Assessment and strengthening masonry arch bridges

C.L. Brookes
Gifford, Southampton, UK

ABSTRACT: This paper describes how during the last 10 years Gifford has been applying a novel numerical technique to accurately assess the strength of masonry arch bridges, and for weak bridges, to design repairs and strengthening. This has involved a major development programme including full-scale laboratory tests, supplementary load tests on bridges in the field, monitoring programmes and verification of the arch bridge structural analysis which has been based on the Finite/Discrete Element technique. The advantages this technique provides over conventional masonry arch bridge analyses, both 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. Some practical issues relating to bridge strengthening and working within national codes of practice are also covered.

1 INTRODUCTION

It is likely that there are at least 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 being ancient in form, masonry arches are notoriously difficult to accurately assess. 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, 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 predicted strength.

The Finite/Discrete Element method, 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, the number of spans, rings and piers that can be modelled. Also, 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 the Finite/Discrete Element method has marked a step change in the rigour 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 all significant non-linear effects, making it possible to assess behaviour at both strength and serviceability limit states. Also, a generalised approach the behaviour of complex bridges can be assessed where for example a concrete saddle may exist, or the bridge is propped and in the case of strengthening, retrofitted reinforcement is introduced.

Through partnering with Cintec International who manufacture and install a masonry anchor system, Rockfield Software who produce the ELFEN (Rockfield 2003) structural analysis software, Gifford have completed over 170 bridge assessments and bridge strengthening designs, mainly in the UK but also in the USA, Australia and India. Known as Archtec, 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 do not need to be strengthened.
2 CONVENTIONAL ASSESSMENT

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

2.1 Semi-empirical methods

Most semi-empirical methods are based on the MEXE (Military Engineering Experimental Establishment) 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 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 calculations of reaction 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 lays 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 strain and displacement. 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.

Like limit analysis most work is carried out using 2D representations, generally plane strain, but 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, 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 THE FINITE/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) (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 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 lay 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 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, masonry arch bridges are 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 Finite Element computer program ELFEN, uses smeared masonry compressive properties and explicit mortar shear and tensile properties. Each brick or block unit is modelled with a separate finite element mesh and each unit becomes a single discrete element. It has been found that units can also be grouped together (Brookes 1998), a blocky arrangement of four or five bricks glued together, to improve computational efficiency without any loss of accuracy. The masonry arch is then assembled using blocky arrangements in hundreds, possibly thousands of discrete elements. Other bridge parts for example, fill, surfacing and backing are similarly represented although the material models are 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 (Hendry 1990, BD 21/01 2001, BS 5628-1 2002). 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 arches that can be represented with FDEM other than those associated with computational resource. However, models are kept as simple as possible to reflect the confidence in material parameters, geometric arrangement and to be reasonably compatible with the codes of practice through...
which all design and assessment work has to be undertaken. Hence, the large majority of simulations are 2D and plane strain.

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 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 static responses are obtained. Permanent loads are introduced through construction sequences, which depending on the barrel shape, may necessitate the use of modelled temporary false work; a process that is always required with real arch bridges.

Although the time required to develop FDEM bridge models exceeds that of comparable limit analysis representations, these models can still be assembled in several hours. Also 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 hours for a typical bridge on a 3.6 GHz PC. 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 the critical case is identified, so this could take several days. With relatively small problem sizes, around 5,000–10,000 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.

4 ARCHTEC

4.1 Description

Archtec strengthening has been described as ‘Key Hole Surgery’ for bridges because of the absence of any major intervention to the arch barrel. Generally construction comprises retrofitting stainless steel reinforcement around the circumference of the arch barrel. The reinforcement is grouted in to holes drilled in to the bridge with a coring rig from the road surface or, alternatively in the case of multi-span structures, from below.

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 more complex arrangements including multi-span arches although failure mechanisms and anchor positioning requires anchors to be placed in different positions.

4.2 Benefits

Compared with conventional arch bridge strengthening such as concrete saddling and lining, the Archtec service has several practical benefits:

1. Through the use of FDEM a good assessment of existing strength and bridge behaviour is obtained. This allows accurate matching of strengthening to the loading requirements if the bridge is under strength, thus minimising any intervention. Alternatively, strengthening may be avoided.

2. Strengthening is invisible which is particularly important for historic and heritage bridges.

3. Construction is small scale and fast to implement.

4. Disruption to bridge users during strengthening is much less than saddling.

5. A more sustainable solution with lower environmental impact, embodied energy and carbon emissions.

6. Because displacement and strain is predictable assessments and strengthening designs can be based on limits states other than purely ultimate strength.

7. Each anchor installation provides a core of information that can be used to confirm the materials and internal arrangement of the bridge.

8. In many instances all these factors equate to reduced cost.

4.3 Working with codes of practice

Archtec 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, masonry strength assessment is often permissible stress based, and bridge specific earthquake rules are geared towards steel and concrete construction. In India the railways have a code of practice for masonry arch bridges which impose 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 codes of practice.

5 VERIFICATION

The process which has been undertaken to verify the FDEM analytical methods employed by Archtec have included a number of key strands and evaluations as follows:

1. Against conventional methods of arch assessment.

2. Against published data from full-scale tests of unstrengthened arches carried out by others.

3. Against full-scale tests by TRL of bridges strengthened by the Archtec method which were specifically commissioned as part of the verification process.

4. Against the results obtained by monitoring bridges in the field including before and after strengthening comparisons.

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 makes it impossible to adjust an individual arch analysis to gain better correlation with tests within a series without influencing all others. Similarly, the analysis of Archtec strengthening follows on from verified and fixed unstrengthened analyses.

A selection of the verification work (Brookes 2003) and recent field trials illustrating the accuracy and flexibility of FDEM arch simulation follows.

6 FULL-SCALE ARCH TESTS

6.1 Strengthened arches

In order to test the practical implementation of Archtec, to validate the FDEM 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 used partially ring separated brick forms to be representative of arches that would warrant strengthening, and were also similar to unstrengthened bridges tested in an earlier series so that experimentally derived comparisons could be easily made.

The anchor 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, anchor arrangements are arranged symmetrically to reflect critical loading positions on both sides of the span.

Comparing the load versus displacement results obtained by FDEM simulation with those obtained from the strengthened test 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 the loading stage.

Making comparisons between the two tests, strengthened versus unstrengthened, show the failure load of the strengthened arch barrel has been increased by a factor of approximately 2, the anchors 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 intended loading.

6.2 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 TRL in the 1980’s, 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 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.
Field 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 Archtec 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. Whilst this method is consistent with current practice, FDEM 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. Corresponding structural analysis of the test arches predicts compressive stresses in the Archtec strengthened arch that are lower than the unstrengthened arch under the same loading. For example, using the bridge proportions of the Archtec 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%. 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 Archtec strengthened bridges has 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 Archtec. Displacement results 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.

Bridge owners and experts in the field recognise the desirability of further research with respect to the serviceability limit state and phenomena such as 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 Archtec strengthening additional checks have been introduced into the design process. As a precautionary measure in the absence of other guidance, the following additional serviceability criteria are included in the design process:

1. 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.
2. 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 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 stresses and strains beyond these limits may 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 Indian Railways with the first part of the programme completed in 2007 and which involved two unstrengthened multi-span brick arch bridges.

The principal aims of the programme were to compare measured barrel vertical displacements and intrados circumferential strains with those predicted using FDEM simulations. Load tests were carried out...
using a 1000 tonne freight train. Wagon loads were recorded at a ministry weigh station and axle loads were recorded using calibrated arrays of strain gauges spot welded to the tracks in several places at each bridge. A series of static tests were carried out with axles in designated positions. Dynamic tests were also carried out with the train running at constant speeds of 10, 40 and 65 km/h. During the dynamic tests vertical accelerations were also recorded.

Vertical displacement results were found to be sensitive to the stiffness of the foundations, which is essentially unknown, and also to the transverse distribution of the live loading. A process involving linear regression was used to take account of these effects. Overall, measured and predicted results compared well for all static load cases considered.

Vertical displacements measured during the dynamic tests were compared with predictions and good correlation obtained. For predictions, the engine and two wagons traversed the bridge. Good correlation was obtained for the first eight axles of the train.

8 CONCLUDING REMARKS

FDEM has now been used successfully for a decade on over 170 arch bridge assessments and strengthening projects as part of the Archtec engineering partnership, and is now recognised as 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 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 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. This has including predicting responses under static and dynamic live load and making comparisons with monitored results. However, until limiting criteria is 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 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.

REFERENCES


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