Spandrel Walls - Managing the Risks

Lessons Learnt

March 2012
Network Rail

Confidential

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Executive Summary

There have been several structural failures of spandrel walls over the last few years. Although there were no direct consequences from each of these incidents, each one has been largely unpredictable and had the potential to cause a serious accident. Network Rail subsequently put in place a staged action plan to manage the risk.

To support the implementation of this action plan, Network Rail requested that Mott MacDonald work with Giffords and potentially other acknowledged experts from academia, to provide technical advice to Network Rail and carry out research work on the stability of spandrel walls of masonry arch bridges.

The works have been undertaken in stages with identified hold points to complement / service the action plan and to facilitate the structured development of the research work. The commission has drawn upon the findings of historical, current and planned masonry bridge research being undertaken on behalf of Network Rail, CIRIA and other related published works such as the assessment of dry stone walls etc.

A hold point within the study has been identified for the end of March 2012, coinciding with approximately two years of work undertaken. This document captures the lessons learnt at this stage, building upon the knowledge gained through the various project stages.

The following key lessons can be learnt from the work completed:

- The type and tonnage of the rail traffic can have an effect on the loads imposed onto a spandrel wall. The inter-relationship between the structural configuration and axle patterns and loading is critical with respect to the load being transferred to the spandrel wall. It has been demonstrated through analysis that the HTA freight wagon is significantly more aggressive than the other types of freight traffic operating on the network.

- Environmental factors have been observed to have an influence on previously cracked spandrel walls. This was observed (with structural monitoring) during a particularly cold spell in Scotland during December 2010.

- A risk based qualitative assessment tool has been developed with a view to understand the likely susceptibility of a masonry arch to spandrel wall defects. The tool can also consider the impact of change. *Note: this tool is currently in a beta version and subject to a trialling and calibration programme.*

- There are correlations between structural forms / configurations and the resulting spandrel wall defects that may occur. This has been corroborated by the review of examination data, the site visits undertaken, and the 3D modelling work undertaken. The structural form / configuration is a key parameter within the developed risk based assessment tool.

- Pattress ties and plates can be an effective mitigation measure for spandrel wall related defects. However, the provision and location of the ties / plates is key to their effectiveness.

- The implementation of a concrete trough at Crawick and Enterkin Burn Viaducts has been effective in curtailing further spandrel wall movement. This was demonstrated with the structural monitoring programme completed for these structures.

- From the asset review undertaken (about 1090 arches), approximately a quarter of the bridges considered have previously been strengthened. It may therefore be proven that although a large number of spandrel related defects have been identified, the past strengthening has mitigated a significant percentage.

- Whilst a significant number of spandrel wall defects were identified during a review of the Network Rail masonry arch bridge stock, only one structure was deemed to be of immediate concern in respect to the operational railway.

- Future entries within the SCMI database would benefit from recording spandrel wall strengthening.

1. Foreword

There have been several structural failures of spandrel walls over the last few years. Although there were no direct consequences from each of these incidents, each one has been largely unpredictable and had the potential to cause a serious accident. Network Rail subsequently put in place a staged action plan to manage the risk.

To support the implementation of this action plan, Network Rail requested that Mott MacDonald work with Giffords and potentially other acknowledged experts from academia, to provide technical advice to Network Rail and carry out research work on the stability of spandrel walls of masonry arch bridges.

The works have been undertaken in stages with identified hold points to complement / service the action plan and to facilitate the structured development of the research work. The commission has drawn upon the findings of historical, current and planned masonry bridge research being undertaken on behalf of Network Rail, CIRIA and other related published works such as the assessment of dry stone walls etc.

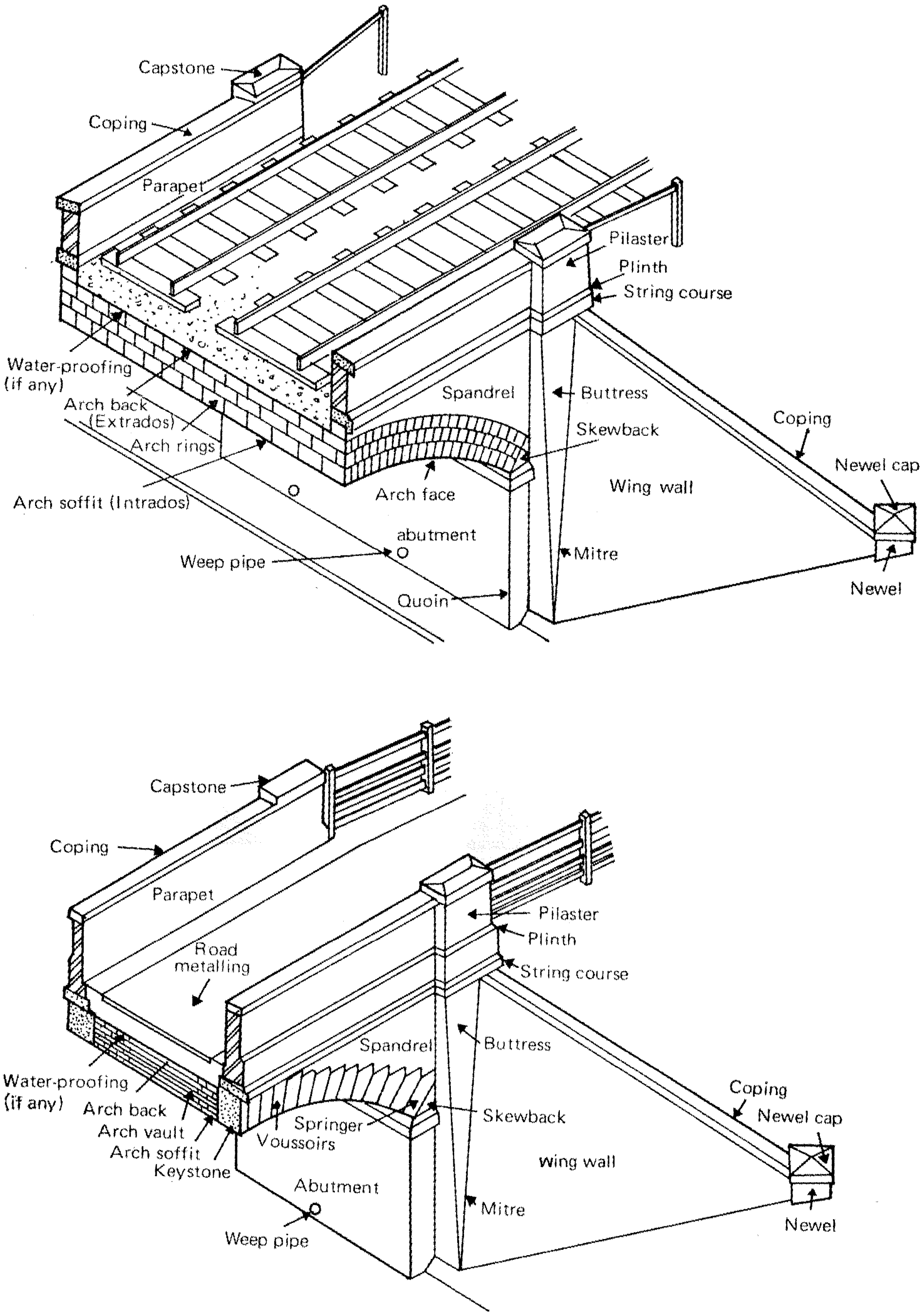
A hold point within the study has been identified for the end of March 2012, coinciding with approximately two years of work undertaken. This document captures the lessons learnt at this stage, building upon the knowledge gained through the various project stages.

1.1 Background to Study

The study commenced in February 2010, following the spandrel wall issues associated with Enterkin Burn Viaduct in Scotland. The following work has been completed to date:

- Review of a sample of the Network Rail masonry arch underbridge asset
- Structural monitoring for a range of masonry arch underbridges
- Parametric modelling using 3D finite element analysis
- Non linear finite element analysis
- Development of Briefing Notes for dissemination to Network Rail
- Development of a risk based qualitative assessment tool
- (Early discussions with Bath University)

Figure 1.1: Structural element terminology



Source: CIRIA C656 Masonry arch bridges – condition, appraisal and remedial treatment

2. Types of Failure

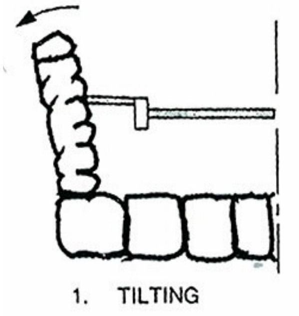
A number of primary failure modes have been identified for spandrel walls. This section provides an overview of these observed modes, and the key features to look for in the identification of such failure types.

2.1 Tilting

This defect is the **forward rotation** of the spandrel wall.

Figure 2.1: Tilting failure

Source: Mott MacDonald, March 2010



Source: CIRIA C656

A key clue to the presence of a tilting defect can be the leaning / mis-alignment of handrailing and / or the stringcourse.

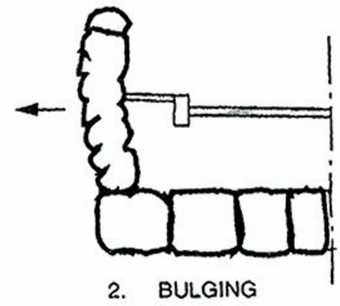
This type of defect can be relevant to all masonry arch bridges, but in particular those structures with significant cover above the arch barrel.

2.2 Bulging

This defect is the **bulging** or **distortion** of the spandrel wall.

Figure 2.2: Bulging failure

Source: Mott MacDonald, March 2010



Source: CIRIA C656

As for the tilting defect, a key clue to the presence of this defect can be the leaning / mis-alignment of handrailing and / or the stringcourse.

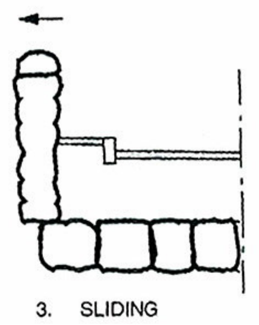
This type of defect can be relevant to all masonry arch bridges, but in particular those structures with significant cover above the arch barrel, or on a curve.

2.3 Sliding

This defect is the **lateral movement** or **oversailing** of the spandrel wall above the arch barrel.

Figure 2.3: Sliding failure

Source: Mott MacDonald, March 2010



Source: CIRIA C656

This defect is characterised by the lateral displacement of brickwork above the arch barrel. The defect can also occur by the lateral displacement of brickwork within the arch face ring.

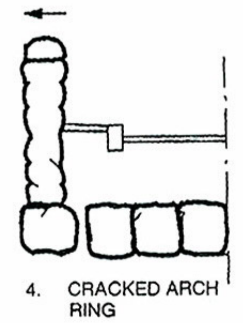
This type of defect can be relevant to all masonry arch bridges.

2.4 Cracked Arch Ring

This defect is a **longitudinal crack** within the arch barrel, located below the spandrel wall.

Figure 2.4: Cracked arch ring failure

Source: Mott MacDonald, March 2010



Source: CIRIA C656

The key clue to look for is evidence of cracking within the arch barrel, including sheared brickwork and leachate / seepage staining.

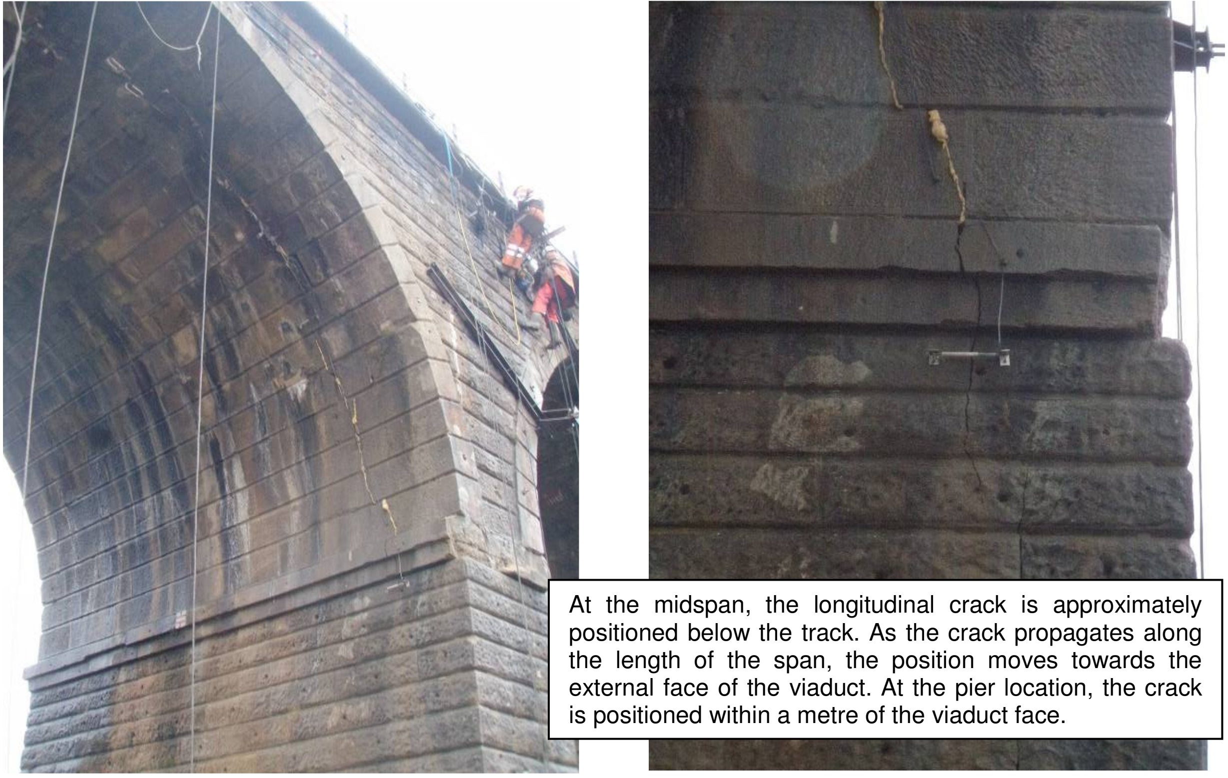
This type of defect can be relevant to all masonry arch bridges, but in particular those structures with a material change between the voussoir and the arch barrel.

2.5 Observed Behaviour

An additional mode of failure was highlighted during a recent Network Rail site visit in Scotland. The defect was observed on stone viaducts, constructed from voussoir sections, such as Crawick Viaduct shown in the photographs below.

The relative stiffness of the arch barrel and spandrel wall will vary across the span length, and this discontinuity has manifested in the formation of significant cracking along the joints between the voussoirs. Whereas a brick barrel will have numerous joints to accommodate the torsional effects, the long voussior stones (and therefore lack of joints) will cause the cracking to develop in a saw tooth arrangement at the joints between adjacent voussoirs.

Figure 2.5: Cracks between voussoirs, Crawick Viaduct, Scotland



At the midspan, the longitudinal crack is approximately positioned below the track. As the crack propagates along the length of the span, the position moves towards the external face of the viaduct. At the pier location, the crack is positioned within a metre of the viaduct face.

Source: Mott MacDonald, March 2010

At this stage, this mechanism is not yet fully understood.

2.6 Environmental Factors

During December 2010, following a prolonged period of cold weather and significant drop in the temperature, crack movements were detected by the monitoring equipment at Slateford Viaduct, Scotland. The movements occurred over a 4 to 5 hour period, and the timing of the movements aligned with the significant drop in temperature. The crack movement was subsequently attributed to the cold weather, and possible frost heave effects. The crack movement has since stabilised.

This has demonstrated that the **environmental conditions can have a significant impact on the performance of a spandrel wall**, and can be characterised by a number of parameters:

- The extreme of temperatures experienced by a bridge
- The location of the bridge, e.g. rural, urban etc.
- The bridge drainage, considering the effectiveness of the waterproofing and drainage systems (e.g. downpipes, gulleys etc.)

2.7 Key Criteria

At this stage of the study, **key parameters have been identified that can be considered critical with respect to the likelihood of spandrel wall related defects occurring within masonry arch underbridges.**

An assigned level of risk, based on the knowledge gained, has been attributed to the parameters considered. This is summarised in the table below:

Parameters considered and assigned level of risk

Parameter	Type of Parameter	Determining Method	Level of Risk
Type of rail traffic	Applied loading	Quantitative	High
Tonnage of rail traffic	Applied loading	Qualitative	High
Number of spans	Geometrical	Quantitative	High
Material discontinuities	Material	Qualitative	High
Horizontal track alignment	Geometrical	Quantitative	High
Existing spandrel defects	Condition	Qualitative	High
Environment / drainage	Environmental	Qualitative	High / Medium
Span length	Geometrical	Quantitative	Medium
Pier geometry	Geometrical	Quantitative	Medium
Vertical track alignment	Geometrical	Quantitative	Medium
Parapet height	Geometrical	Quantitative	Medium
Track curvature	Geometrical	Qualitative	Medium
Backing material (if any)	Geometrical	Qualitative	Medium / Low
Speed of rail traffic	Applied loading	Semi-quantitative	Low *
Skew angle	Geometrical	Quantitative	Low

Source: Network Rail / Mott MacDonald / Giffords (part of Ramboll), November 2011

* subject to review.

The parameters considered and the level of risk assigned have been used in the development of a qualitative risk based assessment tool as described within Section 3.

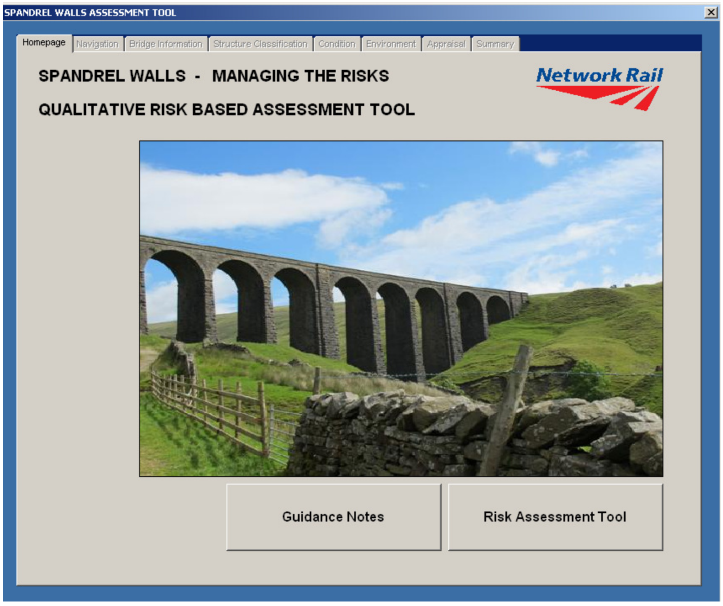
3. Assessment Tool

One of the key outputs from the Network Rail action plan, was the development of a **qualitative risk based assessment tool**. The tool has been developed using knowledge gained to date, and from works undertaken including:

- Review of Network Rail's masonry arch underbridge asset
- Structural monitoring of masonry arch underbridges
- Parametric / validation modelling using linear 3D finite element analysis
- Non linear finite element analysis

The risk assessment process is designed for use by Network Rail Engineers.

Figure 3.1: User interface – Qualitative Risk Based Assessment Tool



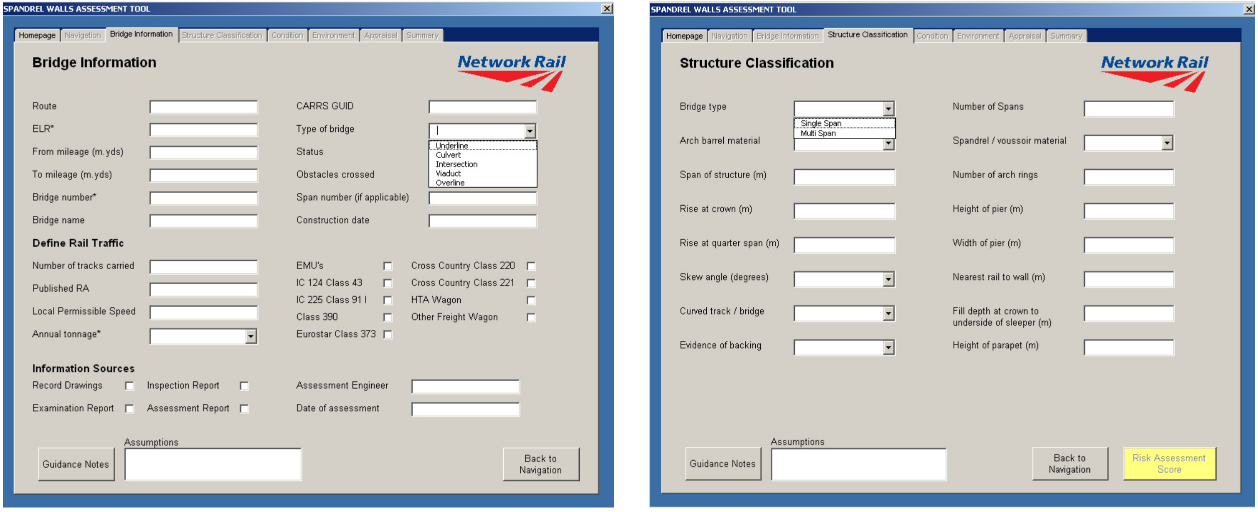
The basis of the tool considers **the system** by which the management of an underbridge asset can be categorised, primarily:

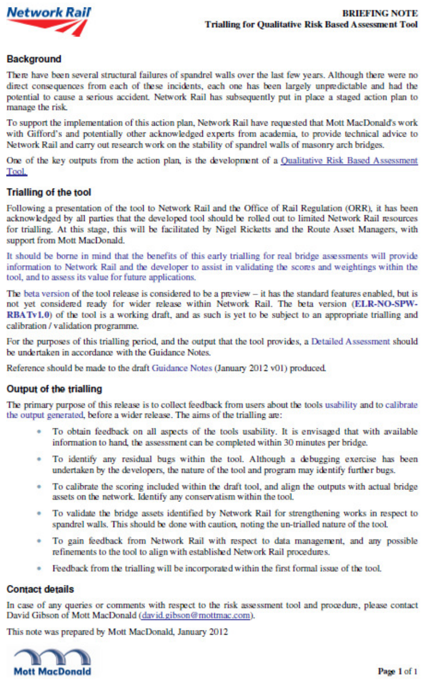
- Operations (e.g. speed, volume, laden / unladen)
- Trains / vehicles (e.g. axle loads / spacings, train configurations)
- Trackform (e.g. alignment, ballast depths, track curvature)
- Sub base (e.g. backing material, waterproofing / drainage)
- Superstructure (e.g. arch geometry, materials)
- Substructure (e.g. pier geometry / stiffness) and foundations

The risk assessment tool will provide a **risk score** based on the above parameters for a specific masonry arch bridge. The user is able to determine a risk score under **steady state conditions**, but also consider the impact of introducing a **change**, e.g. a change to freight traffic.

The tool will also provide **recommended actions** to Network Rail, dependent on the risk score generated.

Figure 3.2: Screen shots from tool





Network Rail

BRIEFING NOTE
Trialling for Qualitative Risk Based Assessment Tool

Background

There have been several structural failures of spandrel walls over the last few years. Although there were no direct consequences from each of these incidents, each one has been largely unpredictable and had the potential to cause a serious accident. Network Rail has subsequently put in place a staged action plan to manage the risk.

To support the implementation of this action plan, Network Rail have requested that Mott MacDonald's work with Gifford's and potentially other acknowledged experts from academia, to provide technical advice to Network Rail and carry out research work on the stability of spandrel walls of masonry arch bridges.

One of the key outputs from the action plan, is the development of a Qualitative Risk Based Assessment Tool.

Trialling of the tool

Following a presentation of the tool to Network Rail and the Office of Rail Regulation (ORR), it has been acknowledged by all parties that the developed tool should be rolled out to limited Network Rail resources for trialling. At this stage, this will be facilitated by Nigel Ricketts and the Route Asset Managers, with support from Mott MacDonald.

It should be borne in mind that the benefits of this early trialling for real bridge assessments will provide information to Network Rail and the developer to assist in validating the scores and weightings within the tool, and to assess its value for future applications.

The beta version of the tool release is considered to be a preview – it has the standard features enabled, but is not yet considered ready for wider release within Network Rail. The beta version (**ELR-NO-SPW-RBATv1.0**) of the tool is a working draft, and as such is yet to be subject to an appropriate trialling and calibration / validation programme.

For the purposes of this trialling period, and the output that the tool provides, a Detailed Assessment should be undertaken in accordance with the Guidance Notes.

Reference should be made to the draft Guidance Notes (January 2012 v01) produced.

Output of the trialling

The primary purpose of this release is to collect feedback from users about the tools usability and to calibrate the output generated, before a wider release. The aims of the trialling are:

- To obtain feedback on all aspects of the tools usability. It is envisaged that with available information to hand, the assessment can be completed within 30 minutes per bridge.
- To identify any residual bugs within the tool. Although a debugging exercise has been undertaken by the developers, the nature of the tool and program may identify further bugs.
- To calibrate the scoring included within the draft tool, and align the outputs with actual bridge assets on the network. Identify any conservatism within the tool.
- To validate the bridge assets identified by Network Rail for strengthening works in respect to spandrel walls. This should be done with caution, noting the un-trialled nature of the tool.
- To gain feedback from Network Rail with respect to data management, and any possible refinements to the tool to align with established Network Rail procedures.
- Feedback from the trialling will be incorporated within the first formal issue of the tool.

Contact details

In case of any queries or comments with respect to the risk assessment tool and procedure, please contact David Gibson of Mott MacDonald (david.gibson@mottmac.com).

This note was prepared by Mott MacDonald, January 2012

Mott MacDonald

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Figure 3.3: Briefing Note – Trialling for Qualitative Risk Based Assessment Tool

Following a presentation of the tool to Network Rail and the Office of Rail Regulation (ORR), it was acknowledged by all parties that the developed tool should be rolled out to Network Rail for trialling. At this stage, this was facilitated by Network Rail and the Route Asset Managers, with support from Mott MacDonald.

It should be borne in mind that the benefits of this early trialling for real bridge assessments will provide information to Network Rail and the developer to assist in validating the scores and weightings within the tool, and to assess its value for future applications.

Guidance Notes were also produced to supplement the beta version of the tool.

The primary purpose of the release is to collect feedback from users about the tools **usability** and to **calibrate the output generated**, before a wider release. The aims of the trialling are:

- To obtain feedback on all aspects of the tools usability. It is envisaged that with available information to hand, the assessment can be completed within 30 minutes per bridge.
- To identify any residual bugs within the tool. Although a debugging exercise has been undertaken by the developers, the nature of the tool and program may identify further bugs.

- To calibrate the scoring included within the draft tool, and align the outputs with actual bridge assets on the network. Identify any conservatism within the tool.
- To validate the bridge assets identified by Network Rail for strengthening works in respect to spandrel walls. This should be done with caution, noting the un-trialled nature of the tool.
- To gain feedback from Network Rail with respect to data management, and any possible refinements to the tool to align with established Network Rail procedures.

4. Current Guidance

At this stage of the study, the following interim guidance and advice has been provided to Network Rail.

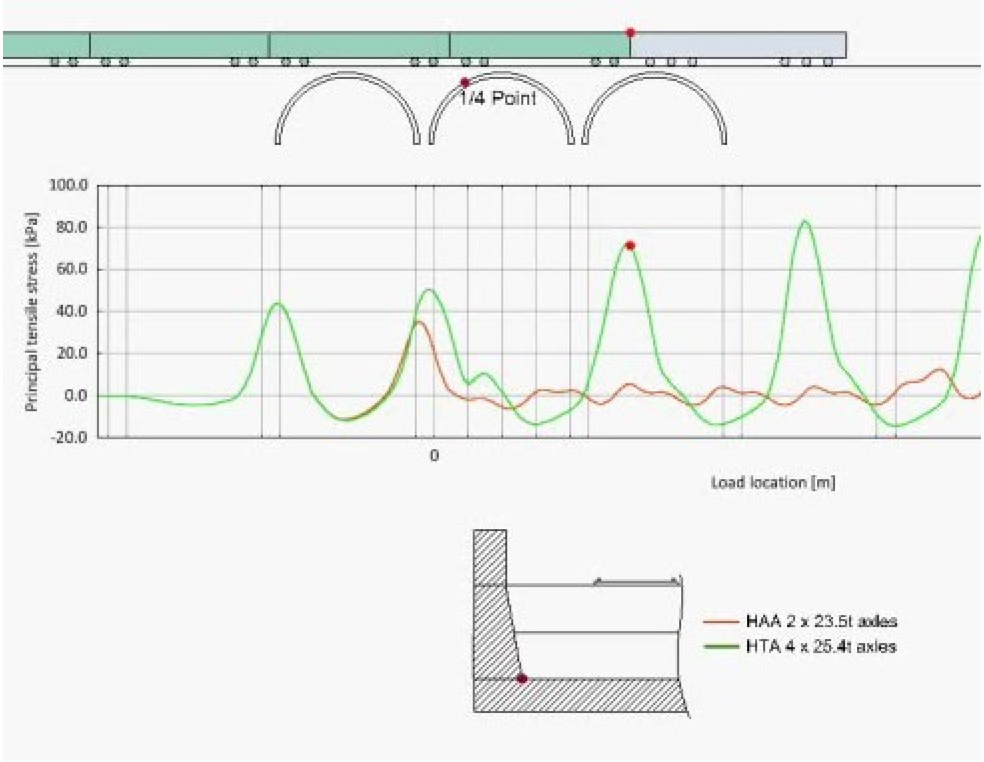
4.1 The Cause

Axle patterns can be critical in understanding the load transferred to the spandrel wall, and the likelihood of defects occurring / worsening.

The worst loading condition for an arch is when a high load is applied in the area of the quarter point of span with no load on the opposite quarter point. As the load traverses across the span a reversal of this effect takes place. The joint between the spandrel and the barrel is then subject to high cyclic stresses increasing the risk of fracture.

It can be seen then that different wagon wheelbase will affect different span lengths to a greater or lesser extent depending on whether the maximum and minimum loading occur simultaneously. In most cases this is the HTA wagon that has a long wheelbase and high load (two adjacent 50 tonne bogies on one side of the arch whilst spanning beyond the far abutment hence leaving the other side of the arch span unloaded).

Figure 4.1: Animation illustrating HTA load effects at the quarter point



Source: Giffords (part of Ramboll), 2011

The criticality of the axle patterns in relation to span is still being studied and further guidance may be provided following the completion of the current analysis work.

A reduction in clearance between the spandrel wall and track position will increase the load on the spandrel wall and the likelihood of spandrel wall defects occurring.

This may seem an obvious statement because the closer the track is to the spandrel wall the greater the forces on it. However, it serves as a reminder to take notice of the track position; is it the same or is it closer at one point caused by a curve or due to realignment i.e. the realignment of a curve onto a straight viaduct.

The outside of curves are particularly vulnerable to spandrel wall defects. For the purposes of this guidance, a curve constitutes a radius of 1500m or below.

The radius of 1500m has been chosen because it is the point at which continuous flange contact occurs and is consistent with track standards so that there is no confusion as to what constitutes curved track.

The radius of the curve can be obtained from the track diagrams.

Spandrel wall defects have also been observed on the inside of curves.

Engineers should be alert to the fact that this can occur and is most likely when track is canted and freight significantly transfers load to the lower rail on the inside of the curve. In most cases track will be canted for higher speeds than achieved by freight and this effect will therefore be magnified.

The likelihood of spandrel wall defects will generally be increased with deep cover levels.

The definition of deep cover levels needs to be understood; the key dimension is from the level of the arch backing to top of ballast. The backing level is usually apparent from angle and / or position of original drainage outlets. In addition, original drawings often show the section change between spandrel and parapet indicating original intended ballast depth.

Not all structures are at greater risk from increased ballast levels - some arch barrels with low cover benefit from an increase in depth. With these a balance has to be struck between risk of either spandrel or arch barrel defects caused by low cover.

4.2 The Defect

Structures with brick barrels and a stone voussoir (e.g. multi span viaducts with tall / slender piers) with spandrel wall defects, typically exhibit longitudinal cracks in the arch intrados between the brick and stone components.

Figure 4.2: Slender multi span viaduct, Arten Gill, Cumbria

The reason for this is that there is a significant change of elasticity and stiffness between the two components / materials coupled with change in bond and difference in weathering. This results in a discontinuity that will concentrate cracking at that point.

Multi span brick viaducts with stocky piers (and spandrel wall defects), typically exhibit lateral displacements of the spandrel wall.

Figure 4.3: ‘Stocky’ type viaduct, Brixton, London

Viaducts with stocky piers are constrained and generally have much less global flexibility and lower deflections. Because of this the change in stiffness between the spandrel and barrel is less significant and the shear forces on the horizontal mortar joint become more dominant hence the spandrel is more likely to be displaced laterally.

Viaducts with stocky piers can be considered to act more like a series of individual spans and where defects occur in adjacent spans the engineer should also consider the possibility that the pier settlement may have occurred.

Multi span viaducts with medium height piers (typically constructed of stone) are less likely to exhibit spandrel wall defects.

Figure 4.4: Viaduct with medium height piers

The proportions of this type of viaduct (e.g. relative stiffness of arch barrel and piers) may be the ‘optimum arrangement’ (with respect to detrimental spandrel wall behaviour), and as such will exhibit fewer spandrel wall defects.

This type of viaduct may also have been constructed from stronger and better bonded material, that is less prone to fracture and shear.

4.3 What to Look For

Viewing the stringcourse along the line of the spandrel walls and along the length of the structure may highlight spandrel wall defects (e.g. bulging or tilting of wall).

Figure 4.5: Mis-aligned stringcourse, Burnton Viaduct

The original function of the string course was cosmetic; it was primarily there to disguise the initial deflection that occurred in the arch on striking the centring. On many single short span arches this was unnecessary but the string course was retained as an architectural feature.

By viewing along the string course any bulging or tilting of the spandrel can be easily seen. Often there is also sagging over each span usually a caused by long term creep.

Given the age of rail arches perfect alignment is unlikely and there will be some limited indication of such movements in most arches. However excessive bulging, tilting and potential instability can be easily established using this technique.

Following the asset review (1090 'high risk' arches), 20 to 25% of the structures were subject to previous strengthening work. However, this work did not always appear effective or comprehensive, leading to spandrel wall problems in other parts of the structure.

In some instances, the installation of tie rods and pattress plates has been found to be poor both in terms of provision and location. Spandrel ties need to be located either at the centroid or about the centroid (in the case of multiple ties) of the area of masonry being retained.

In the latter case consideration should be given to linking multiple ties with steel wailings; typically bull head rails were used for this in the past.

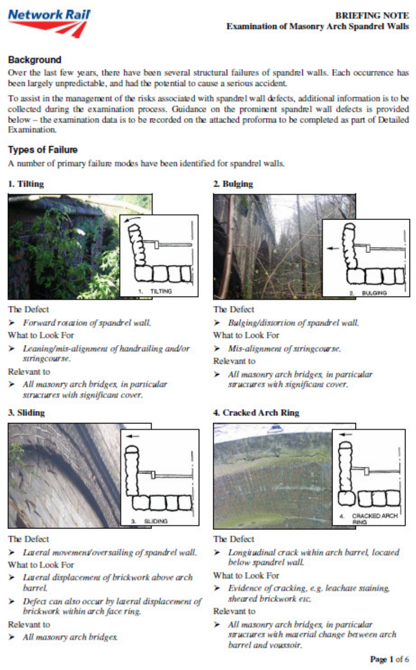
Figure 4.6: Extensive strengthening, Chelsea River Bridge northern approach

In determining where to place ties the level of the arch backing needs to be established so that the true shape of the spandrel and hence its centroid can be determined. If this is not done there is a risk of tying through the backing and producing a stress concentration. This will occur at the level of the backing which results in further fracture and continued movement of the spandrel above this level.

Note: the word centroid above refers to the geometric centroid; the centroid of forces can be assumed to approximate to this unless the detached spandrel is deep or a large section of masonry as in a high viaduct. In which case a more detailed assessment to establish the forces acting and enable the design and location of ties to be determined.

4.4 Briefing Note for Examiners

To assist with the management of the risks associated with spandrel wall defects, a Briefing Note was developed and disseminated to Network Rail during mid 2011.



BRIEFING NOTE
Examination of Masonry Arch Spandrel Walls

Background

Over the last few years, there have been several structural failures of spandrel walls. Each occurrence has been largely unpredictable, and had the potential to cause a serious accident.

To assist in the management of the risks associated with spandrel wall defects, additional information is to be collected during the examination process. Guidance on the prominent spandrel wall defects is provided below – the examination data is to be recorded on the attached proforma to be completed as part of Detailed Examination.

Types of Failure

A number of primary failure modes have been identified for spandrel walls.

1. Tilting

The Defect
- *Forward rotation of spandrel wall.*

What to Look For
- *Leaning/mis-alignment of handrailing and/or stringcourse.*

Relevant to
- *All masonry arch bridges, in particular structures with significant cover.*

2. Bulging

The Defect
- *Bulging/distortion of spandrel wall.*

What to Look For
- *Mis-alignment of stringcourse.*

Relevant to
- *All masonry arch bridges, in particular structures with significant cover.*

3. Sliding

The Defect
- *Lateral movement/oversailing of spandrel wall.*

What to Look For
- *Lateral displacement of brickwork above arch barrel.*
- *Defect can also occur by lateral displacement of brickwork within arch face ring.*

Relevant to
- *All masonry arch bridges.*

4. Cracked Arch Ring

The Defect
- *Longitudinal crack within arch barrel, located below spandrel wall.*

What to Look For
- *Evidence of cracking, e.g. leachate staining, sheared brickwork etc.*

Relevant to
- *All masonry arch bridges, in particular structures with material change between arch barrel and voussoir.*

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Figure 4.7: Briefing Note – The Examination of Masonry Arch Spandrel Walls

The Briefing Note was developed for use by Bridge Engineers and Examiners, and provides the following information:

- The types of spandrel wall failure
- Practical interim advice
- Proforma to be completed as part of the Detailed Examination process
- Structural element terminology

The Briefing Note is a ‘live’ document, and will be subject to updates and amendments as further findings and knowledge are gained through the latter stages of the study.

The briefing note is included within Appendix A.

5. Best Practice Mitigation

The following section introduces mitigation measures that can be implemented should spandrel wall behaviour and associated defects warrant Network Rail intervention. Where possible, the guidance below builds upon established best practice and the observations made during the study.

Generally, the management of masonry arch structures should follow established Network Rail asset management procedures, e.g. examination / assessment cycles.

5.1 Temporary Measures

5.1.1 Overview

In the short term, temporary measures can be implemented to mitigate the risk of spandrel wall movement and to safeguard the (operational) railway. These temporary mitigation measures include, but should not be limited to:

- Temporary speed restrictions over the bridge
- Temporary operational restrictions over the bridge, e.g. single track operations or diversions
- Temporary traffic restrictions over the bridge, e.g. weight restrictions
- Special / sensitive examinations
- Manual monitoring using traditional surveying techniques
- Structural monitoring using automated instrumentation. Refer to Section 5.1.2
- Temporary strengthening works, e.g. external tie bars. Refer to Figure 5.1

Figure 5.1: Crawick Viaduct, Scotland

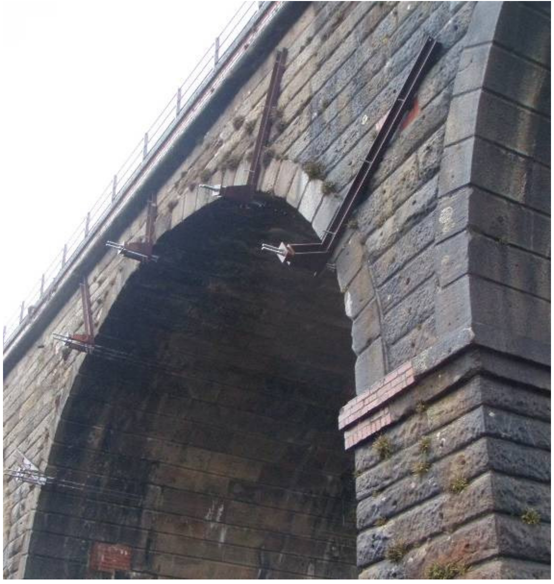


Figure 5.2: Coldharbour Lane, London

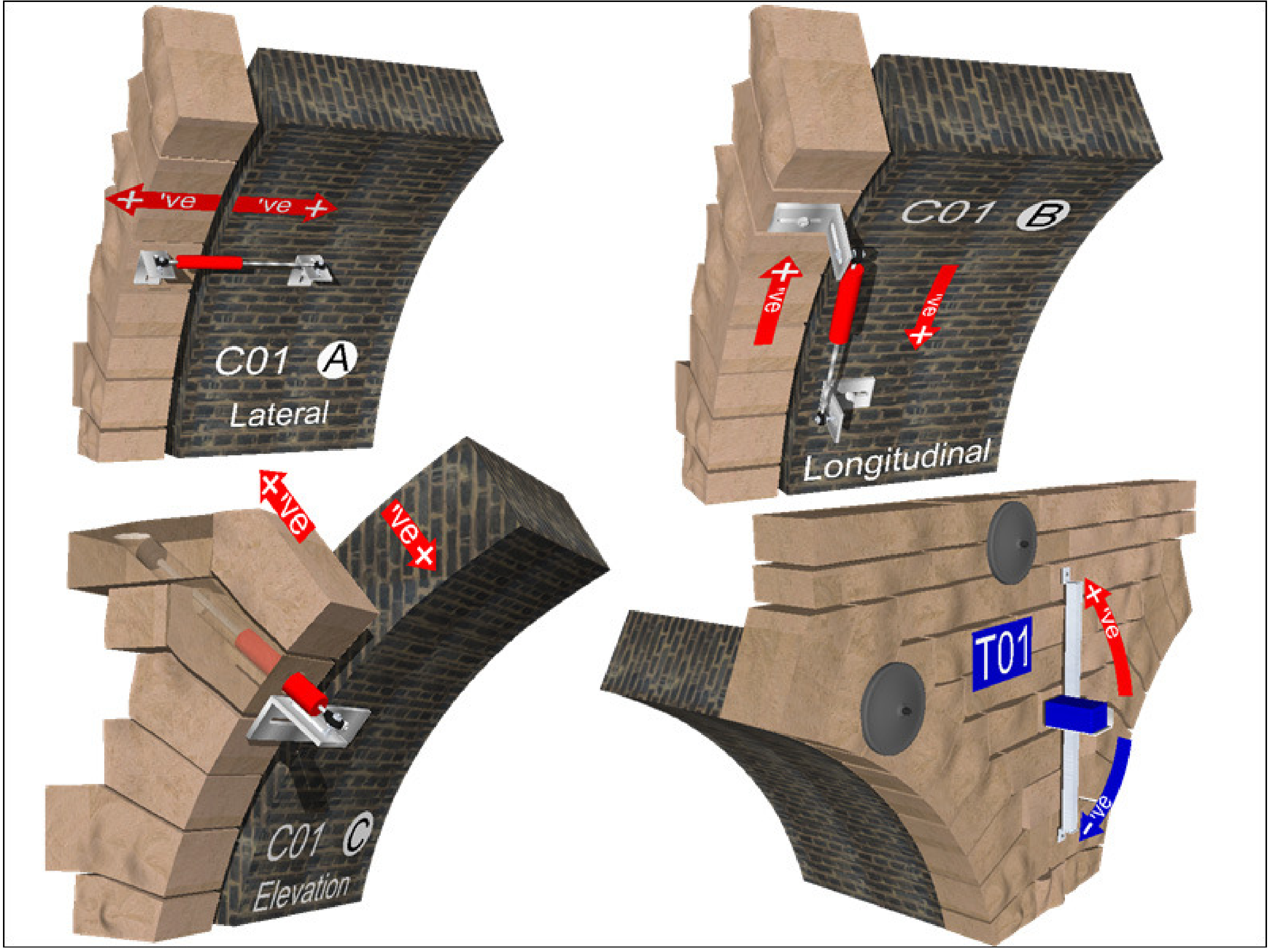
It should be noted that the above is for guidance only, and as such the severity of the spandrel wall issues will dictate the temporary mitigation measures employed. The measures that are implemented will generally be determined by the Asset Steward.

5.1.2 Structural Monitoring

To safeguard the operational railway and to understand the nature and behaviour of the spandrel wall defect(s) observed, a programme of structural monitoring may be deemed appropriate.

During the Spandrel Walls study, a monitoring programme was developed with an established Contractor. The specification was designed such that spandrel wall separation could be monitored in three dimensions, providing static and dynamic response data for on-line, real-time reporting. The monitoring instrumentation is diagrammatically represented in Figure 5.3 below.

Figure 5.3: Displacements and rotations captured by monitoring instrumentation



Source: Datum Monitoring, February 2010

The data collected for a bridge can be used to safeguard any immediate risk to the operational railway (e.g. by establishing ‘trigger’ levels), and to better understand spandrel wall behaviour over the short term (e.g. the passage of a train) or over a longer period (e.g. due to seasonal / creep effects).

An established monitoring programme can also validate the effectiveness of permanent strengthening works post implementation.

5.2 Permanent Measures

5.2.1 Pattress Plates and Ties

Historically, the installation of tie rods and pattress plates can be been found to be poor both in terms of provision and location.

However, the provision of appropriately located tie rods and pattress plates can be an effective method of curtailing further spandrel wall movement.

During the design of such a scheme, the following should be considered (it should be noted that this list is not exhaustive):

- Wherever possible, and appropriate, the designer shall adopt the **Network Rail Standard Design Details** (e.g. NR/CIV/SD/120 and NR/CIV/SD/121 for pattress ties and plates).

- Spandrel ties need to be located either at the centroid or about the centroid (in the case of multiple ties) of the area of masonry being retained. In the latter case consideration should be given to linking multiple ties with steel wailings; typically bull head rails were used for this in the past. Refer to Figure 5.4 overleaf.

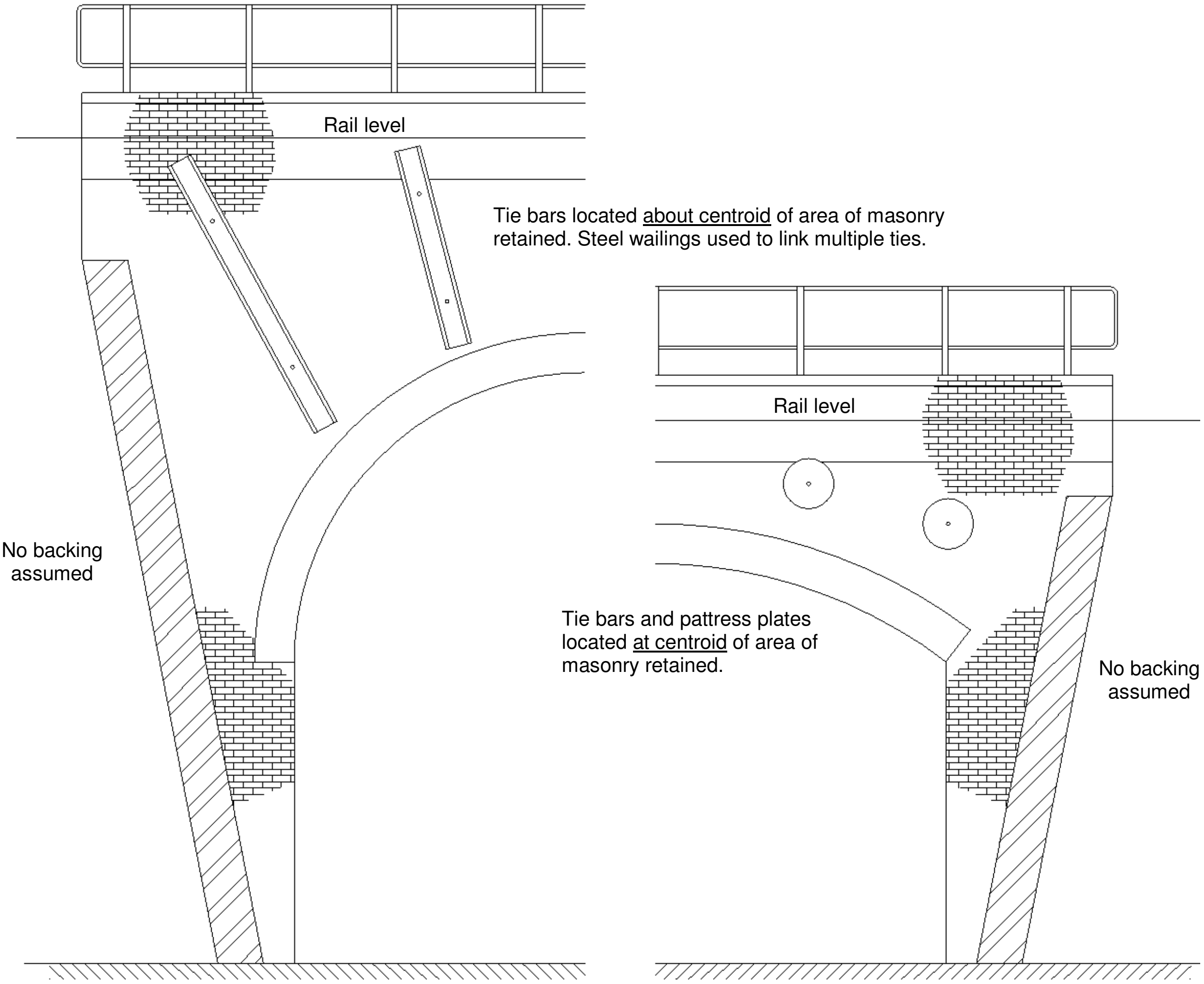
- In determining where to place ties the level of the arch backing needs to be established so that the true shape of the spandrel and hence its centroid can be determined. If this is not done there is a risk of tying through the backing and producing a stress concentration. This will occur at the level of the backing which results in further fracture and continued movement of the spandrel above this level.

  Note: the word centroid above refers to the geometric centroid; the centroid of forces can be assumed to approximate to this unless the detached spandrel is deep or a large section of masonry as in a high viaduct. In which case a more detailed assessment to establish the forces acting and enable the design and location of ties to be determined.

- The tie bars should have sufficient cross sectional area to avoid large strains, and therefore ensure effective restraint is applied at the spandrel wall / pattress plate interface.

- The interface between the new ties / plates and the existing infrastructure, such as buried services, stringcourses etc. requires careful consideration.

Figure 5.4: Positioning of spandrel ties / wailing beams



Source: Mott MacDonald, March 2012

5.2.2 Concrete Saddle

This method of strengthening is implemented to essentially ensure that the existing (defective) spandrel walls are redundant. The new concrete trough provides lateral support to the ballast / fill material, and is usually only implemented on multi span structures that suffer from severe or extensive spandrel wall defects that are beyond simpler repair solutions.

Recent examples were implemented at Crawick and Enterkin Burn Viaducts in Scotland.

Figure 5.5: Construction of concrete saddle at Enterkin Burn, Scotland

Source: Network Rail, 2011

6. Key Lessons Learnt

At this stage of the study, the following key lessons can be learnt from the work completed and the knowledge gained:

- The type and tonnage of the rail traffic can have an effect on the loads imposed onto a spandrel wall. The inter-relationship between the structural configuration and axle patterns and loading is critical with respect to the load being transferred to the spandrel wall. It has been demonstrated through analysis that the HTA freight wagon is significantly more aggressive than the other types of freight traffic operating on the network.

- Environmental factors have been observed to have an influence on previously cracked spandrel walls. This was observed (with structural monitoring) during a particularly cold spell in Scotland during December 2010.

- A risk based qualitative assessment tool has been developed with a view to understand the likely susceptibility of a masonry arch to spandrel wall defects. The tool can also consider the impact of change. *Note: this tool is currently in a beta version and subject to a trialling and calibration programme.*

- There are correlations between structural forms / configurations and the resulting spandrel wall defects that may occur. This has been corroborated by the review of examination data, the site visits undertaken, and the 3D modelling work undertaken. The structural form / configuration is a key parameter within the developed risk based assessment tool.

- Pattress ties and plates can be an effective mitigation measure for spandrel wall related defects. However, the provision and location of the ties / plates is key to their effectiveness.

- The implementation of a concrete trough at Crawick and Enterkin Burn Viaducts has been effective in curtailing further spandrel wall movement. This was demonstrated with the structural monitoring programme completed for these structures.

- From the asset review undertaken (about 1090 arches), approximately a quarter of the bridges considered have previously been strengthened. It may therefore be proven that although a large number of spandrel related defects have been identified, the past strengthening has mitigated a significant percentage.

- Whilst a significant number of spandrel wall defects were identified during a review of the Network Rail masonry arch bridge stock, only one structure was deemed to be of immediate concern in respect to the operational railway.

- Future entries within the SCMI database would benefit from recording spandrel wall strengthening.

Appendix A. Briefing Note for Examiners

Background

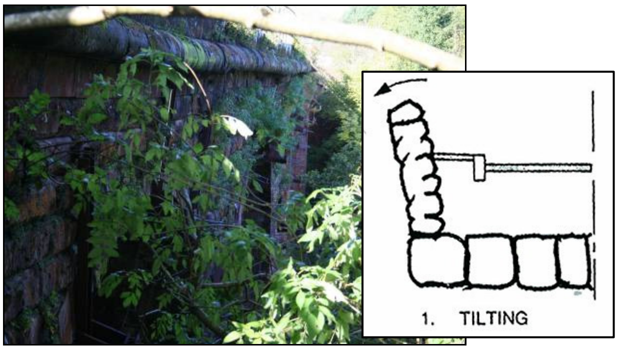
Over the last few years, there have been several structural failures of spandrel walls. Each occurrence has been largely unpredictable, and had the potential to cause a serious accident.

To assist in the management of the risks associated with spandrel wall defects, additional information is to be collected during the examination process. Guidance on the prominent spandrel wall defects is provided below – the examination data is to be recorded on the attached proforma to be completed as part of Detailed Examination.

Types of Failure

A number of primary failure modes have been identified for spandrel walls.

1. Tilting



The Defect

- *Forward rotation of spandrel wall.*

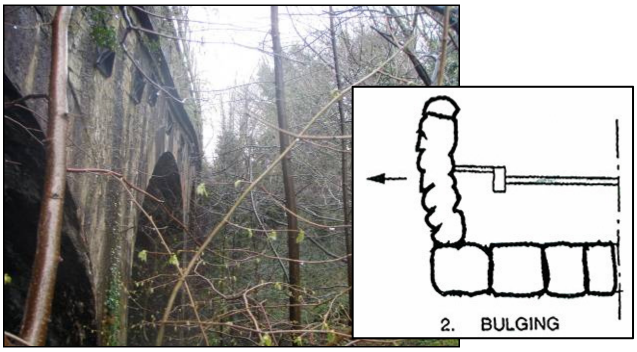
What to Look For

- *Leaning/mis-alignment of handrailing and/or stringcourse.*

Relevant to

- *All masonry arch bridges, in particular structures with significant cover.*

2. Bulging



The Defect

- *Bulging/distortion of spandrel wall.*

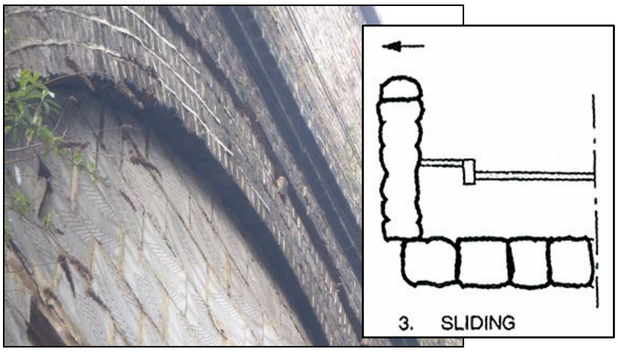
What to Look For

- *Mis-alignment of stringcourse.*

Relevant to

- *All masonry arch bridges, in particular structures with significant cover.*

3. Sliding



The Defect

- *Lateral movement/oversailing of spandrel wall.*

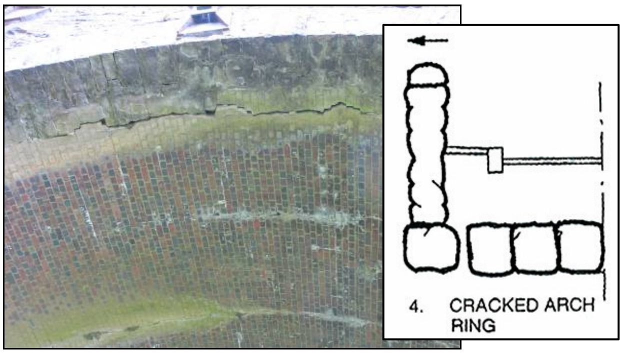
What to Look For

- *Lateral displacement of brickwork above arch barrel.*
- *Defect can also occur by lateral displacement of brickwork within arch face ring.*

Relevant to

- *All masonry arch bridges.*

4. Cracked Arch Ring



The Defect

- *Longitudinal crack within arch barrel, located below spandrel wall.*

What to Look For

- *Evidence of cracking, e.g. leachate staining, sheared brickwork etc.*

Relevant to

- *All masonry arch bridges, in particular structures with material change between arch barrel and voussoir.*

Practical Interim Advice

Note: this is emerging guidance, and is subject to further work.

1. The outside of curves are particularly vulnerable to spandrel wall defects. For the purposes of this guidance, a curve constitutes a radius of 1500m or below.

   The radius of 1500m has been chosen because it is the point at which continuous flange contact occurs and is consistent with track standards so that there is no confusion as to what constitutes curved track.

   The radius of the curve can be obtained from the track diagrams.

2. Spandrel wall defects have also been observed on the inside of curves.

   Engineers should be alert to the fact that this can occur and is most likely when track is canted and freight significantly transfers load to the lower rail on the inside of the curve. In most cases track will be canted for higher speeds than achieved by freight and this effect will therefore be magnified

3. Structures with brick barrels and a stone voussoir (typically multi span viaducts with tall / slender piers) exhibit longitudinal cracks in the arch intrados between the brick and stone components.

   The reason for this is that there is a significant change of elasticity and stiffness between the two components / materials coupled with change in bond and difference in weathering. This results in a discontinuity that will concentrate cracking at that point.

4. Multi span brick viaducts with stocky piers typically exhibit lateral displacements of the spandrel wall.

   Viaducts with stocky piers are constrained and generally have much less global flexibility and lower deflections. Because of this the change in stiffness between the spandrel and barrel is less significant and the shear forces on the horizontal mortar joint become more dominant hence the spandrel is more likely to be displaced laterally.

   Viaducts with stocky piers can be considered to act more like a series of individual spans and where defects occur in adjacent spans the engineer should also consider the possibility that the pier settlement may have occurred.

5. Multi span viaducts with medium height piers (typically constructed of stone) are less likely to exhibit spandrel wall defects.

   This is not yet fully understood but may be a similar to (4) above but constructed from stronger better bonded material less prone to fracture and shear. Further work may provide a better understanding of this at which time this will be updated.

6. A reduction in clearance between the spandrel wall and track position will increase the load on the spandrel wall and the likelihood of spandrel wall defects occurring.

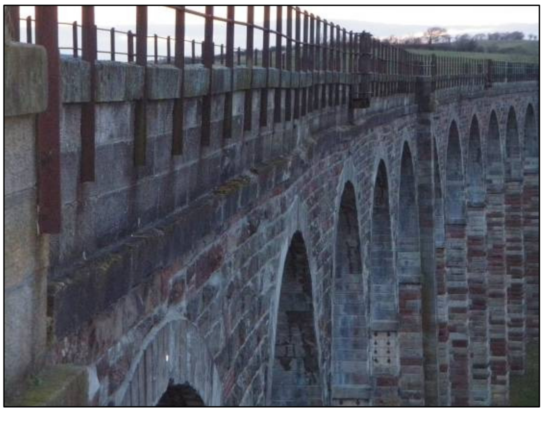
   This may seem an obvious statement because the closer the track is to the spandrel wall the greater the forces on it. However, it serves as a reminder to take notice of the track position; is it the same or is it closer at one point caused by a curve or due to realignment i.e. the realignment of a curve onto a straight viaduct.

7. The likelihood of spandrel wall defects will generally be increased with deep cover levels.

   The definition of deep cover levels needs to be understood; the key dimension is from the level of the arch backing to top of ballast. The backing level is usually apparent from angle and / or position of original drainage outlets. In addition, original drawings often show the section change between spandrel and parapet indicating original intended ballast depth.

   Not all structures are at greater risk from increased ballast levels - some arch barrels with low cover benefit from an increase in depth. With these a balance has to be struck between risk of either spandrel or arch barrel defects caused by low cover.

8. Viewing the stringcourse along the line of the spandrel walls and along the length of the structure may highlight spandrel wall defects (e.g. bulging or tilting of wall).



   The original function of the string course was cosmetic; it was primarily there to disguise the initial deflection that occurred in the arch on striking the centring. On many single short span arches this was unnecessary but the string course was retained as an architectural feature.

   By viewing along the string course any bulging or tilting of the spandrel can be easily seen. Often there is also sagging over each span usually a caused by long term creep. Given the age of rail arches perfect alignment is unlikely and there will be some limited indication of such movements in most arches. However excessive bulging, tilting and potential instability can be easily established using this technique.

9. Following the asset review (1090 'high risk' arches), 20 to 25% of the structures were subject to previous strengthening work. However, this work did not always appear effective, and may also lead to spandrel wall problems in other parts of the structure.

   The installation of tie rods and pattress plates has been found to be poor both in terms of provision and location. Spandrel ties need to be located either at the centroid or about the centroid (in the case of multiple ties) of the area of masonry being retained.

   Example of poor pattress tie and plate provision

   In the latter case consideration should be given to linking multiple ties with steel wailings; typically bull head rails were used for this in the past.

   In determining where to place ties the level of the arch backing needs to be established so that the true shape of the spandrel and hence its centroid can be determined. If this is not done there is a risk of tying through the backing and producing a stress concentration. This will occur at the level of the backing which results in further fracture and continued movement of the spandrel above this level.

   Note: the word centroid above refers to the geometric centroid; the centroid of forces can be assumed to approximate to this unless the detached spandrel is deep or a large section of masonry as in a high viaduct. In which case a more detailed assessment to establish the forces acting and enable the design and location of ties to be determined.

10. Axle patterns can be critical in understanding the load transferred to the spandrel wall, and the likelihood of defects occurring / worsening.

    The worst loading condition for an arch is when a high load is applied in the area of the quarter point of span with no load on the opposite quarter point. As the load traverses across the span a reversal of this effect takes place. The joint between the spandrel and the barrel is then subject to high cyclic stresses increasing the risk of fracture.

    It can be seen then that different wagon wheelbase will affect different span lengths to a greater or lesser extent depending on whether the maximum and minimum loading occur simultaneously. In most cases this is the HTA 100tonne wagon that has a long wheelbase and high load (two adjacent 50 tonne bogies on one side of the arch whilst spanning beyond the far abutment hence leaving the other side of the arch span unloaded).

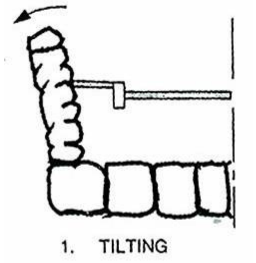
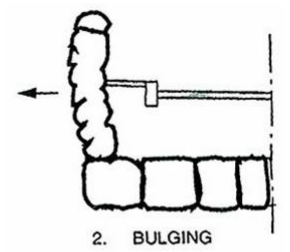
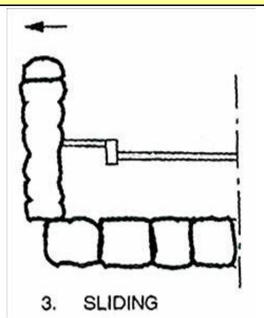
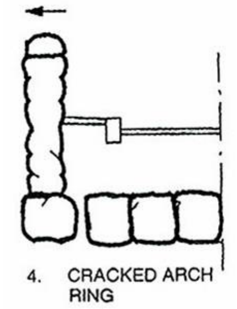
    The criticality of the axle patterns in relation to span is still being studied and further guidance will be provided following the completion of the current analysis work.

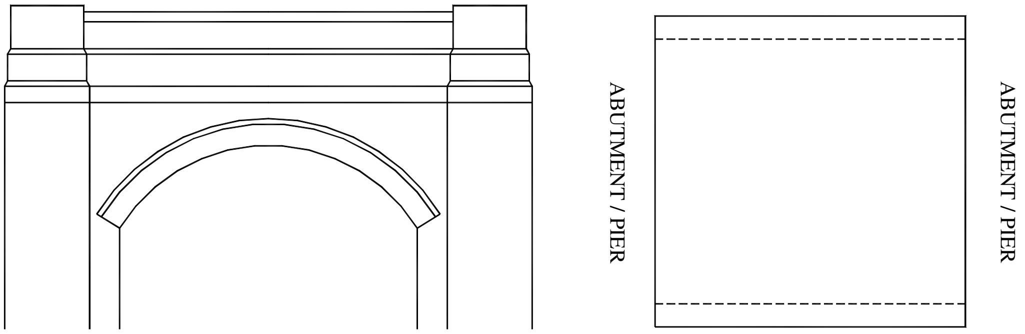
Network Rail	**BRIDGE & STRUCTURE EXAMINATION REPORT** **SPANDREL WALLS**	

ELR:		Mileage:	m	yds	ch	Struct. Ref	

To be Completed as part of Detailed Examination

A. Spandrel Wall Defects Identified

 1. TILTING	 2. BULGING	 3. SLIDING	 4. CRACKED ARCH RING

Location and Extent of Defect(s) – Elevation & Plan	Details of Defect
	• Up side • Dn side • Magnitude of defect e.g. crack width, over sail etc.

Have the previous Detailed Examination Reports been reviewed prior to the examination?	Yes / No
Has the defect(s) condition significantly changed since the last examination? If yes, provide details below…	Yes / No

B. Enter Data as Appropriate

Inaccessible Parts		Previous Strengthening	
Tell Tales / Grout Tabs		Tactile Examination	
Examined Under Live Load			

C. Further Comments

D. Further Action Required

Review at next Detailed Examination		Defect Photograph
Review defect(s) during Visual Examination		
Recommend for Sensitive Examination		
Immediate Action Required (add detail below)...		

Version 01 19/03/2012

Structural Element Terminology

The following terminology has been used in the development of this Briefing Note: