brick*. Depending on location, the tunnel lining now consists of either six or seven rings (layers) of brickwork, and is up to 0.8 metres thick.

Figure 2: Balcombe tunnel north portal (photograph courtesy of ORR)

13 Balcombe tunnel has had significant water ingress since the time of its construction. This has caused rail corrosion, short circuiting of third rail electrification equipment and the formation of icicles during cold weather. To improve operational reliability, five water catchment trays (numbered 2 to 6) were installed in the roof of the tunnel in 1998/9. These trays were built with a combined length of 152 metres and were positioned over the railway tracks above train roof level (figure 3). All were located under ventilation shafts, with the exception of tray 2 which was located between shafts 1 and 2. A sixth water catchment tray (tray 1) was installed close to the London end of the tunnel in 2006/7 beneath shaft 1, but this was to a different design and is not discussed further in this report.

[3] A shaft rising from the roof of the tunnel to ground level.

[4] Tunnel management strategy for Balcombe tunnel, Network Rail.

Figure 3: Water catchment tray 5 from north end in February 2012

14 The trays were designed to catch water dripping from the ventilation shafts and seeping through the brickwork in other areas of the tunnel. Pipe work then conveyed the water into the tunnel's drainage system.

15 In addition to the water catchment trays, water seeping through the brickwork in some other areas of the tunnel is directed into the tunnel drainage system by polypropylene or metal sheeting attached to the tunnel lining.

Organisations involved

16 Network Rail owns and manages the infrastructure, having taken over this responsibility from Railtrack plc in October 2002.

17 WS Atkins plc (Atkins) carried out a study of water ingress into the tunnel for Railtrack in 1997, and undertook structural examinations of the tunnel under contract to Railtrack, then Network Rail, as an examinations contractor between the mid-1990s and April 2009.

18 Amey plc (Amey) took over the examination work from Atkins in May 2009, working under a 'Civil Examinations Framework Agreement' (CEFA) with Network Rail.

19 Dyer and Butler also undertook a *design and build contract* for water catchment trays 2 to 6 by Railtrack plc and was *principal contractor* for the works. This company also undertook minor maintenance work in the tunnel under separate contractual arrangements during the period covered by this report.

20 Dyer and Butler subcontracted some parts of its design and build contract. The design work for trays 2-6 was subcontracted to consultants Scott Wilson. In 2010, Scott Wilson Ltd was acquired by URS Corporation.

Events following the incident

21 Services between Three Bridges and Haywards Heath were suspended for about 22 hours until 03:30 hrs on Saturday 24 September 2011 to allow a full inspection of the tunnel and implementation of emergency repairs to support the detached beams.

The investigation

22 The following sources of evidence were used:

- witness statements;
- site photographs and measurements;
- observations at the site;
- a review of previous reported occurrences in the tunnel; and
- a review of previous RAIB investigations that had relevance to this incident.

23 Ceram Research Ltd (Ceram), a ceramics research organisation, provided specialist advice and testing relating to the performance of resin in brickwork. This work was commissioned by Network Rail and included requirements specified by the RAIB.

24 The extent to which design and/or installation each contributed to the unsatisfactory performance of the water catchment tray cannot be determined because records of design requirements, design loads, construction methodology etc are no longer available.

25 Dyer and Butler has stated that a handover file including as-built drawings and test certificates was compiled and issued to the client (Railtrack), who undertook a quality assurance audit on it. It is probable that this material was intended for the *Health and Safety File*[5] for the water catchment trays, but no traceable record of the handover file remains and Network Rail has no record of receiving it. The Health and Safety file should have provided a permanent record of design, construction and maintenance issues.

[5] The Health and Safety File should have been retained in accordance with the Construction (Design & Management) Regulations 1994 (updated 2007).

Key facts and analysis

Background information

Catchment tray design and installation

26 In February 1997, Railtrack plc commissioned WS Atkins to investigate water ingress within Balcombe tunnel and to develop options for waterproofing the tunnel lining. Following input from Railtrack, Atkins produced a report containing outline design drawings showing five water catchment trays placed above train roof level and beneath the crown of the tunnel. These drawings showed plastic coated steel roof sheeting supported by transverse beams at six metre intervals. The ends of these beams are shown as being built into holes cut in the tunnel lining.

27 Dyer and Butler was awarded the contract to design and build the water catchment trays based on Atkins' outline design. Scott Wilson, as Dyer and Butler's designer, developed Atkins' scheme, and issued fabrication drawings in February and March 1998.

28 The trays, as designed by Scott Wilson, comprised a profiled metal deck supported by five longitudinal beams (ie parallel with the track) which in turn rested on transverse beams. The three central longitudinal beams spanned between transverse beams and were not continuous (ie a separate section of steel was used for each span, figure 4). The two outer longitudinal beams (ie one on each side) were continuous, with cover plates bolted across each joint. The transverse beams were approximately six metres long and spanned across the tunnel at four metre intervals (figures 3 and 4). The trays were inclined at a gradient of 1 in 40 so as to shed water towards a gutter above the down line. The design drawings showed that the trays were to be installed a minimum of 4.69 m above rail level.

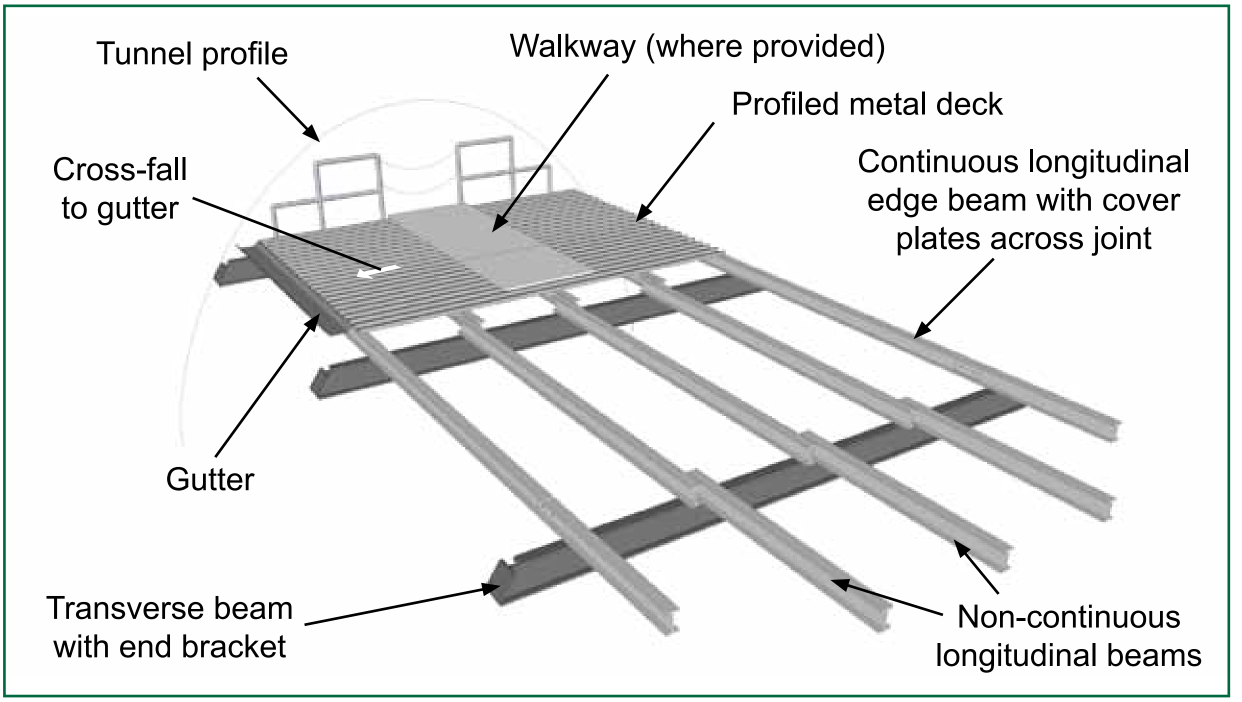

Figure 4: Diagram of water catchment tray structure

29 Four of the five trays (2, 3, 4 and 6) are 20 metres long, each supported by six transverse beams. Tray 5 is similar, but before being shortened following the incident, was 72 metres long and supported by 19 transverse beams, covering the area beneath shaft 4 (figure 5). The beams supporting tray 5 are numbered from 1 (at the north end) to 19.

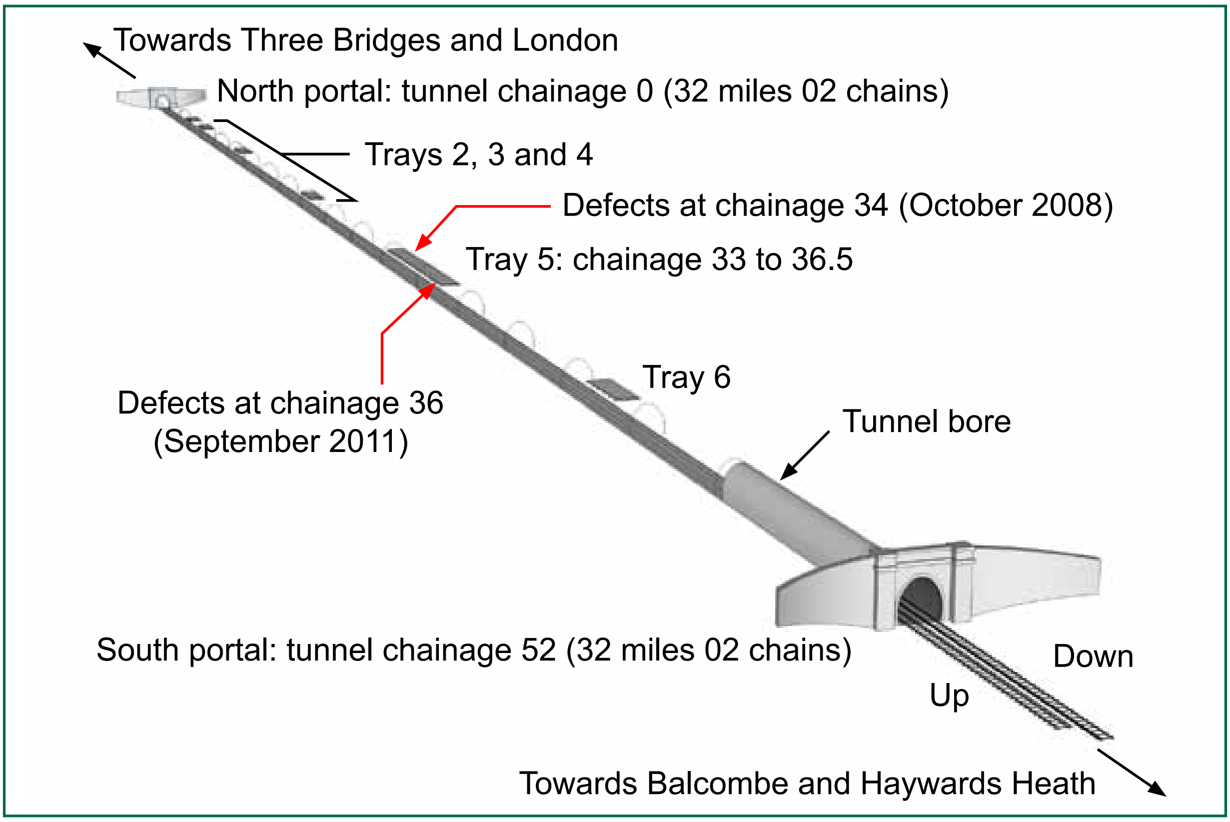

Figure 5: Diagram of Balcombe tunnel showing location of water catchment trays and defects

30 Atkins' outline design showed the ends of the transverse beams being inserted into holes cut in the tunnel lining and being directly supported by the brickwork. Scott Wilson's design did not adopt this arrangement, but instead the beams were connected to brackets which were attached to the tunnel lining by four 20 mm diameter threaded stainless steel rods (studs), two each side of the beam end. The studs were anchored into 22 mm diameter holes drilled into the tunnel brickwork at an angle of approximately 30° to the horizontal (figures 6 and 7) with a proprietary resin (Metoset multi-anchor resin is specified on Scott Wilson drawings). Once the bracket was in position, a washer and two nuts were added to each stud to secure it (figure 8).

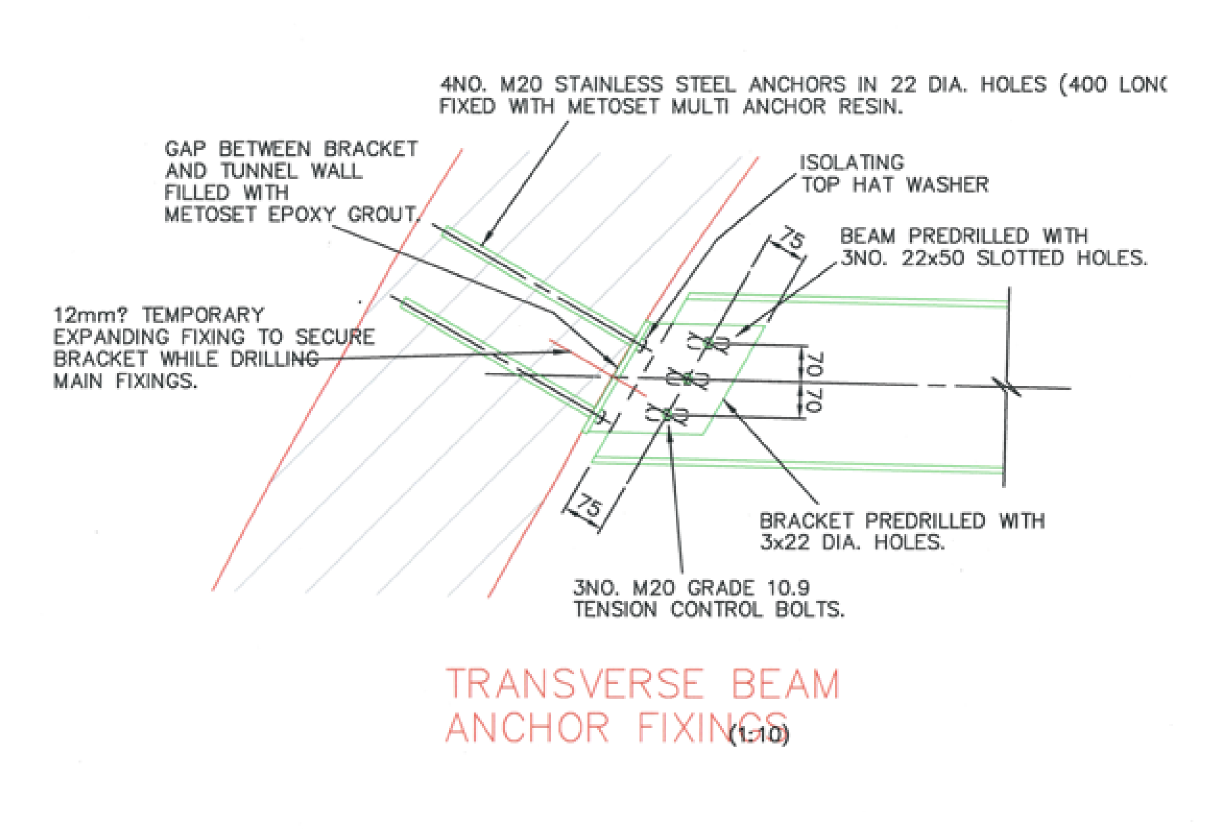

Figure 6: Scott Wilson's design drawing showing transverse beam end fixing

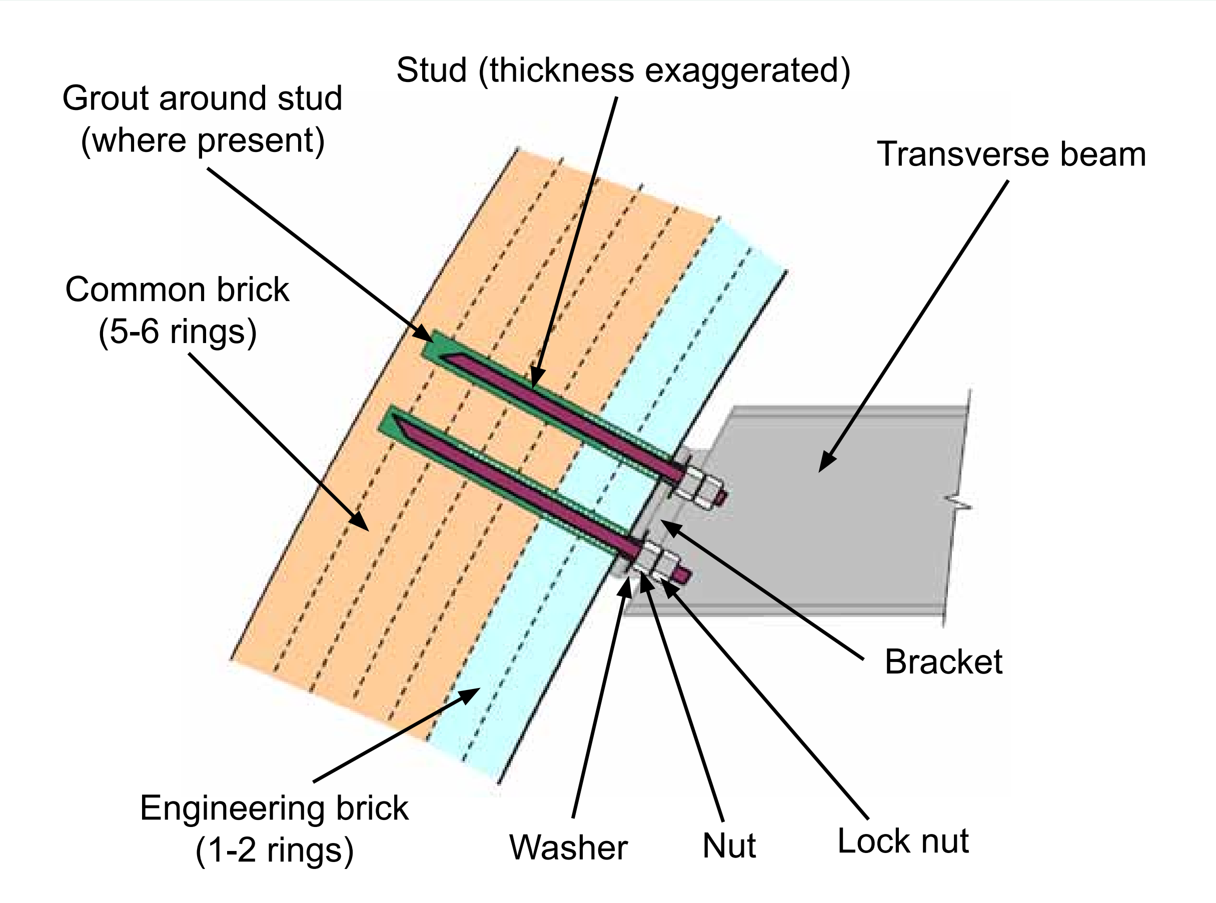

Figure 7: Simplified diagram of transverse beam end fixing

Figure 8: Transverse beam (as designed) supported by two studs on each side of the beam end

31 Witness evidence suggests that this solution was adopted to minimise disturbance to the tunnel lining and to make it easier to check the condition of the connection where corrosion could occur. It also reduced the amount of work necessary during track possessions in the tunnel. Where practical, engineering designs normally avoid situations where failure of a single component leads to a catastrophic collapse without advance warning. The Scott Wilson design relied on the polyester grout to prevent the studs falling from the brickwork. However, the continuous longitudinal edge beams and the strengthening effect provided by fixing the deck to the supporting steelwork (figure 4) meant that, as demonstrated by the incident, the structure could accommodate the accidental loss of several wall fixings without immediate catastrophic collapse. However, the RAIB observes that extending the beams into the tunnel lining would have avoided reliance on the resin, and made the integrity of the connection less dependent on the selection of materials or quality of installation.

32 Records of the contract show that work was completed in 1999. However, tunnel examination reports from October 2000 onwards state that tray 5 was incomplete (refer to appendix E). Some reports refer to the lack of a walkway on the deck, as is fitted to other trays, as being the reason the tray was incomplete. The design drawings indicate that a 1.2 m wide deck crawling panel was to be provided down the centre of each tray to allow for staff access (figure 4). This was missing on tray 5 making access more difficult (figure 10).

Post-incident condition

33 An initial inspection on 23 September 2011 by on-call staff identified that three transverse beams near the south end of tray 5 (beams 16, 17 and 18 near chainage 36) had become detached from the tunnel lining above the up line.

34 Network Rail structures engineers, supported by staff from Amey, undertook a more detailed post-incident inspection later the same day and found that all 12 studs connecting the three beams to the tunnel lining above the up line were missing. The loss of support had caused this part of the structure to sag (figures 9 and 10).

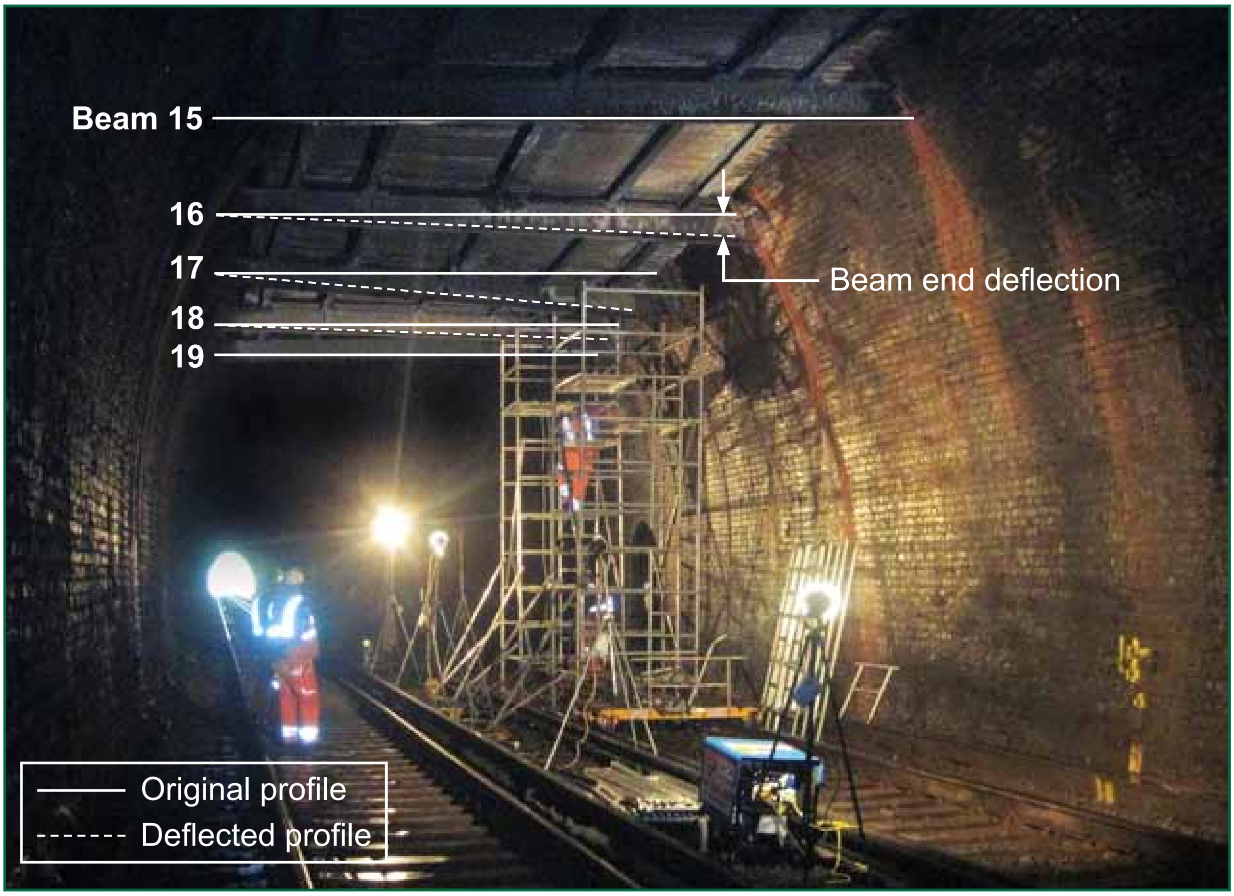

Figure 9: View of deflected structure on 23 September 2011 (photograph courtesy of ORR)

Figure 10: View of deflected structure from above, looking towards the south end of the tunnel, showing the twisted deck on the right-hand side (photograph courtesy of Amey)

35 Nine of the missing studs were found. One was at the side of the up line outside the tunnel, one beside the up line in the tunnel beneath tray 5, and the remainder in four different *refuges* set into the tunnel lining at track level close to tray 5. Two other studs were subsequently located at Network Rail's Brighton depot after being found on the track in March 2011 (refer to paragraph 101).

36 The post-incident inspection included a physical check of all similar studs within the tunnel with the exception of 13 beam-ends (52 studs). These were located within an exclusion zone, established by Network Rail, to keep staff away from the deflected structure while temporary brackets were installed, or in areas obstructed by equipment. This inspection identified that, in addition to the studs that were missing at the end of the deflected beams, a further six studs were missing (figure 11) and five studs were loose (ie could be removed by hand, figure 12). Within the tunnel, a total of 29 studs had one or more nuts loose (table 1).

Figure 11: Bracket with lower stud found missing (photograph courtesy of Amey)

Figure 12: Loose stud outside incident area removed by hand during inspection on 23 September 2011 (photograph courtesy of Amey)

Tray number	Total number of studs (8 per beam)	Number of studs checked	Numbers of studs missing		Number of studs loose		Number of studs with loose or missing nuts	
			Up side	Down side	Up side	Down side	Up side	Down side
2	48	46	0	0	0	0	3	0
3	48	48	0	0	0	0	2	1
4	48	48	0	0	1	0	3	1
5	152	100*	14**	4***	3	1	5	4
6	48	48	0	0	0	0	8	1
Total	**344**	**290**	**18**		**5**		**28**	

* Excludes 13 beam-ends (52 studs) which could not be checked (paragraph 36).

** Includes 12 studs missing from beams 16, 17 and 18 (paragraph 34).

*** Studs first reported missing by Atkins' tunnel examiner following a routine tunnel examination in October 2008 (refer to paragraph 68).

Table 1: Condition schedule of water catchment tray studs

Identification of the immediate cause[6]

37 **A structure above the railway tracks became partially detached and began to sag.**

38 Studs securing the ends of three consecutive transverse beams came loose from the tunnel lining and fell out causing the beams to drop downwards from their normal position. The factors that led to this outcome are described in the following sections.

Identification of causal factors[7]

39 The accident occurred due to a combination of the following causal factors:

- The design of the connection between the studs and tunnel lining was inadequate (paragraph 40) for one or more of the following reasons:
  - the resin was incompatible with the brickwork (paragraph 46);
  - the resin may have been softened by water percolating through the brickwork (paragraph 50); and
  - resin shrinkage may have reduced the bond between studs, resin and brickwork (paragraph 56).
- It is probable that there was insufficient resin around some of the studs when they were installed (paragraph 57).
- It is probable that the resin, which has since proven to be unsuitable, was selected using inadequate technical data (paragraph 63).
- The Structures Management Engineer did not recognise the significance of missing studs reported in October 2008 (paragraph 67).
- Network Rail did not provide the Structures Management Engineer with the support needed to compensate for his limited experience (paragraph 78).
- Information about missing studs was not passed on by Network Rail when responsibility for examinations transferred between contractors in April 2009 (paragraph 87).
- Studs falling to track level before the incident were found, but not reported to the Structures Management Engineer (paragraph 100).

Each of these factors is now considered in turn.

Connection of the transverse beams to the tunnel lining

40 **The design of the connection between the studs and tunnel lining was inadequate.**

41 The water catchment trays are connected to the tunnel lining by studs (threaded stainless steel rods) anchored with resin into holes drilled into the tunnel lining. The purpose of the resin is to transfer load from each stud into the adjacent brickwork. To achieve this, the resin in each hole must:

- interlock with the thread on the stud;

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[6] The condition, event or behaviour that directly resulted in the occurrence.

[7] Any condition, event or behaviour that was necessary for the occurrence. Avoiding or eliminating any one of these factors would have prevented it happening.

- at the far end of the drilled hole, surround the chisel end of the stud, thus preventing stud rotation;
- adhere to the brickwork over a length sufficient to transfer applied loads into the brickwork; and
- at the near end of the hole, prevent the lateral movement (play) of the stud because this would loosen resin around the studs.

42 The connection between the studs and the tunnel lining was inadequate. Studs found in the tunnel after the incident were complete (ie not broken) and most still had their nuts and washers although some were not in the correct position when found (figure 17). This shows that the failure mode was studs falling from the holes, rather than nuts unwinding. Some studs were bent, but it is probable that this occurred when a stud was partially out of the hole, but still supporting the tray.

43 Examination of the holes in the brickwork from which the studs had fallen showed an imprint of the threaded bar at some locations (figure 13). Some holes exhibited signs of wear and had deformed (figure 14), indicating that the stud had oscillated upwards and downwards, rather than simply rotated (unscrewed) out of the hole.

Figure 13: Hole in brickwork from which studs had fallen, showing thread pattern imprint

Figure 14: Deformed hole in brickwork core removed from tunnel lining

44 Vertical oscillation of the studs is consistent with the fluctuating vertical loading caused by the aerodynamic forces due to trains passing through the tunnel. Post-incident analysis undertaken by Mott MacDonald on behalf of Network Rail has shown that these forces were greater than the structure's self-weight (dead load), and that after the main pressure waves passed, the tray was subject to further oscillating pressure waves that last for about one minute. As tray 5 was significantly longer than the other trays (paragraph 29), it had the largest surface area which meant it experienced the most onerous aerodynamic loading. Its greater length also meant that there was a greater probability that two trains would pass beneath it. This may explain why, with one exception, all the loose and missing studs were from tray 5 (table 1).

45 The studs were able to move up and down due to lack of support from the engineering brick caused by inadequate bond between the resin and these bricks and/or insufficient resin in this zone (refer to paragraph 48).

The resin was incompatible with the brickwork

46 The properties of the brickwork and resin were established by Ceram (paragraph 23) from cores extracted from the tunnel lining. Seven 200 mm diameter cylindrical cores were drilled to a depth of 500 mm close to the location of the missing studs at chainage 36 (figure 15). The location of the cores was selected to include one sample of solid brickwork, three which incorporated studs that had remained fixed in place, and three which included the empty holes from which studs had been lost. Samples of resin and water were also collected.

Figure 15: Core taken from tunnel lining during investigation, showing engineering brickwork (right). Core split into two sections during removal (photograph courtesy of Network Rail).

47 The cores confirmed that the inner one or two rings of brick (ie those closest to the railway) were constructed of engineering brick, whereas the outer rings were constructed of 'common' brick made of poorly mixed clay. A blue-coloured gel was injected into one hole to keep the sample intact and to highlight cracks in the brickwork (typically gaps between bricks which are normally filled with mortar) through which resin could be lost. Detailed observations for each core are included in appendix D.

48 The examination and testing by Ceram, reinforced by observations made by Network Rail and the RAIB, showed that:

- the resin was polyester based;
- the surface of the engineering brick was smooth, dense and absorbed water fairly slowly;
- the resin did not adhere to the engineering brick;
- the amount of resin around the studs in the engineering brick was insignificant;
- the bond of the studs to the *common bricks* was fairly poor in some samples when the inner surface of the hole was very smooth; and
- significant amounts of resin were found in a plug beyond the stud where holes were significantly longer than the embedded length of stud (refer to paragraph 60).

49 Ceram observed that the low porosity of the engineering brickwork may have contributed to the non-adherence of the resin.

The resin may have been softened by water percolating through the brickwork

50 Some parts of the tunnel are extremely wet. The RAIB observed water running from holes from which studs were missing at chainage 36 (figure 16).

Figure 16: Former position of transverse beam 16 (up side) - note running water

51 The water percolating through the brickwork and into the tunnel was analysed by Ceram and found to be slightly alkaline (with a pH value of 7.9).

52 Polyester resin can soften in some circumstances if water is present. A London Underground Ltd (LUL) civil engineering technical advice note, issued in April 2009, gives this as a reason for LUL prohibiting use of polyester resin in damp or wet environments. LUL's action followed the publication of an academic paper[8] in 1997 which casts doubt on the long term performance of polyester resins in submerged conditions. This issue occurs because of a loss of bond strength at the resin and host material interface, and softening of the resin.

53 The 1997 paper followed earlier research published in 1990 by the US Army[9]. This research found that the overall average pullout strength of polyester resin placed and cured in holes in concrete under submerged conditions was 35% less than the strength of the same resin placed and cured in dry conditions. The largest reductions in strength occurred at ages of 6 months and 16 months.

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[8] Yahia, Khayal and Benmokrane, "Ground Anchorages and Anchored Structures", Proceedings of the International Conference, Institution of Civil Engineers, 1997.

[9] Floyd Best and McDonald, "Evaluation of polyester resin, epoxy, and cement grouts for embedding reinforcing steel bars in hardened concrete", Department of the Army, United States of America, 1990.

54 The RAIB notes that the 1990 research does not relate directly to use of polyester resin in brickwork, and that the 1997 paper relates to resin in submerged conditions rather than a tunnel lining environment. Although none of this work directly replicates the frequently wet brickwork at Balcombe, it is probable that the 1990 and 1997 findings are applicable to conditions at Balcombe in so far as the strength of the resin was affected by the damp conditions.

55 The content of the 1997 paper may not have been assimilated into routine design practice by early 1998 when Scott Wilson designed the water catchment trays. It was not recognised by LUL until 2009. It was not recognised by Network Rail until the matter was identified by the RAIB as a finding of this investigation.

Resin shrinkage may have reduced the bond between studs, resin and brickwork

56 In April 2009, LUL also prohibited the use of polyester resin for overhead fixings because this material has a tendency to shrink over time. A polyester resin manufacturer confirmed to the RAIB that shrinkage of up to 6% is possible over a 14 year period. Shrinkage would affect the bond, making this type of anchorage unsuitable for use in overhead applications where the fixing could fall out under gravity.

57 **It is probable that there was insufficient resin around some of the studs when they were installed.**

58 During the post-incident investigation by Ceram, some holes from which studs had fallen were found to contain very little resin (paragraph 48 and appendix D).

59 Witness evidence indicates that the 22 mm diameter holes were drilled using hand-held rotary percussion drills, and that each drilling gang had a kit box of equipment. This included spare drills, a bottle brush for cleaning holes, Metoset resin cartridges and cartridge gun, a tape measure and spanners. A tape marker around the drill was used to determined the depth of the hole. The quantity of resin inserted into each hole was pre-calculated.

60 The length of studs found (figure 17) varied from about 440 mm to about 520 mm, while the depth of the holes, established by a post-incident endoscope survey, ranged from 380 mm to 500 mm. With a fixed quantity of resin, shorter bars or longer holes would encourage the formation of a resin plug at the end of the hole, and gaps in the brickwork would cause loss. Both these features had the potential to reduce the amount of resin at the intended location around the stud. The extent of supervision and quality control of the site work is unclear due to the lack of records. Witness evidence indicates that Railtrack staff were not on site during installation.

61 The resin had to be injected into a long, upwardly inclined hole before a stud was inserted. It is possible that water egress through the holes or dampness could have prevented a fully effective bond developing between the resin and the brickwork.

62 The method of testing specified by the designer did not reveal any shortcomings in the stud installation process. Three brackets were tested to a vertical proof load of 10,000 kg using a reaction bracket installed above the working bracket and a calibrated hydraulic jack between. It is unlikely that these tests would have identified issues, such as softening, shrinkage and the effects of vibration, which can develop relatively slowly after installation.

Figure 17: Selection of missing studs found in the tunnel - note variation in length

63 It is probable that the resin was selected using inadequate technical data.

64 The design drawings specified that studs should be fixed with Metoset multi-anchor resin. A manufacturer's data sheet for the product probably used in the tunnel states that this is a two-part polyester resin, suitable for fixing studs into brickwork free from oil, grease and loose debris. It specifies that a 22 mm hole is required for 20 mm studs (the size used at Balcombe) and that if the holes are produced by diamond drilling, the surface of the hole must be thoroughly roughened.

65 The data sheet gives no indication of any limitations on the type of brick with which the product can be used. It states that Metoset is insoluble in water, but makes no reference as to whether water affects its properties.

66 Witness evidence indicates that there was no on-site testing during the design phase to establish:

- whether the tunnel lining was in a suitable condition to accept the proposed stud (eg extent of voids present);
- whether polyester resin was compatible with the tunnel brickwork; and
- whether polyester resin was compatible with the tunnel environment including the short and long term effects of dampness and the possibility of resin being affected by water percolating through the brickwork.

Recognition of problems with the transverse beam connections

Missing studs at chainage 34

67 **The Structures Management Engineer did not recognise the significance of missing studs identified in 2008 and 2009.**

68 An Atkins tunnel engineer, responsible for the tunnel between 2004 and March 2009, found the first evidence of a problem with the transverse beam studs near chainage 34 (44 metres from the September 2011 incident) during a routine examination in about October 2008. He found all four studs missing from a beam-end above the down line. The minutes of a progress meeting held between Atkins and Network Rail that month include the note: 'undertake repairs to shaft platforms [trays], notably replace missing bolts.'

69 The October 2008 examination was part of a *detailed examination* which was not completed on site until January 2009. However, in November 2008, Atkins' tunnel engineer sent an email to Network Rail's South East Territory Structures Management Engineer Tunnels (SME1) providing further information on the missing studs as an interim measure. He attached photographs of the unsupported beam end to the email (figures 18 and 19) and stated:

> 'This is the specific platform beam bearing where all the bolts are inexplicably missing/sheared at the support that we discussed, discovered following limited access to this area at the latest detailed examination possession.'
>
> 'I have sprayed the wall adjacent to highlight the defect... However, early placement of a full set of bolts at the support here must [be] the safest future solution.'

70 Although the email stated that the missing studs were located at tunnel chainage 36, the transverse beam affected was beam 5 of tray 5 above the down line. This beam is located at tunnel chainage 34, and will be referred to at this location hereafter. Some tunnel chainage marker plates were missing or wrongly spaced within the tunnel, making it difficult for examiners to accurately record the location of defects.

71 In response to these reports of missing studs, SME1 attempted to arrange for them to be replaced. SME1 has stated that during a site meeting in the tunnel, he spoke to the tunnel maintenance contractor, Dyer and Butler, about adding stud replacement to an existing schedule of works. There is no evidence confirming that SME1 issued a written instruction to cover this. SME1 did not have the information necessary to specify the repair required, and as a consequence, it was not possible for Dyer and Butler to do the work.

72 In March 2009, Atkins' tunnel engineer sent a series of emails to SME1 highlighting defects within the tunnel. He included photographs of the missing studs at chainage 34 (figures 18 and 20), and stated:

> 'The defect that worries me most of all is the platform beam ch34-36 as sprayed on site with no bearing bolts at all fixing the beam end into the wall. Really important that this structural work is carefully done.'

73 In his emails sent in March 2009, Atkins' tunnel engineer also advised SME1 to assume that 50 studs needed replacing or redrilling (25 on each side throughout the tunnel) and enclosed a photograph of a typical loose stud (figure 20).

Figures 18 and 19: Missing studs at chainage 34 in November 2008 (photographs courtesy of Network Rail)

Figure 20: Loose stud sent to SME1 in March 2009 (photograph courtesy of Network Rail)

74 In March 2009, SME1 recorded the need to replace the four studs in Network Rail's asset management database (CARRS). He raised a works order (number 891139) to cover several items of minor work including the replacement of the missing studs. SME1 also emailed the Network Rail project team responsible for minor works, requesting that this work be carried out during a pre-planned possession of the tunnel in April 2009.

75 On 23 March 2009, Network Rail's project team raised a work order in their database (MONITOR), number S0006, to cover the items identified in CARRS work order 891139. However, the possession in April 2009 was cancelled and work order S0006 appears to have been cancelled without any of the work identified in CARRS item 891139 actually being carried out. SME1 was not informed of this.

76 CARRS item 891139 was marked as complete in April 2010 based on a certificate which showed work order S0006 had been completed. This certificate actually related to a project for fixing loose sheeting in the tunnel which had been completed in March 2008 (ie 12 months earlier) and had also been allocated work order S0006. The reuse of this number was an administrative error.

77 SME1 did not take any action to investigate Atkins' advice that a significant number of studs might need replacing (paragraph 73). He did not take further action to determine whether the missing studs were indicative of problems elsewhere in the water catchment tray.

Management of staff competence

78 **Network Rail did not provide the Structures Management Engineer with the support needed to compensate for his limited experience.**

79 SME1 joined Network Rail in 2003, having previously worked outside the railway and civil engineering. He completed a Higher National Certificate in civil engineering in 2005 and transferred to structures work the same year. He took on tunnel engineer duties in August 2006, a role requiring him to review and evaluate examination reports for about 120 tunnels within Network Rail's South East Territory, to define and instruct maintenance work.

80 SME1 completed his civil engineering degree in June 2009, but was not certified by Network Rail as competent to be a structures manager (Network Rail standard NR/SP/CTM/017, competency STE 1) until October 2010 due to the need to gain sufficient experience. He was not able to sign-off examination reports until October 2010.

81 Between August 2006 and mid-2009, SME1 had responsibility for Balcombe tunnel. During this period, he reported to the South East Route Structures Engineer, who was two management grades above him.

82 When SME1 was appointed to the role in August 2006, the Route Structures Engineer recognised that SME1 would require support because recruitment difficulties within Network Rail meant that he had been appointed to a role for which he didn't yet have the required experience. The Route Structures Engineer therefore arranged for two senior Network Rail engineers to provide mentoring. However, he did not have an intermediate manager to oversee his work and provide day to day support, and there was no formal review process to check that the mentoring was effective. This should have verified that SME1 was gaining the knowledge and experience needed, and that he had not made errors or overlooked anything.

83 SME1's mentoring arrangements were not formalised, and required him to recognise a problem and ask for support. Initially he spent one day per week with a senior engineer who had national responsibility for tunnels. The support focused primarily on renewal items rather than tunnel maintenance and the amount of mentoring time reduced after a few months. SME1 did not report to his mentors, and without an immediate line manager, there was no structured review of his decisions.

84 It is likely that SME1's lack of experience in dealing with structures meant that:

- he did not recognise that the problem affecting the transverse beam connections was very unusual and that he should seek advice;
- he did not fully appreciate the risk due to the missing studs because he assumed, without carrying out any checks, that additional beam-end support was provided by a *shear plate* built into the tunnel lining (a feature he had seen in other tunnels); and
- he did not consider that there might be a more widespread problem that required investigation.

85 The Route Structures Engineer headed a small department with a significant workload. As a consequence, the individual had incomplete oversight of SME1's work, and a lack of management time to make sure that the mentoring process was working effectively. From early 2009, a change in reporting lines meant that SME1 started to report to a senior asset engineer, rather than directly to the route structures engineer. However, there is no evidence that this change was a factor in the incident.

86 The Route Structures Engineer, who held ultimate responsibility for the safety of the structure, was unaware that studs were falling out and that there was evidence of a possible inherent design deficiency with the stud connections.

Transfer of examination responsibility

87 **Information about missing studs was not passed on by Network Rail when responsibility for examinations transferred between contractors in April 2009.**

88 Network Rail standard NR/L3/CIV/006 'Handbook for the Examination of Structures', and its predecessor NR/SP/CIV/085, required tunnels to be examined by engineers certified as competent by Network Rail. In the case of Balcombe tunnel, the significant water ingress meant that it was within the 'higher risk' category of tunnels. For such tunnels, NR/L3/CIV/006 required a maximum interval between detailed examinations of one year[10] unless an extension was justified by a risk assessment. Although Network Rail employed examinations contractors to undertake this task, it retained responsibility for ensuring compliance with the standards including making provision for sufficient access.

89 Amey was responsible for examining the tunnel under the newly-introduced CEFA contract (paragraph 18) from April 2009. Although some Atkins staff transferred to Amey at that time, this did not include Atkins' tunnel engineer who had knowledge of the missing studs. Atkins had already planned many of the possessions and isolations required for the initial period of Amey's contract, but the hand-over, which was managed by Network Rail, did not include a technical hand-over meeting, and did not provide Amey with all the information it required.

90 As part of the preparation for a detailed examination, examiners are required to review the previous examination report[11] to identify the nature of existing defects and to determine if the condition of a structure has changed. Network Rail gave Amey a task list showing examinations required between April 2009 and March 2010, but it was unable to provide it with the most recent examination reports for some tunnels.

91 Network Rail was experiencing problems at this time with uploading some tunnel reports onto its structures examinations database (CARRS). Tunnel examination reports had started to be entered onto CARRS the previous year, but historic data errors meant that Network Rail had not issued all the examination ID numbers needed to complete the upload process. As a consequence, some reports were not uploaded.

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[10] Standard NR/L3/CIV/006 section 1C 'Risk Categories and Examination Intervals' (December 2009).

[11] Network Rail standard NR/L2/CIV/006/1D.

92 Atkins' last report on Balcombe tunnel dealt with the detailed examination completed in January 2009 (paragraph 69) and was dated 29 March 2009. The report included reference to the missing studs at chainage 34, and a photograph (figure 19). The RAIB has obtained a copy of this report but Network Rail has no record of receiving it and it was not uploaded onto CARRS. As a consequence Atkins' report was not available to Amey's examiners. The latest report available to Amey was the April 2007 report which pre-dated discovery of the missing studs.

93 Amey staff experienced difficulty in getting access to the tunnel (refer to paragraph 112) and were unable to undertake a detailed examination during the first year of their contract. Amey's tunnel examiners therefore walked through the tunnel to conduct a *visual examination* from track level in April 2010. They did not record the missing studs.

94 Amey's first detailed examination took place in July 2010. Examiners, one with previous experience of the tunnel, worked from rail-mounted scaffold towers on each line. However, the lack of Atkins' last report meant that the examiners were not prompted to pay particular attention to the studs at chainage 34, other than by the yellow arrows painted onto the tunnel lining (figure 19). The examiner working on the down line side of the tunnel reported various brickwork faults, but did not report the missing studs at chainage 34 (figures 18 and 19). No reason can be found for Amey's examination report not mentioning the defect.

95 The next detailed examination was planned for June 2011. This was to commence during two overnight possessions with two weekend possessions planned later in the year to complete the task. On the first night, Amey's examiners were not allowed access into the possession due to a problem with the possession planning. On the second night, the two examiners were allowed into the tunnel for a short period, but could not put their scaffold tower onto the track because there were on-track machines working nearby. This also prevented them from using their normal lighting equipment, which was carried on a rail-mounted trolley because of its weight.

96 The examiners decided to use the possession to examine the tunnel sidewalls only (ie the section visible from track level) as they did not have the lighting or access to cover the remainder of the structure. While in the tunnel, an examiner noticed the yellow arrows painted on the down side tunnel lining and observed the missing studs at chainage 34. He took a photograph of the defect (figure 21).

97 Amey's examiner was sufficiently concerned to send the photograph in an email to his manager immediately after the possession. His email states that while Network Rail was probably already aware of the defect, he felt it was still worth reporting. The manager forwarded the examiner's email to SME1, who in turn forwarded the email to the Structures Management Engineer, Sussex (SME2) the same day.

98 SME1 forwarded the email to SME2 because by June 2011, following an internal reorganisation, he was no longer responsible for Balcombe tunnel. However, as he was now a structures manager (paragraph 80), he provided advice and guidance on tunnel issues to other staff as required. In his email to SME2, SME1 stated "the beam fixing should be resolved but can be planned". This would have suggested to SME2 that the work was not of an urgent nature. This may explain why SME2 had taken no action to address the defect at chainage 34 before the incident on 23 September 2011.

Figure 21: Missing studs at chainage 34 (June 2011) (photograph courtesy of Amey)

99 The detailed examination was completed after the incident.

Identification of studs found in the tunnel

100 Studs falling to track level were found but not reported to the Structures Management Engineer.

101 In March 2011, a train conductor reported an unusual noise as their train passed through the tunnel on the down line. Track (permanent way) maintenance staff from Brighton depot were dispatched to check the tunnel the same night and found two studs on the track which they took back to their depot. Entries in the Network Rail control log state:

> "Brighton P-WAY reported finding an 18 inch studding bar on the track used to pin drain water from the roof of the tunnel. No track damage and no other issues. Full inspection undertaken and no immediate issue."

> "Studding bar is possibly part of a structure to keep corrugated iron sheets in place to enable water to run down the tunnel walls."

102 On the basis of the control log report, Network Rail requested Amey to undertake a special examination of the tunnel the following night. A senior examiner was allocated to this task. He had not previously been into Balcombe tunnel, but was available at short notice and was a structures examiner, competent to examine metallic structures.

103 Amey's record of the briefing received from Network Rail states "Studding bar reportedly fell off sheeting and struck train" and "P Way walkthrough confirms that studding bar has come away from drainage sheeting." Amey's examiner was not informed that two (rather than one) studs had been found, or from where in the tunnel, and they were not made available for him to inspect (figure 22).

Figure 22: Studs recovered in March 2011 (courtesy of Network Rail)

104 Amey's senior examiner, accompanied by a Network Rail mobile operations manager, inspected the tunnel using high powered torches, but found no indication of anything metal having come away. Nothing of significance was found, other than a piece of torn polypropylene sheeting found adrift from the tunnel lining. The examiner made a point of checking the tunnel refuges and has stated that there were no studs in the refuges at that time. Witness evidence, confirmed by a RAIB site inspection, shows that from ground level it would have been difficult to see if the studs were still in place, and from the information given, the examiner was looking for loose sheeting rather than missing studs from the catchment trays.

105 If the examiner had been given details of the studs before undertaking the inspection, it is possible that he would have recognised that the studs had fallen from a water catchment tray and that this probably represented a significant risk to railway safety. In these circumstances, it is almost certain that he would have reported his findings to the Structures Management Engineer responsible for the tunnel.

106 Seven studs were found in refuges immediately after the incident (paragraph 35). They could not have fallen directly into these locations, and it is very unlikely that they were knocked into the refuges by passing trains. It is therefore almost certain that they were picked up from the track and moved by track patrollers or other railway maintenance staff. As Amey's examiner had not found any studs in the refuges in March 2011, it is probable that the studs found in the refuges had been picked up and put in the refuges between March and September 2011. The stud found on the track beneath tray 5 may have fallen shortly before the incident.

107 Balcombe tunnel was subject to a basic visual inspection (patrol) each week by permanent way staff. These staff were based at Brighton depot until April 2011 when responsibility transferred to staff at Three Bridges depot. None of the weekly patrol reports for the 12 months prior to the incident record the finding of any long studs in the tunnel.

108 It is probable that the staff who found these studs did not appreciate where they had come from or did not realise their significance, but they should have reported finding them. Due to a lack of reporting, information about the studs was not passed to the structures management engineers responsible for managing the tunnel structure.

Severity of the consequences

109 The probable sequence of failure is that the studs supporting one transverse beam failed first. This would have allowed a greater range of deflection, promoting the failure of the studs supporting adjacent transverse beams. As the structure became freer, it would have been increasingly responsive to aerodynamic loads from passing trains, causing the rate of deterioration to accelerate.

110 The RAIB has estimated, from analysing photographs taken within the tunnel on 23 September 2011, that beam 17 which exhibited the greatest deflection, may have rotated by up to 6º (figure 9). This equates to the free end of beam 17 dropping by up to 0.6 m. With an installed clearance of 4.84 m above up line rail level, the soffit of beam 17 may have dropped to about 4.24 m above rail level. The maximum height of rail vehicles cleared for this route is 3.97 m (*W8 gauge*), so the design clearance of 0.87 metres reduced to a residual clearance of approximately 0.3 m. This value makes no allowance for movement of the structure under the aerodynamic loading caused by passing trains so the actual clearance was probably less than this.

111 Based on the observed performance of transverse beams 16 to 18 and testing of one of the four studs supporting transverse beam 15 above the up line (core 6), it is probable that the end connections of further beams (or possibly other parts of the catchment tray structure) would have failed if aerodynamic loads had continued to be applied by passing trains. The failure of another connection would have resulted in greater deflection and might have caused partial collapse of the structure. If a transverse beam had deflected sufficiently to have been struck by a train, it is probable that the beam would have detached from the structure, creating significant risk to trains. A stud of this size hitting the windscreen of a train travelling at 90 mph would also risk severe consequences for the driver.

Underlying factors[12]

Access to Balcombe tunnel

112 Limited access meant that tunnel examinations were not always undertaken in accordance with Network Rail standards, which required that Balcombe tunnel received a detailed examination each year (paragraph 88). A detailed examination required examiners to gain access to all parts of a structure, generally within touching distance. To reach the upper parts of the tunnel, examiners worked from rail-mounted mobile tower scaffolds, which needed to be erected, put on the track, and pushed into position before work could start. This means that short duration or interrupted possessions were not an adequate substitute for long possessions with uninterrupted access.

113 Both Atkins and Amey staff found that Balcombe tunnel was a particularly difficult location to gain sufficient access for examination work. The long possessions required for tunnel examination were seldom available because of:

- an intensive daily train service;
- an overnight gap in services of less than three hours; and
- the lack of a diversionary route.

114 The lack of possession opportunities meant that access was in demand by track and signalling maintenance teams, particularly as the wet conditions in the tunnel caused accelerated degradation of their assets. This combination of factors (ie a wet tunnel with limited access) applied to about 10 of the 129 tunnels within Network Rail's former South East Territory (now the Anglia, Kent, Sussex and Wessex routes).

115 Witness evidence shows that Network Rail expected that examinations should share possessions booked for other work and that maintenance work should be prioritised over examinations. The practice of examinations sharing maintenance possessions did not provide uninterrupted access, and significantly increased the risk of the examinations being disrupted or curtailed. On some occasions, Atkins and Amey examiners attended site but were denied access, or not permitted to use rail mounted towers due to other works or equipment being used within the tunnel. This led to a history of delayed or incomplete examinations and put the examination regime into a state of constant backlog.

116 The summary of the examination records attached as appendix E shows:

- the period between examinations often exceeded the 12 month maximum specified by Network Rail standards;
- between April 2003 and September 2011 (the date of the incident), a complete detailed examination was recorded on four occasions, as against the eight required by Network Rail standards; and
- even when where the examination was marked as "complete", the areas above the trays were often not examined, either due to a lack of time or due to an ongoing concern about walking on the trays (refer to paragraph 122).

[12] Any factors associated with the overall management systems, organisational arrangements or the regulatory structure.

117 Network Rail monitored the progress of examinations at progress meetings with Atkins and then Amey. The issue of delays caused by lack of access to Balcombe tunnel was recorded in the minutes of these meetings. In addition, a 2008 report by Network Rail into a minor incident involving loose sheeting in Balcombe tunnel in October 2007 recorded that while possessions were booked correctly, late notice changes in favour of [track] maintenance and renewals frequently impacted on the planned works. This report recommended that South East Territory "provide appropriate access for structures examination in general and tunnel examination, in particular recognising the safety implications of the examination process."

118 In March 2010, Network Rail established an official escalation process for responding to inadequate tunnel access for examinations. However, this did not prevent the completion of the detailed examination being deferred from June 2011 (paragraph 95) until the next available possession in February 2012, increasing the interval between detailed examinations to 19 months. As two studs were found on the track in March 2011 (paragraph 101), it is possible that a detailed examination of the up side in July 2011 would have found loose and/or missing studs, either on the track, or in tunnel refuges near chainage 36.

119 Although the Balcombe tunnel examinations were carried out by contractors (Atkins and Amey), Network Rail was responsible for ensuring that the examinations were properly undertaken. Network Rail staff were aware that access limitations meant that this was not happening and had implemented measures intended to improve the situation. At that time, Network Rail accepted non-compliant examination frequencies as an unavoidable consequence of the limited access in the belief that the associated risks were low.

Observations[13]

Adequacy of the examination regime

120 The water catchment trays were not subject to a bespoke examination regime. Network Rail had assumed that Amey were examining the trays as there was a contractual obligation on Amey to declare if they were not examining a structure that they were aware of. Part 1D of Network Rail's standard for the examination of structures, NR/L3/CIV/006 refers to previously unrecorded structures and states 'if a structure is found that is not recorded in the relevant Network Rail database, details of the structure shall be provided to the Structure Manager.' There is no evidence that the trays were identified as being unrecorded.

[13] An element discovered as part of the investigation that did not have a direct or indirect effect on the outcome of the accident but does deserve scrutiny.

121 Network Rail's expectation was that Amey would examine the trays but it had not provided the practical means to achieve this. The trays, despite their size, were not listed on Network Rail's schedule of (non-tunnel) structures to be examined, and there was no additional provision in Amey's contract in terms of either additional time or resources. Furthermore, the reporting arrangements specified for masonry tunnel examinations, which divided the tunnel up into 20 metre lengths, were not well suited to a structure which effectively had a double roof and required recording of individual defects in the metallic structures.

122 Examination staff did not walk on top of the water catchment trays as they were concerned whether the deck would support an examiner's weight and the surface was also very slippery. They had observed areas where the trays appeared to be either damaged or incomplete (paragraph 32 and appendix E). Atkins' tunnel engineer reported that some of the sheeting was missing, and some of the fixings for the sheeting were not secure. He made a recommendation in his reports that the trays should be structurally assessed as he considered that the defects were sufficient to warrant this.

123 Network Rail did not respond to this recommendation, or to the question of whether it was safe to walk on the trays. This issue was not resolved until 2012, so most examinations between 1998 and 2011 excluded those sections of the tunnel roof (crown) located above the trays. As the excluded areas included the base of the five tunnel shafts which were specifically required to be examined, this was a significant omission.

Network Rail's asset knowledge

124 Network Rail's structures management engineers lacked information on the design of the water catchment trays, because neither the Health and Safety file nor construction records were available (paragraph 25). As a consequence, SME1 did not have the information required to fully understand how the structure was supported, or provide guidance on whether the trays could be safely walked on. This had a direct effect on the examination regime (paragraph 122).

125 Network Rail's asset knowledge was also affected by the non-availability of some examination reports which were either outstanding at the time of the handover between Atkins and Amey in 2009, or not uploaded correctly onto Network Rail's reports database (paragraph 91).

Awareness of published information on the performance of polyester resin

126 There is no evidence to suggest that Network Rail and its designers were aware of published information which indicated a problem with the durability of polyester resin in damp conditions (paragraph 55).

Previous RAIB recommendations relevant to this investigation

127 The following recommendations, which were made by the RAIB as a result of its previous investigations, have relevance to this investigation. Recommendations which address factors identified in this investigation are listed, and are not remade so as to avoid duplication.

Derailment of a passenger train near Dryclough Junction, Halifax on 5 February 2011. RAIB report number 17/2011, published 20/10/2011

A lineside retaining wall failed causing rubble to fall onto the track which derailed a train. The investigation found deficiencies in the examination of the wall by Network Rail's examination contractor. The underlying causes included omissions in the examination reports produced by the examiner which were not identified by the examining engineer, and lack of independent checking of the examiner's work which is therefore vulnerable to the risk of error by omission.

Recommendation 2

Network Rail should implement a process that:

- *identifies and highlights structures examinations that are overdue, or whose examination report has not been effectively transferred to Network Rail's computer system;*
- *defines what action is to be taken regarding these missing examination reports; and*
- *identifies and highlights structures whose examination due date is imminent but no examination has been scheduled.*

The Office of Rail Regulation has confirmed to the RAIB that Network Rail has taken the above recommendation into consideration, and taken action to implement it.

Summary of conclusions

Immediate cause

128 The incident occurred when a structure in the roof of the tunnel became partly detached from the tunnel lining and deflected downwards, reducing the clearance to trains passing through the tunnel (**paragraph 37**).

Causal factors

129 The following causal factors have been identified:

a) The design of the connection between the studs and tunnel lining was inadequate (**paragraph 40, Recommendations 1 and 2**). This was because:

i) the resin was incompatible with the brickwork (paragraph 46);

ii) the resin may have been softened by water percolating through the brickwork (**paragraph 50**); and

iii) resin shrinkage may have reduced the bond between studs, resin and brickwork (**paragraph 56**).

b) The Structures Management Engineer did not recognise the significance of missing studs reported in October 2008 (**paragraph 67, Recommendation 4**).

c) Network Rail did not provide the Structures Management Engineer with the support needed to compensate for his limited experience (**paragraph 78, Recommendation 5**).

d) Information about missing studs was not passed on by Network Rail when responsibility for examinations transferred between contractors in April 2009 (**paragraph 87**).

e) Studs falling to track level were found but not reported to the Structures Management Engineer (**paragraph 100, Recommendation 6**).

130 It is probable that the following factors were causal:

a) Insufficient resin was placed around the studs during installation (**paragraph 57**).

b) The resin was selected using inadequate technical data (**paragraph 63, Recommendation 3, Learning Point 1**).

Underlying factors

131 Inadequate access meant that tunnel examinations were not undertaken in accordance with Network Rail standards (**paragraph 112, Recommendation 7**).

Observations

132 The water catchment trays were not subject to a bespoke examination regime (**paragraph 120, Recommendations 1 and 8**).

133 The tunnel examination regime was not fully effective because examination staff could not readily access the roof of the tunnel and the ventilation shafts above the water catchment trays. This was due to a concern that the trays were incomplete, an issue identified in October 2000, but not resolved until after the incident (**paragraph 122, Recommendation 8**).

134 Network Rail lacked information on the design of the water catchment trays and this made it difficult to fully understand the nature of the defect (**paragraph 124, Recommendation 9**).

135 There is no evidence that Network Rail and its designers were aware of published reports which indicated a problem with the durability of polyester resin in damp conditions (**paragraph 126, Learning Point 2**).

136 The location of the missing studs at chainage 34 was missed by staff undertaking a visual examination from track level in April 2010 (**paragraph 93, Learning Point 3**).

Actions reported as already taken or in progress relevant to this report

137 Network Rail arranged for temporary brackets to be fabricated and installed to support the three detached beam-ends in their deflected positions (figure 23) before the tunnel was reopened to traffic on 24 September 2011.

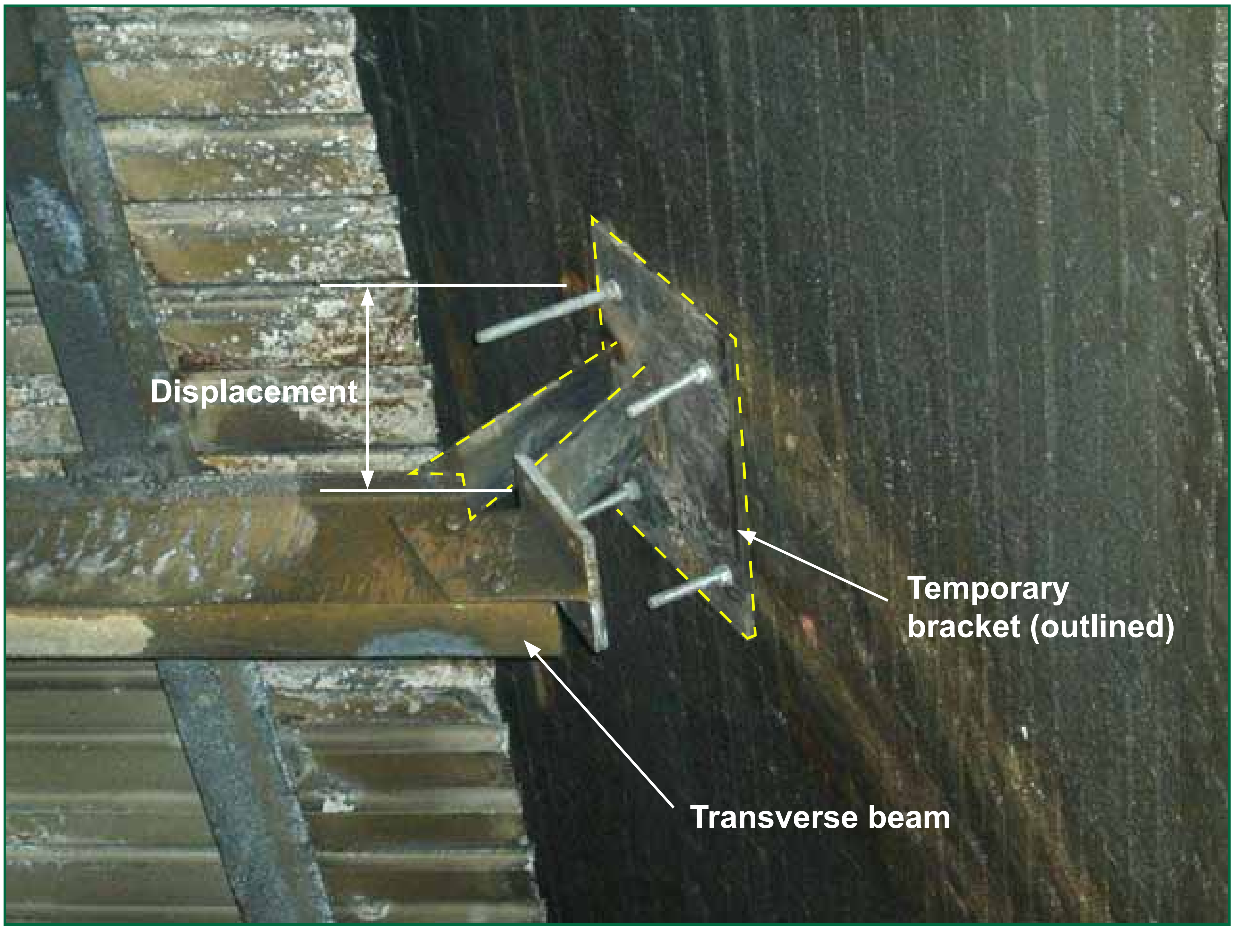

Figure 23: Temporary bracket supporting end of detached transverse beam 16

138 The five southernmost beams of tray 5, including the three deflected beams, were subsequently removed, which resulted in the tray being shortened by 20 metres. Further work undertaken in the tunnel included the provision of brackets to provide additional support to the transverse beams remaining in the tunnel (figure 24).

139 Immediately after the incident, Network Rail undertook a review to determine whether any other tunnels contained structures similar to those at Balcombe. In addition to tunnels containing overhead line and signalling supports, five tunnels contained minor supporting or reinforcing structures. Network Rail considered that none of these gave rise to significant levels of risk.

140 Network Rail's asset management function, which includes the structures management engineers, has introduced a process to record and track actions requested as a result of tunnel examinations.

Figure 24: Transverse beam end after fitting of additional support bracket post-incident

141 Network Rail has overhauled its examination procedures in response to an Enforcement Notice issued by the Office of Rail Regulation (ORR) in May 2011. This has included measures intended to provide adequate possession availability. Network Rail has also commenced a national review to identify structures where there are recurring problems in gaining access for examination, and will develop an action plan to verify that improvement is being achieved.

142 In 2011, Network Rail restructured its asset management organisation. As a part of this restructuring, the territory-based structures teams were replaced by a structures manager based in each Route reporting to the Director of Route Asset Management. This is intended to facilitate better communication and understanding between asset management engineers and operational management teams.

143 During 2011, Network Rail upgraded its CARRS database. One of the improvements is a facility to provide users with greater visibility of the status of examination reports.

Learning points[14]

144 The RAIB has identified the following learning points for the railway industry:

1. The need to ensure that designers and contractors give critical consideration to the adequacy of information contained in manufacturer's data sheets (paragraph 130b).

2. The need for designers to maintain an awareness of relevant published material relating to materials proposed for construction activity (paragraph 135).

3. The benefit of clearly marking the location of significant defects in a tunnel on the sidewall below the location of the defect such that they are visible from track level and increase awareness of the defect (paragraph 136).

[14] Learning points' are intended to disseminate safety learning that is not covered by a recommendation. They are included in a report when the RAIB wishes to reinforce the importance of compliance with existing safety arrangements (where the RAIB has not identified management issues that justify a recommendation) and the consequences of failing to do so. They also record good practice and actions already taken by industry bodies that may have a wider application.

Recommendations

145 The following recommendations are made[15]:

1 *The intention of this recommendation is to identify fixings at risk of failure based on current knowledge.*

Network Rail should, where failure could result in risk, identify where polyester resin anchors have been used to support structures (including overhead electrification and signalling equipment), and develop an appropriate regime to detect loose fixings including tactile testing where appropriate (paragraphs 129a and 132).

2 *The purpose of this recommendation is to prevent the further use of polyester resin anchors where their long-term performance may compromise safety.*

Network Rail should implement procedures to prevent the use of polyester resin anchors in circumstances where dampness or shrinkage may affect the safe performance of an asset (paragraph 129a).

3 *The purpose of this recommendation is to promote additional investigation prior to specifying materials where performance is critical.*

Network Rail should review, and if necessary amend its processes, such that designers of structures are required to positively confirm the compatibility of materials with their intended application and environment, including fixing metallic structures to masonry, if the application is safety critical (paragraph 130b).

continued

[15] Those identified in the recommendations, have a general and ongoing obligation to comply with health and safety legislation and need to take these recommendations into account in ensuring the safety of their employees and others.

Additionally, for the purposes of regulation 12(1) of the Railways (Accident Investigation and Reporting) Regulations 2005, these recommendations are addressed to the Office of Rail Regulation (ORR) to enable it to carry out its duties under regulation 12(2) to:

(a) ensure that recommendations are duly considered and where appropriate acted upon; and

(b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

Copies of both the regulations and the accompanying guidance notes (paragraphs 200 to 203) can be found on RAIB's website www.raib.gov.uk.

4 *The intention of this recommendation is to provide an effective asset management response when structure defects (or suspected defects) are reported.*

Network Rail should review and, if necessary, modify the management arrangements that are now in place to provide an appropriate engineering response when structure defects are reported. This should include assessing the risk in the period prior to rectification, the means to verify that work requested has been carried out, and whether the reported defect is an indication of a wider problem (paragraph 129b).

5 *The intention of this recommendation is to improve the quality of decision making in the management of structures.*

Network Rail should undertake a comprehensive review and, if necessary, implement a time-bound plan to modify its levels of staffing and competency requirements so that all technical tasks associated with the management of structures are performed or checked in a timely manner by sufficiently qualified and experienced staff (paragraph 129c).

6 *The intention of this recommendation is to improve the effectiveness of Network Rail's investigations when abnormal events are reported.*

Network Rail should revise its arrangements for the briefing of staff or contractors who are sent to investigate reported defects, so that all relevant available information is provided, and correct any deficiencies found in those arrangements (paragraph 129e).

7 *The intention of this recommendation is to provide adequate opportunities for examination and maintenance activities.*

Network Rail should review, and if necessary amend, its processes to include adequate safeguards such that sufficient track access is provided for the examination needs of all structures in a manner commensurate with the risk they pose to railway safety (paragraph 131).

8 *The intention of this recommendation is to improve the effectiveness of Network Rail's examinations regime for structures within tunnels.*

Network Rail should clarify arrangements, including its relationship with its contractors, for examining structures which are within tunnels, but are not fully encompassed by the normal tunnel management regime (paragraphs 132 and 133).

9 *The intention of this recommendation is to improve the quality of information available to staff responsible for the management of structures including provision of information not required within the statutory Health and Safety File.*

Network Rail should review, and if necessary improve, arrangements for recording, storing and retrieving data so that all relevant information is readily available to staff undertaking the examination, evaluation and maintenance of structures (paragraph 134).

Appendices

Appendix A - Glossary of abbreviations and acronyms

CARRS	Civil Asset Register and Electronic Reporting System
CEFA	Civil Examinations Framework Agreement
LUL	London Underground Ltd
ORR	Office of Rail Regulation
SME	Structures Management Engineer

Appendix B - Glossary of terms

All definitions marked with an asterisk, thus (*), have been taken from Ellis's British Railway Engineering Encyclopaedia © Iain Ellis. www.iainellis.com.

Common brick	The term is used in this report to indicate a brick made locally to the tunnel from poorly mixed weald clay with some large inclusions. The bricks had been fairly crudely produced, as the swirling patterns from the clay mixing remain evident.
Design and build contract	A form of contract arrangement where the successful contractor is responsible for the detailed design and construction.
Detailed examination	A close examination of all accessible parts of a structure of sufficient quality to produce a report that includes a record of the condition of all parts of the structure and recommendations for remedial action and other information that when evaluated will permit Network Rail to be able to maintain the safety and performance of the structure.
Down line	A track on which the normal passage of Trains is in the Down direction, ie away from London.*
Engineering brick	The term is used in this report to indicate a high-strength brick with a dense smooth surface, blue in colour.
Health and Safety File	A file, or other record in permanent form, containing the information required by regulation 14(d) of The Construction (Design and Management) Regulations 1994. This will contain information included with the design and any other information relating to the project which it is reasonably foreseeable will be necessary to ensure the health and safety of any person at work who is carrying out or will carry out construction work or cleaning work in or on the structure or of any person who may be affected by the work of such a person at work.
Principal Contractor	A principal contractor has to be appointed for construction projects which last more than 30 days or involve 500 person days of construction work. The principal contractor's role is to plan, manage and co-ordinate health and safety while construction work is being undertaken. The principal contractor is normally the main or managing contractor for the work.
Refuges	Recesses formed in tunnel lining intended to provide a refuge in which track workers stood while trains passed.
Shear plate	Plate built-in to the tunnel lining, designed to provide a secondary means of support.
Third rail	A single conductor rail positioned on the sleeper ends.*

Tunnel management strategy	A Tunnel management strategy is intended to be a single source of information for the tunnel, to be used in the management of the asset. Network Rail commissioned tunnel management strategies for each tunnel on the network in 2003.
Up line	A track on which the normal direction of trains is in the Up direction (ie towards London).*
Visual examination	An examination of the condition of a Structure undertaken from safe observation locations without using special access equipment or arrangements but using permanent access ladders and walkways and, where necessary, binoculars and hand-held lighting.
W8 gauge	A standard vehicle gauge for container vehicles carrying standard 8' 6" containers.*
Water catchment tray	Structure used to catch water entering the tunnel from the surrounding ground and channel it into the tunnel drainage system.

Appendix C - Key standards current at the time

NR/SP/CIV/085. First issued April 2004. Renumbered NR/L2/CIV/085.	Examination of Tunnels
NR/L3/CIV/006. First issued December 2009, subsequently revised.	Handbook for the examination of Structures
NR/L3/CIV/006/4A. First issued September 2009	Handbook for the examination of Structures Part 4a Lined tunnels
NR/SP/CTM/017. First issued June 2006. Renumbered NR/L2/CTM/017.	Competence & Training in Civil Engineering

Appendix D - Summary of observations by Ceram

Brickwork core characteristics

Core location	Side	Summary of observations
Solid brickwork control sample taken between beams 17 and 18 (evidence box 5)*	Down	• Core 690 mm long with two rings of engineering brick and four rings of common brick. • Fairly good adhesion between mortar and both types of brick. • Poorer adhesion between engineering brick and common brick.
Beam 16 connection (open hole, stud missing) (evidence box 6)	Up	• Core broken during extraction. • Hole enlarged from 22 mm to 32 mm in section of common brick. • Thread pattern imprint on both brick types.
Beam 16 connection (open hole, stud missing) (evidence box 1)	Up	• Core broken during extraction. • Evidence of two brick types and two mortar types. • Thread pattern imprint on both brick types. • Hole distortion in engineering brick, which may be due to displacement of stud before or at removal.
Beam 17 connection (open hole, stud missing) (evidence box 3)	Up	• Core broken during extraction. • Evidence of two brick types. • Thread pattern imprint on both brick types. • Hole distortion in common brick (figure 14) • Thread pattern imprint on thick pieces of hardened resin.
Beam 18 connection (open hole, stud missing) (evidence box 4)	Up	• Core 800 mm long with one ring of engineering brick. • Core extracted intact (in two parts) after injecting hole with polyurethane gel to aid removal (figure 15). • Numerous joints in brickwork filled with gel.
Beam 15 connection (stud present) (evidence box 8)	Up	• Core 665 mm long with two rings of engineering brick. • Core extracted intact with stud present. • Very little resin adhering to stud in engineering brick section. • Thread pattern imprint on brick surface. • Thin layer of brittle resin in common brick section. • Stud could be rotated by hand in the resin. • Hole slightly longer than stud.
Beam 17 connection (stud present) (evidence box 7)	Down	• Core extracted intact with stud present. • Core drilled through seven rings of brick into clay. • Two rings of engineering brick which could be easily slipped off the stud. Hole was smooth and elliptical. • Stud surface in engineering brick was fairly clean and shiny. • Stud in common brickwork was covered in resin. • Stud could be rotated in common brickwork with resin rotating with stud. • 60 mm plug of resin at end of hole beyond stud. • Brickwork slipped down stud when held vertically.

Beam 18 connection (stud present) (evidence box 2)	Down	• Core 450 mm long plus 330 mm exposed stud. • Core extracted intact with stud present. • Engineering brickwork slipped very easily from stud revealing a very shiny surface to the stud. • Thread pattern imprint on engineering brick. • Resin existed as thin layer in common brickwork section only. • 35 mm plug of resin at end of hole beyond stud. • Stud could not be rotated by hand.

* Evidence box numbers used by Ceram to identify cores.

Appendix D (continued) - Brick characteristics

Brick type	Characteristic	Value	Summary of observations
Common brick	Description: Bricks made from poorly mixed clay with large inclusions.		
	Water absorption (%):	10.1 - 16.1	Within expected range.
	Initial rate of suction (Kg/m²/min):	1.0 – 2.0	Within expected range.
	Compressive strength (N/mm²):	19.1 – 34.3	Values reasonable and form basis for good quality brickwork
Engineering brick	Description: Bricks have dense smooth surface, blue in colour and a red core.		
	Water absorption (%):	3.2% - 3.8	Within range for good quality engineering bricks
	Initial rate of suction (Kg/m²/min):	0.2 – 0.6	Absorbs water fairly slowly.
	Compressive strength (N/mm²):	85.9 - 131.8	Very high

Appendix E - Summary of tunnel examinations

Date of examination (Examiner)	Interval since previous detailed examination (months)*	Examination Type	Comments and observations
26/02/1999 (Atkins)	12	Detailed	Trays incomplete
28/10/1999 (Atkins)	8	Detailed	Report not available
01/10/2000 (Atkins)	12	Detailed	Trays 5 and 6 incomplete (decking and walkways missing)
04/10/2001 (Atkins)	12	Detailed	Trays 5 and 6 incomplete (walkways missing)
19/12/2002 (Atkins)	14	Detailed	Trays 5 and 6 incomplete (walkways missing)
19/11/2003 (Atkins)	11	Detailed	Trays 5 and 6 incomplete (walkways missing)
25/05/2005 (Atkins)	18	Detailed	No examination of tunnel roof above trays due to time restrictions. Completeness of trays 5 and 6 queried.
01/04/2007 (Atkins)	23	Detailed (partial)	Examination incomplete due to insufficient time. Completeness of trays 5 and 6 queried. Tray 1 under construction (paragraph 13).
26/01/2009 (Atkins)	21	Detailed	Trays incomplete. Report includes photograph and reference to missing studs at chainage 34. Report completed in March 2009 (paragraph 92), but not included on CARRS database.
15/04/2010 (Amey)	8	Visual	Visual examination of whole tunnel.
15/07/2010 (Amey)	18	Detailed	Several areas of tunnel roof above trays not examined. Missing studs observed and reported at chainage 34.
09/06/2011 (Amey)	-	Detailed (commenced)	Examination incomplete due to insufficient time. Examination of sidewalls from track level. Missing studs at chainage 34 photographed and notified to Network Rail by email on 10/06/11 (paragraph 96). Examination completed post-incident.

* Maximum interval between detailed examinations should be 12 months (one year).

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