Report No. B1660A/V10/R03
August 2003

ARCHTEC

VERIFICATION OF STRUCTURAL ANALYSIS

ARCHTEC

VERIFICATION OF STRUCTURAL ANALYSIS

CONTROLLED DOCUMENT

Gifford and Partners Document No:	**B1660A/V10/R03**		
Status:	Final	*Copy No:*	
	Name	*Signature*	*Date*
Prepared by:	Carl Brookes		27 August 2003
Checked:	Matthew Collings		27 August 2003
Gifford Approved:	Matthew Collings		27 August 2003

Revision Record					
Rev.	*Date*	*By*	*Summary of Changes*	*Chkd*	*Aprvd*

Cintec International Ltd
Cintec House
11 Goldtops
NEWPORT
NP20 4PH

Gifford and Partners Ltd
Carlton House
Ringwood Road
Woodlands
SOUTHAMPTON
SO40 7HT

ARCHTEC

VERIFICATION OF STRUCTURAL ANALYSIS

C O N T E N T S

Page

EXECUTIVE SUMMARY

Archtec is an innovative system that has been developed for assessing and strengthening masonry arch bridges. In many circumstances it offers considerable advantages over other alternatives and since its creation in 1998 it has been used widely in the United Kingdom on Local Authority owned bridge stock and several projects have also been undertaken overseas. More than 120 bridges have now either been assessed or strengthened using the system.

At the heart of the strengthening system is the method of structural analysis used to assess arch bridge behaviour. This analysis is based on numerical simulation and the Finite/Discrete Element technique using the program ELFEN. The technique, never used before to model arch bridges, enables good prediction of strength and displacement and permits features such as rings in arches, multiple spans, slender piers, aspects of deterioration and strengthening to be fully quantified.

Extensive verification work has been undertaken to confirm the suitability and accuracy of the numerical methods employed, including evaluation against specifically commissioned full-scale tests and published data from tests by others, and against conventional methods of arch assessment.

Further to discussions with various client organisations through the offices of the Bridge Owners Forum (BOF) - Masonry Arch Sub-Group (United Kingdom), this report has been prepared to document the key aspects of the verification work that has been completed. It is intended to facilitate a better understanding of the basis of the system.

The verification undertaken demonstrates that the predictions of behaviour carried out using ELFEN correlate well with the broad range of test results considered and also with conventional methods of arch assessment, where they are directly comparable.

On the basis of this verification and subject to the use of the relevant material properties and parameters upon which the verification has been carried out, the use of ELFEN in the way described to determine the strength of both unstrengthened and Archtec strengthened masonry arch bridges (which are square or near square (up to the order of 20˚ skew)) is considered justified.

Finite/Discrete Element analysis of masonry structures also provides several significant new capabilities over conventional methods of assessment, namely;

- Explicit representation of defects such as ring separation, local distortion and mortar loss is possible and the verification process using ELFEN has established that these can also be reliably modelled.
- Deflections and serviceability behaviour can be predicted. This has not before been possible. The verification process has established that deflections can be reliably predicted using ELFEN and this provides the basis for significant and exciting new capabilities for modelling arch behaviour at serviceability limit states.

1. INTRODUCTION

Archtec is an innovative system that has been developed for assessing and strengthening masonry arch bridges. In many circumstances it offers considerable advantages over other alternatives and since its creation in 1998 it has been used widely in the United Kingdom on Local Authority owned bridge stock. Several projects have also been undertaken overseas in the USA and Australia. More than 120 bridges have now either been assessed or strengthened using the system.

At the heart of the strengthening system is the method of structural analysis used to assess arch bridge behaviour. This analysis is based on numerical simulation and the Finite/Discrete Element technique using the program ELFEN. The technique, never used before to model arch bridges, enables good prediction of strength and displacement and permits features such as rings in arches, multiple spans, slender piers, aspects of deterioration and strengthening to be fully quantified.

Extensive verification work has been undertaken to confirm the suitability and accuracy of the numerical methods employed, including evaluation against specifically commissioned full-scale tests and published data from tests by others, and against conventional methods of arch assessment.

Further to discussions with various client organisations though the offices of the Bridge Owners Forum (BOF)-Masonry Arch Sub-Group (United Kingdom), this report has been prepared to document the key aspects of the verification work which has been undertaken. It is intended to facilitate a better understanding of the basis of the system and assist in its more widespread use.

It follows a report prepared for Railtrack/Network Rail in July 2002 (B1660A/W10/R01)[1] and provides greater detail with respect of the verification process.

2. THE ARCHTEC METHOD OF STRENGTHENING

Archtec has been described as 'Key Hole Surgery' for bridges and comprises retrofitting stainless steel reinforcement around the circumference of the arch barrel; a typical arrangement of reinforcement is illustrated in Figure 2.1. The reinforcement is grouted in to holes drilled in to the bridge with a coring rig from the road surface (refer to Figure 2.2) or, alternatively in the case of multi-span structures, from below.

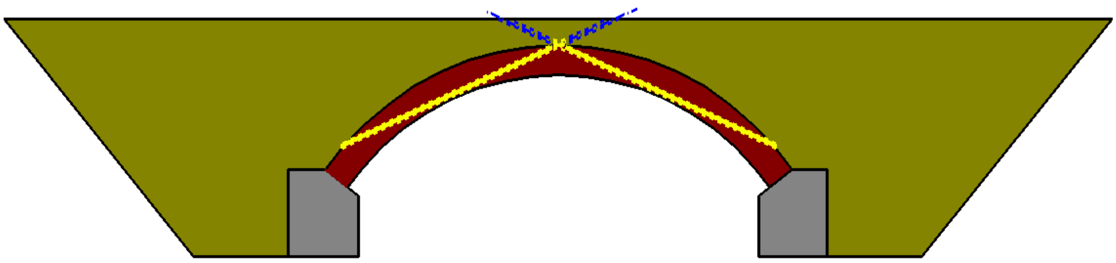


Figure 2.1 Typical Arrangement of Reinforcement
Simplified diagram of a single span with from-above installation

Figure 2.2 Installation using Precisely Aligned Diamond Drilling Coring Equipment

Masonry arches, whilst being one of the oldest forms of bridge are in fact complex structures that are difficult to analyse. Accurate analysis is made more difficult by geometry and material variability. The tool at the heart of the Archtec design process is the computer program ELFEN. Using the Finite/Discrete Element (DE) technique to generically model masonry this software is used to represent the behaviour of arch barrels allowing accurate prediction of structural behaviour, as illustrated in Figure 2.3. Simply, each brick or block is modelled and the contact between them automatically calculated as load is applied.

Arches conventionally fail by the development of four hinges leading to a mechanism. The design basis for the strengthening is to locate the reinforcement so as to provide bending strength at the critical locations thereby resisting the development of the hinges. By providing bending resistance the arch barrel is able to resist the critical loading conditions more efficiently and the peak compressive stresses in the masonry are reduced. A similar procedure is applied to multi-span arches although failure mechanisms and anchor positioning is often more complex.

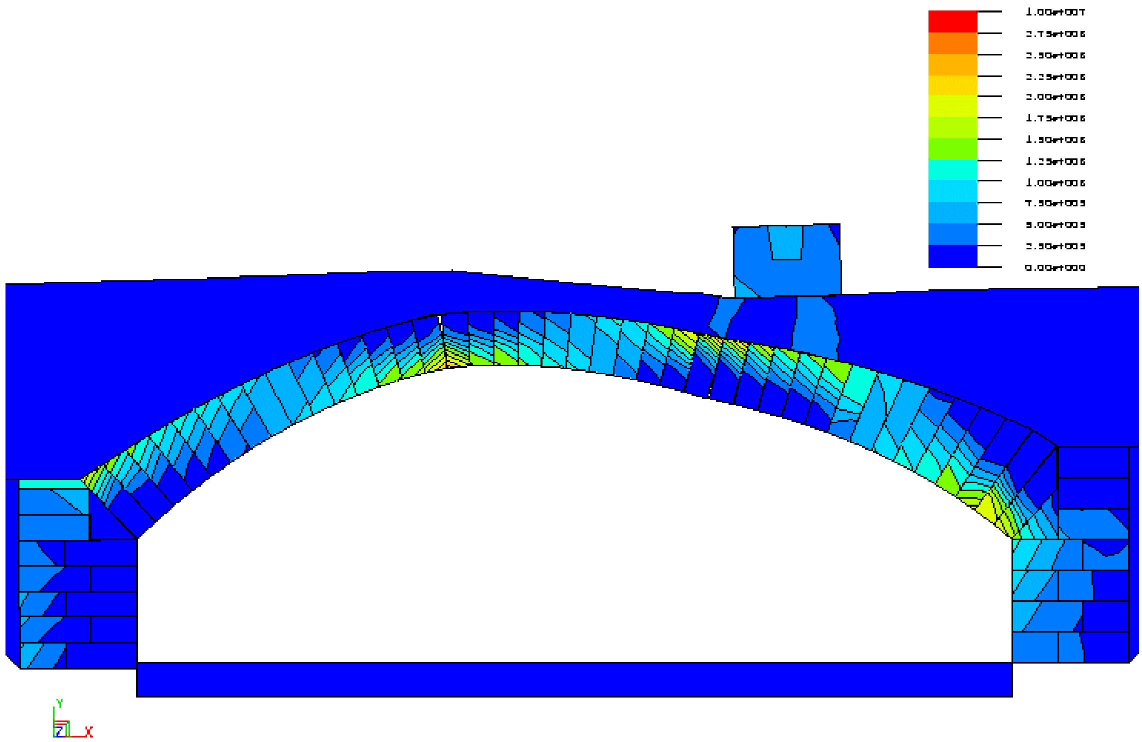


Figure 2.3 Typical Numerical Simulation of the Failure of Masonry Arch
Results shown are Von Mises equivalent stresses

Archtec has been developed by a partnership comprising Cintec International who are responsible for overall project management and also manufacture the anchoring system used, Rockfield Software who produce the ELFEN structural analysis software and Gifford who developed the strengthening concept and provide the engineering design on each individual project.

Although Archtec was originally conceived for efficient, economic and sympathetic strengthening of arches the method of structural analysis also provides accurate strength assessment of existing bridge stock.

3. VERIFICATION PROCESS

The process which has been undertaken to verify the analytical methods employed by Archtec includes a number of key stands as follows:

i) Evaluation against conventional methods of arch assessment

ii) Evaluation against published data from full-scale tests of unstrengthened arches carried out by others, including the LINK funded programme.

iii) Evaluation against full-scale tests by TRL of bridges strengthened by the Archtec method which were specifically commissioned as part of the verification process.

These are covered in the following sections.

Additionally, a philosophy of freezing material parameters for whole series of tests where similar masonry construction has been employed (compressive strength of bricks, mortar type etc.) has been adopted. This makes it impossible to adjust an individual arch analysis within a series without influencing all others. Similarly the analysis of Archtec strengthening follows on from verified and frozen unstrengthened analyses.

4. CONVENTIONAL ARCH STRENGTH ASSESSMENT METHODS

4.1 Overview

The ELFEN Finite/Discrete Element analysis employed at the heart of Archtec forms one of several computer based arch assessment methods each of which is appropriate in different circumstances. Generally more approximate non-computer based approaches to strength assessment, such as the modified MEXE (Military Load Classification (of Civil Bridges) by the Reconnaissance and Correlation Methods) method, have not been included in any comparisons.

The principal, conventional, methods of assessment are reviewed in the following sections.

Comparison of the results of these methods with both ELFEN and tests are included in later sections.

4.2 ARCHIE and ARCHIE-M

Archie[2] originally developed at the University of Dundee in 1983 is perhaps the most popular method of strength assessment for masonry arches after the modified MEXE hand calculation method. The latter, whilst often being fit for purpose for approximate assessments, is somewhat subjective. Running under DOS this computer program implements an improved version of the mechanism analysis first published by Heyman[3] in 1980. The chief improvement was the inclusion of horizontal soil pressures in the formulation. In the past, much work has been under taken to verify this program and it is listed in BA 16[4].

Archie is used to undertake strength assessments by entering idealised bridge geometry along with basic material properties for the component parts of the bridge, namely the barrel, fill and surfacing. Dead loads are automatically generated from the bridge geometry and live load arrangements are user defined including how load is distributed transversely. Generally transverse load distribution is based on BD 21[5].

The solution process uses a modified mechanism method to calculate a line of thrust in the arch under dead and live loads. A routine first establishes the locations of four hinges in the span followed by calculation of reactions and then vector algebra is used to position the resultant line of thrust. The method produces a lower bound solution. In other words, if a load path can be found that lays entirely within the masonry then the modelled arch is capable of sustaining that load even if it is not the true load path.

Although Archie is an excellent tool for first visit strength assessments it has several restrictions that can be important as follows.

i) Displacements cannot be calculated as the solution is derived from force equilibrium calculations alone.

ii) The arch barrel is assumed to be monolithic and, therefore, the behaviour of multi-ring arch barrels cannot be represented if shearing between rings occurs or rings are separated.

iii) Failure is based on four hinges developing. Other types of failure cannot be identified.

iv) True multi-span behaviour cannot be easily assessed. Subject to the same limitations for single arch analysis the program Multi has been developed to provide multi-span assessments where further hinges develop. However, considerable skill and experience of the software is required to obtain reasonable solutions.

v) The influence of concrete saddles, arch ribs, internal spandrel walls, reinforcement, complex boundaries and settlement cannot be investigated.

vi) The use of a passive soil pressure participation factor is subjective, however useful for bounding solutions. This factor determines the maximum proportion of horizontal passive pressure that is applied to the ring at the position of maximum possible movement. The authors suggest that a value no greater than 0.3 should be used, as the soil displacements necessary to achieve a higher factor would also have resulted in a failure of the arch.

Archie-M[(6)] by Obvis Ltd was first produced in 1999, is written for PC Window environments and uses essentially the same principles in the analysis as the original version. However, the treatment of soil passive pressure and longitudinal distribution of live load as summarised below is slightly different. Consequently, the assessed arch strength is likely to be slightly different from solutions obtained with Archie.

When applied, Archie-M determines the proportion of passive pressure that would be needed to bring the thrust just into the arch at the springing and applies that. In the analysis a new hinge is generated at the springing. If the thrust is outside the arch at a higher point, then the hinge is moved upwards incrementally increasing the passive pressure applied above and removing that applied below until a position is reached where passive pressure is consistently distributed. Clearly, full passive pressure requires a large movement in the fill to mobilize its full shear strength and, therefore, it is recommend by the authors not to exceed half full passive pressure in assessment work. Above half full passive pressure it is likely that the geometry of the bridge would have to change appreciably, a condition that occurs beyond peak strength capacity, before this level of pressure could be realised.

Apart from the alteration in the treatment of passive pressure, the longitudinal live load distribution through the fill has been somewhat rationalised since Archie was first written and has been smoothed to remove step changes in load pressure implied in BD 21 that cannot occur in reality. In this respect Archie-M is perhaps more realistic than Archie.

4.3 RING

RING[(7)] is the product of more than 10 years of development at the Bolton Institute and the University of Sheffield. The version used in this verification is a PC Windows based program and represents the most comprehensive implementation of the mechanism method of all commercially available programs based on this technique.

Potentially, RING provides several advantages over Archie and could be used to provide the next stage in an assessment program. However, it is not yet widely used in the industry and nor is it listed in BA 16[(4)]. The chief advantages over Archie are the ability to represent multi-ring behaviour and flag potential shear failures but some similar restrictions exist as follows:

i) Using a similar but more complex implementation of mechanism analysis, displacements cannot be calculated as the solution is derived from force equilibrium calculations alone.

ii) Because of i) strains and damage cannot be calculated. Hence, although solutions are useful for ultimate limit state assessments, which is current practice, serviceability limit states cannot be meaningfully investigated.

iii) Failure associated with buckling where the non-linear effects of relatively large displacements are critical cannot be considered. Buckling behaviour is important for slender and flat arch barrels.

iv) The influence of concrete saddles, arch ribs, internal spandrel walls, reinforcement, complex boundaries and settlement cannot be easily investigated.

v) As with Archie the use of passive soil pressure participation remains somewhat subjective, but again useful for bounding solutions. Options include uniform horizontal pressure or classical passive pressure, varying with depth.

5. ELFEN

5.1 Overview

The use of ELFEN Finite/Discrete Element software provides the opportunities to model the fundamental behaviour of arches in a way that has not before been possible. In particular, the analysis can embrace the following aspects:

i) Representation of the material characteristics (elastic and plastic behaviour) of the brick/stone units and mortar so that buckling, crushing and composite behaviour can be simulated.

ii) Modelling of contact-gap-friction effects along mortar/dry joints so that limiting tension, cracking, sliding and hinges can be represented.

iii) Modelling of steel reinforcement including bond failure so that reinforcement based strengthening can be investigated, for example existing reinforced concrete saddles and Cintec anchors.

iv) Explicit representation of defects such as ring separation, local distortion and mortar loss.

v) A solution procedure including the calculation of displacement, strain and stress to efficiently facilitate the modelling of the constitutive behaviour in i), ii) and iii) above and perform global structural analysis.

Crucially it is the ability of ELFEN to model the interaction of the masonry with the retrofitted reinforcement which provides the analytical basis for Archtec.

5.2 Rockfield Software Limited

The ELFEN software has been developed by Rockfield Software Limited over nearly 20 years since the company was founded in 1984. It has been deployed in numerous applications for an international client base with interests in a diverse range of industrial disciplines (including basic engineering, foods, manufacturing, geotechnical, defence, etc).

Rockfield are a high technology company established to provide leading edge numerical based simulation systems and their industrial applications. Their principal aim is to provide industry with support of advanced technology problems through computational modelling. To meet this objective, the company is committed to computational developments and applications in both existing and emerging disciplines and the undertaking of collaborative research programmes with industry, universities and research organisations. Rockfield is based in Swansea, UK being closely allied to the University of Wales, Swansea, with offices in Australia (Queensland) and in USA (Maryland).

ELFEN undergoes a stringent testing procedure to ensure the software is verified for each application. For example, Rockfield have worked on masonry arches with Gifford to ensure that the software is being correctly applied and have run independent verification exercises to check arch simulations. The software has also been benchmarked for a variety of classes of engineering problems against industry standard tests to ensure that all results are correct.

Rockfield Software Ltd has developed ongoing relationships with leaders in virtually every industry around the world. Some of Rockfield's ELFEN clients include: BP, Total Fina Elf, Royal Haskoning, Fugro, DML, Corus, Rexam Beverage Can Europe, Crown Cork & Seal, Unilever, Procter & Gamble, DeBeers, Rio Tinto, ORICA, DSTL, QinetiQ, Cintec International, Gifford & Partners and many more.

5.3 The Finite/Discrete Element Algorithm

The algorithm essential for all of the structural analysis undertaken with ELFEN is based on Finite/Discrete Element (DE) method. This is an improvement on the Distinct Element method first developed by Cundall(8) in 1971 in which the concept of individual elements being separate and reacting with their neighbours by contact through friction/adhesion was first successfully applied to geotechnical and granular flow problems. Here elements were considered rigid but later developments for example by Munjiza et al(9) in 1995 included the addition of element deformations and fracturing, with some overlap with traditional finite element theory; the DE method was born.

The DE formulation available in the explicit dynamic version of ELFEN has been adopted for Archtec. Explicit solvers (solution of transient dynamic problems by central difference explicit time integration) are intrinsically dynamic and are well suited to the analysis of structures with discontinuous behaviour such as masonry. Equilibrium difficulties, particularly during softening, often encountered with more traditional implicit solvers are completely avoided although more reliance is required on verification.

5.4 Application to Arch Strength Assessment

Using ELFEN[(10)] and the DE technique to generically model masonry and fill, this software is used to represent the behaviour of arch barrels allowing prediction of structural behaviour. Simply, each brick or block is modelled and the contact between them automatically calculated as load is applied. Non-linear material models and contact interface models are used to represent the masonry and mortar joints. Stationary loads to reproduce tests or traversing loads to model moving vehicle axles can be easily represented as separate bodies. Unlike specialist arch analysis software and similar to conventional finite element software there is no limit to model complexity. However, for efficient and fully verified operation a carefully controlled modelling approach implemented by a data processing system is always used.

Arches are modelled in two dimensions, with a view to simplifying the analysis as far as possible, using plain strain assumptions. The necessary transverse load distribution criteria for live loading is normally based on rules in BD 21.

Non-linear material models are used to model crushing in the masonry and plastic shearing and tensile behaviour in the fill. The fill material can be modelled either as a non-linear Rankine continua with a tension cut off or as a non-linear Mohr-Coulomb continua, which uses conventional soil parameters angle of internal friction and cohesion. Mobilisation of active and passive pressure effects will be calculated directly by the analysis. Passive and active pressures develop as the barrel deforms with the fill being able to support carriageway loading and develop thrust lines by biaxial compression.

Construction sequence analysis is implicit to the approach with the initial and permanent stress state calculated as a construction event before the introduction of the live loading. Occasionally, depending on the shape of the barrel, formwork has to be represented and used for support until all permanent loads have been applied.

The two pictures in Figure 5.1 show typical ELFEN results, in this case a strength assessment failure. The twin axle loading is moving onto the arch from the left. Red indicates the highest compressive stresses. Significant tensile stresses cannot occur since in the event of tensile forces occurring joints simply open to redistribute them.

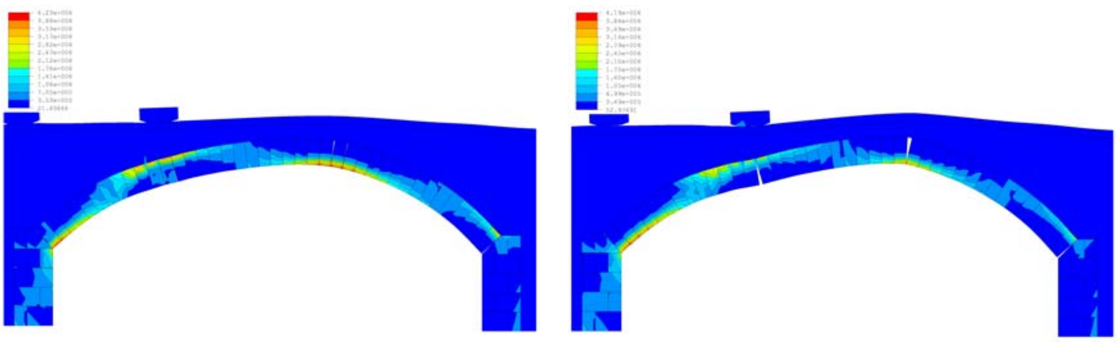


Figure 5.1 Typical Numerical Simulation of the Failure of a Masonry Arch
Results shown are Von Mises equivalent stresses

6. FULL-SCALE ARCH TESTS

6.1 Objectives

In undertaking comparisons with full-scale tests of arches the key objective is to demonstrate the accuracy of analytical solutions and the appropriateness of simplifying assumptions that it is always necessary to make. In all cases vertical displacement at load intervals have been used for result comparisons.

Full-scale tests have been selected where boundaries and loading are two-dimensional so that the validity of comparing their results with two-dimensional analyses has not been compromised by three-dimensional behaviour. Skew arch barrels and spandrel walls are examples of bridge features that generally give rise to three-dimensional structural behaviour.

6.2 TRL Laboratory Tests

The Transport Research Laboratory (TRL) ran a LINK funded programme in the nineties aimed at quantifying the benefits and limitations of various repair and strengthening methods used on masonry arch bridges. The programme was entirely experimental and consisted of a series of tests using identical brick arch arrangements. Comparisons with predicted results have been made with the two unstrengthened arches tested before the LINK programme got underway and on which the LINK arches were styled. These tests are described in papers by S K Sumon(11) and N Ricketts(12) and summarised in the following paragraphs.

6.2.1 Arrangement

The arch bridge has a 5m span, a rise of 1.25m at the crown and was 2m wide. The bridge including principal dimensions is shown in Figure 6.1. Each arch barrel comprised three brick rings each with stretcher bonding. The barrel was founded at its springings on two reinforced concrete abutments held rigidly to the Laboratory floor. A 2m wide steel box was constructed around the arch to retain the fill. The 2m wide loading, supports and retaining box ensure that the bridge behaviour is two-dimensional. All ultimate failure tests were carried out with line loads at the span quarter point.

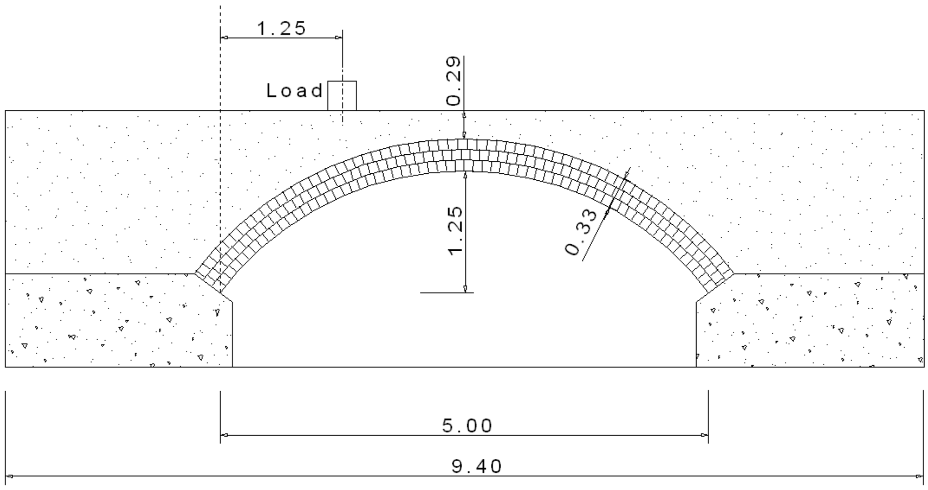


Figure 6.1 5m Span TRL Laboratory Arch – Mortared and Separated Rings

The two unstrengthened tests selected for comparison with predicted results were similar except for the circumferential joints between the rings.

In one case, and for the remainder of the strengthened arch test series, these joints consisted of dry sand in order to reproduce the effects of partial ring separation (no gap but with eroded cohesion, full separation would need to include a physical gap and would be weaker still).

In the other case the circumferential joints were fully mortared.

6.2.2 Masonry

The arch barrel was assembled from non-engineering bricks, lime mortar and built to be representative of many bridges constructed before 1900. Hand made bricks with a compressive strength of 18.4 N/mm^2 were laid with a 1:3:12 cement:lime:sand mortar with a compressive strength in the range 1.3 to 2.3 N/mm^2. Brickwork prisms were tested which gave a mean compressive strength of 5.3 N/mm^2 which is fairly consistent with Figure 4.2 in BD 21[(5)].

6.2.3 Fill

Type 2 road base material was used for the fill which was compacted in layers using a hand operated vibrating plate.

6.3 Bolton Laboratory Tests

6.3.1 General

C Melbourne has lead a number of studies where full-scale brick arches have been built and tested. These have included ultimate tests of multi-ring brickwork arches and multi-span brick arch bridges in various conditions under laboratory conditions.

The following lists the tests that have been selected for comparisons with predicted results. All of these arches were constructed with similar materials and had detached spandrel walls.

6.3.2 Single 3m arch with two rings of brick

This is one of four tests (original test identification number 3-1) carried out to investigate the behaviour of multi-ring brickwork arch bridges by C Melbourne and M Gilbert[13]. The test arrangement showing principal dimensions is shown in Figure 6.2. Both rings were laid using stretcher bonding and mortar used to bond between the rings. A knife edge load was applied across the full width using a hydraulic system and reaction rig at ¼ span[14]. The width of the barrel, fill and distance between the separated spandrel walls was 2.88m.

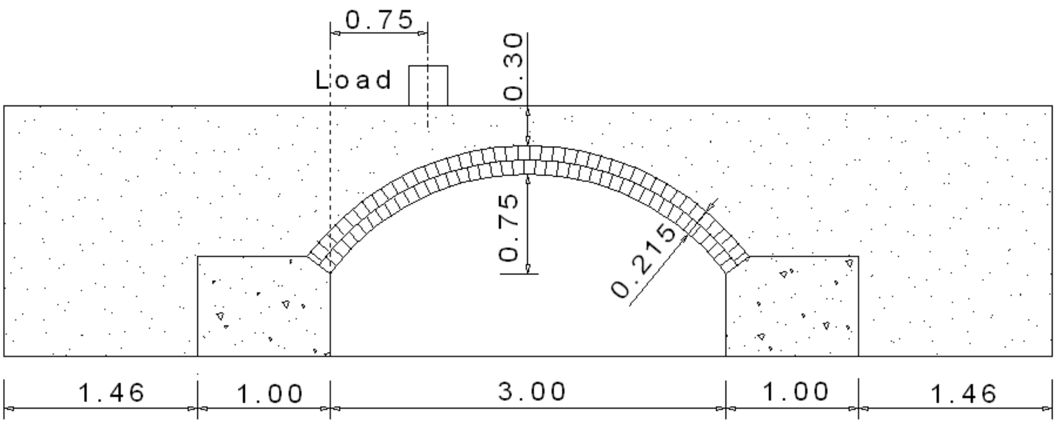


Figure 6.2 3m Span Bolton Arch – Mortared Rings

6.3.3 Single 5m arch with four rings of brick

These are two of a series of three tests (original test identification numbers 5-2 and 5-3) again carried out to investigate multi-ring behaviour[13,14]. The test arrangement showing principal dimensions is shown in Figure 6.3. All four rings were laid using stretcher bonding and either mortar or sand used to bond between the rings. Hence two conditions were considered; fully bonded rings and partially ring separated (no gap but with eroded cohesion). Here load was applied at the ¼ span using ties passing through the arch and a prestressing system. The width of the barrel, fill and distance between the separated spandrel walls was slightly greater than the 3m arches at 3.01m

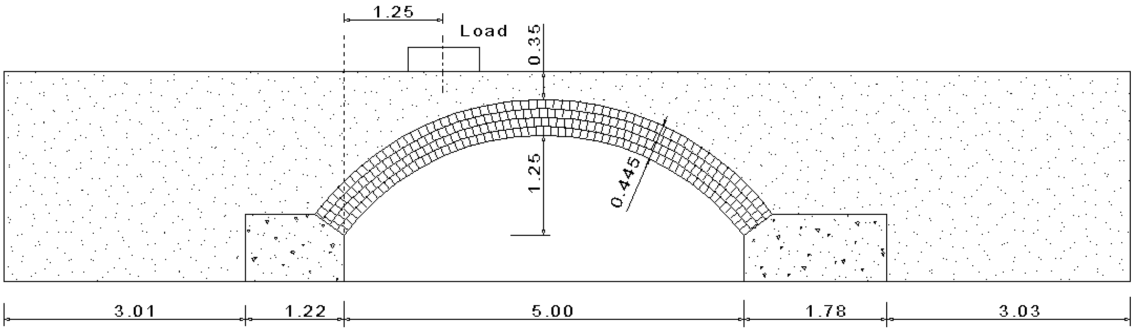


Figure 6.3 5m Span Bolton Arch – Mortared and Separated Rings

6.3.4 3 x 3m multi-span arch bridge

This is one of three tests (original test identification number 2) carried out to investigate the behaviour of multi-span masonry arch bridges by C Melbourne, M Gilbert and M Wagstaff[15,16]. Each span is based on the single span arrangement described in 6.3.1. The test arrangement showing principal dimensions is shown in Figure 6.4. For this test a knife edge load was applied across the full width using a hydraulic system and reaction rig at ¼ span position over span 2. The width of the barrel, fill and distance between the separated spandrel wall was 2.88m.

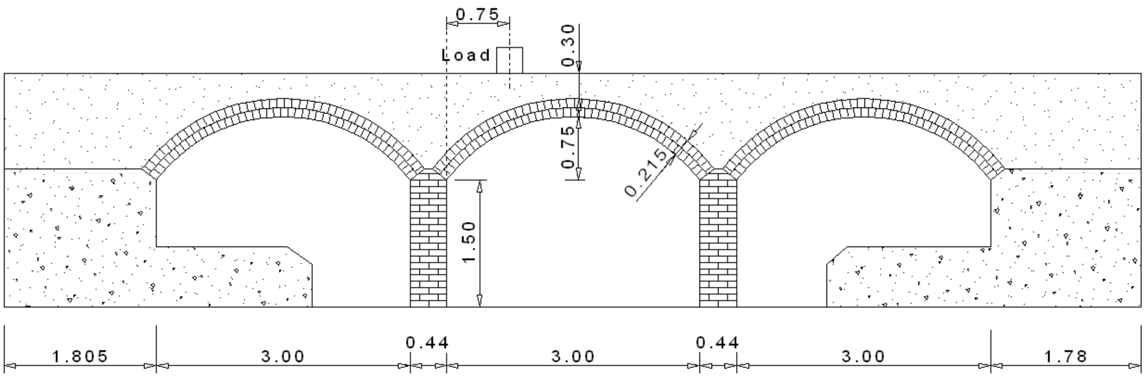


Figure 6.4 3 x 3m Span Bolton Arch – Mortared Rings

6.3.5 Masonry

All of the tests described in section 6.3 were built with similar masonry using solid class ‘A’ engineering bricks and laid with a 1:2:9 cement:lime:sand mortar (BS 5628 mortar designation (iv)). The bricks had very high compressive strengths tested between 115 and 154 N/mm^2 and the mortar a compressive strength in the range 1.9 to 3.2 N/mm^2. Tested brickwork prisms gave an overall mean compressive strength of 25.8 N/mm^2 which is significantly outside the bounds of strength properties given in BD 21[5] and, interestingly, according to BS 5628[17] is similar to masonry with a much stronger mortar such as 1:0:3 cement:lime:sand designation (i).

Brickwork in the barrels was laid in stretcher bond in separate rings either fully bonded with mortar to adjacent rings or partially separated with sand.

6.3.6 Fill

50mm Graded crushed Limestone was used for the fill which was compacted in layers using a hand operated vibrating plate. Using a large shear box the fill material was confirmed cohesionless and had a measured angle of internal friction of 60°.

6.3.7 Tests not used for comparisons

Further tests at the Bolton Institute were carried out at the same time and considered other conditions including header bonding in barrels and spandrel walls. Header bonding, used to mechanically connect adjacent brick rings, has not been investigated here since allowance for brick fracturing would be necessary to predict ultimate failure. Modelling the necessary localised failure mechanisms would add further indeterminacy and analytical complexity to numerical models. Similarly, predicting tests including spandrel walls have also been avoided as more complex models with three dimensional representations and accompanying computational overheads would be necessary.

6.4 TRRL Field Tests

6.4.1 General

The Transport and Road Research Laboratory (TRRL) undertook a research programme to re-examine the MEXE method of assessing the traffic load carrying capacity of brick and stone arch bridges. The programme of research comprised the development of analytical models, a series of load tests to destruction of eight redundant bridges and a series of model tests.

Strathmashie Bridge[18,19], selected from the tests of redundant bridges, was not skewed and had a longitudinal crack in the barrel parallel to the back face of the south most spandrel wall. Hence, at least on one side of the bridge the spandrel wall was separated and would not have significantly influenced the test. The segmental arch barrel of the bridge had a span and rise of 9.43m and 2.99m respectively and was constructed from random rubble masonry. The bridge was dimensionally in good condition although the state of pointing was poor. Figure 6.5 shows the bridge principal dimensions.

Most of the other tests cannot be easily used for comparison with two dimensional analyses for any of the following reasons:

i) the arch barrel is significantly skewed;

ii) the spandrel walls were fully attached to the barrel; and

iii) the spandrel walls as well as the fill were directly loaded by the loading beam during the test

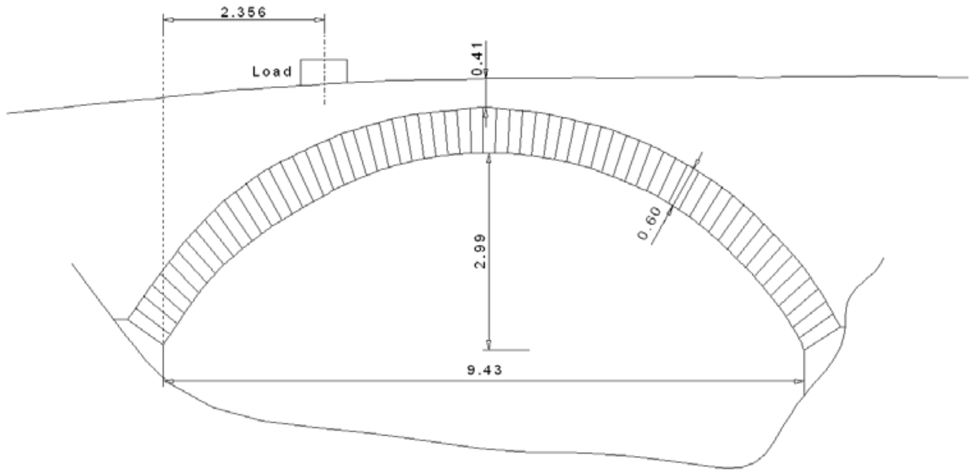


Figure 6.5 Strathmashie Bridge – 9.43m Random Rubble Arch

6.4.2 Masonry

No quantitative tests were undertaken on the masonry. The individual stones were typically 100mm with quit thin joints near the edges whilst being wider and more variable towards the centre. The mortar type was not noted but as the bridge was built around 1830 was probably lime based.

6.4.3 Fill

No quantitative tests were undertaken on the fill but it was described as cobbles graded down to sand.

6.5 Archtec Strengthened Tests

6.5.1 General

In order to test the practical implementation of Archtec, to validate the method of structural analysis, to help quantify key strength parameters and to illustrate the degree of strengthening that could be archived two full-scale tests of Archtec strengthening were carried out at TRL. Both tests were based on the arch arrangement developed for the LINK programme, as described in Section 6.2, so that unstrengthened test comparisons could easily be made. Both tests also used the partially ring separated form of the arch; Figure 6.1 shows the principal dimensions. The anchor arrangements were configured for the stationary test and, therefore, were arranged asymmetrically with respect to the span. It was recognised that in practice, with moving axle loads, anchor arrangements would have to be symmetric to reflect critical loading positions on both sides of the span. The first test was carried out in January 1998 and the second in June 2001.

This work was conducted outside of the LINK programme and was privately funded.

6.5.2 Archtec Test 1

The arrangement of the first Archtec[20] test is shown in Figure 6.6 and used the Standard Cintec anchor shown in Figure 6.7. The Standard Cintec anchor arrangement used for the test comprises a 25mm diameter stainless steel ribbed reinforcement bar grouted in a 65mm diamond cored hole. Anchors were arranged in three rows, A, B and C with the anchors in row B (total length of 10.8m) providing most of the added strength. Anchors A and B were drilled through the inner most ring of bricks with a minimum cover of approximately 20mm near the quarter-span position at the intrados. Anchors in row C were drilled through the middle ring of bricks on the opposite side of the span to the load.

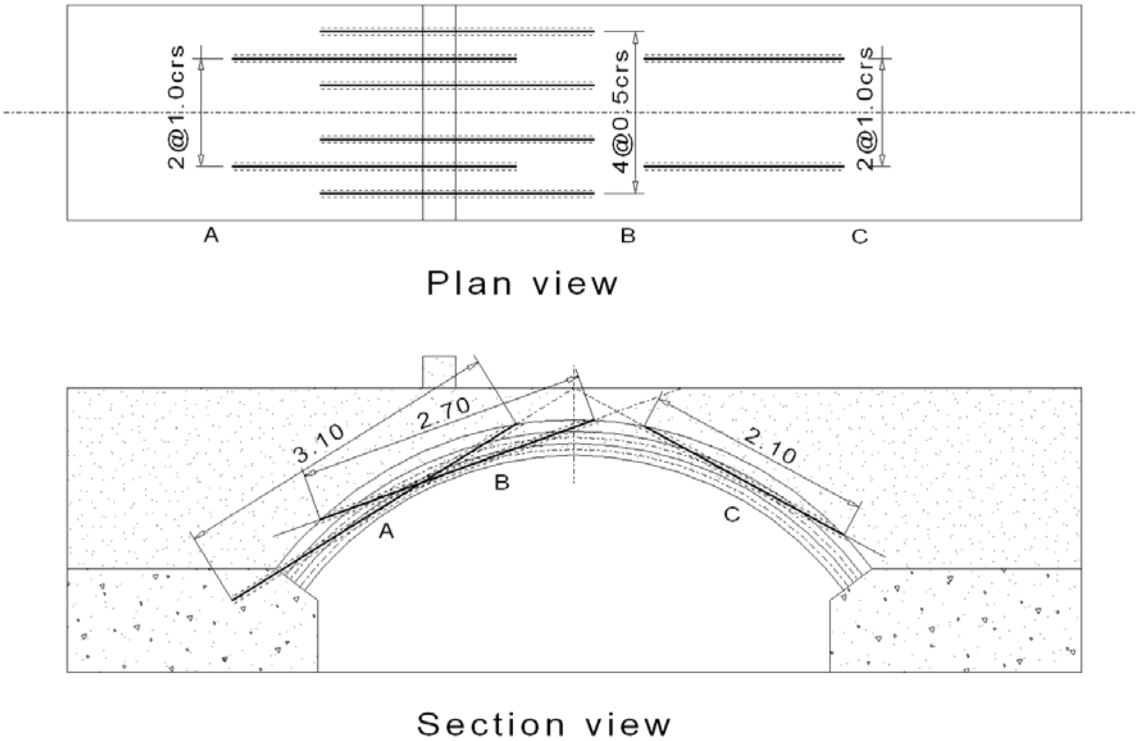
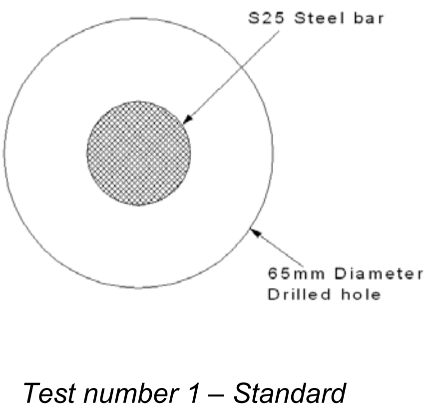
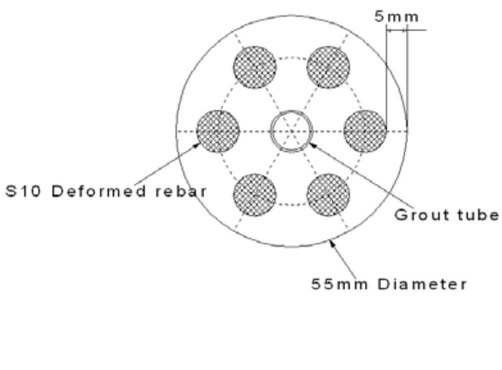


Figure 6.6 Archtec Test Number 1
Based on TRL 5m arch with separated rings





Test number 1 – Standard *Test number 2 – Multibar*

Figure 6.7 Cintec Anchors used in Arctec Tests

6.5.3 Archtec Test 2

A second Archtec(21) test was carried out to provide further confirmation of strength parameters and test the Multibar form of the anchoring system. The arrangement is shown in Figure 6.8 and used the Multibar Cintec anchor illustrated in Figure 6.7. The Multibar anchor used in the test comprises of six 10mm diameter stainless steel ribbed reinforcement bars arranged in a ring and grouted in a 55mm diamond cored hole. Again anchors A and B were drilled through the inner most ring of bricks with minimum cover of approximately 20mm near the quarter-span position at the intrados. Anchors in row C were also drilled through the innermost ring of bricks in recognition that the anchors work well in compression as well as in tension.

The area of steel is approximately equivalent to the Standard 25mm case. Multibar anchors whilst not providing any significant advantages over the Standard arrangement with regard to strength do however have several practical advantages during the installation process.

As with the first test, anchors were arranged in three rows A, B and C with the anchors in row B (total length of 15m) providing most of the added strength. However, more anchors were used with the overall arrangement expected to represent the strongest array of anchors that could be practically used in an arch of this size. It was predicted that any further increases in strength by anchoring would diminish as the influence of masonry strength would become increasing important in determining the arch ultimate strength; analogous to an over reinforced concrete beam.

In the second test two anchors from row B had electrical resistance strain gauges attached so that predicted and measured strains could be compared and, therefore, help verify predicted anchor stresses (axial reinforcement, grout to masonry bond).

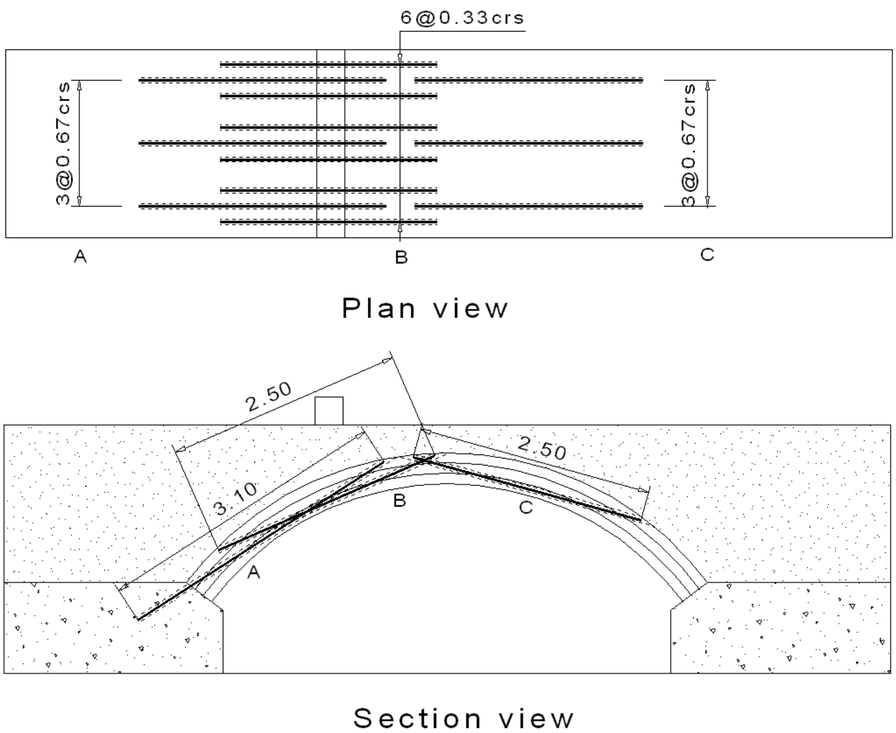


Figure 6.8 Arctec Test Number 2
Based on TRL 5m arch with separated rings

7. UNSTRENGTHENED ARCHES - COMPARISON OF TEST AND PREDICTED RESULTS

7.1 General

Predicted and experimental load versus displacement characteristics have been compared for each of the full-scale single span arch tests and for each different arch assessment program. Where the method of analysis is independent of displacement, which is the case for Archie, Archie-M and RING, horizontal lines at constant load are plotted alongside other results. For multi-span arch comparisons only those results calculated with ELFEN have been presented since similar mechanism analysis is considered too subjective for inclusion here.

All graphs of displacement are of results measured or calculated at the position of the applied load. Additional data that was often recorded during tests, displacements and strains, has been considered in the verification of ELFEN but is not included here.

Peak load measured during the full-scale tests has been defined as the failure load and values are separately summarised in tables for each arch together with normalising factors with the test data. Despite many of the tests having different widths all loads have been converted to load per unit width measured across the bridge (kN/m).

Appendix A shows typical output produced by the mechanism programs Archie, Archie-M and RING. Appendix B includes colour contour diagrams of ELFEN results, vertical displacement, principal compressive stress and Von Mises equivalent (effective) stress for each of the arches investigated at the failure load. The mode of failure is also included.

7.2 TRL Unstrengthened Arches

7.2.1 Mortar Bonded Brick Rings

Figure 7.1 compares the load versus displacement results obtained by all methods of analysis with those obtained from the test. Failure loads are summarised in Table 7.1 and contours of ELFEN results are given in Figure B.1 in Appendix B.

Predictions made with both Archie and ELFEN are almost exact, considered to be somewhat fortuitous, with both failure load predictions within 2% of test results. The best RING prediction was very conservative at just 52% failure load.

The prediction of stiffness by ELFEN was reasonable throughout the load range with displacements within 15% of test results at all stages. Clearly, the conventional arch analysis programs can provide no information on displacement and stiffness.

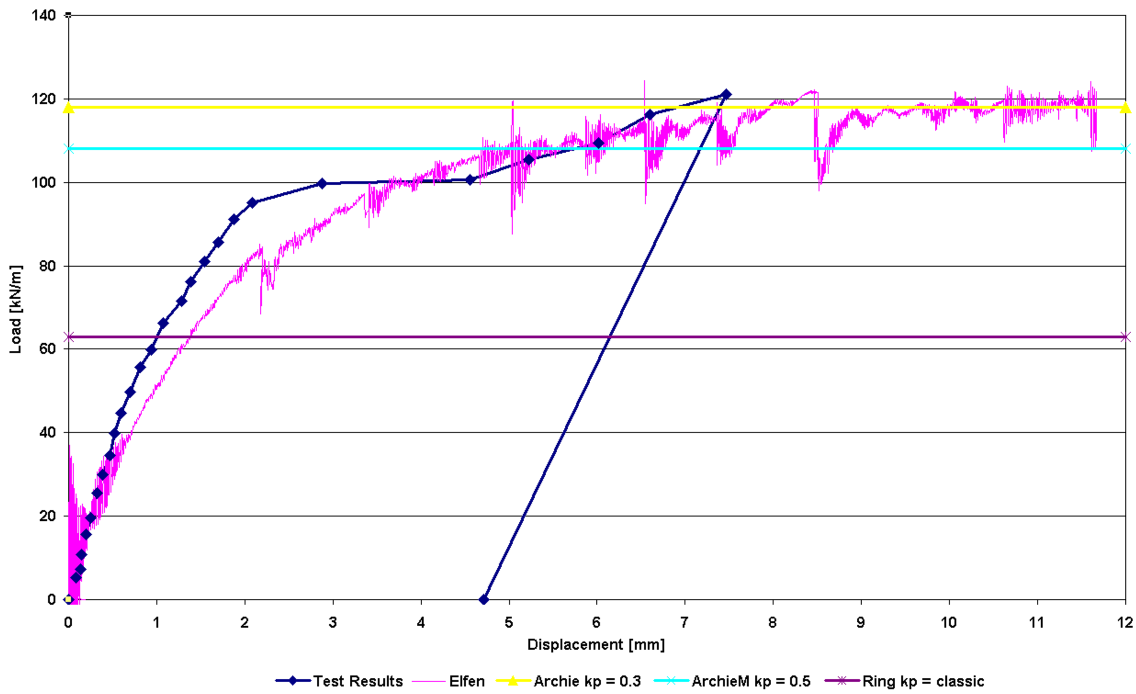


Figure 7.1 5m Span TRL Laboratory Arch – Comparison of Predicted and Test Results - Mortar Bonded Brick Rings

Load versus vertical displacement under the line load

It is not clear why the full-scale test exhibited a plateau at around 100 kN/m after which further load could be carried and why the test was stopped at failure and not continued in displacement control. Perhaps the bridge exhibited very little ductility and the researchers anticipated imminent collapse.

Table 7.1 Summary of Test and Predicted Failure Loads

Description 5m Span TRL Laboratory Arch - Mortar Bonded Brick Rings		**Load**	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	Loaded in displacement control	121	1.00
Archie	0.1 Passive pressure	95	0.79
Archie	0.3 Passive pressure	118	0.98
Archie-M	At rest pressure	78	0.64
Archie-M	0.5 Passive pressure	108	0.89
RING	No horizontal pressure	37	0.31
RING	Classical horizontal pressure	63	0.52
ELFEN	Mohr Coulomb soil model	122	1.01

7.2.2 Separated Brick Rings

Figure 7.2 compares the load versus displacement results obtained by all methods of analysis with those obtained from the test. Again failure loads are tabulated appearing in Table 7.2 and contours of ELFEN results are given in Figure B.2 in Appendix B.

Again predictions made with ELFEN are almost exact and within 2% of test results. In this case the best of the conventional analysis programs is Archie-M. Using the highest recommended passive pressure factor the predicted failure is 92% failure load. Interestingly the same analysis with at rest soil pressures yields a predicted failure load of 69% the test result. As displacements cannot be calculated by conventional mechanism analysis the most appropriate soil pressure model has to be judged by the assessment engineer.

As with the mortar bonded case, the prediction of stiffness by ELFEN was reasonable throughout the load range with displacements within 17% of test results at all stages, but with the largest difference occurring during the loading stage between deflections of 2mm and 10mm.

It is suspected that the tested arch during most of the loading was in fact softer than would have been expected had the arch not been damaged before the test and subsequently repaired. It is believed that the repaired arch remained defective for the following reasons.

i) Some distortion had been introduced into the arch profile where the load ¼ point was 10mm high, the crown 55mm low and the ¾ point on average 40mm high compared with the intended shape. Hence the segmental arch had become a slightly lopsided ellipse with the span to crown rise ratio increased by 5%.

ii) There is some doubt how effective the repair of any damaged masonry in the barrel would have been and so failure of the repaired arch may have been inadvertently preconditioned.

It is unlikely that these factors have significantly affected the failure load but, as has been investigated separately with ELFEN, are the cause of the loading stage stiffness differential.

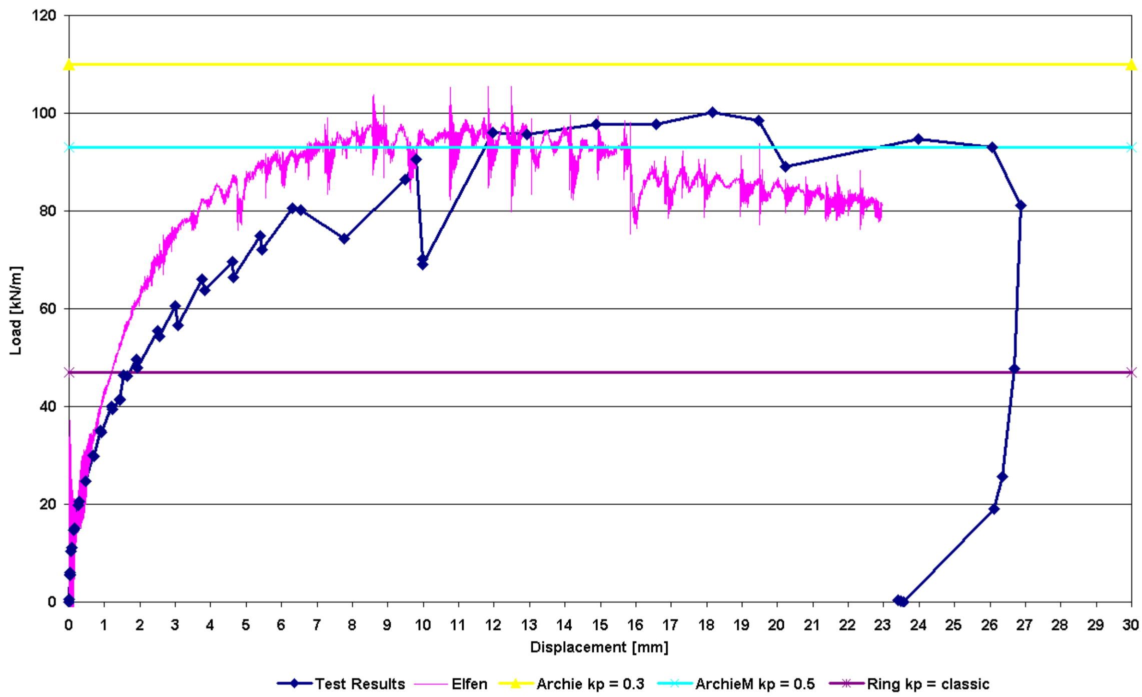


Figure 7.2 5m Span TRL Laboratory Arch – Comparison of Predicted and Test Results Separated Brick Rings

Load versus vertical displacement under the line load

Table 7.2 Summary of Test and Predicted Failure Loads

Description 5m Span TRL Laboratory Arch - Separated Brick Rings		Load	
Method	**Details**	[kN/m width]	Ratio to test
Test	Loaded in displacement control	100	1.00
Archie	0.1 Passive pressure	90	0.90
Archie	0.3 Passive pressure	110	1.10
Archie-M	At rest pressure	69	0.69
Archie-M	0.5 Passive pressure	93	0.93
RING	No horizontal pressure	20	0.20
RING	Classical horizontal pressure	47	0.47
ELFEN	Mohr Coulomb soil model	98	0.98

7.3 Bolton Arches

7.3.1 5m Single Span Brick Arches

The load versus displacement results obtained by all methods of analysis with those obtained from the tests for the ring separated and mortar bonded arches are shown in Figures 7.3 and 7.4 respectively. As before failure loads are tabulated with the ring separated failure loads summarised in Table 7.3 and the mortar bonded arch results given in Table 7.4. Contours of ELFEN results are given in Figures B.3 and B.4 in Appendix B.

Predictions made with ELFEN are closest to both test results with the calculated failure loads 14% greater and 12% lower than the test results for the separated and bonded cases respectively. These predictions are matched closely by RING using classic passive soil behaviour in the separated case but ring gives a very conservative result of 46% the failure load for the mortar bonded case.

There is little correlation between the results obtained with Archie and Archie-M and the Test Results. This appears to be entirely due to the limitation of not being able to represent discrete arch ring behaviour. Clearly, this limitation has to be accounted for in any arch bridge strength assessment.

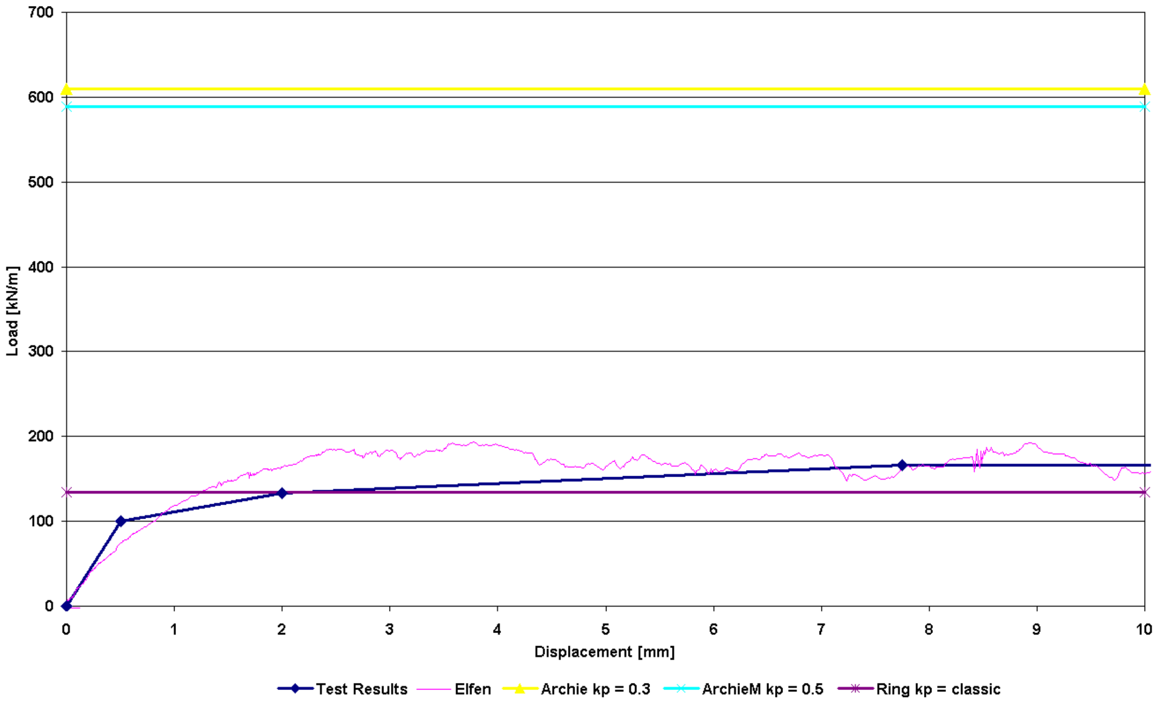


Figure 7.3 5m Span Bolton Arch – Comparison of Predicted and Test Results Separated Brick Rings

Load versus vertical displacement under the line load

Table 7.3 Summary of Test and Predicted Failure Loads

Description 5m Span Bolton Arch - Separated Brick Rings		**Load**	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	Loaded in displacement control	166	1.00
Archie	0.1 Passive pressure	410	2.47
Archie	0.3 Passive pressure	610	3.67
Archie-M	At rest pressure	255	1.54
Archie-M	0.5 Passive pressure	589	3.55
RING	No horizontal pressure	66	0.40
RING	Classical horizontal pressure	134	0.80
ELFEN	Mohr Coulomb soil model	189	1.14

Although good correlation of predicted and test failure loads for both 5m arches has been achieved with ELFEN comparisons of stiffness in the loading stage is not so good. In the mortar bonded case the test stiffness was approximately double the predicted stiffness. The reason for this disparity is believed to be attributed to the tensile strength of the mortar used in the tests. The mortar, presumably intended to be of designation (iv) did in fact possess compressive characteristics of designation (i), see section 6.3.5, and very likely had some tensile strength.

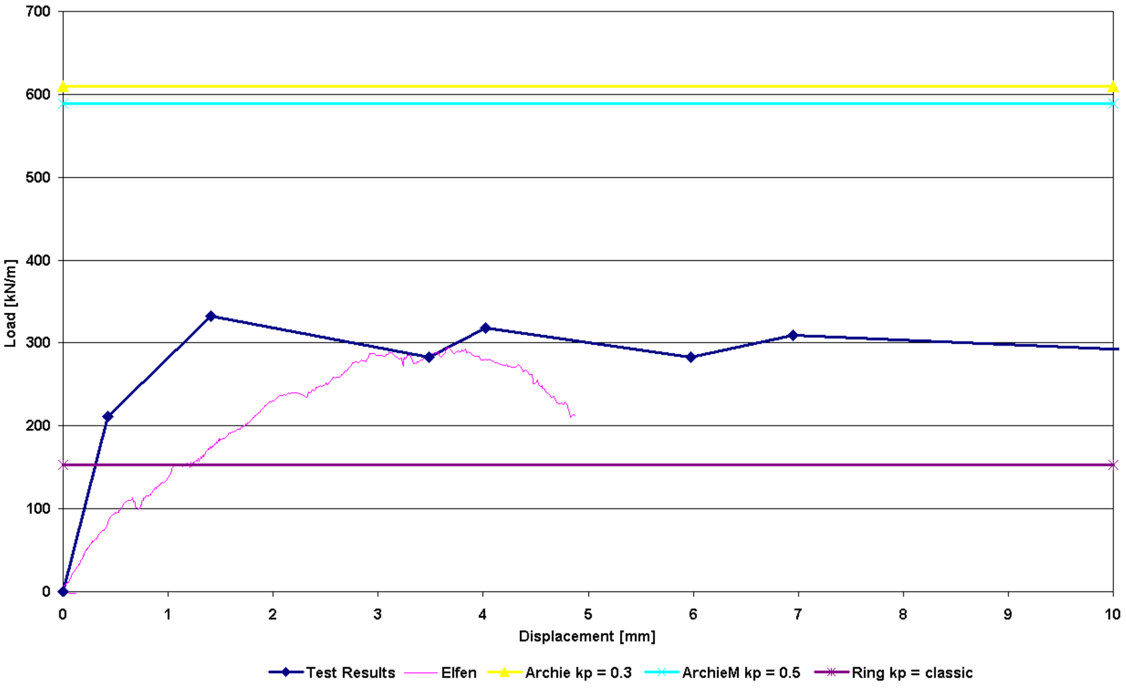


Figure 7.4 5m Span Bolton Arch – Comparison of Predicted and Test Results Mortar Bonded Brick Rings

Load versus vertical displacement under the line load

The interface model used to represent mortar joints in ELFEN currently does not include tensile strength nor the accompanying fracture energy to define softening. This type of model, necessary for modern masonry construction, is generally not appropriate for traditional construction of the past two or three centuries; relatively soft bricks and weak mortar.

Table 7.4 Summary of Test and Predicted Failure Loads

Description 5m Span Bolton Arch - Mortar Bonded Brick Rings		**Load**	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	Loaded in displacement control	332	1.00
Archie	0.1 Passive pressure	410	1.23
Archie	0.3 Passive pressure	610	1.84
Archie-M	At rest pressure	255	0.77
Archie-M	0.5 Passive pressure	589	1.77
RING	No horizontal pressure	75	0.23
RING	Classical horizontal pressure	153	0.46
ELFEN	Mohr Coulomb soil model	293	0.88

7.3.2 3m Single Span Arches and Multi-span Brick Arches

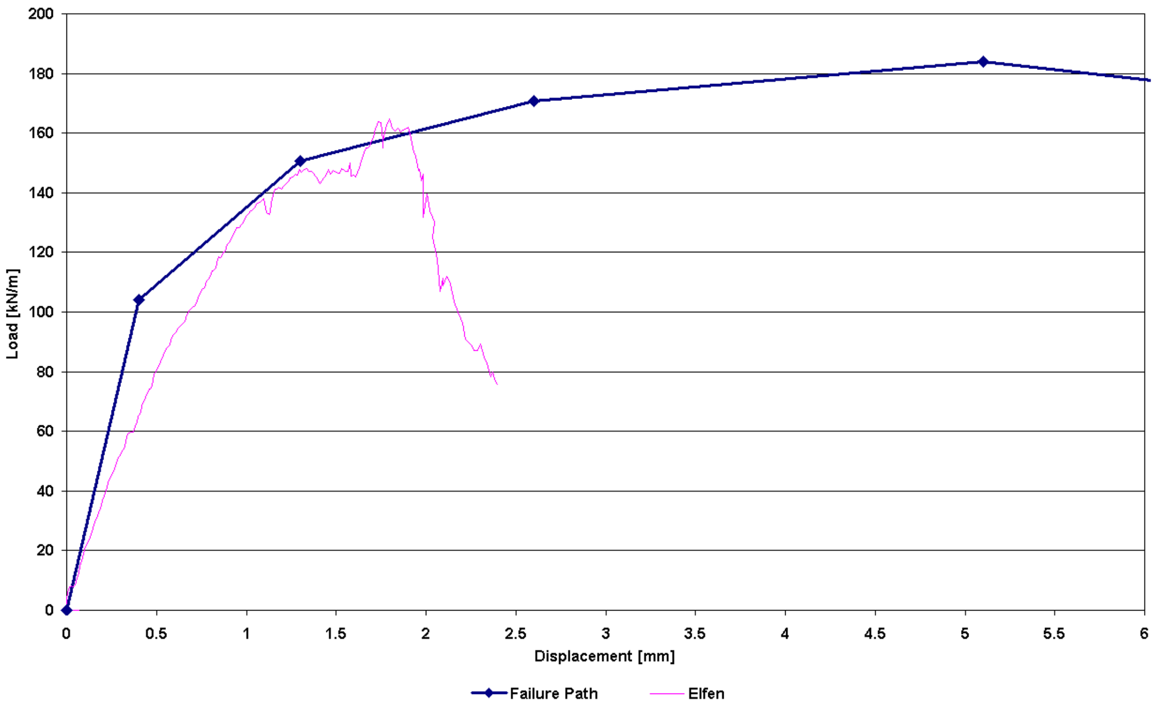


Figure 7.5 3m Single Span Bolton Arch – Comparison of Predicted and Test Results Mortar Bonded Brick Rings

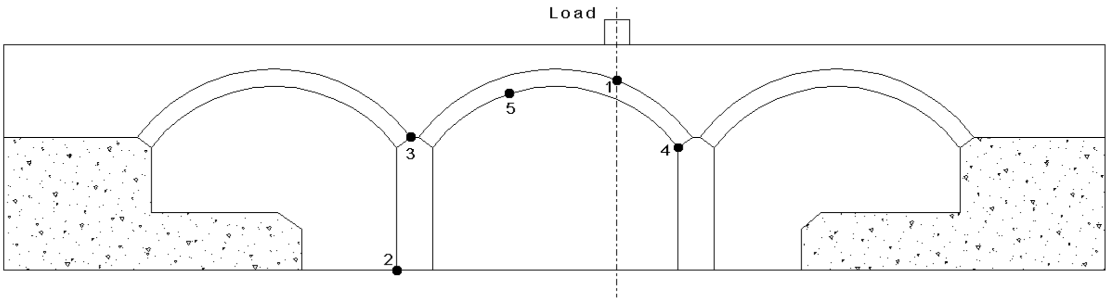
Load versus vertical displacement under the line load

The load versus displacement results obtained by all methods of analysis with those obtained from the tests for the mortar bonded single and multiple arch bridge test are shown in Figures 7.5 and 7.7 respectively. Failure loads have been tabulated together in Table 7.5. Contours of ELFEN results are given in Figures B.5 and B.6 in Appendix B.

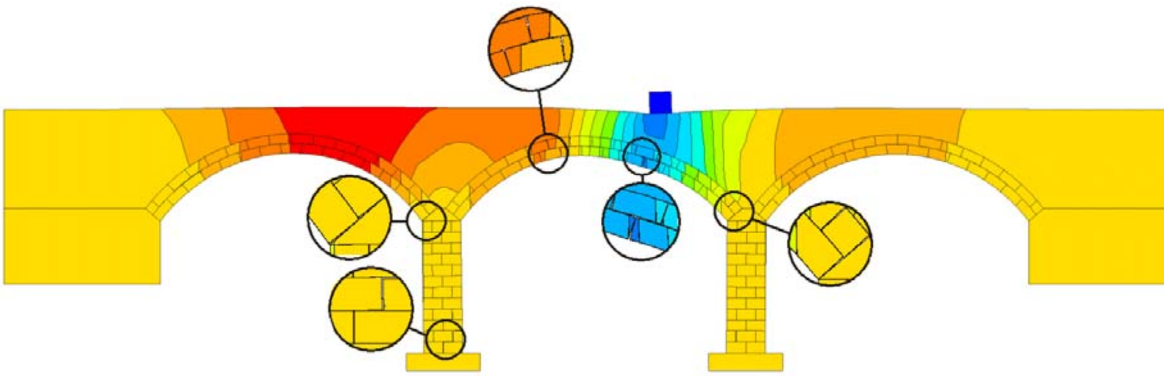
Multi-span results have not been obtained with the convention arch analysis programs since there use here is too subjective for valid comparisons with ELFEN simulations.

Table 7.5 shows that in both single and multi-span cases ELFEN predictions of failure load are 90% of the test results. Stiffness correlation is also reasonable. As to be expected, the influence of multi-span behaviour including piers, with a height to thickness ratio of 3.5, has been to reduce the single span test result by approximately 40%. This trend is reflected by the ELFEN simulations.

Also noteworthy is the test failure mechanism which as shown in Figure 7.6 was matched very closely by the ELFEN analysis. During the test a mechanism involving four hinges in the loaded span and fifth hinge at the base of the first pier, away from the loaded side of the arch, developed. A very similar pattern emerged in the ELFEN simulation after the failure load had been reached and as the modelled bridge softened, see second inset in Figure 7.6.



Hinge positions recorded during Bolton Test



ELFEN Simulation showing evolving hinge positions, shows contoured vertical displacements

Figure 7.6 3m Multi-span Arch - Predicted Failure Mechanism

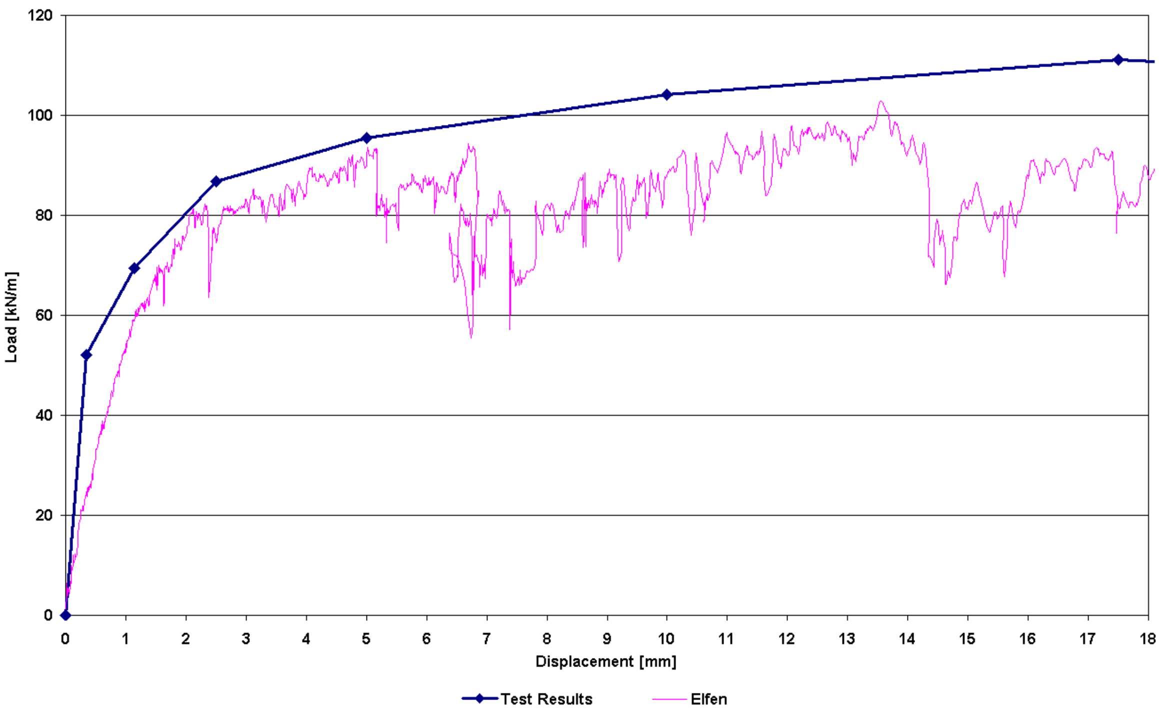


Figure 7.7 3m Multi-Span Bolton Arch – Comparison of Predicted and Test Results Mortar Bonded Brick Rings

Load versus vertical displacement under the line load

The ELFEN model of the multi-span test described in Section 6.3.4 differed slightly from the actual test in terms of the boundary provided by the spandrel walls. Although the walls in the test were separated from the three arch barrels they were built on and connected to the outer edges of the piers and abutments. Hence their behaviour would have been to provide some strutting across the spans which may have contributed to an elevated test failure load compared with the completely separated spandrel wall equivalent. It was this idealised equivalent spandrel wall that has been modelled. Inclusion of spandrel strutting may have improved the correlation of ELFEN predictions with the test results.

Table 7.5 Summary of Test and Predicted Failure Loads

Description 3m Span Bolton Arch - Mortar Bonded Brick Rings		**Load**	
Method	**Details**	[kN/m width]	Ratio to test
Test	Loaded in displacement control	188	1.00
ELFEN	Mohr Coulomb soil model	165	0.90
3m Multi-Span Bolton Arch - Mortar Bonded Brick Rings			
Test	Loaded in displacement control	111	1.00
ELFEN	Mohr Coulomb soil model	100	0.90

7.4 TRRL Arches

7.4.1 9.5m Single Span Stone Arch

The load versus displacement results obtained by all methods of analysis with those obtained from the test are shown in Figures 7.8. An additional set of ELFEN predicted results where the influence of mortar softening has been represented are shown in Figure 7.9. All failure loads are summarised in Table 7.6. Contours of ELFEN results where mortar softening has been included are given in Figures B.7 in Appendix B.

Predictions made with ELFEN shown in Figure 7.8 are closest the test results with a calculated failure within 5% test result. Predictions by RING using classic passive soil behaviour are also good and within 10% the test value. The results obtained with both forms of Archie are reasonable and conservative.

The correlation of stiffness between ELFEN and the test was markedly poor in the second half of the loading stage between a load of 160 kN/m to 250 kN/m. It is believed the reduced stiffness exhibited in the test is attributed to the mortar behaviour. To explore this possibility, and to illustrate the flexibility of numerical simulation, a separate ELFEN analysis was undertaken with modified masonry parameters. Essentially a lower characteristic strength for the masonry was used but with additional strain hardening until the original masonry strength was reached. The results are shown in Figure 7.9 and illustrate improved stiffness correlation.

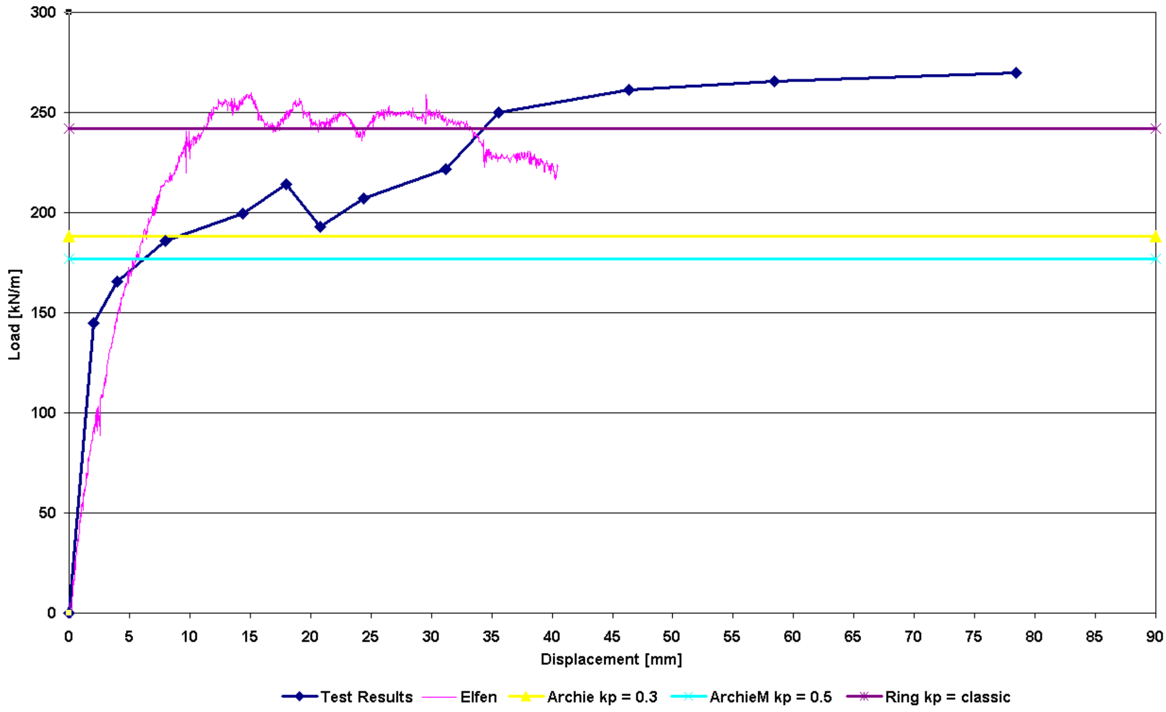


Figure 7.8 Strathmarshie Bridge – Comparison of Predicted and Test Results 9.5m Span Random Rubble Barrel

Load versus vertical displacement under the line load

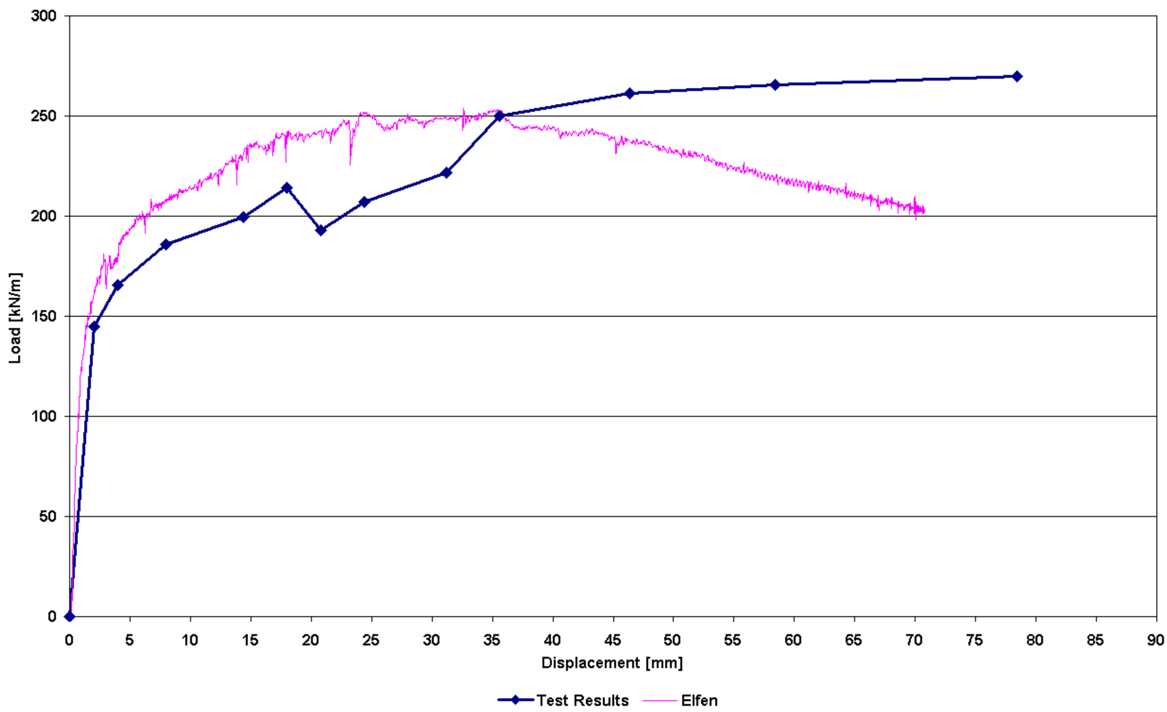


Figure 7.9 Strathmarshie Bridge – Comparison of Predicted and Test Results
9.5m Span Random Rubble Barrel – Mortar Softening
Load versus vertical displacement under the line load

Table 7.6 Summary of Test and Predicted Failure Loads

Description		Load	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	Loaded in load control	270	1.00
Archie	0.1 Passive pressure	142	0.53
Archie	0.3 Passive pressure	188	0.70
Archie-M	At rest pressure	118	0.44
Archie-M	0.5 Passive pressure	177	0.66
RING	No horizontal pressure	103	0.38
RING	Classical horizontal pressure	242	0.90
ELFEN	Mohr Coulomb soil model	257	0.95
ELFEN	Mohr Coulomb soil model with mortar softening in barrel	252	0.93

8. ARCHTEC STRENGTHENED ARCHES - COMPARISON OF TEST AND PREDICTED RESULTS

8.1 Archtec Test 1

Figure 8.1 compares the load versus displacement results obtained by ELFEN with those obtained from the first Archtec test[20] and also with the comparable unstrengthened ring separated arch. Failure loads are summarised in Table 8.1 and ELFEN contoured results at failure, including strengthening reinforcement stresses, are given in Figure C.1 in Appendix C.

Predictions made with ELFEN are almost exact with the failure load within 2% of test result and with very good stiffness correlation, displacements remaining within approximately 5% of test values, throughout the loading stage.

The composite behaviour of the Cintec anchors behaving as embedded reinforcement with the barrel masonry cannot be represented with the conventional analysis programs and so no comparable results can be provided.

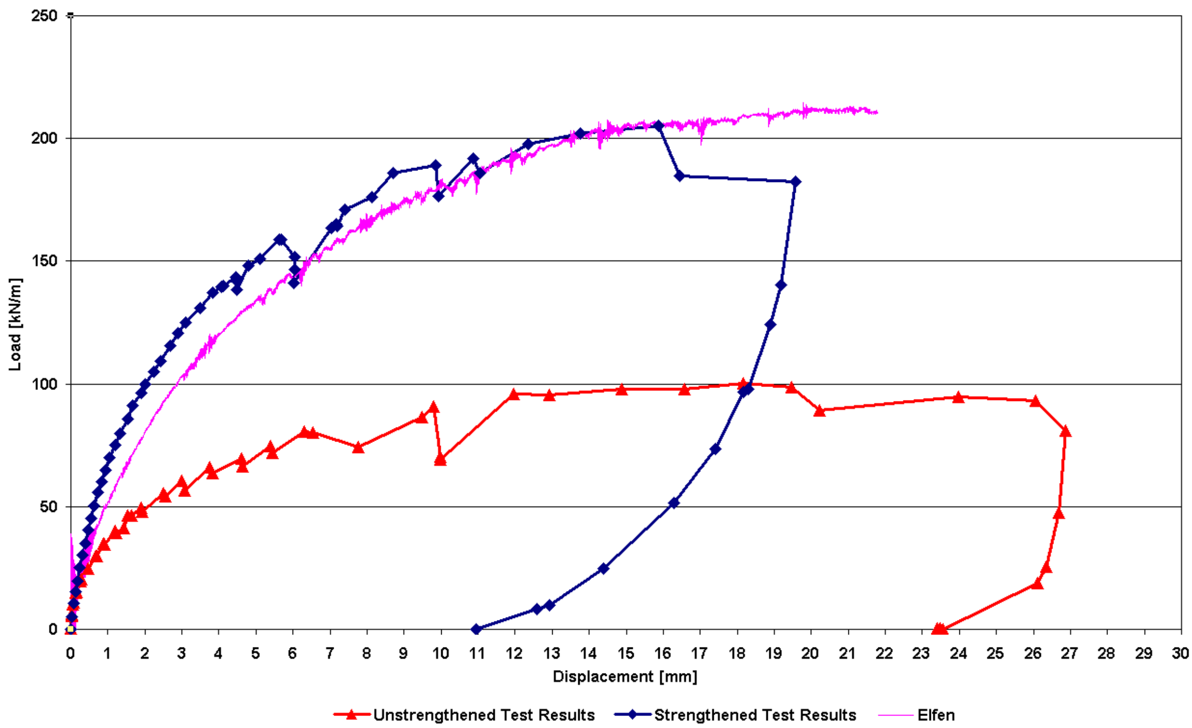


Figure 8.1 5m Span Archtec Test 1 – Comparison of Predicted and Test Results Separated Brick Rings

Load versus vertical displacement under the line load

Making comparisons between the two tests, strengthened versus unstrengthened, TRL was able to make the following principal conclusions:

i) The failure load of the strengthened arch barrel has been increased by a factor of 2.05.

ii) The first -installed anchors delayed the formation of hinges

iii) The anchors added considerable strength to the arch barrel

iv) The arch failed in a gradual and a ductile manner

Table 8.1 Summary of Test and Predicted Failure Loads

Description 5m Span Archtec Test 1 - Separated Brick Rings		**Load**	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	First loaded in load controlled followed by displacement control	205	1.00
Test	Comparable unstrengthened arch, see Figure 7.2	100	0.49
ELFEN	Mohr Coulomb	209	1.02

8.2 Archtec Test 2

Figure 8.2 compares the load versus displacement results obtained by ELFEN with those obtained from the second Archtec test[21] and also with the comparable unstrengthened ring separated arch. Again, failure loads are summarised in Table 8.2 and ELFEN contoured results at failure, including strengthening reinforcement stresses, are given in Figure C.2 in Appendix C.

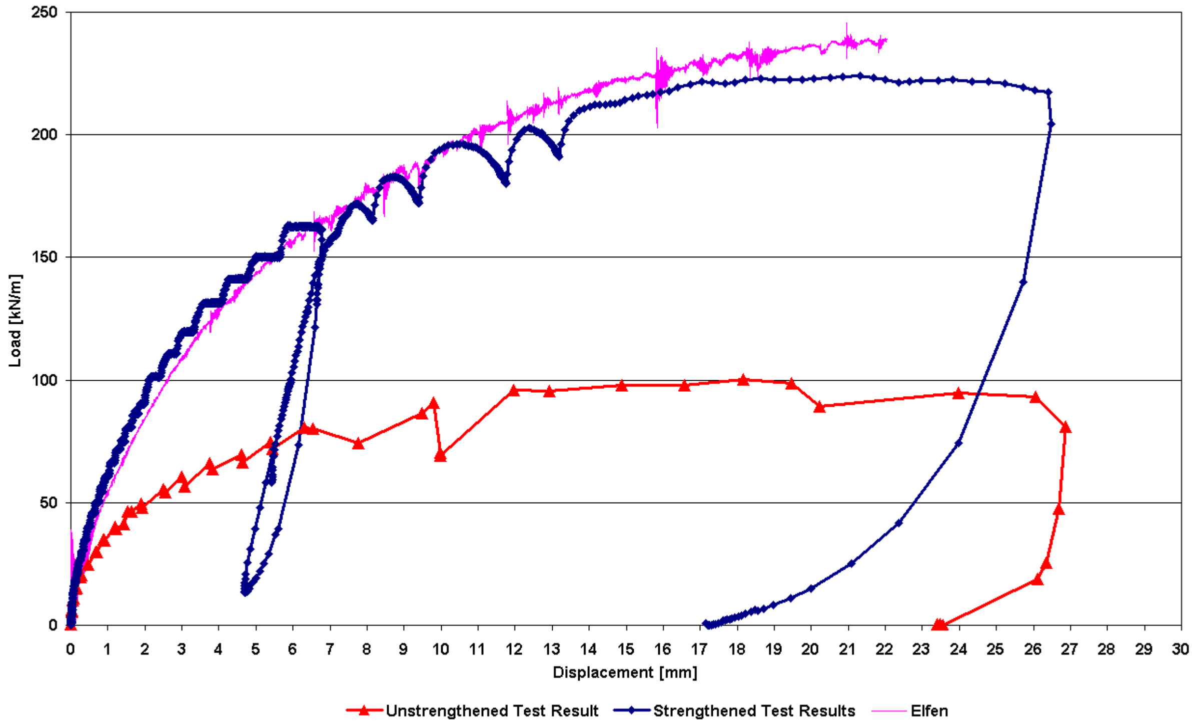


Figure 8.2 5m Span Archtec Test 2 – Comparison of Predicted and Test Results Separated Brick Rings

Load versus vertical displacement under the line load

Predictions made with ELFEN are almost exact and with the failure load within 1% of test result and with very good stiffness correlation. Ignoring a short period of unloading, calculated displacements remained within approximately 5% of test values throughout the loading stage.

Apart from confirming the findings of the first Archtec test the TRL were able to draw the following new principal conclusions:

i) The failure load of the strengthened arch barrel has been increased by a factor of 2.24.

ii) The behaviour of the Multibar anchor is similar to the Standard Cintec anchor tested previously.

Table 8.2 Summary of Test and Predicted Failure Loads

Description 5m Span Archtec Test 2 - Separated Brick Rings		**Load**	
Method	**Details**	**[kN/m width]**	**Ratio to test**
Test	First loaded in load controlled followed by displacement control	224	1.00
Test	Comparable unstrengthened arch, see Figure 7.2	100	0.49
ELFEN	Mohr Coulomb	226	1.01

9. FAILURE BEHAVIOUR AND SERVICEABILITY

9.1 Failure Behaviour

The TRL tests confirmed that arches strengthened by the Archtec method 'failed in gradual but ductile manner' [20,21].

Strengthened arch barrels crack similarly to unstrengthened barrels and the first signs of cracking occur at similar proportions of their ultimate failure loads. Typical results are summarised in Table 9.1. Peak load capacity is achieved in both the unstrengthened and strengthened arches at similar deflections. Like reinforced concrete, the introduction of reinforcement increases overall ductility of the strengthened arches and severe overloading results in progressive cracking and distortion and not sudden collapse.

Table 9.1 Development of Barrel Cracking with Load

Test Details		Description of Cracking			
Ref	Description	Event Description	Total Load [kN]	Proportion of Ultimate Failure Load [factor]	Displacement at Peak Load (mm)
2	Unstrengthened with ring separation[11]	First significant crack	60	0.3	
		Hinge 1 development	130	0.65	
		Hinge 2 development	170	0.85	
		Hinge 3 and 4 development, Collapse	200	1.0	25
3	Archtec test 1[20]	First significant crack	100	0.24	
		Hinge 1 development	280	0.68	
		Hinge 2 development	320	0.78	
		Hinge 3 and 4 development, load continues to be applied	350	0.85	
		Collapse	410	1.0	20

The main observations are:

i) Progressive development of cracks and hinges occur for both the unstrengthened arch and the strengthened arch.

ii) The first significant cracks were observed at approximately 1/3 the failure load for the unstrengthened arch and at just under 1/4 the failure load for the strengthened case.

iii) A failure mechanism occurs in the unstrengthened arch immediately after hinges 3 and 4 are formed, whereas in the strengthened case the arch barrel continues to carry load; more warning is given of an imminent failure mechanism.

Figure 9.1 contains a series of photographs taken during the second Archtec test indicating the high degree of ductility exhibited prior to final collapse. In each case the arch remained stable under at least its self weight and further load/displacement had to be applied by the jack to cause further distress.

In addition, it should be noted that design in accordance with the relevant standards[5] results in an ultimate capacity of the arch well in excess of double the maximum envisaged service load.

Figure 9.1 Failure of strengthened arch observed in the second Archtec test at TRL
(Note that between each stage the arch remains stable under a minimum of its own self weight and further load/displacement had to be applied via the jack to progress the failure)

9.2 Serviceability

No clear definition of serviceability exists for masonry arches[22]. Deflections and cracking behaviour is normally used to define a serviceability limit state. However, in arches these quantities are generally small and very difficult to detect under expected service loads and they cannot be calculated by conventional structural analysis. However, results from monotonic and cyclic load tests have been used to derive masonry stress limits in terms of a limiting factor of the ultimate capacity below which permanent damage does not occur from repeated loading.

Based on work done by TRL in the 1980's, the Highways Agency[5] (United Kingdom) assessment standards for arches are based on serviceability being maintained provided applied loads do not exceed half the ultimate capacity.

Cyclic loading on bridge piers has been investigated by British Rail Research[23] and some progress made in linking fatigue of brickwork with a serviceability limit state. It was concluded that, for dry brickwork, if applied loads do not exceed half the ultimate capacity an infinite number of load cycles could be sustained. However, for saturated brickwork lower load levels are required.

Both observations of monotonic loading and cyclic loading have lead to the recommendation of a 50% rule and are in effect stress limit based. The current Archtec design method, based on the Highways Agency[5] standards, embraces the serviceability limit state implicitly within the load and material factors used at the ultimate limit state. Whilst this method is consistent with current practice, the Finite/Discrete Element analysis used in the design of Archtec strengthening enables the behaviour of the arch under serviceability loading to be investigated in ways never before possible.

Comparison of results from the unstrengthened and Archtec tests show that under identical loads, displacements are very similar, see Figure 9.2. Corresponding structural analysis of the test arches predicts compressive stresses in the Archtec strengthened arch are lower than the unstrengthened arch under the same loading, see Figure 9.3. For example, at the maximum service load (refer to Appendix B in the earlier Gifford report[1]), the maximum compressive stress in the masonry at the load line is reduced from 1.3 MN/m^2 to 1.1 MN/m^2; a reduction of approximately 15%. The reduction in stress is due to the fact that the strengthening introduces bending capacity into the arch barrel, which can therefore resist the applied loading at the critical points more effectively. Hence, on the basis that serviceability can be defined by a stress limit, the reduction of stress levels in the masonry in strengthened bridges has a beneficial effect on serviceability.

It is understood that some clients are concerned that specific deteriorated conditions in arch barrels, such as loose bricks, could be exacerbated by strengthening. The risk here is that debris falling from a bridge would represent an unacceptable hazard. Arguably, an example of an arch barrel in a weakened condition that could develop loose bricks as a result of partial ring separation was one of the series of LINK arches tested[11], test ref. 2 in Table 9.2. Displacement results for this test are included in Figure 9.2. They show that Archtec strengthening significantly increases the stiffness of the ring separated barrel restoring it to that of the fully bonded case (as-built condition). The implication is that strains in the intrados have been reduced and the risk of bricks loosening is thereby also reduced. Provided an arch is maintained in reasonable condition the risk of bricks loosening should be reduced compared to an unstrengthened arch. There is also no reason to doubt that similar trends in behaviour will occur if the inner ring itself is in a deteriorated condition.

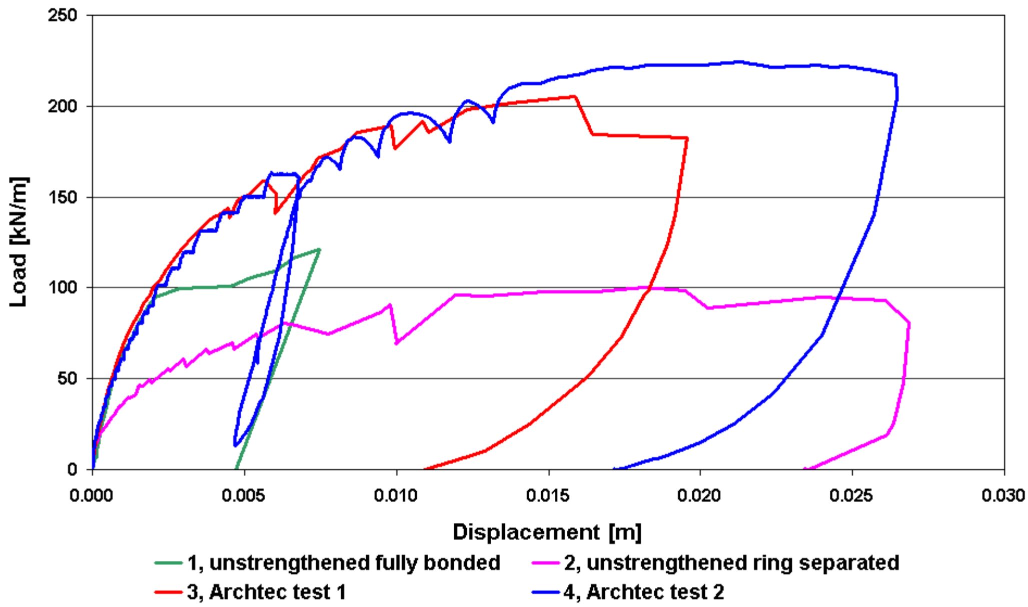


Figure 9.2 Test Load versus Displacement in Barrel at Load Position

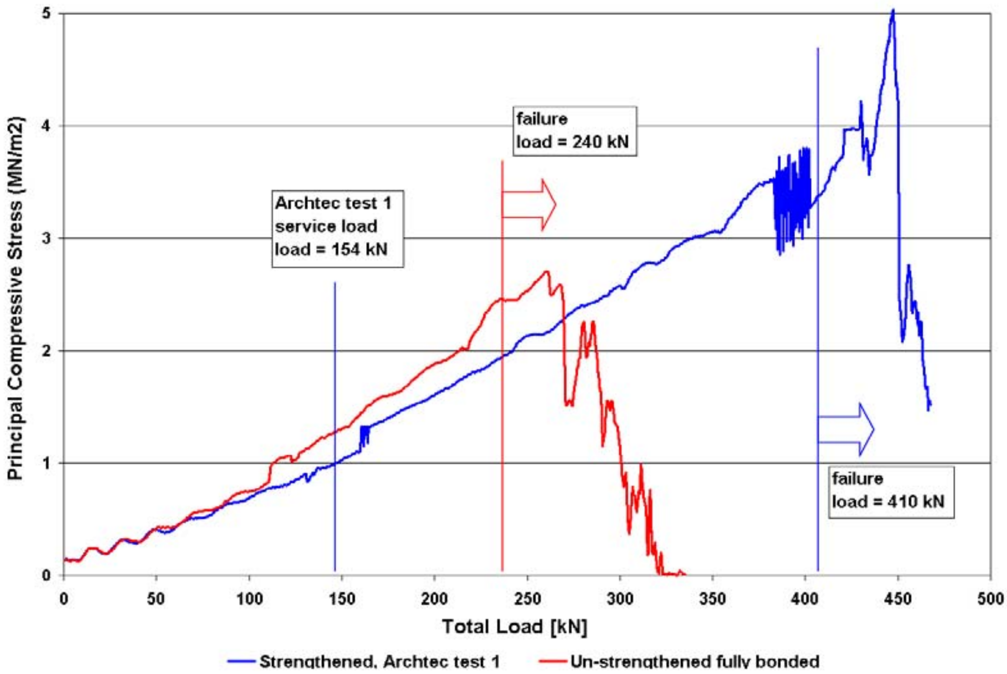


Figure 9.3 Predicted Principal Compressive Stresses in Masonry

Under line load, close to extrados at hinge 1 position

Bridge owners and experts in the field recognise the desirability of further research with respect to the serviceability limit state in arch bridges and it is understood that the CSS and Bridge Owners Forum, amongst others, are currently looking in to this. However, at the current time no specific guidance or criteria exist with respect to explicit evaluation of the serviceability state in arches.

Table 9.2 Comparison of Ultimate Failure Loads in the TRL Tests

Test Details		Ultimate Failure Load	
Ref	Description	Total [kN/m]	Comparison [factor]
1	Unstrengthened fully bonded(12)	120	1
2	Unstrengthened with ring separation(11)	100	0.83
3	Archtec test 1(20)	210	1.75
4	Archtec test 2(21)	225	1.88

To provide increased confidence that the serviceability of a bridge would not be compromised by Archtec strengthening additional checks can be introduced into the design process with the Client's agreement. It has been proposed that the following additional serviceability criteria are included in the design process for Network Rail bridges;

a) Either check that stresses under the required live loading do not exceed those in the unstrengthened bridge under existing live loading, or alternatively check that stresses in the strengthened bridge are below an agreed serviceability limit state value.

b) To be sure that existing defects are not made worse, or for that matter introduced into arch barrels by Archtec strengthening strains along the intrados under the required live loading will be checked to ensure they do not exceed those in the unstrengthened bridge under existing live loading. Strains would need to be calculated over a reasonable length so that an estimate of radial joint cracking, critical to loosening of bricks, is included.

These criteria are considered very conservative and stresses and strains beyond these limits may be quite safe and have no adverse serviceability effects. However, further fundamental research is required to establish the limiting criteria, which is beyond the scope of a single organisation.

10. CONCLUSIONS

A summary of the failure loads predicted by ELFEN against the failure loads determined in the various tests that have formed the basis for the verification are included in Table 10.1. (Fuller details and discussion of the respective results, including comparisons with conventional arch assessment methods can be found in the respective parts of Sections 7 and 8 of this report).

The predicted failure loads determined by ELFEN correlate extremely well with the test results, for all the various forms of arch considered, including unstrengthened brick arches with and without partial ring separation, a random rubble stone arch, a multi-span arch and Archtec strengthened brick arches.

The results of the ELFEN analysis also correlate well with conventional methods of assessment in most instances, although the ELFEN predictions are generally closer to the test results than conventional methods. As has been noted by others, in some particular cases, conventional methods of assessment can give poor and non-conservative predictions of strength; for example it may not be possible to take account of multi-ring brick arch behaviour and so strength could be overestimated.

On the basis of the verification process documented in this report and subject to the use of the relevant material properties and parameters upon which the verification has been carried out, the use of ELFEN, in the way described, to determine the strength of both unstrengthened and Archtec strengthened masonry arch bridges (which are square or near square (up to the order of 20˚ skew)) is considered justified.

In addition, Finite/Discrete Element analysis of masonry structures provides several significant new capabilities over conventional methods of assessment, namely;

- Explicit representation of defects such as ring separation, local distortion and mortar loss is possible and the verification process using ELFEN has established that these can be reliably modelled; that is predictions of behaviour of both ring separated and fully bonded arches have been satisfactorily undertaken.

- Deflections and serviceability behaviour can be predicted. This has not before been possible. The verification process has established that deflections can be reliably predicted using ELFEN and this provides the basis for a significant and exciting new capability for modelling arch behaviour at the serviceability limit state.

Table 10.1 Summary of ELFEN Prediction Against Tests

Description of Test	Section Ref. For Full Results	Test Failure Load KN/m	ELFEN Predicted Failure Load KN/m	Ratio of ELFEN Prediction to Test
5m Span TRL Laboratory Arch – Mortar Bonded Brick Rings	7.2	121	122	1.01
5m Span TRL Laboratory Arch – Separated Brick Rings	7.2	100	98	0.98
5m Span Bolton Arch – Separated Brick Rings	7.3	166	189	1.14
5m Span Bolton Arch – Mortar Bonded Brick Rings	7.3	332	293	0.88
3m Single Span Bolton Arch – Mortar Bonded Brick Rings	7.3	188	165	0.90
3m Multispan Bolton Arch – Mortar Bonded Brick Rings	7.3	111	100	0.90
TRRL – 9.5m Single Span Stone Arch - Strathmarshie Bridge () indicates with mortar softening	7.4	270	257 (252)	0.95 (0.93)
Archtec Strengthened Arch – 5m Span Separated Brick Rings	8.1	205	209	1.02
Archtec Strengthened Arch – 5m Span Separated Brick Rings	8.2	224	226	1.01

11. REFERENCES

1. Gifford and Partners. July 2002. *Archtec – The application to Railtrack Bridges. Report number B1660A/V10/R01.*

2. Wolfson Bridge Research Unit. 1991. *Archie & multi: masonry arch assessment software.*

3. Heyman, J. 1980*. The estimation of the strength of masonry arches*. Proceedings of the Institute of Civil Engineers, 69, 921-

4. The Highways Agency. 1997. *Design Manual for Roads and Bridges, BA 16/97 The Assessment of highway bridges and structures.*

5. The Highways Agency. 2001. *Design Manual for Roads and Bridges, BD 21/01 The Assessment of highway bridges and structures.*

6. Obvis Ltd. 1999*. Archie-m: masonry arch assessment software.*

7. Gilbert M. 2001*. RING: User Guide*. University of Sheffield.

8. Cundall, P.A. 1971. *A computer model for simulating progressive, large scale movement in blocky systems.* Proceedings: Symp. ISRM, Nancy, France, Vol. 2, 129-136.

9. Munjiza A., Owen, D.R.J., Bicanic, N. 1995*. A combined finite/discrete element method in transient dynamics of fracturing solids*. Engineering computations, 12, 145-174.

10. Rockfield Software Limited. 1997-2003. *ELFEN version 3.0.4 (Elfendyn v3.3.24) Archtec version*. University of Wales Swansea.

11. S K Sumon. 1997. *Repair and strengthening of a damaged arch with built-in ring separation.* 7th International conference on structural faults and repair, Edinburgh.

12. Sumon S K and Ricketts N. 1995. *Repair and strengthening of masonry arch bridges.* Proceedings of the First International Conference on Arch Bridges, Bolton. Pages 501-508

13. Melbourne C and Gilbert M. 1995. *The behaviour of multi-ring brickwork arch bridges.* The Structural Engineer / Volume 73 / No 3.

14. Gilbert M and Melbourne C. 1995. *Analysis of multi-ring brickwork arch bridges*. Proceedings of the First International Conference on Arch Bridges, Bolton. Pages 225-238

15. Melbourne C, Gilbert M and Wagstaff M. 1995*. The behaviour of Multi-span Masonry arch bridges.* Proceedings of the First International Conference on Arch Bridges, Bolton. Pages 489-497

16. Melbourne C and Wagstaff M. 1993. *Load tests to collapse of three large-scale multi-span brickwork arch bridges*. Bridge Management 2 – inspection, maintenance, assessment and repair.

17. British Standards Institution. 2002. *BS 5628-1:1992, Code of practice for use of masonry, Part 1: Structural use of unreinforced masonry.*

18. Page J. 1989. *Load tests to collapse on two arch bridges at Stathmashie and Barlae.* Transport and Road Research Laboratory, Research Report 201.

19. Page J. 1993. *State-of-the-art-review: Masonry Arch Bridges*. Transport Research Laboratory.

20. Sumon, S.K. 1998*. Load test to failure on a ring-separated arch repaired using Cintec Anchor Systems.* Transport Research Laboratory, Unpublished project report PR/CE/61/98.

21. Sexton, A and Crabb, G.I. 2001*. Loading to failure of an Archtec strengthened brick arch using Cintec Multi-bar anchors.* Transport Research Laboratory, Unpublished report PR/IS/59/01.

22. Choo, B.S. and Hogg, V. 1995. *Determination of the serviceability limit state for masonry arch bridges.* Arch Bridges, Proceedings of the First International Conference on Arch bridges, Bolton. Pages 529-536.

23. Clark, G. 1994. *Bridge analysis, testing and cost causation project, serviceability of brick masonry.* British Rail Report No. LR-CES-151.

APPENDIX A

TYPICAL CONVENTIONAL ARCH ANALYSIS RESULTS

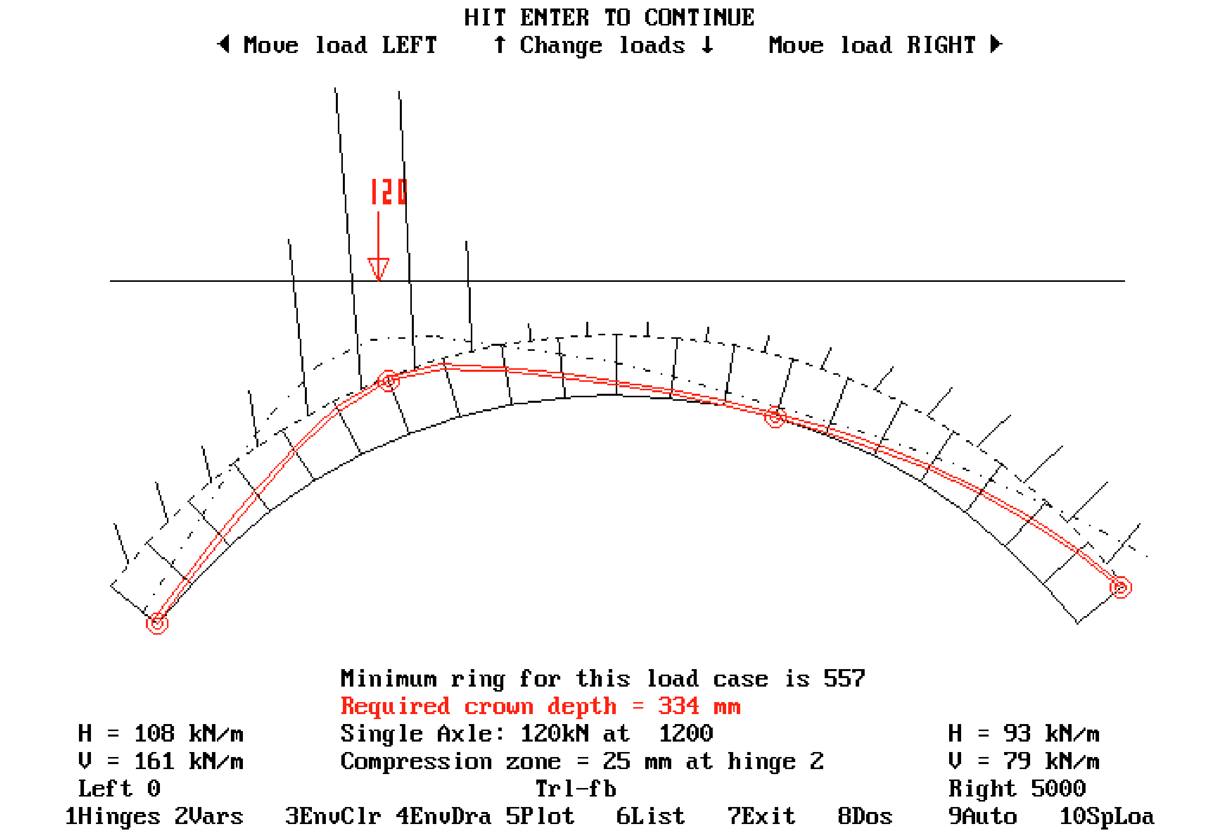


Figure A.1 Archie Analysis - 5m Span TRL - Mortar Bonded Rings

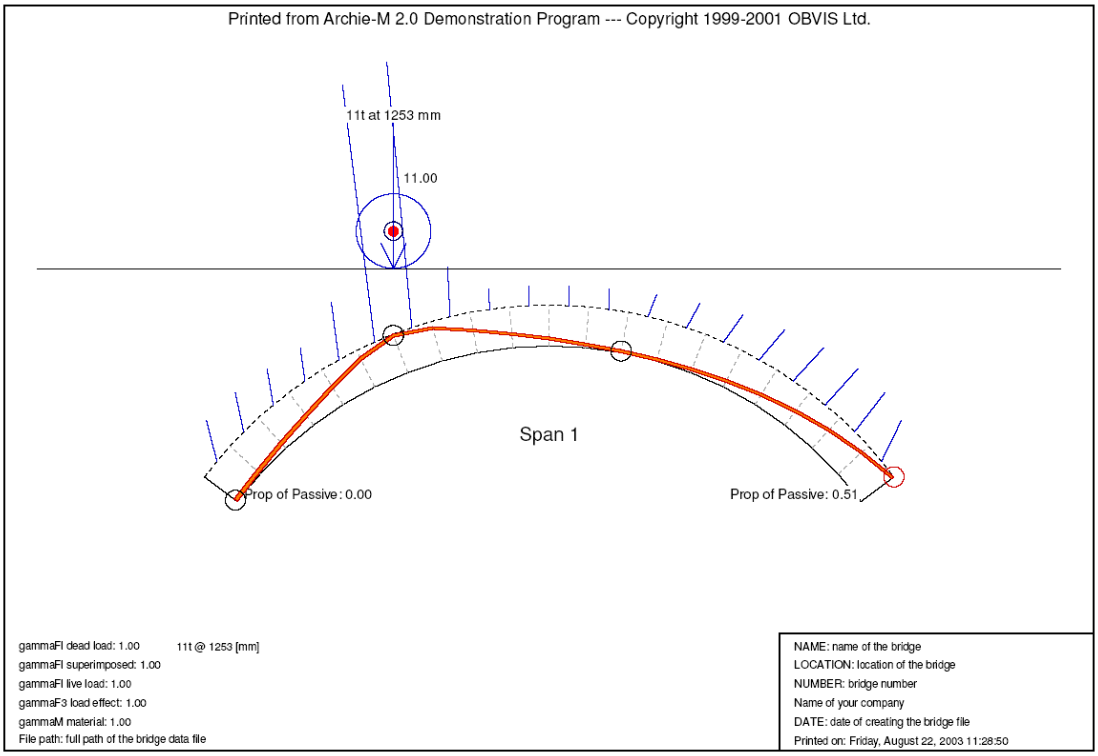


Figure A.2 Archie-M Analysis - 5m Span TRL - Mortar Bonded Rings
(Corresponding tabular printout omitted)

Summary

Bridge name	ELR	Bridge no.	Mileage	Stations at or between
not entered	not entered	not entered	not entered	not entered

Date of assessment	Name of assessor	Assessing organization
22/8/2003	not entered	not entered

Bridge type
not entered

Analysis result
Critical load factor = 63.39 (load case 1)

Critical failure mechanism:

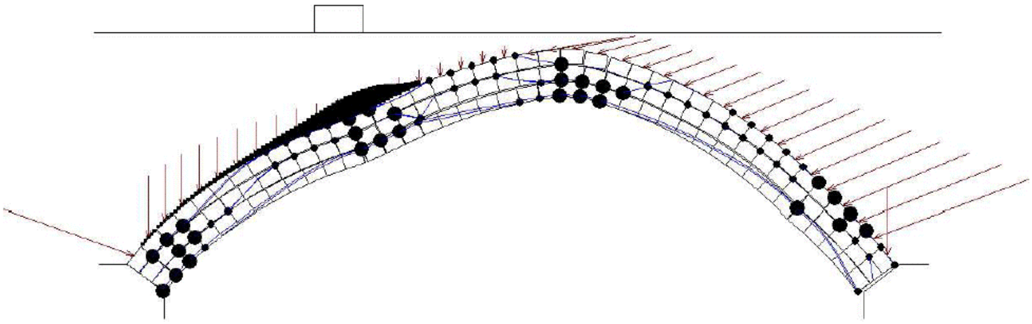
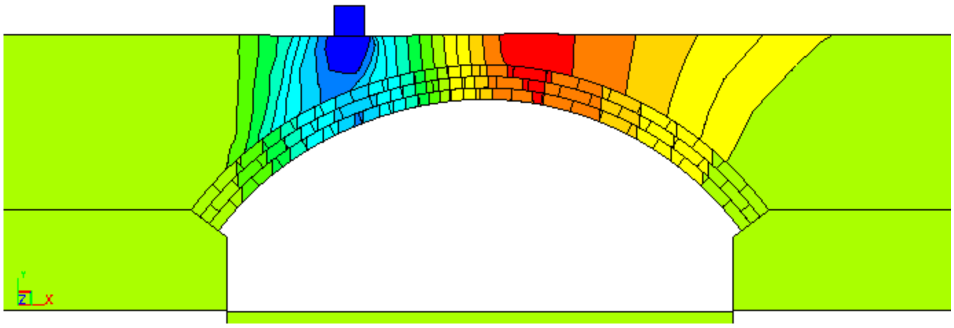


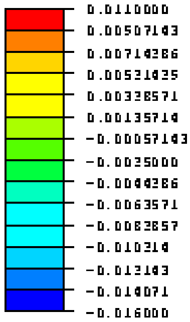
Figure A.3 RING Analysis - 5m Span TRL - Mortar Bonded Rings

APPENDIX B

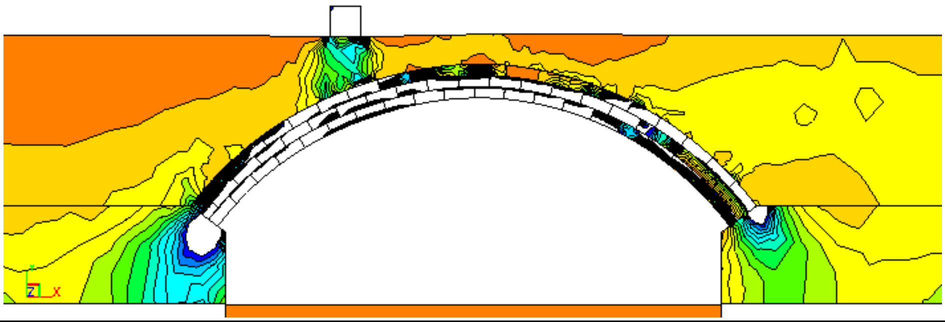
ELFEN RESULTS – UNSTRENGTHENED ARCHES

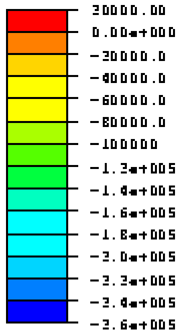
Result Diagram	Legend



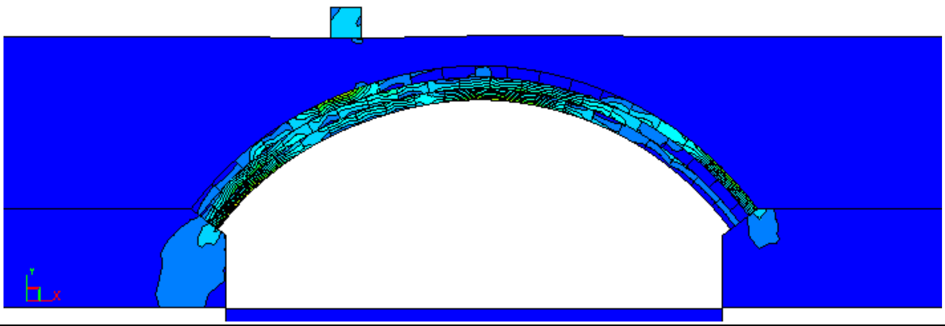


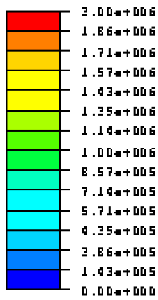
Vertical Displacement at Peak Load — [m]



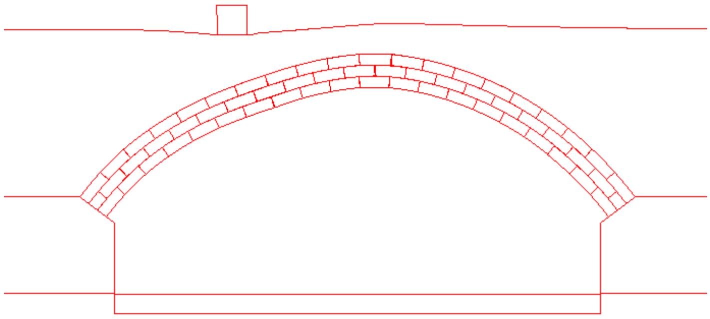


Principal Compressive Stress at Peak Load — [N/m^2]





Von Mises Equivalent Stress (Effective) at Peak Load — [N/m^2]



Failure Mode

Figure B.1 5m TRL Arch - Mortar Bonded Rings

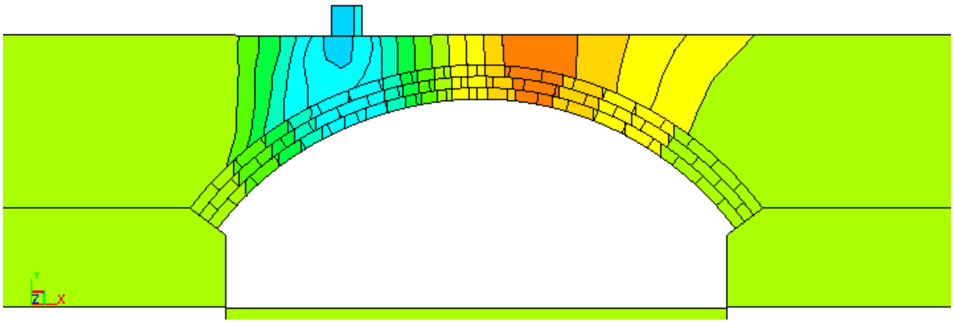
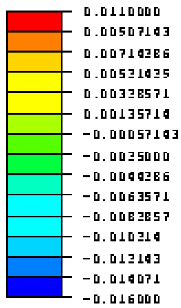
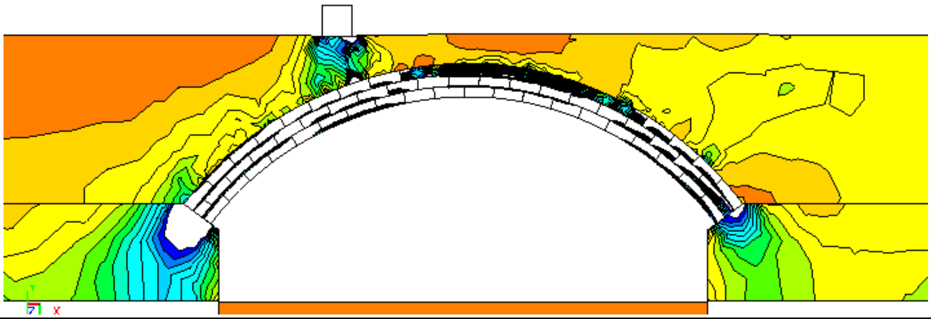
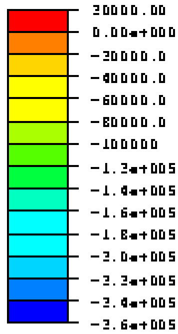
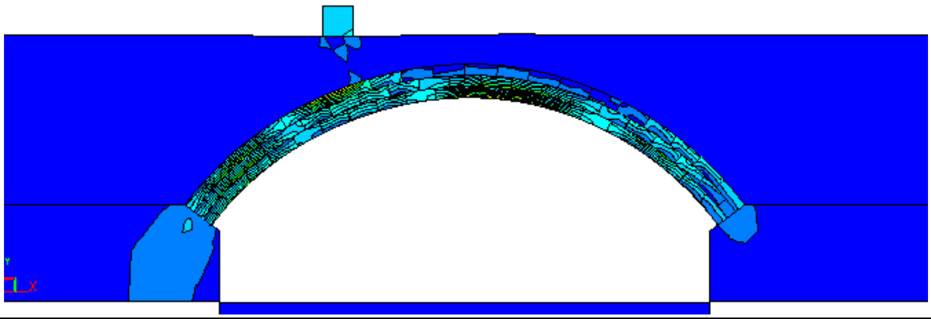
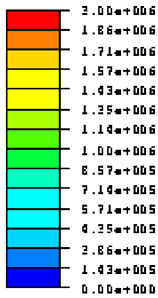
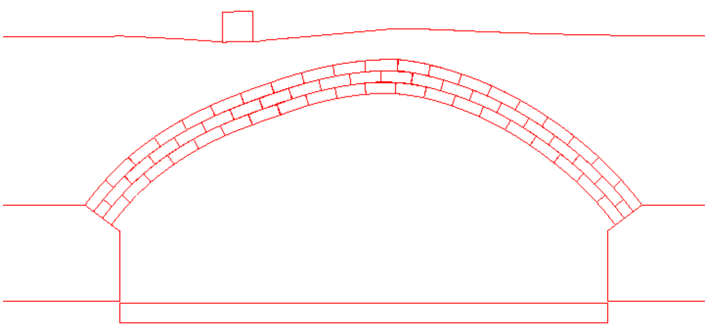
Result Diagram	Legend
	
Vertical Displacement at Peak Load	[m]
	
Principal Compressive Stress at Peak Load	[N/m^2]
	
Von Mises Equivalent Stress (Effective) at Peak Load	[N/m^2]
	
Failure Mode	

Figure B.2 5m TRL Arch - Separated Rings

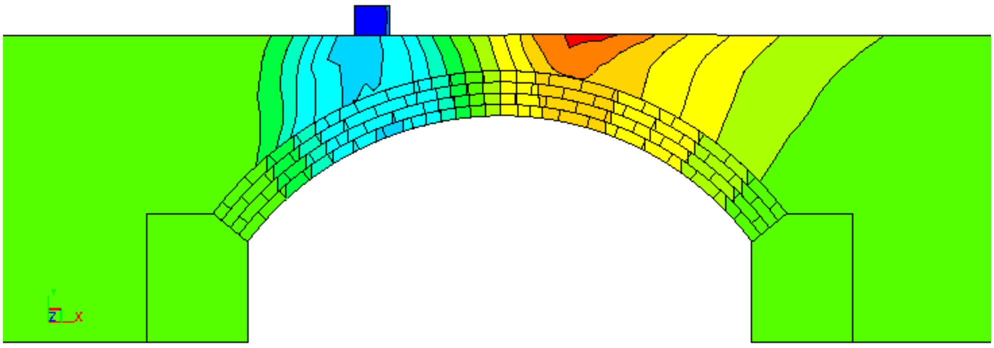
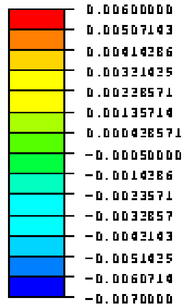
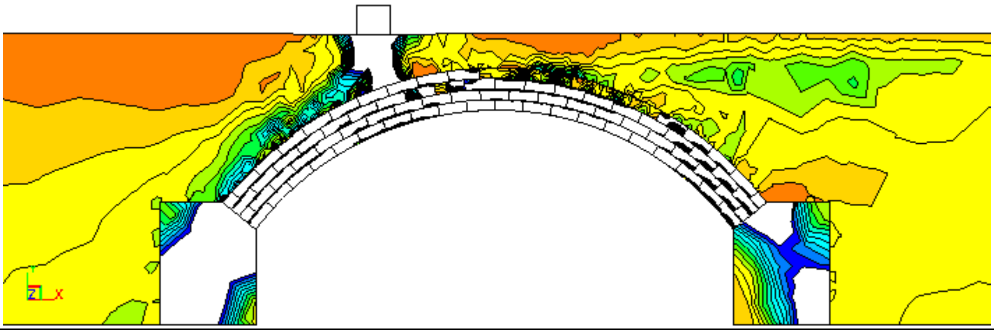
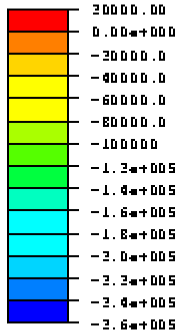
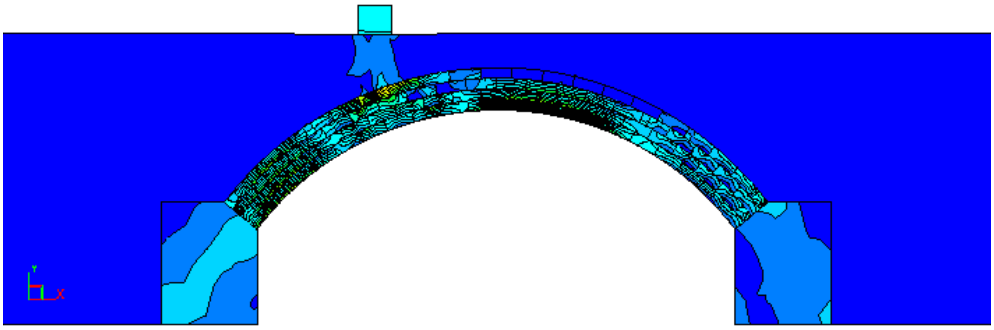
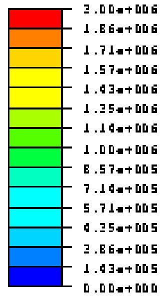
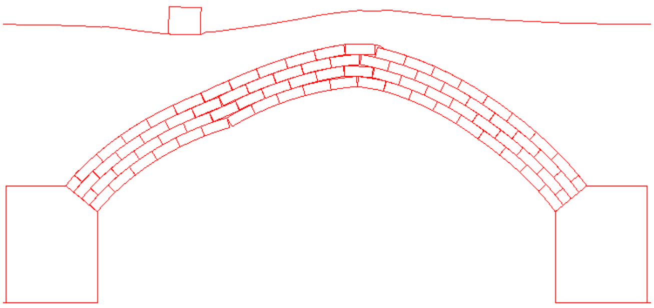
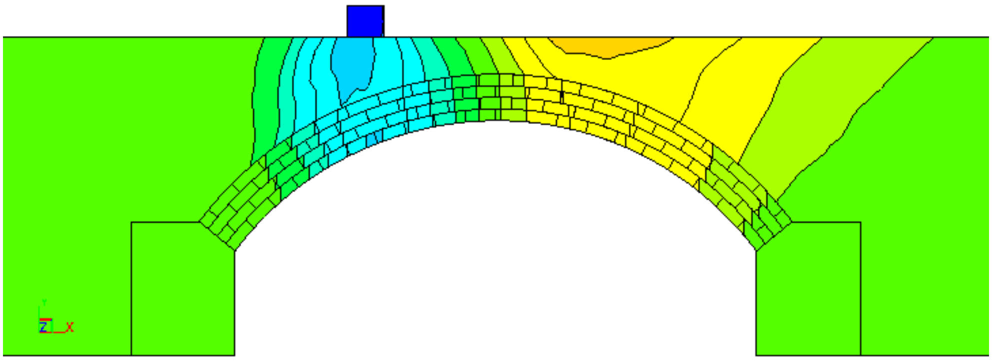
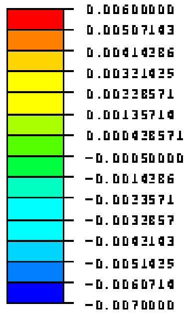
Result Diagram	Legend
	
Vertical Displacement at Peak Load	[m]
	
Principal Compressive Stress at Peak Load	[N/m^2]
	
Von Mises Equivalent Stress (Effective) at Peak Load	[N/m^2]
	
Failure Mode	

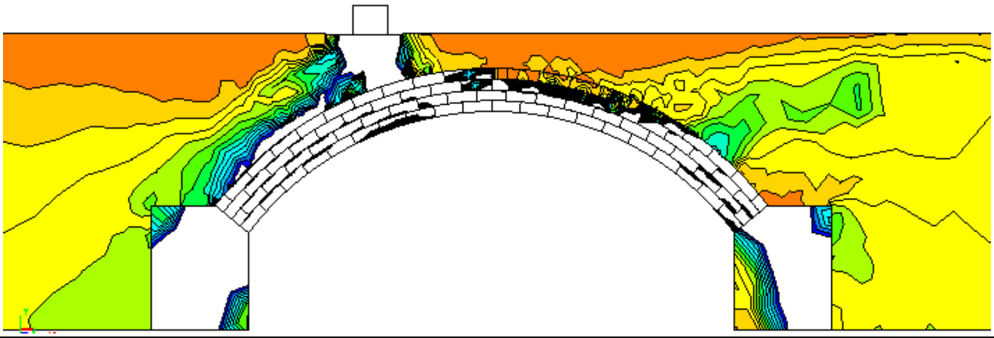
Figure B.3 5m Bolton Arch - Separated Rings

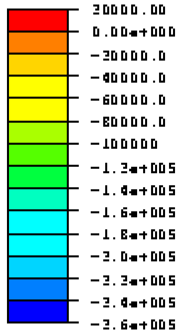
Result Diagram	Legend



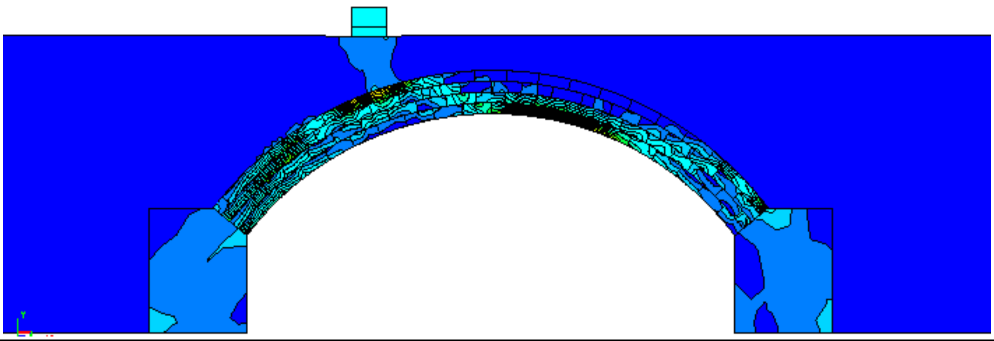


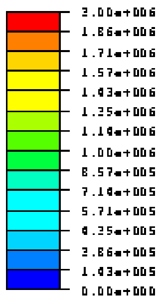
Vertical Displacement at Peak Load — [m]



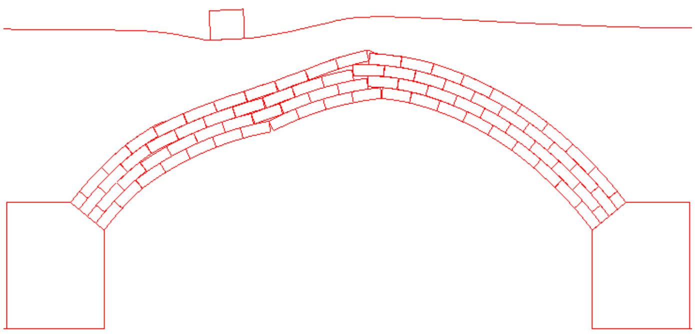


Principal Compressive Stress at Peak Load — [N/m^2]





Von Mises Equivalent Stress (Effective) at Peak Load — [N/m^2]



Failure Mode

Figure B.4 5m Bolton Arch - Mortar Bonded Rings

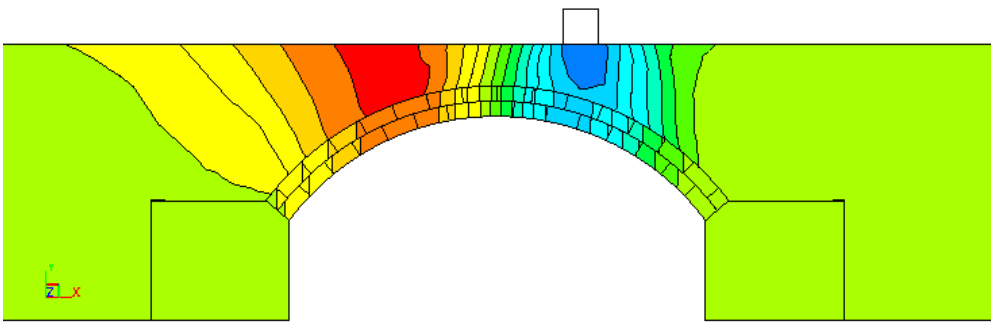
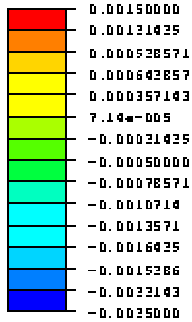
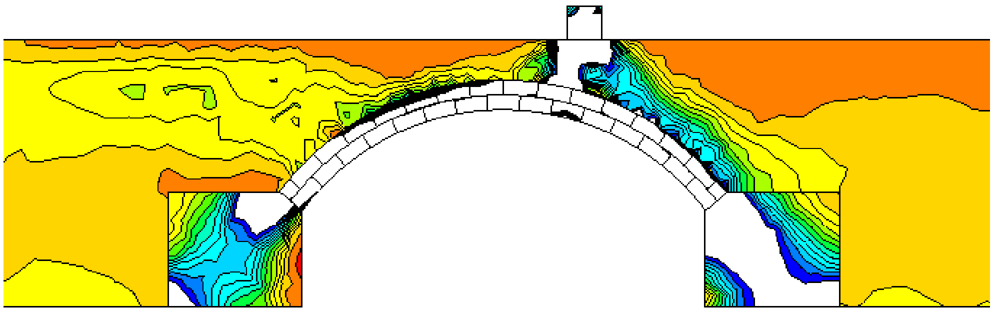
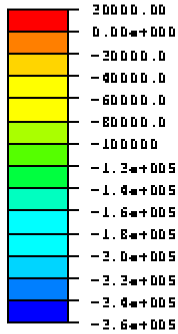
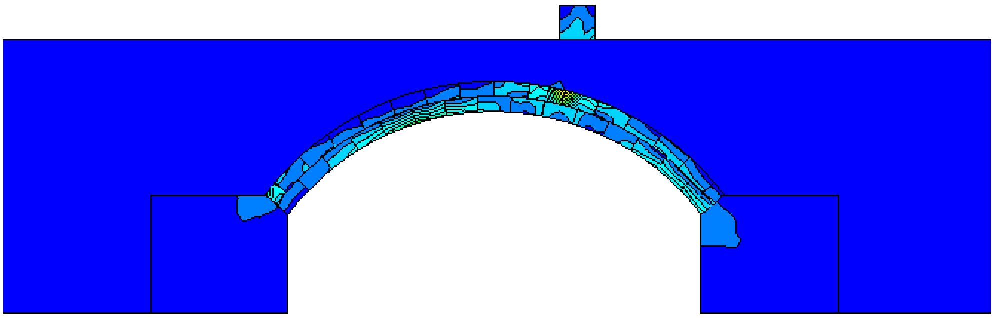
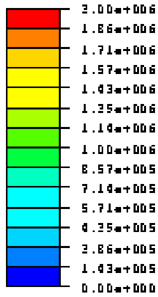
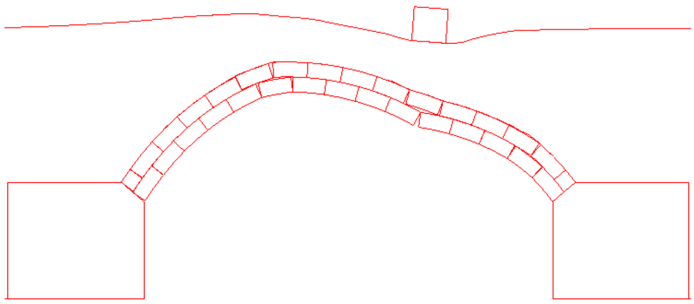
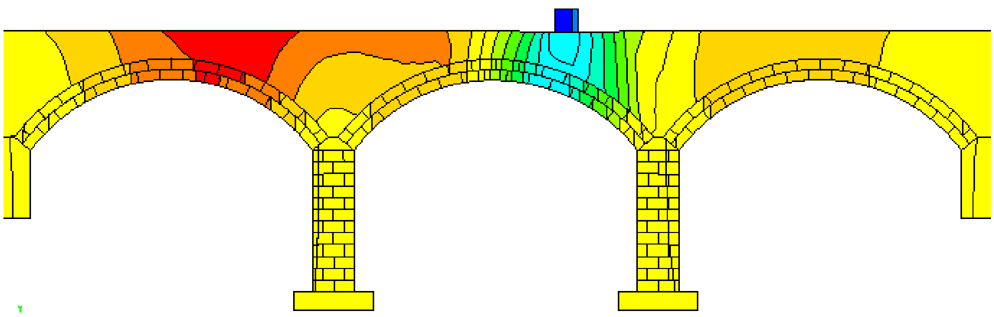
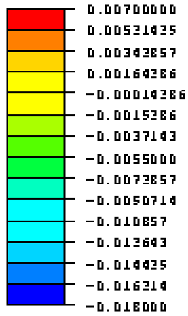
Result Diagram	Legend
	
Vertical Displacement at Peak Load	[m]
	
Principal Compressive Stress at Peak Load	[N/m^2]
	
Von Mises Equivalent Stress (Effective) at Peak Load	[N/m^2]
	
Failure Mode	

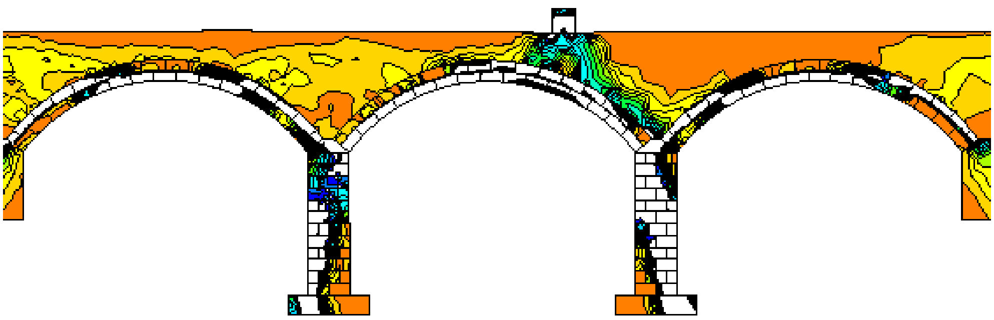
Figure B.5 3m Bolton Arch - Mortar Bonded Rings

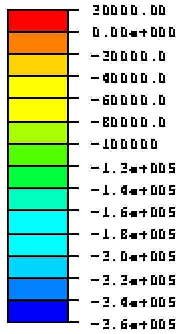
Result Diagram	Legend



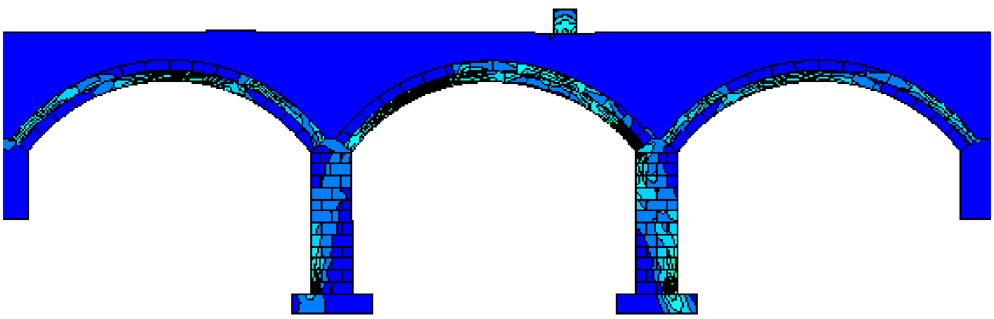


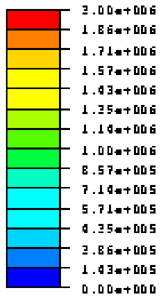
Vertical Displacement at Peak Load [m]



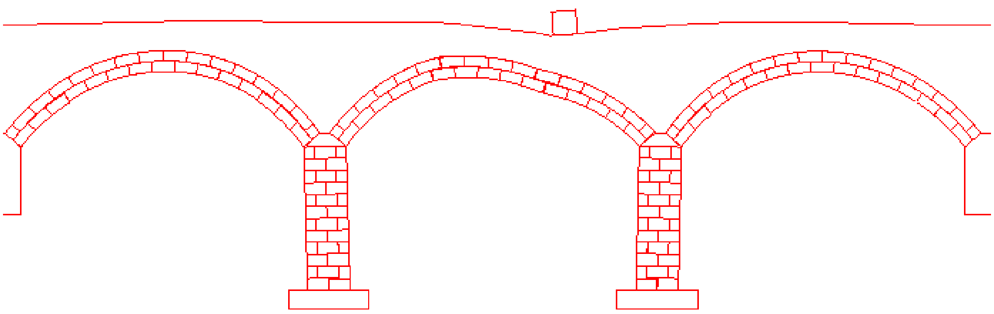


Principal Compressive Stress at Peak Load [N/m^2]





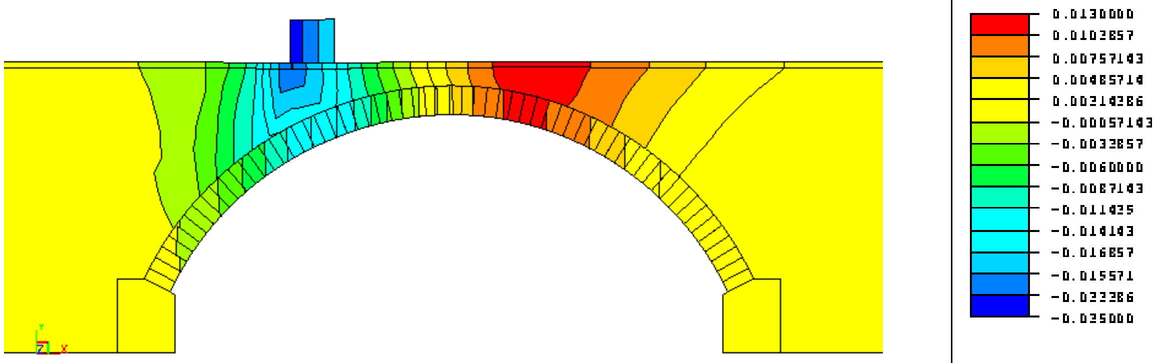
Von Mises Equivalent Stress (Effective) at Peak Load [N/m^2]



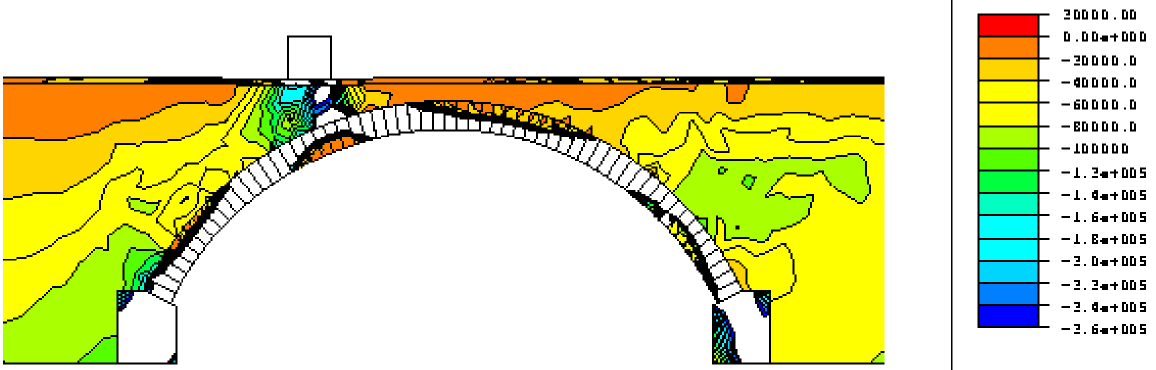
Failure Mode

Figure B.6 3m Multi-Span Bolton Arch - Mortar Bonded Rings

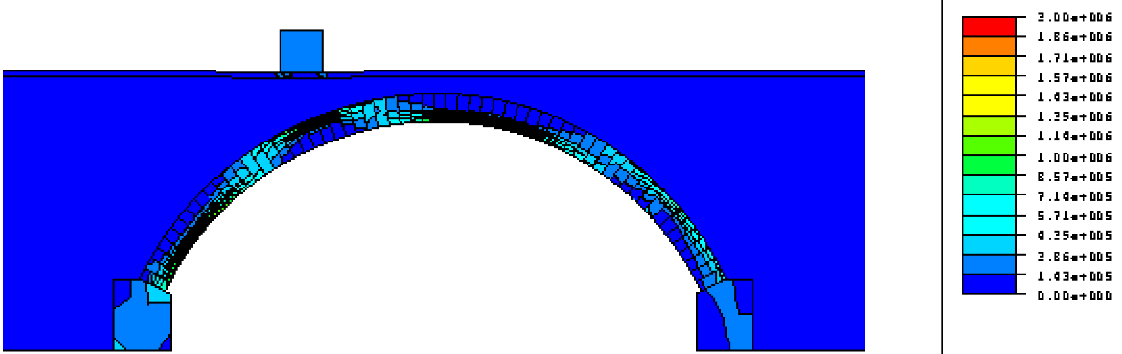
Result Diagram	Legend



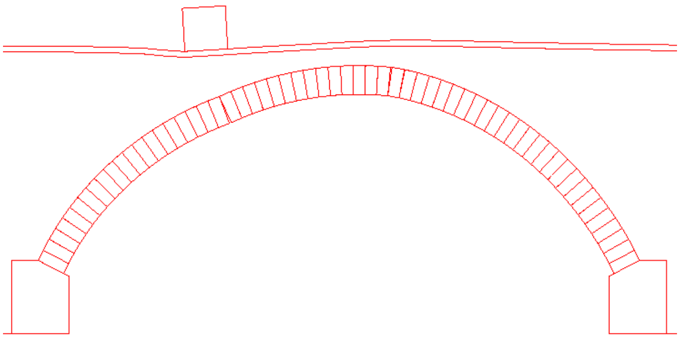
Vertical Displacement at Peak Load [m]



Principal Compressive Stress at Peak Load [N/m^2]



Von Mises Equivalent Stress (Effective) at Peak Load [N/m^2]



Failure Mode

Figure B.7 TRRL Strathmarshie Bridge - Random Rubble

APPENDIX C

ELFEN RESULTS – STRENGTHENED ARCHES

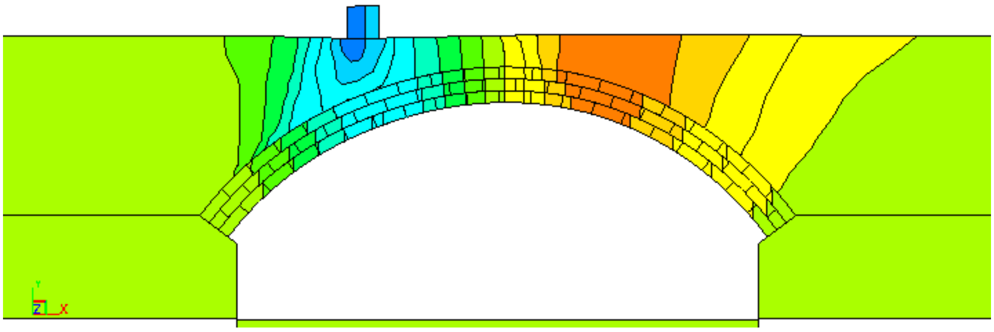
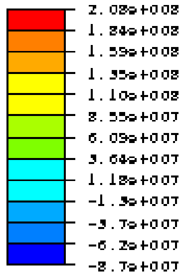
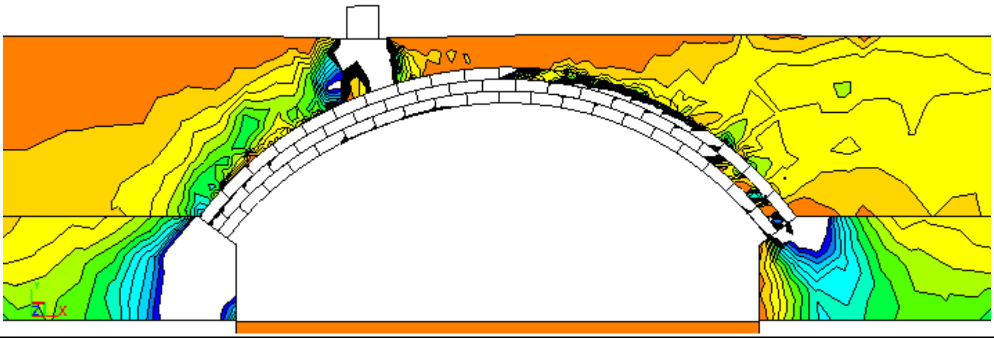
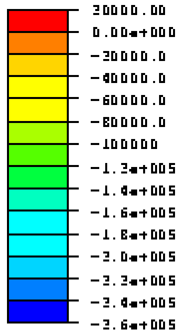
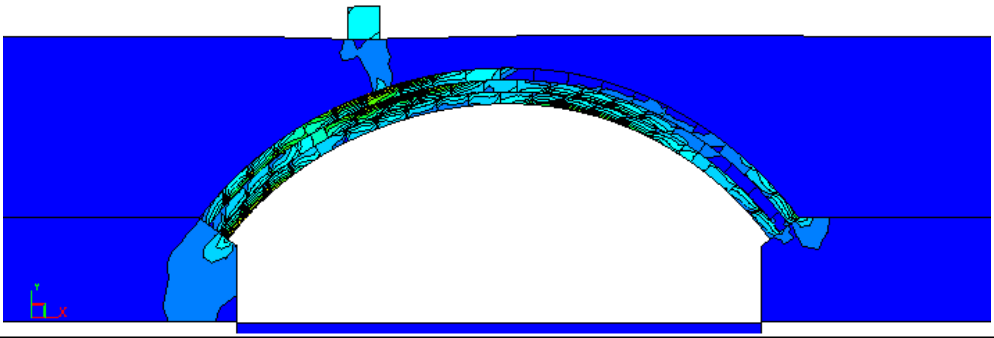
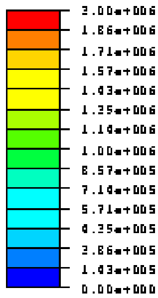
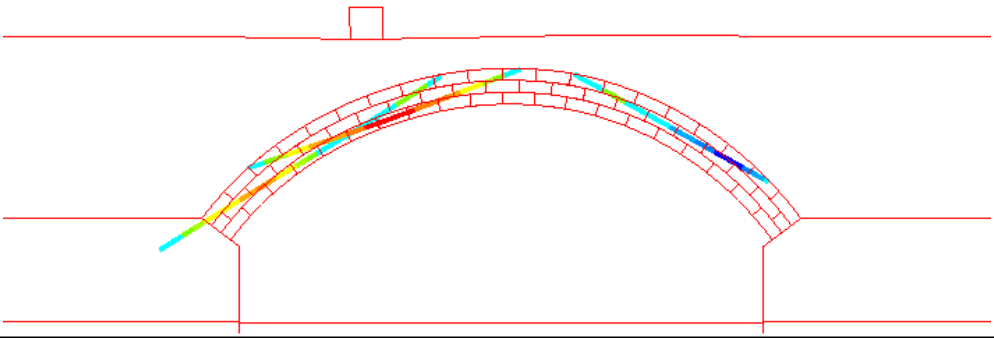
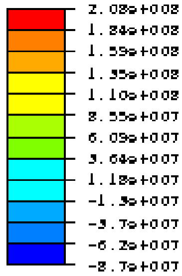
Result Diagram	Legend
	
Vertical Displacement at Peak Load	[m]
	
Principal Compressive Stress at Peak Load	[N/m^2]
	
Von Mises Equivalent Stress (Effective) at Peak Load	[N/m^2]
	
Axial Stress in Reinforcement (Cintec Anchors)	[N/m^2]

Figure C.1 Archtec Test 1 – 5m TRL Arch with Separated Rings

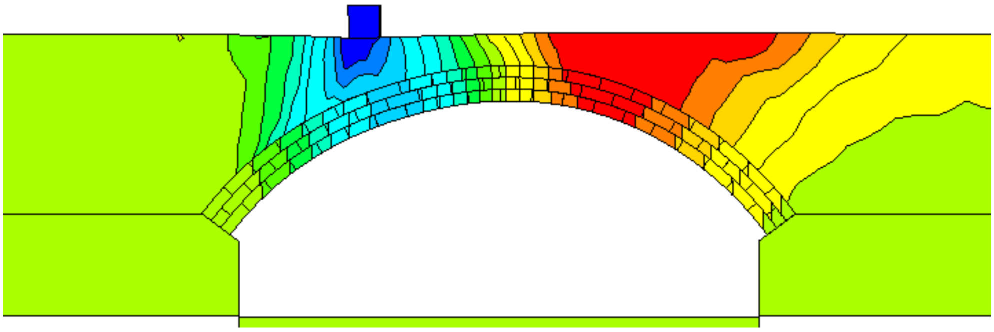
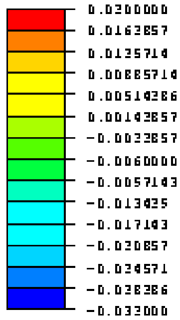
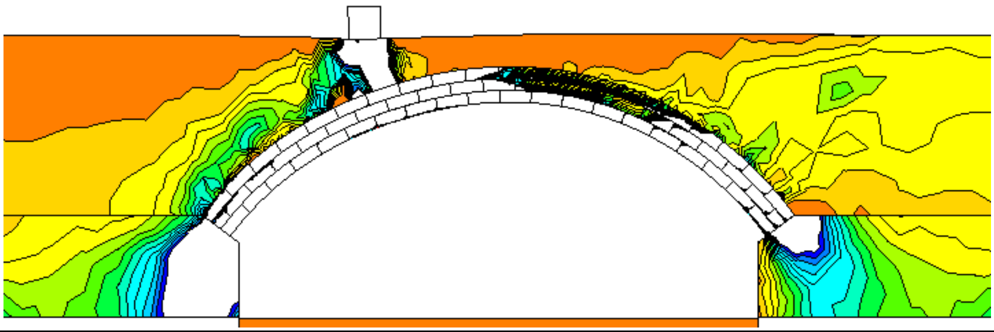
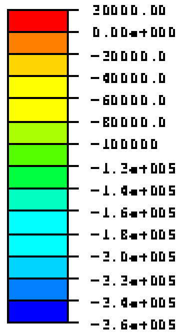
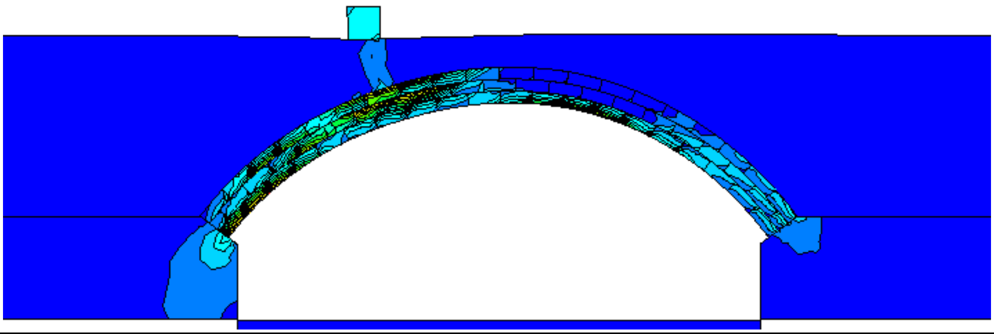
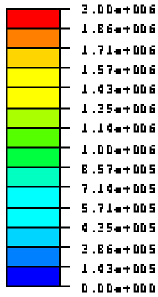
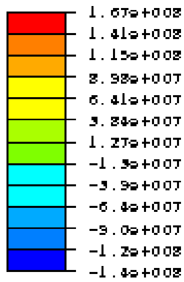
Result Diagram	Legend
	
Vertical Displacement at Peak Load	[m]
	
Principal Compressive Stress at Peak Load	[N/m²]
	
Von Mises Equivalent Stress (Effective) at Peak Load	[N/m²]
	
Axial Stress in Reinforcement (Cintec Anchors) at Peak Load	[N/m²]

Figure C.2 Archtec Test 2 – 5m TRL Arch with Separated Rings