Masonry arch bridges form a vital part of the transport infrastructure. There are approximately 60,000 in daily use on highways and railways in the UK alone, many of which are historic structures over 100 years old. Since construction, and particularly in recent years, traffic loads have increased dramatically. The structural assessment of these bridges is therefore key to their continued service. Clearly, a reliable assessment method is required to ensure that strengthening is used only where necessary, and is as economical and efficient as possible.


Figure 1:
A typical masonry arch bridge

Applied Discrete Element Technology: The Assessment and Strengthening of Masonry Arches

Paul Mullett, of Gifford & Partners, and Jon Rance of Rockfield Software discuss assessment methods for masonry arch bridges.

Existing traditional methods of assessment include mechanism analysis and the semi-empirical Modified Mexe Method. There are several mechanism based computer programs available that all rely on calculating the position and limiting load to produce a four hinge failure mechanism. The Modified Mexe Method has been developed from an experience based rule system created by the British military to quickly assess the ability of masonry arch bridges to support military vehicles. Both these methods are used widely by practising engineers and are important in establishing approximate strength however are limited in capability and accuracy. They are often subjective and have many limitations including the inability to accurately represent arch shape, arch-soil interaction, barrel condition, multiple rings and multiple spans. In addition, the type of failure mechanism is predefined.

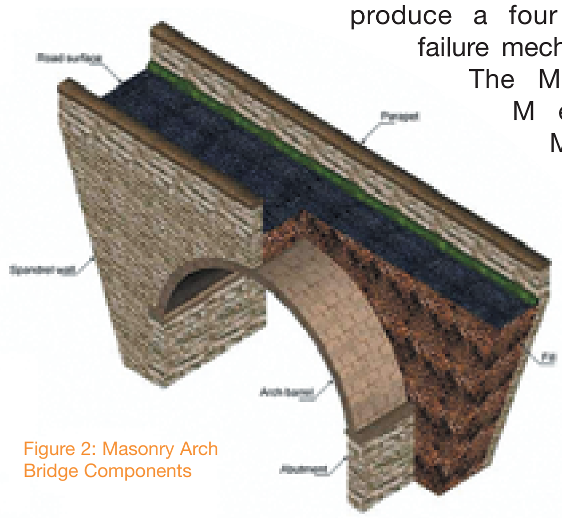

Figure 2: Masonry Arch Bridge Components

Continuum based numerical techniques such as the Finite Element (FE) method can be complex and expensive to apply to the analysis of masonry arch bridges. These techniques are limited because of the inherent difficulty in representing non-linear brittle material behaviour of the masonry and fill, and the complex discontinuous interactions between the various components of the structures. Such difficulties can be overcome by the use of discontinuous numerical techniques, and in particular the application of the combined Finite Element/Discrete Element (FE/DE) technique.

The Finite Element/Discrete Element Method

The FE/DE technique combines the advantages of the FE and Discrete Element (DE) technology to enable the solution of both discontinuum and continuum to discontinuous problems.

DE technology was founded on the distinct element methodology in which the concept of individual rigid bodies being separate and reacting with their neighbours by contact through friction/adhesion was first successfully applied to geotechnical and granular flow problems. The heart of the DE technique is concerned with automatic contact detection between surfaces of separate block components. Global search algorithms are used to provide short lists of potential contacts, rather than considering all those possible. Local search algorithms are then used to identify actual contact potential. Finally, using the penalty method and defined interface properties, normal and tangential forces between the blocks are resolved.

By combining FE and DE technology the homogeneous material within each discrete body may be modelled, facilitating elastic and non-linear material behaviour. During the deformation of the bodies, failure criterion can be applied to detect if the stress/strain state reaches defined limits at which point fracturing may occur. When these thresholds are exceeded the FE/DE technique allows for the discrete bodies to fracture. The fracture paths are computed and not predefined as in other techniques.

Gifford have developed the application of the FE/DE technique, available in the explicit dynamic version of ELFEN (Rockfield Software Limited), for the analysis of masonry arches. The 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. In general, fracturing techniques are not used for the analysis of masonry arches, with mortar joint discontinuities represented by predefined discrete element components. With this approach it is possible to accurately represent arch shape, arch-soil interaction, barrel condition, multiple rings and multiple spans, without having to predefine the type of failure mechanism.

Verification and Testing

The application of non-linear FE or FE/DE requires careful validation for each class of problem. In addition, the modelling methodology and the assumptions made in the analysis require confirmation against the actual problem under consideration. A stringent verification and testing programme has therefore been carried out to confirm the reliability and accuracy of predicted results. Full-scale tests have therefore been completed at the Transport Research Laboratory (TRL), and on real bridges.

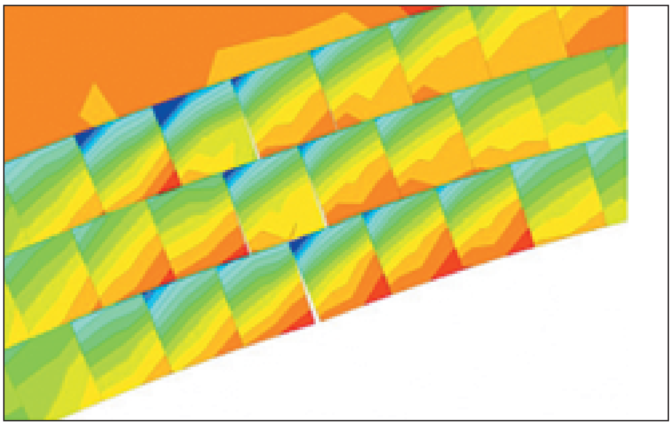

Figure 3. Individual masonry blocks represented using Discrete Elements

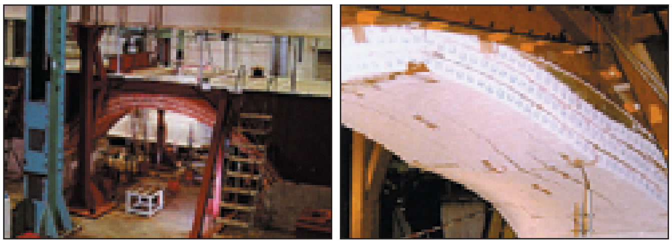

Figure 4. Full-scale masonry arch tests at the TRL

The laboratory tests at the TRL (see Figure 4) were carried out on a purpose built brick masonry arch. The arch was constructed with a span of 5.0m, a rise at mid-span of 1.25m and a width of 2.0m. Loading was applied by means of a hydraulic jack positioned on a beam so that a nominal line load was applied across the top of the bridge at the quarter point - usually the weakest location.

A 2D plane strain DE model of the arch was developed using ELFEN including the arch barrel, fill, abutments and loading beam (see Figure 5). The arch barrel was modelled with discrete elements representing the individual masonry components, each block having the ability to deform and crush. The fill was represented as a continuum using a limiting tension Rankine material model and the abutments modelled elastically.

Apart from the elastic material properties, material data was also required for the crushing strength of the masonry and the tension cut-off stress for the fill. Mohr-Columb friction properties were also essential for the mortar interfaces. Such material and interface properties were easily available from material tests or relevant codes of practice.

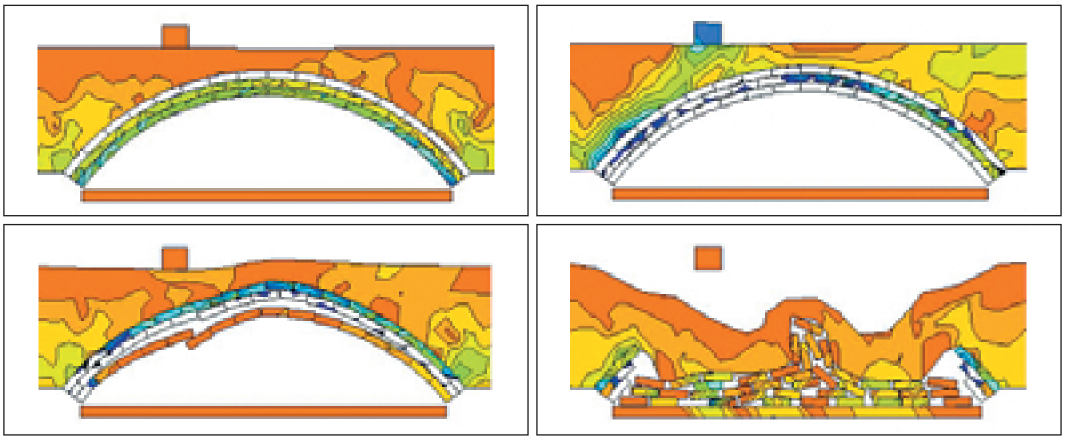

Figure 5. DE analysis of the test arch

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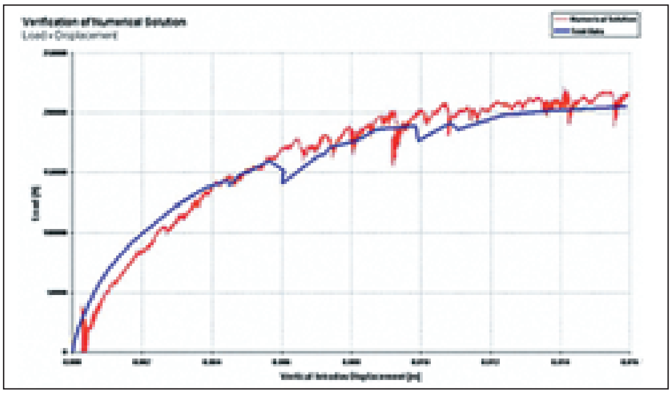

Figure 6: Typical load-deflection response

Figure 6 shows an example of load deflection characteristics and compares the test arch with analysis predictions. The predicted response demonstrates excellent correlation with the actual test results. The test arch failed at a total load of 20 tonnes compared to a calculated failure load of 21.5 tonnes.

Further verification work against other full-scale arch tests, often involving redundant bridges, also demonstrated similar acceptable accuracy when considered in relation to the levels of variability in construction and materials. Results therefore demonstrated that the FE/DE technique can reliably predict the ultimate strength and displacement characteristics of masonry arches.

Assessment

The FE/DE technique and the use of ELFEN has been efficiently integrated into an assessment process for masonry arch bridges. Using axle arrangements, partial load factors and material properties in accordance with the Highways Agency "The Assessment of Highway Bridges and Structures" BD 21/01, vehicles can be simulated effectively traversing across the arch bridge structures.

Again, the material properties required are generally relatively easy to determine, and can either be obtained from relevant codes of practice or from site investigations. Additional software written internally also facilitates quick and efficient arch model construction from actual survey data.

The analysis can take into account many factors that are inherently difficult to represent with other methods including unusual arch shapes, poor barrel condition, defects, multi-ring barrels and multi-span arches (as shown in Figure 7). In this way, failure modes can be accurately predicted for any arch arrangement. Often additional "hidden" strength can be identified, and bridges otherwise targeted for strengthening or replacement can be demonstrated to be adequate.

Strengthening

Combining the FE/DE technology of Rockfield Software, engineering expertise of Gifford, anchor manufacturing of Cintec International and specialist drilling contractors, a novel method of strengthening masonry arches has been developed. The method involves the insertion of retrofitted stainless steel reinforcement tangential to the arch intrados, by drilling accurately through the road surface. This method of reinforcement provides the arch barrel with bending capacity and thereby delays the formation of plastic hinges at the critical locations.

In further full-scale tests carried out at the TRL the strengthening method was demonstrated to increase the ultimate strength of the arch significantly. The FE/DE technique can be applied in the same way as for the arch assessments, to determine the strength deficiency and to design the required amount of reinforcement.

The only additional feature required in the analysis was the incorporation of grout-bonded reinforcement. This is represented by mesh independent elasto-plastic line elements. The elements are connected to the masonry mesh internally with Multi-Point Constraint equations, and shear coupling elements with a prescribed stress-strain relation whose parameters relate to the bond failure determined from anchor pull-out tests. Once again, the application of the FE/DE technique was verified against the full-scale tests.

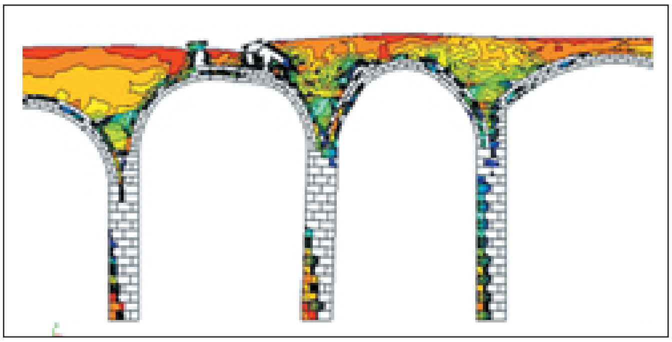

Figure 7: The assessment of a multi-span structure

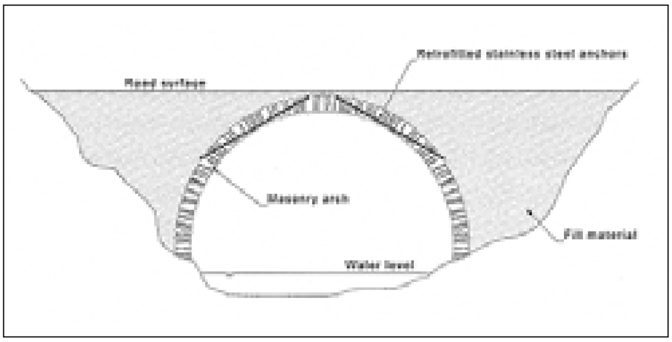

Figure 8: Retrofitted stainless steel reinforcement

To date, the strengthening method has been used on over 70 arch bridges worldwide and has won numerous awards including an Engineering Council Environment Award and a prestigious Queens Award for Enterprise (Innovation).

Figure 9: Strengthening in Progress

Concluding Remarks

The use of advanced discrete element technology for the assessment and strengthening of masonry arch bridges has proven to be highly successful and cost effective. A significant amount of verification and development has been necessary to have complete confidence in the specific application of the technique. The result is an efficient, reliable and flexible method of assessing bridge strength.

The application of advanced analysis to such variable, non-homogeneous and non-engineered structures requires more than analytical considerations. Imperative to the assessment process is an understanding of the wider context of the analysis and the influence of other engineering factors. Engineering decisions made on the basis of factors determined from visual inspections, material sampling and geometric surveys have a broader influence on results and therefore make a pure analyst unsuitable for such work. It is therefore essential that analysts involved have a broad engineering understanding, and participate in all aspects of the assessment or design process. The assessment of masonry arch bridges is an inexact science, balancing advanced analysis with engineering judgement in order to achieve a safe and realistic result.

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NAFEMS
The International Association for the
Engineering Analysis Community

CFD Awareness Seminar
" Industrial Turbulent Flows: CFD Simulation and Validation "
6th Feb 2003. IMechE, London

Do you trust the results of your CFD analysis?

How do you justify that trust and demonstrate it to your boss and customers?

These are the questions addressed by the next NAFEMS CFD seminar "Industrial Turbulent Flows: CFD Simulation and Validation".

This one-day awareness seminar will be held at the

Institution Of Mechanical Engineers,
1 Birdcage Walk, London
on February 6th 2003.

Objective/Aims

Simulation validation may be defined as: 'the process of determining the degree to which a model is an accurate representation of the real world, from the perspective of the intended uses of the model.'

But how do you know if your simulation is accurate? Simulations of turbulent flows in particular can be difficult to validate and one of the comments frequently made when analysts try to obtain information to validate simulations is that if there were detailed data (either experimental or analytical) available on the simulated flow, then the simulation of that flow would be unnecessary. This is a popular misconception.

Come to this seminar and learn how validation is carried out in the real world, how real industrial analyses are validated and how you can apply these practices to your simulations. This seminar will be useful to anyone who carries out CFD, uses the results from CFD, requests CFD or manages a CFD capability.

The aims of this seminar are to demonstrate the effective use of CFD in understanding industrial turbulent flows and as a tool to aid the solution of flow related problems and improve designs. It is intended that this will be achieved by the presentation of case study style papers that illustrate the simulation of industrial flows and their validation with appropriate data. While it is understood that it is rarely practical to validate every CFD analysis, it is generally accepted that some form of validation is required for each flow or product type simulated. Comments on accuracy improvements, simulation dangers and pitfalls and common errors are encouraged. This is an ideal opportunity for exchange of experiences and networking with users across a wide spectrum of industrial applications.

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