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Application of the finite/discrete element method to arches

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During the last 10 years UK engineering consultancy Gifford has been assessing masonry arch bridges and using the finite/discrete-element method to predict their structural behaviour. In the majority of cases this work has followed bridge strength assessments based on traditional techniques where under-strength bridges are first identified. Over 200 bridges have now been investigated ranging from small rural bridges in the UK to massive structures used by Indian Railways, and a significant economic and environmental benefit gained through their continued use. This paper describes how the finite/discrete-element method has been applied and verified and covers the description of a development programme including full-scale laboratory tests, supplementary load tests on bridges in the field, and several monitoring programmes. The advantages this technique can provide over conventional arch bridge analyses, both limit analysis (mechanism) and traditional finite-element modelling, are described and how through partnering an innovative assessment and strengthening service is being delivered. The relevance of this approach to emerging serviceability limit state arch bridge assessment, which is seen as being particularly important for railways, is also discussed.

1. INTRODUCTION

It is very likely that there are well over half a million masonry arch bridges in use throughout the world today, principally carrying road and rail. European railways alone account for 200 000 bridges (Orbán, 2004). These bridges form a vital asset. Their replacement cost is almost incalculable yet a worldwide insatiable appetite for economic growth is in some cases pushing their use to the limit.

Despite masonry arches being ancient in form, it remains notoriously difficult to accurately assess their strength. At all limit states their behaviour is complex, deriving their overall behaviour from the interaction of individual parts, blocks, bricks, mortar and fill. Several methods for assessing the strength of arch bridges have become well established, a vital activity where traffic loads increase, but their generalised use is limited and their application for designing strengthening difficult. Finite-element analysis, which has to be non-linear to predict strength, has also been successfully applied but the choice of tensile material properties can be problematic as this can artificially influence the outcome.

The finite/discrete-element method (FDEM), which involves the automatic computation of interacting bodies is, therefore, a natural choice for representing masonry and this type of non-homogenised structure. Like the conventional finite-element method, being a generalised approach also means that, subject to verification, any geometric form of masonry can be simulated. Consequently, there are no restrictions to the arch bridge form, and the number of spans, rings and piers that can be modelled. Furthermore, unlike many simpler strength assessment methods, there is no adherence to predetermined failure mechanisms – for instance, a set number and pattern of hinges.

The application of FDEM has marked a step change in the sophistication that can now be applied to the structural analysis of masonry arch bridges. Not only can it be used to accurately assess strength but also to determine bridge deformation, including important non-linear effects, making it possible to assess behaviour at both strength and serviceability limit states. Being a generalised approach, the behaviour of complex bridges can be assessed where, for example, a concrete saddle may exist, a bridge has been propped and, in the case of strengthening, retrofitted reinforcement is introduced.

UK engineering consultancy Gifford has completed over 200 bridge assessments and bridge strengthening designs, mainly in the UK but also in the USA, Australia and India. This service was originally conceived for efficient, economic and sympathetic strengthening of arches, but the method of structural analysis can also provide accurate strength assessment of existing bridges and on many occasions has been used to show that bridges previously identified to require strengthening need no further engineering to support planned loads.

2. CONVENTIONAL ASSESSMENT

Methods of strength assessment have been categorised (McKibbins *et al.*, 2006) as semi-empirical, limit analysis and solid mechanics methods.

2.1. Semi-empirical methods

Most semi-empirical methods are based on the Military Engineering Experimental Establishment (MEXE) method which evolved from work undertaken in the 1930s for the military to rapidly assess arch bridges. It is often still used as a first pass strength assessment but its use is highly subjective and there

are many limitations. It is of little value for any detailed work such as the design of strengthening.

2.2. Limit analysis methods

Most conventional bridge assessments are now carried out using computerised versions of limit analysis, also known as mechanism analysis. In its simplest form these methods consider a two-dimensional (2D) arch comprising a series of blocks of infinite compressive strength, which cannot slide against each other and cannot carry tension. A routine is used to establish the locations of hinges in the span, followed by calculation of reactions and then vector algebra 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 lies entirely within the masonry then the modelled arch is capable of sustaining that load, even if it is not the true load path.

Limit analysis techniques have proved to be excellent tools for first phase strength assessments but several restrictions exist that are important in the design of strengthening. The most important of these is the inability to calculate strains and displacements. Consequently, it is not possible to determine the distribution of stress at operational load levels, it is difficult to assess the serviceability of bridges and, in the case of strengthening, it is not possible to determine the share of load between the existing bridge and the strengthening.

2.3. Solid mechanics methods

The established technique used to model continuum-based phenomena in solid mechanics such as deformability is the finite-element method (FEM). Not surprisingly this has also become the most popular solid mechanics method used for arch bridge analysis, and there are numerous well-developed industry quality computer programs available.

As is the case in limit analysis, most work is carried out using 2D representations, generally plane strain, but three-dimensional (3D) shell and solid models are used for special assessments.

Although these techniques can be good for determining displacements, strains and stresses at operational load levels, they quite often become difficult to use to predict ultimate strength and damage. This is generally because of the type of solver that is used, normally an implicit solver involving matrix factorisation (Owen and Hinton, 1980), and the effort required to ensure internal forces are in equilibrium with external loads, as brittle materials such as masonry soften and redistribute load. The solution to the equilibrium problem is normally to use a hypothetical masonry tensile strength but choosing a suitable value, large enough to achieve equilibrium conditions are met but small enough not to influence the result, can be a challenge.

3. DISCRETE ELEMENT METHOD

3.1. Description

Numerical techniques have been devised to represent discontinua where body or particle interaction defines overall behaviour (Cundall, 1971). Perhaps the most advanced technique that describes this behaviour is the discrete-element method (DEM). The relatively new finite/discrete-element

method (FDEM) described by Munjiza (Munjiza, 2004) is a combination of FEM and DEM and provides a more natural approach to the simulation of many materials and structures. It has been applied to a diverse range of engineering and scientific problems from food processing to rock blasting. Through automated adaptive modelling, even the transition from continua to discontinua and the fracturing and fragmentation process can be represented.

FDEM is aimed at problems involving transient dynamic systems comprising large numbers of deformable bodies that interact with each other. Models involve typically thousands, but in extreme cases millions, of separate finite-element (FE) meshes automatically interacting with each other using DEM contact algorithms. The solution of the continuum equations associated with FEM is well established, the algorithms within DEM less so.

Contact detection and contact interaction lie at the heart of DEM. Contact detection is aimed at identifying discrete elements that can potentially come into contact with each other and eliminating those far away from subsequent contact interaction algorithms. Different algorithms have been developed for different packing densities, for example sparse and moving or dense and static. The chief aim here is to reduce computing effort. Contact interaction applied to the surfaces of discrete elements coupled through the detection process is where interface behaviour is calculated. Here interface laws are applied according to the surface characteristics of the contacting discrete elements, for example frictionless no-tension contact. During the solution of transient dynamic problems of even quite modest size, millions of contacts will be detected and resolved.

Another key aspect of FDEM is that the analysis involves all equations of motion, is therefore dynamic and uses an explicit central difference solution scheme (Owen and Hinton, 1980). This involves a time-stepping procedure that is conditionally stable, but unlike many conventional FE solvers that use an implicit solution scheme, does not involve computationally intensive matrix factorisation. Solutions are achieved only through the use of very small time steps. The critical time step size below which steps must remain for stability and accuracy is given by the time taken for a stress wave to travel across the smallest finite element. The efficiency of DEM contact detection and the avoidance of equilibrium calculations allows FDEM simulations to predict failure, collapse and post-failure kinematic behaviour.

3.2. Application to masonry arch bridges

Masonry is a non-homogenised material, can be regarded as a discontinuum and as such is ideally suited to FDEM. Simply, a masonry arch bridge is a special form of masonry structure, which is an important consideration when faced with complex bridge arrangements.

The approach that has been developed for arch bridges, applied using the implementation within the FE computer program ELFEN (Rockfield Software Ltd, 2003), uses smeared masonry compressive properties and explicit mortar shear and tensile properties. Each brick or block unit is modelled with a separate FE mesh and each unit becomes a single discrete element. It

has been found that units can also be grouped together (Brookes and Mehrkar-Asl, 1998); a blocky arrangement of four or five bricks glued together can improve computational efficiency without any loss of accuracy. The masonry arch is then assembled using blocky arrangements in hundreds, possibly thousands of discrete elements. Figure 1 shows part of a meshed arch barrel. Other bridge parts, for example fill, surfacing, abutments, piers and backing, are similarly represented although the material models may be different.

FDEM arch bridge models will develop failure mechanisms consistent with limit analysis results if these are critical as well as providing displacements, stresses and strains consistent with solid mechanics.

Another key aspect to the use of FDEM and the adopted modelling approach is that representing masonry at a fundamental scale requires only commonly available and basic material parameters to be used in order to accurately characterise bridge structural behaviour. Non-linear material models are used to define the deformable behaviour of the masonry in compression and the fill in tension. A perfectly plastic von Mises yield criterion is generally used to cap compressive strength, and a Rankine yield criterion used to give a simple no-tension soil model.

The behaviour of mortar, as well as other contacting surfaces such as masonry to fill, is included by using interface material models. Interface models give the surface of discrete elements appropriate mechanical properties. Mortar is represented differently depending on the type of construction. Historic construction involving lime mortar joints is represented using a no-tension Mohr–Coulomb friction relationship. Modern masonry with cement mortar produces masonry with some tensile strength. In these instances good predictions of masonry behaviour can only be made by including mortar tensile strength and a fracture energy formulation to model the development of cracking. Generally, masonry arches are historic constructions and do not include cement mortar.

For most types of masonry the generic material characteristics, compressive strength, Young's modulus, mortar friction and mortar cohesion, necessary for FDEM simulations are readily available (BSI, 2001; Hendry, 1990; Highways Agency, 2001). They are no more demanding to obtain than those parameters required for conventional limit state analyses. An estimate for Young's modulus for different types of fill in compression is similarly available.

There are no limitations to the geometric arrangements of

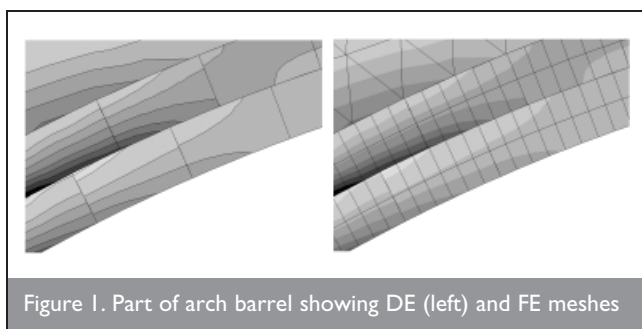


Figure 1. Part of arch barrel showing DE (left) and FE meshes

arches that can be represented with FDEM other than those associated with computational resource. As an illustration, Figure 2 shows a model of a deformed two-tier arch arrangement. However, models are kept as simple as possible to reflect the confidence in material parameters, geometric arrangement and to be reasonably compatible with codes of practice rules through which most design and assessment work is undertaken. Hence, the large majority of simulations are 2D and plane strain.

Models always include abutments and the supported fill as the strength of arch bridges is often sensitive to the abutment construction, particularly flat arches with high span-to-rise ratios.

In assessment and design, live load is generally applied by explicit representation of axle loads using discrete elements. Weight is applied to these elements and the axles moved across the span with a prescribed velocity, as illustrated by the sequence of images in Figure 3. As transient dynamic solutions are obtained, regard has to be given to acceleration arising from sudden movement and inertia effects. Consequently, loads are applied smoothly and slowly to ensure near static responses are obtained and dynamic effects are negligible. Permanent loads are introduced through construction sequences which, depending on the barrel shape, may necessitate the use of modelled temporary formwork to support the barrel self-weight while the fill is added – a process that is always required when constructing real arch bridges. Figure 4 shows an elliptical arch barrel and modelled formwork. It has been found that modelled elliptical barrels always require the construction sequence to include formwork support to avoid collapse during initial dead loading.

Although the time required to develop FDEM bridge models exceeds that of comparable limit analysis representations, these models can still be assembled in 1 or 2 h. Furthermore, solution times, which are continuously tumbling as ever faster computers become available, are modest compared with similar FEM representations, with strength analysis completed in around 4 h for a typical bridge on a 3.6 GHz personal computer. This includes the calculation of permanent loads and the traverse of a single vehicle. To complete an assessment or design, several axle arrangements have to be considered to be sure that the

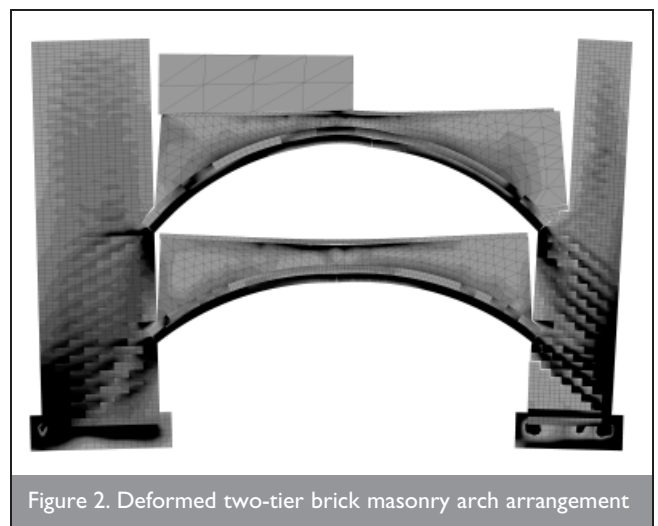


Figure 2. Deformed two-tier brick masonry arch arrangement

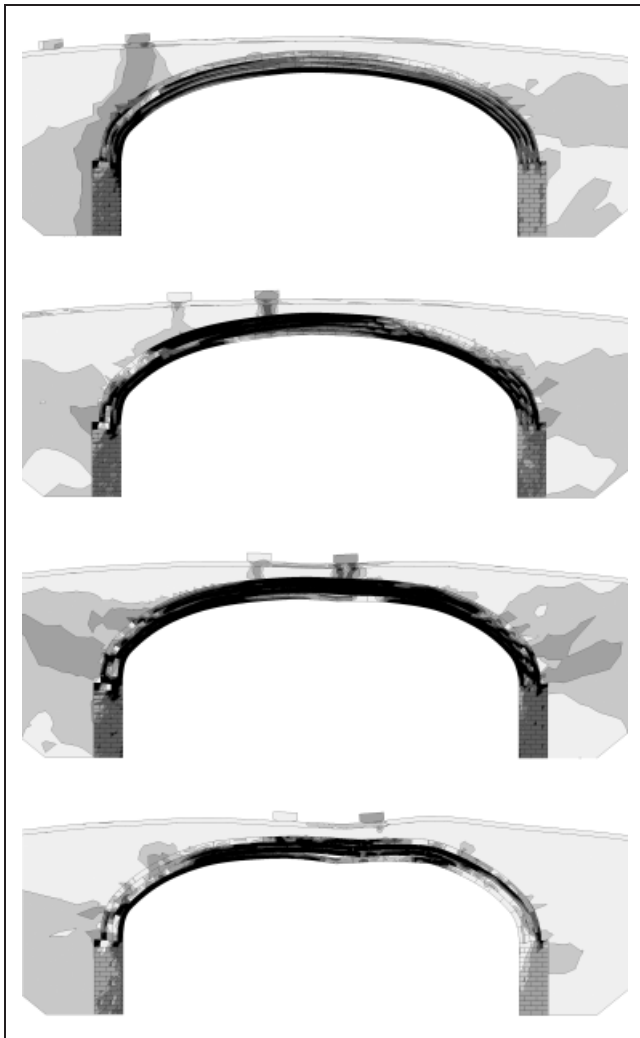


Figure 3. Sequence showing failed load assessment

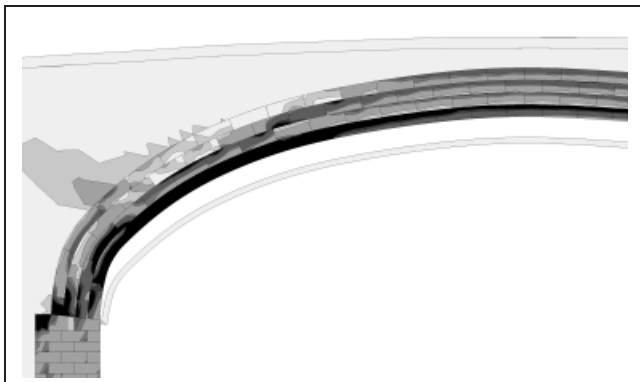


Figure 4. Modelled formwork to provide temporary support

critical case has been identified, so this could take several days. With relatively small problem sizes, around 5000 to 10 000 degrees of freedom, mass scaling techniques to accelerate the solution process are never used to obtain solutions, but are useful to quickly check the simulation process.

3.3. Modelling reinforcement

The FE technique is used to model steel reinforcement independently meshed from the masonry using a partially constrained spar formulation (Roberts, 1999). Modelling reinforcement is an important aspect to strength prediction

where it is proposed for strengthening, but is seldom encountered in existing bridges. Connection between the reinforcement and the masonry FDEM representation is achieved through non-linear bond elements. These provide the transfer of axial shear force between the reinforcement, the grout used for providing bond, and the masonry. Modelling of reinforcement arrangements is completely automated without the need for topologically consistent element meshes, thus accelerating the modelling process and permitting rapid comparison of designs. Where reinforcement elements cross masonry joints, transverse shearing strength or dowel effect is ignored. This is a simplifying assumption and provides a conservative approach to estimating strength.

4. STRENGTHENING

4.1. Description

The method of strengthening that has been developed comprises retrofitting stainless steel reinforcement around the circumference of the arch barrel. The reinforcement is then grouted into holes drilled into the bridge with a coring rig from the road surface or, alternatively in the case of multi-span structures, from below. Once the work is completed there is no evidence of any major intervention to the bridge, a characteristic that is particularly important for historic structures.

Arches conventionally fail by the development of four hinges leading to a mechanism. The design basis for the strengthening is to locate reinforcement to improve bending strength where hinges are predicted to develop. By providing additional strength in this way the arch barrel is better able to resist live load, and peak compressive stresses in the masonry are reduced in comparison with similar unstrengthened cases. The same procedure is applied to more complex bridge arrangements including multi-span arches although failure mechanisms and reinforcement positioning require different locations to be considered in design. Figure 5 shows the simplest arrangement of reinforcement which in this instance is installed from above, and Figure 6 illustrates the installation process for a multi-span bridge.

Accurate 3D geometric modelling is required not only to develop the FDEM model but also for setting out calculations and the accurate positioning of reinforcement. Three-dimensional laser surveys are being used increasingly to provide the high-density survey measurements (point clouds), saving time and improving efficiency. Figure 7 shows a typical laser survey and the developed computer-aided design 3D

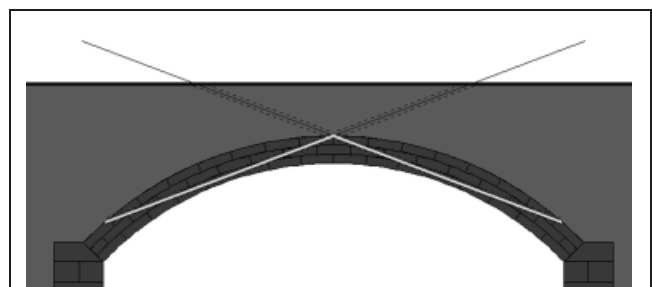


Figure 5. Arrangement of retrofitted strengthening reinforcement



Figure 6. Installation of reinforcement, drilling from below

surface geometry model, including reinforcement and a zone where buried utilities have to be avoided.

4.2. Benefits

In comparison with conventional arch bridge strengthening such as concrete saddling and lining, retrofitted reinforcement designed using FDEM simulation has several practical benefits, which includes the following.

- (a) Good assessment of existing strength and bridge behaviour is obtained and the results can be used to justify safe and continued use of an existing bridge, providing an alternative to bridge replacement.
- (b) Where a weak bridge is identified, detailed prediction of bridge behaviour allows accurate matching of strengthening to the loading requirements, thus minimising any intervention.

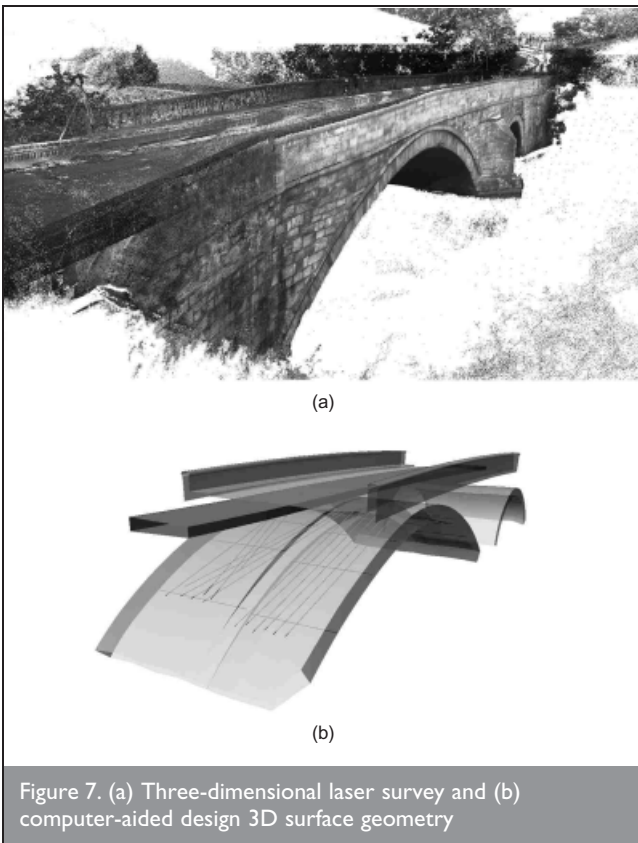


Figure 7. (a) Three-dimensional laser survey and (b) computer-aided design 3D surface geometry

- (c) Strengthening is invisible, which is particularly important for historic and heritage bridges.
- (d) Construction is small scale and fast to implement.
- (e) Disruption to bridge users during strengthening is much less than conventional strengthening such as concrete saddling.
- (f) Provides a more sustainable bridge strengthening solution with lower environmental impact, embodied energy and carbon emissions.
- (g) Because displacements and strains are predictable, assessments and strengthening designs can be based on limit states other than purely ultimate strength.
- (h) Each reinforcement bar installation provides a core of information that can be used to confirm the materials and internal arrangement of the bridge.
- (i) In many instances all these factors equate to reduced cost.

4.3. Working with codes of practice

Assessment and strengthening services have to be provided within a framework which embraces as far as possible national codes of practice. Unfortunately, outside of the UK, there are few rules to help engineers assess arch bridges. For example, live loading is almost always developed for beam arrangements of bridges where load support is primarily through bending, and masonry strength assessment is often permissible stress based. In earthquake regions bridge rules again tend to be geared towards steel and concrete construction. Arbitrary and outdated rules can also be a problem. In India the railways have a code of practice for the design of masonry arch bridges which imposes almost arbitrary performance limits on deflection.

The use of FDEM to simulate arch bridges is a performance-based method, useful for limit state assessment and design, but cannot be directly used for rules that have been developed for linear, often inaccurate, working stress approaches. In these instances to satisfy bridge technical authorities, hybrid analyses are run alongside the more realistic and reliable limit state work. The results allow additional checks to be made with local code of practice rules and guidelines.

5. VERIFICATION

The process which has been undertaken to verify the FDEM analytical methods employed in arch bridge assessment and strengthening design has included a number of key strands, and comparisons, that are listed here.

- (a) Conventional methods of arch assessment.
- (b) Published data from full-scale tests of unstrengthened arches carried out by others.
- (c) Full-scale tests by the Transport Research Laboratory (TRL) of bridges strengthened using retrofitted reinforcement specifically commissioned as part of the verification process.
- (d) The results obtained by monitoring bridges in the field including the comparison of performance between before-and-after strengthening.

Additionally, a philosophy of fixing 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 prevents an individual arch

analysis being adjusted to gain better correlation with tests within a series without influencing all the others. Similarly, the analysis of strengthening follows on from verified and fixed unstrengthened analyses.

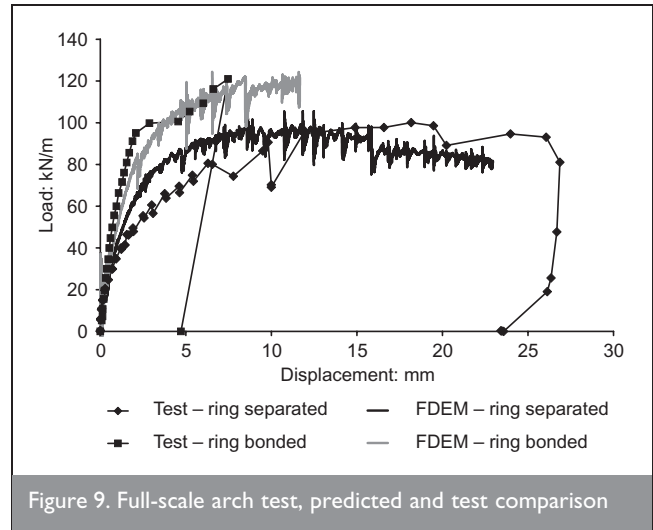
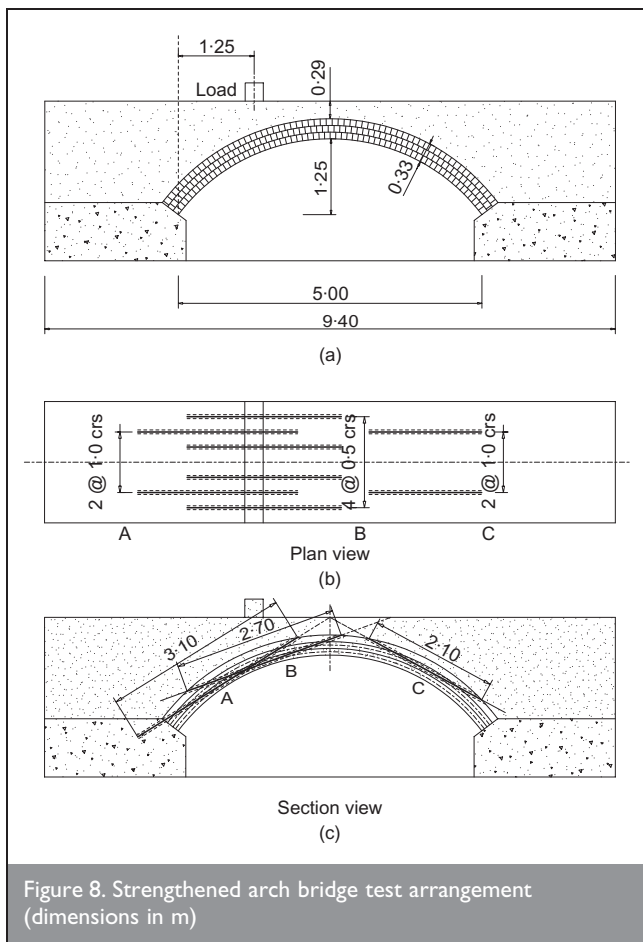
A small sample of the verification work (Brookes, 2004) and recent field trials illustrating the accuracy and flexibility of FDEM arch simulation follows.

6. FULL-SCALE ARCH TESTS

6.1. Unstrengthened arches

In undertaking comparisons with full-scale tests of arches the two key objectives were to demonstrate the accuracy of numerical solutions and the appropriateness of simplifying assumptions. Full-scale arch bridge tests have been selected where boundaries and loading are two-dimensional so that the validity of comparing their results with 2D FDEM analyses has not been compromised by 3D behaviour. Skew arch barrels and spandrel walls are examples of bridge features that generally give rise to 3D structural behaviour.

Comparisons with full-scale tests (Brookes, 2004) have included those carried out by the Transport and Road Research Laboratory (TRRL) on redundant bridges in the 1980s, and laboratory tests by TRL and The Bolton Institute in the 1990s. Figure 8(a) shows the arrangement of the arches used by TRL as well as those used later to test the strengthening. Figure 9 compares test results, vertical displacement measured at the position of the load, with FDEM predictions for arches in two conditions: with brick masonry rings unbonded (partially ring



separated) and with rings bonded. Unbonded and bonded conditions were constructed to be representative of arch barrels in poor and good conditions, respectively. The figure shows good agreement in both strength and displacement response with strength predicted to within 5%.

6.2. Strengthened arches

In order to test the practical implementation of strengthening, to further validate the FDEM method of structural analysis, to help quantify key strength parameters and to illustrate the degree of strengthening that could be achieved, two full-scale tests of strengthening designs were carried out at TRL (Brookes, 2004). The arch arrangements were based on earlier unstrengthened arch tests. Figure 8 also shows the reinforcement arrangement used in the first of these tests. The second test was very similar but used slightly more reinforcement and used spaced bundled reinforcement, in place of single bars. Both tests used partially ring-separated barrels to be representative of arches in poor condition and those most likely to warrant strengthening.

The reinforcement arrangements were configured for a stationary point load test and, therefore, were arranged asymmetrically with respect to the span. In practice, with moving axle loads, reinforcement arrangements are generally arranged symmetrically to cater for any axle load position.

Figure 10 compares the graphs of load plotted against displacement results obtained by the FDEM simulations with those obtained from the two strengthened tests. Again measured displacement is at the position of the load. The figure shows strength predictions to be within 2% of test results. There is also very good stiffness correlation, displacements remaining within approximately 5% of test values throughout loading.

Making comparisons between strengthened versus unstrengthened tests, illustrated in Figure 11, shows the failure load of both strengthened arch barrel tests to have been increased by a factor of approximately 2. The reinforcement has delayed the formation of hinges and added considerable strength to the arch barrel, and the arch failed in a gradual and a ductile manner. In practice the characteristics of the arch barrels are improved sufficiently for the intended loading.

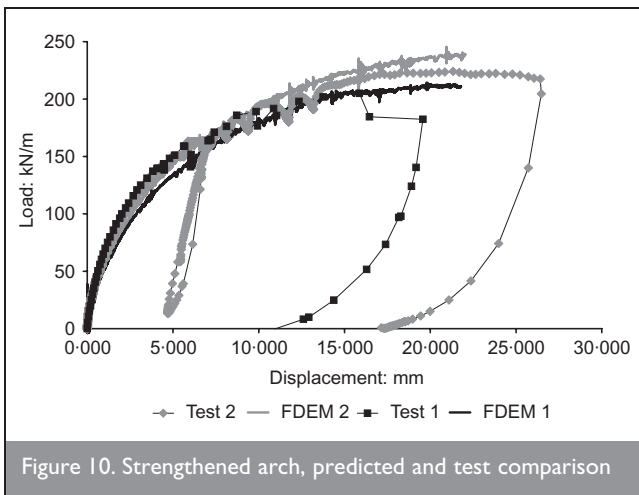


Figure 10. Strengthened arch, predicted and test comparison

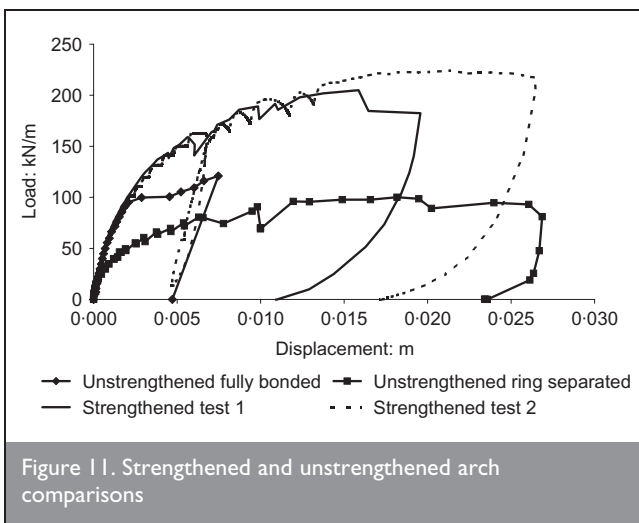


Figure 11. Strengthened and unstrengthened arch comparisons

6.3. Observations relating to serviceability

No clear definition of serviceability exists for masonry arches. 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 TRRL in the 1980s, the Highways Agency 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 (Clark, 1994) 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 unlimited 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 led to the recommendation of a 50% rule and are in effect stress limit based. The current strengthening design method,

which uses load factors based on the UK Highways Agency standards, embraces the serviceability limit state implicitly within the load and material factors used at the ultimate limit state. Although this method is consistent with current practice, FDEM analysis used in the design also enables the behaviour of the arch under serviceability loading to be investigated.

Comparisons of results between unstrengthened and strengthened tests show that under identical loads, displacements are very similar. Corresponding structural analysis of the test arches predicts compressive stresses in strengthened arches to be lower than that of the unstrengthened arch under the same loading. For example, using the bridge proportions of the strengthened arch tests and UK highway 40/44 tonne vehicle axle loading, under the maximum service load the maximum compressive stress in the masonry barrel was reduced by approximately 15%. For this case Figure 12 compares maximum levels of compressive stress. 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 of strengthened bridges should have a beneficial effect on serviceability.

Other aspects of bridge serviceability might be concerned with specific deteriorated conditions in arch barrels, such as loose bricks and ring separation. The risk here is that debris falling from a bridge would represent an unacceptable hazard. An example of an arch barrel in a weakened condition that could develop loose bricks as a result of partial ring separation has been tested and used in comparison with strengthened barrel tests. Displacement results show that strengthening significantly increases the stiffness of the ring-separated barrel, restoring it to that of the fully bonded case (as-built condition); see Figure 11. 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 in comparison with 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.

Bridge owners and experts in the field recognise the

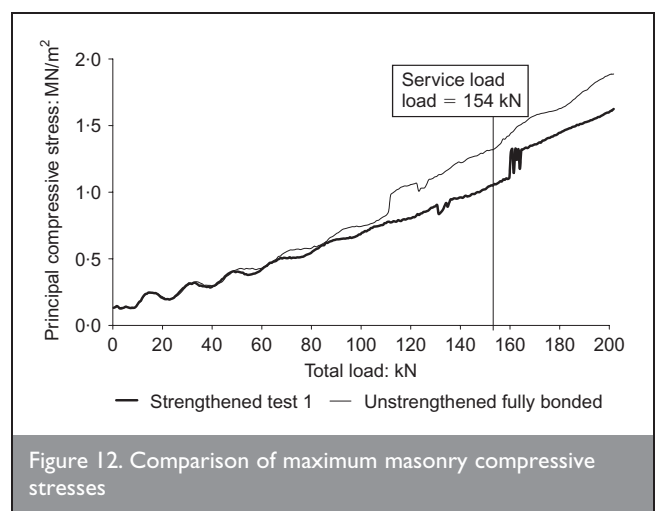


Figure 12. Comparison of maximum masonry compressive stresses

desirability of further research with respect to the serviceability limit state and phenomena likened to masonry fatigue. However, at the current time no specific guidance or criteria exist with respect to explicit evaluation of the serviceability state in arches.

To provide increased confidence that the serviceability of a bridge is being improved by strengthening designs, the following additional checks have been introduced into the design process.

- (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 strengthening, strains along the intrados under the required live loading are checked to ensure they do not exceed those in the unstrengthened bridge under existing live loading. Strains are 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 have been introduced as a precautionary measure. It is likely that stresses and strains beyond these limits will be quite safe and have no adverse serviceability effects. However, further fundamental research is required to establish appropriate limiting criteria.

7. FIELD MONITORING

Several bridge monitoring programmes have been undertaken during the last decade to help verify FDEM arch simulations, and for strengthened bridges, to make before-and-after behaviour comparisons. The most recent of these was for the Massachusetts Highway Department with the first part of the programme, which involved live load testing of a four-span unstrengthened stone arch bridge carrying a two-lane highway, being completed in December 2009. Figure 13 shows the bridge, the FDEM model and sketches of the test vehicles.

As part of a rehabilitation programme Ames Street Bridge in

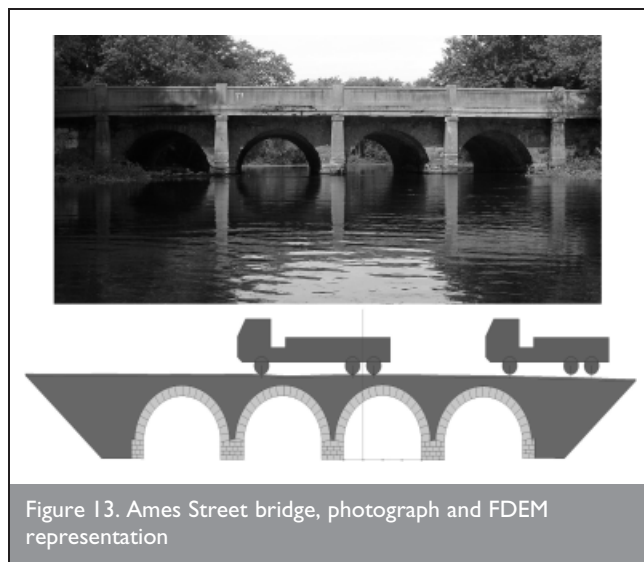


Figure 13. Ames Street bridge, photograph and FDEM representation

Dedham, Massachusetts is to be over-spanned by a new reinforced concrete deck. The deck construction will firstly involve strengthening the existing arch bridge and protecting the masonry arch barrels from possibly damaging loads while in its weakened condition during construction. Although the efficacy of this over-spanning approach often used in North America is questionable, as many of the advantages of strength assessment and strengthening are not realised, the opportunity to provide some valuable test data was nonetheless available.

The programme of work included a series of tests and FDEM simulations to verify the strengthening process. A small sample of the findings of the first series of physical tests and accompanying simulations providing baseline information relating to the existing unstrengthened bridge is given here. Further work is planned during 2010 on the strengthened bridge before over-spanning work starts.

Physical testing involved monitoring the bridge whilst applying controlled vehicle loads with the bridge closed to normal traffic. Intrados circumferential strain and vertical displacement of the arch barrels were recorded at 36 positions on two adjacent spans. These measured bridge responses along six longitudinal and three transverse lines for each monitored span. Two ballasted three-axle dump trucks were used to traverse the bridge in several driving patterns at walking pace, with continuous recording of vehicle position as well as all displacement and strain results. FDEM simulations were used to mirror the tests.

Generally, predictions of bridge behaviour rely on a 2D plane strain analysis to model longitudinal behaviour, and hand calculations to determine the spread of the load effect in the transverse direction. Referred to as transverse load distribution, these hand calculations are developed along code of practice guidelines developed in the UK for the assessment of arch bridges (Highways Agency, 2001) and are known to be conservative. However, where comparisons are made with monitored bridges and it is not possible to load the full width of the bridge, it is often necessary to look at transverse load distribution more accurately to achieve good correlation. In the case of Ames Street bridge, an adjustment to allow for the combined effects of the live load transverse position and the transverse location of the instrumentation had to be made as full-width loading was not possible.

Figures 14 and 15 show comparisons between measured and predicted results for displacements, and intrados circumferential strains, respectively. Here one of the test vehicles traversed the bridge close to the edge of the arch barrels and the results shown correspond to a single quarter-span position. Although this is a small snapshot of the data collected, the good correlation that is shown is a reasonable representation of the broader range of comparisons that have been made.

8. CONCLUDING REMARKS

FDEM has been successfully applied for a decade in over 200 arch bridge assessments and strengthening projects, and the method is now recognised as a special assessment tool. During this period, verification of this technique has been carried out by making comparisons with the results of full-scale tests, with

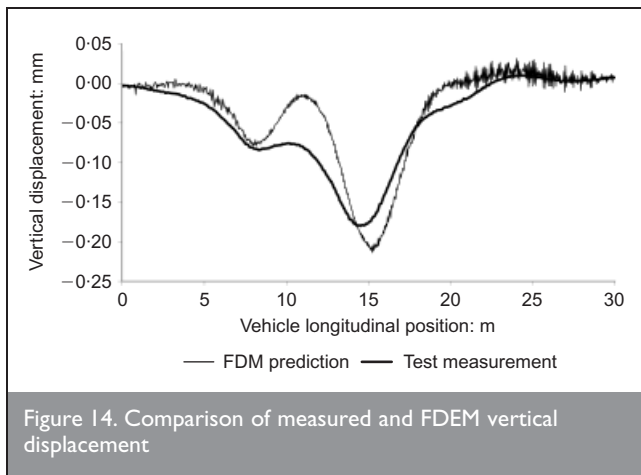


Figure 14. Comparison of measured and FDEM vertical displacement

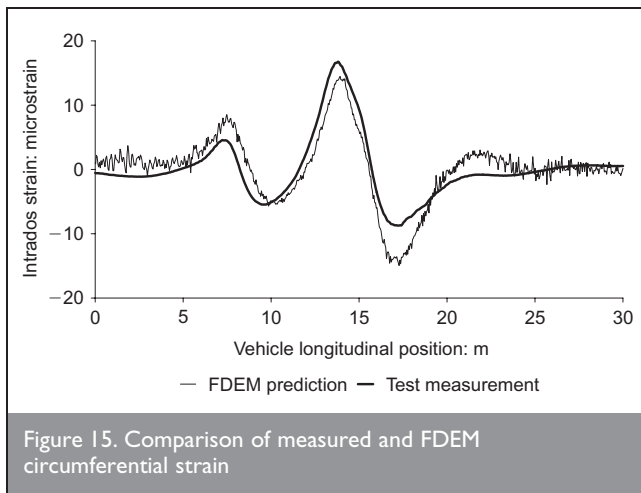


Figure 15. Comparison of measured and FDEM circumferential strain

data published by others on arch tests, with the results obtained by conventional arch bridge assessment methods and with the results obtained from monitoring programmes in the field. In all instances broadly good comparisons of strength and stiffness have been made.

Recognising that arch bridge displacement, strain and damage can also be predicted, and that these factors are important to bridge serviceability, further work has been carried out to investigate in-service bridge behaviour. However, until limiting criteria are developed, whether strain, stress, crack or fatigue based, and until the serviceability behaviour of masonry arch bridges is better understood, a method has been developed that ensures that stress and strain conditions when strengthening for larger loads do not exceed those in existing arch barrels under existing loading.

By representing the constituents of masonry arch bridges in a

natural and non-homogenised way, FDEM can provide realistic simulation of structural behaviour for use in both special assessment and strengthening design.

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