The development of in-situ stress in masonry tunnels

T.G. Hughes and L. Wu
Cardiff University, School of Engineering, Cardiff, Wales, UK

ABSTRACT: Rehabilitation strategies for dealing with the aging masonry tunnel stock are severely limited by our inability to predict their current state. This paper looks at two areas of interest in relation to this issue. The first issue, for consideration, is to determine the actual insitu stress state. The paper contains some outcomes from the results of previously unreported flatjack tests undertaken on brickwork railway tunnels in the UK. The tests were undertaken as part of the development work of the flatjack system and were generally undertaken at the tunnel sides about 1 m above the running surface and at the crown. The results generally indicate little or no stress at the crown coupled with significant stresses at the sides. The second area of interest is the effect of long term creep on the predicted insitu stress state in a typical brickwork tunnel. The creep strain is modelled as a simple power equation relating the strain to both time and applied stress. The equation is initially calibrated against relatively short term laboratory experiments and then applied via a 2-D plane strain FE analysis to a typical UK tunnel section. The results indicate the positive influence of the creep in reducing the eccentricity of the thrust at the crown and sides but also generally reducing the initially predicted high stresses around the entire arch barrel.

1 INTRODUCTION

Masonry tunnels, constructed principally of brickwork, continue to play a significant role in the UK drainage and transport infrastructure. Their sizes vary from, at the smaller end, drainage culverts to, at the larger end, significant engineered mainline rail tunnels often several kilometres long. Whilst some of the rail structures have been abandoned many continue to carry significant numbers of vehicle, often at increased speeds; both types of structures require regular assessment.

Tunnels visually appear similar over decades yet progressive changes are occurring due to environmental material degradation, creep within the masonry and ground movement. Tunnels can potentially move to a critical position with little or no visual warning. Most considerations of rehabilitation works are undertaken using stress/strain analysis, where the stress histories are dominant in the analysis. In a new build the stress history can be predicted as it is generally short term and is a result of the as-designed construction process. For a 100 year old structure, where the method of construction is largely, in important detail, unknown and where the intervening years will have had a significant but unquantifiable impact it is not generally feasible to undertake an assessment that starts with the original construction. It is therefore absolutely necessary to assess the structure, as it currently is, before considering the impact of rehabilitation work

In recent years the sophistication of the analysis tools readily available to assessment engineers has not been matched by similar developments in in-situ monitoring techniques. Indeed there are no available quantitative tools regularly used to assist in tunnel assessment. For arch bridges, where the structural assessment is more straight forward, as the main live loading is readily determined, there have been significant developments in the analytical tools but the assessment itself is less dependent on the in-situ stress.

The principal problem associated with the advanced analysis of brickwork tunnels is that the in-situ stress tends to dominate the modelling of the structure and that the predicted stresses can be quite extreme, to the extent that they may exceed the assessed compressive strength of the masonry material. The analysis is characterized by high inner skin stresses at and just above the haunches and a predicted opening of the joints at the crown (and invert). Whilst there can be historic evidence of previous stress states approaching this, that is with thinner joints at the haunches and wider joints at the crown there is often little evidence of existing stresses being at on even near failure stresses. The failure of the analysis to reproduce, as a starting condition, something that is considered acceptable, as an initial state, represents a significant hurdle where the intention is to model the effects of some proposed engineering works, for example the trimming of the lining to accept a larger vehicle or the re-ballasting of the invert. If the initial model does not reasonably represent the initial state then there can be no confidence that the change in state, associated with the proposed works, is being properly modelled.

There are a number of approaches possible to better obtain an in-situ stress state. For a new structure it is possible to model the entire construction phase with appropriate time steps to simulate all the significant events. Such an approach relies on a construction phase that can, to a certain extent, be controlled by the designer, as part of the agreed programme. For a structure that is in excess of 100 years old and where there is only limited evidence of the construction procedure, such an approach is fraught with difficulties. The extent of the overcut is not known neither is the method of bracing the cut face from the completed rings. A different approach is to undertake a “wished in place” analysis and then to modify the outcome to fairly represent the as-viewed current condition. That is the approach to be adopted in the current paper where the “modification” to be adopted represents something approaching a reasonable model of masonry creep behaviour.

The aim of the current work is therefore not to model the behaviour of a particular tunnel but simply to assess the effect of a reasonable model of masonry creep behaviour over a suitable period to see whether it would reduce the extremes of stress present in a straightforward analysis.

2 SITE MONITORING OF INSITU CONDITIONS

In order to determine what would likely represent the “average” in-situ behaviour of a brickwork tunnel the results of a series of (unpublished) tests undertaken by one of the authors in the 1990s are considered. The aim of that study was to determine the in- situ stress state in masonry arch bridges (Hughes & Pritchard 1998) but as part of the development on the system a series of tests were undertaken in brickwork tunnels. The reasoning behind the work in the tunnels was interest, within tunnel infrastructure organisations at that time, in developing Flatjack in-situ tests as being a regular quantitative assessment tool.

2.1 Test equipment details

The testing generally comprised of a basic flatjack in-situ stress assessment, as outlined in the BRE and RILEM recommendations (BRE 1995 and RILEM 1994). The method for conducting the tests requires the strain gauging of the area to be investigated. LVDT gauges were used in the Cardiff assessment, measuring displacement from the far field, as opposed to the DEMEC gauges spanning the opening as recommended by BRE and RILEM. An initial set of zero strain readings are taken, which are recorded for later reference. The Cardiff system allows automatic data logging of this information using a purpose designed PC data acquisition system (Hughes and Pritchard, 1997). A rectangular slot is then cut in the brickwork lining. A special slot cutting frame has been developed allowing accurate control of slot dimensions and geometry. The deformation of the slot mouth during cutting is monitored. The slot was cut as a series of progressively deeper full width slots with readings taken at approximately 20mm depth intervals. This information can aid interpretation of the stress field. Upon completion of the slot, the strain readings are recorded and compared to those taken prior to the slot cut. If the strains indicated closing of the slot, then it can be deduced that the material was in compression and if the slot widens, then tension is indicated. A flat jack was then inserted and pressurised, incrementally until recovery of the strain gauges to their pre-slot-cut values occurs. A complete set of readings was taken at each pressure increment. For areas in tension, the same procedure was adopted but it was necessary to undertake back predictions of the tensile stress; this is a less accurate procedure as the initial state is not replicated by the flat jack.

2.2 Data calibration

The strain recovery was achieved by inserting a stainless steel flat jack. The flat jack stiffness ratio for this jack had been previously laboratory calibrated, giving a jack stiffness constant K_{jack} of 0.95. The slot dimensions were measured prior to flat jack insertion, typically giving a jack to slot area ration K_{area} of 0.92. The predicted material stress at strain recovery is given by equation {1},

$$\sigma = K_{area} \text{ x } K_{jack} \text{ x } P_{recovery} \qquad (1)$$

where $P_{recovery}$ is the internal flat jack pressure at strain recovery. The results of the pressurisation showed the displacement, relative to the initial zero, at each gauge and at each stage of the pressurisation.

2.3 Tunnel test results

The results presented are for a typical tunnel. The pressurization results generally show a broadly linear relationship between internal flat jack pressure and slot deformation after which non-elastic behaviour gives a greater displacement with respect to applied load. The predicted in-situ stress for a typical haunch gauge is given in Table 1, which shows the rectifying stresses at different locations along the mouth of the slot.

Table 1: Predicted in-situ stresses at haunch location

Gauge Number	2	3	5	6
Pressure at strain recovery (N/mm2)	0.37	0.23	0.28	0.54

The outcomes of similar tests undertaken at the crowns generally indicated a further progressive opening of the slots as the slots were cut suggesting areas of tension. Typical back predictions (not shown) indicted very low levels of stress. Figure 1 shows the outcome of a typical two line tunnel section. The tests undertaken in the crown yielded a suggested no compressive stress or even a limited tensile stress whereas those undertaken at the haunches generally yield a significant (but not excessive) compressive stress.

3. DEVELOPMENT OF THE CREEP MODEL

In this section, the calibration of a simple brickwork creep model is developed based on some pre existing experimental data. There is no attempt to model the particular brickwork associated with the assessed tunnels but simply to develop a model that is reasonably characteristic of brickwork behaviour. At this stage in the study the type of model is not critical but simply the likely overall effect that such a model will have on the long term development of stresses in tunnel sections.

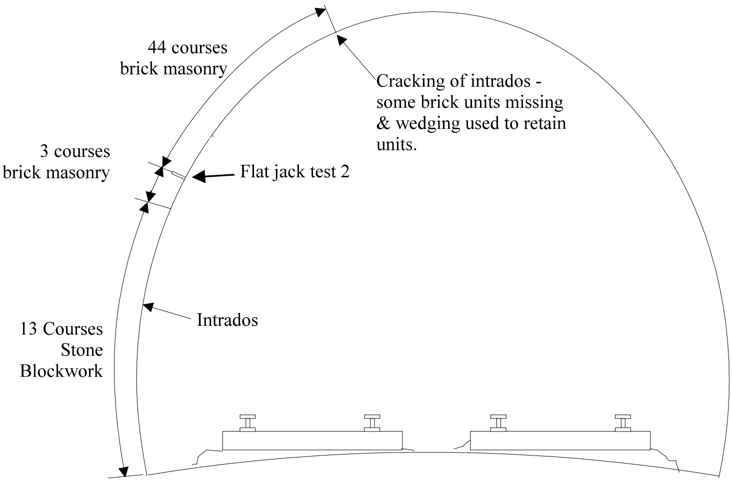

Figure 1 : Typical mainline rail tunnel cross-section

3.1 Creep model

Creep is the inelastic behaviour that occurs when the relationship between stress and strain is time dependent. The creep response is usually a function of the stress, strain, time and temperature history. For the current study the effect of temperature is neglected since tunnels are (with the significant exception of long frequently used tunnels, eg the Channel Tunnel) likely to maintain a reasonably constant ambient temperature throughout their life.

There are a number of simple uniaxial creep laws available in most current commercial FE codes. The work undertaken in the current study used LUSAS (2005) where a time hardening form is available for all laws. Since there was no attempt being made to model a specific tunnel, or indeed masonry material, a relatively simple model was selected for this initial study. The model selected was in the form of a power law (time dependent/strain hardening) and is given as (2)

$$\varepsilon_c = f_1 q^{f_2} t^{f_3} \qquad (2)$$

where: ε_c is the uniaxial creep strain, q is the appropriate stress and t the current time. Here f_1, f_2 and f_3 are to be determined from pre-existing experimental data.

3.2 Experiment data and fit curve

Good long term masonry creep data is in very very short supply. Harvey (1996) undertook a large number of creep experiments using a range of different masonry materials. Equation (2) was fitted to some suitable data using a multi-linear regression and the outcome is given in Figure 2. The equations are clearly not a brilliant fit to the data but within the general shape and, importantly, the final strain rates at the end of the relatively short term tests looks appropriate. The values of the 3 model parameters are given later in the modelling section.

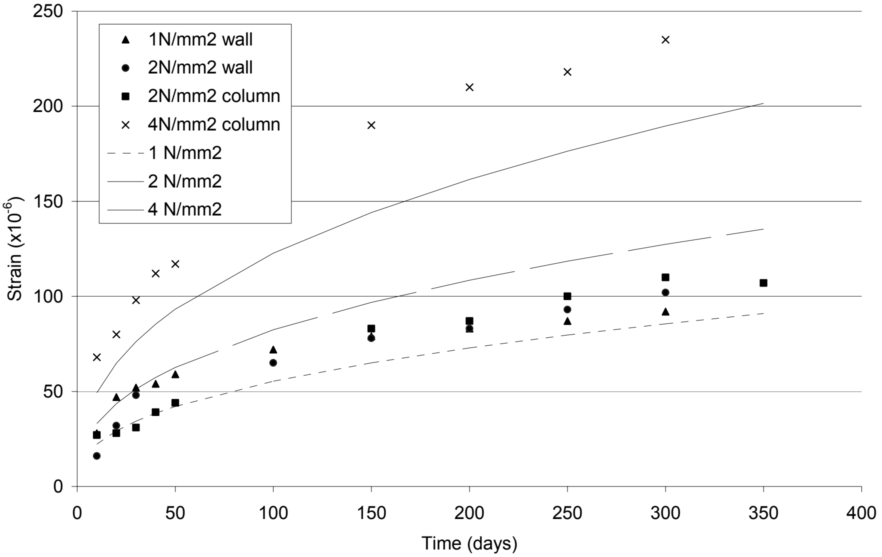

Figure 2 Experimental data and the power law fit curve

3.3 Long term creep curve of different stresses

The power law was used to extend the short term creep curves over long periods to produce the relationship required at the expected age of the tunnels under consideration. The form of the equations suggests significant continued creep even after 100 years (100 years creep is more than twice the 10 years creep) and the deficiency of long term data is seen as a significant omission to our knowledge in this important area although medium term accurate site based data is beginning to appear (Palleres and Hughes, 2007).

4. FEM ANALYSIS

Figure 3 shows the finite element mesh for a horseshoe multi-ring brickwork tunnel with a segmental invert. The shape was taken from the London Metropolitan Tube line. The ring was simulated with 12 elements through the ring thickness. Position Nos.1 to No.17 are equi-spaced around the intrados of the tunnel lining and are identified for later reference.

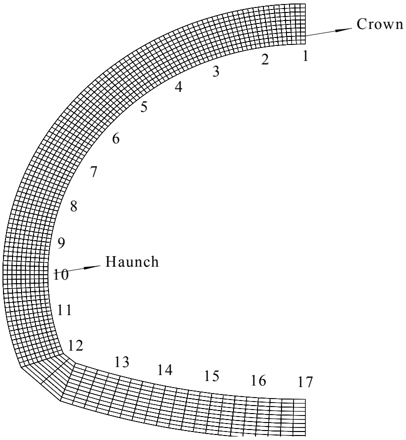

Figure 3 Comparison of the elastic model to the creep model

The FE modelling detail and the material property values used in the analysis are detailed in Table 2. These do not relate to any particular masonry material or tunnel section but were chosen to be representative of the material behaviour.

Table 2 Material properties used to model the tunnel and soil

Material	Material Property	Value
Brickwork		7000N/mm2
	Elastic Modulus	0.2
	Poisson's Ratio	2.4E-6 kg/mm3
	Density	6.2N/mm2
	Uniaxial Compressive Strength	0.3N/mm2
	Uniaxial Tensile Strength	
	Creep power law f1,f2,f3	.00000894,.574,.396
Soil (Mohr-Coulomb)		
	Elastic Modulus	80N/mm2
	Poisson's Ratio	0.33
	Density	1.8E-6 kg/mm3
	Cohesion	0.1 N/mm2
	Hardening parameter	0.2
	Friction Angle	14o

Following a "wished in place" analysis of the tunnel the creep model was allowed to run over a period up to approximately 200years. Figure 4 shows the developed stresses around the inner ring of the tunnel and details the results of an elastic model with no creep, then after 10,000 days, 20,000 days 40,000 days and 80,000 days of creep (tension+ve, compression–ve).

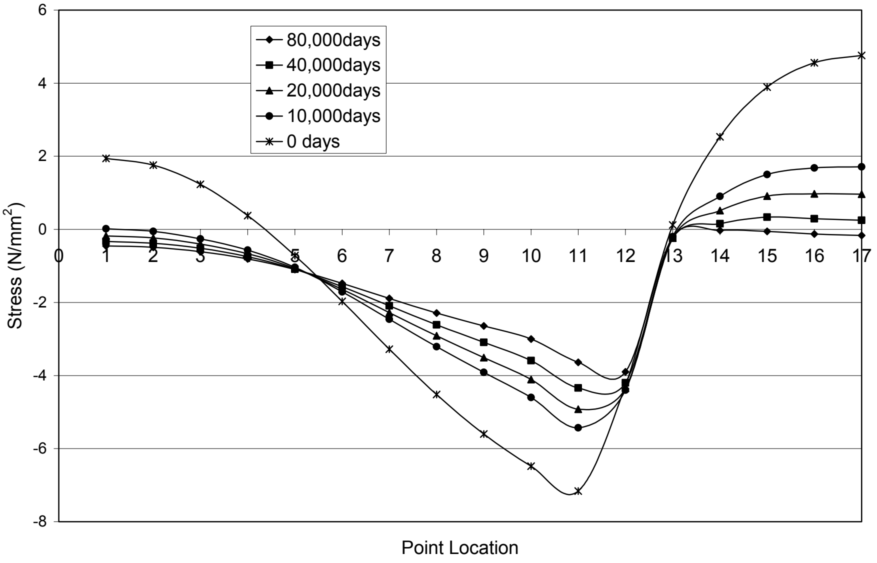

Figure 4 Stress in tunnel inner face showing creep effect

The initial results demonstrate an unsustainable initial tensile stress at the crown (approx 2N/mm^2) and a challenging compressive stress at the haunches (7 N/mm^2). With the passing of time there is a decrease in both the predicted tension and the predicted compression. The tensile stress completely disappears and the maximum compressive stress reduces to a manageable 4N/mm^2. The results indicate the positive influence of the creep to use the masonry's advantage of high compressive strength.

One of the interesting features of Figure 4, which will appeal to practicing assessment engineers, is that the inclusion of creep with a simple elastic model is able to produce a sustainable no-tension stress distribution without the use of more complex material models with which they may be less familiar

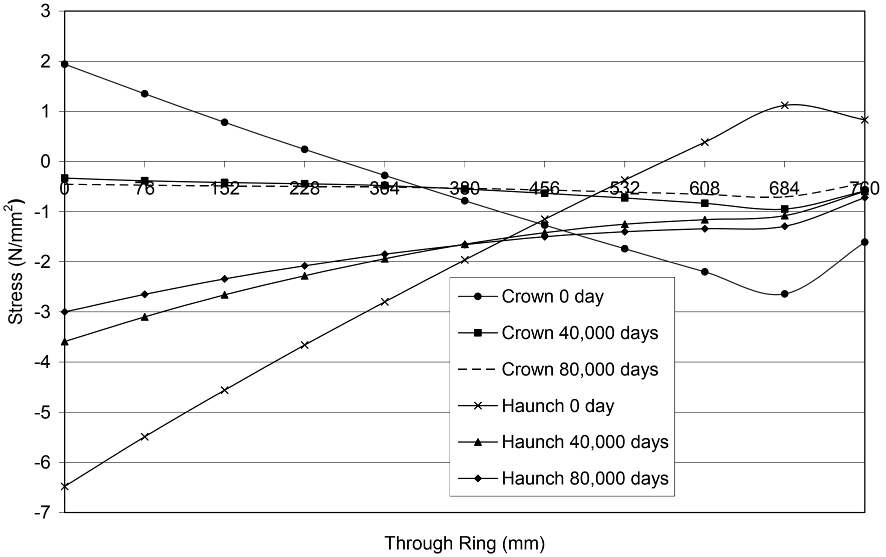

Figure 5 Variation of the through ring stress over time for a 700mm lining

The variation of stress through the ring is detailed at 2 locations in Figure 5, which shows the stress distribution at the crown and the haunch at 0 days, 40k days and 80k days using a more complex non-linear material model.

The initial condition at the crown shows limited compressive stress in the outer ring with less tension on the inner ring than predicted with the simple elastic model (as evidenced by comparison with Figure 4). However as the creep model takes effect the differences become less pronounced and at 40k days both sections are in compression on both the inner and out faces.

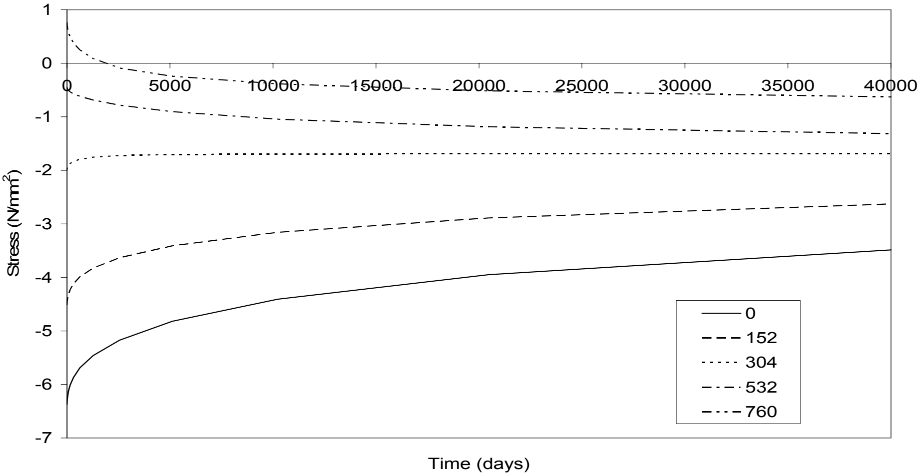

Figure 6 The variation of the through ring stress over time

The development of the stress state over time is shown for the haunch in Figure 6 for a range of locations through the tunnel ring. The high compressive stress quickly decreases over the first year or so with the tensile stress disappearing over a similar time frame at this section.

3 DISCUSSION AND CONCLUSIONS

Analysis of tunnels undertaken using FE methods have previously been reported to the authors as generating unsustainable tensile and compressive stresses. This work sought to identify whether creep modelling of the masonry was a possible mechanism of developing more realistic assessments.

To support assumptions of the general benign state of stress in tunnels some initial consideration has been given to a series of flatjack tests undertaken on a range of UK brickwork tunnels and typical results presented. The results suggest the stress at the crown is at or about zero but that measurable stresses are generated in the haunches, in the example chosen the compressive stress was about 0.5 N/mm^2 at this location but higher stresses are certainly possible. Given the nature of the load carrying within a tunnel this suggests that the rings are likely to be everywhere in compression.

In order to model the development of creep in tunnels a simple creep model was fitted to some historic masonry data. The data itself is not entirely appropriate, nor is the fit that good, but the general time dependency seemed appropriate.

A simple FE analysis of a 2-D tunnel section was undertaken which confirmed the eccentric nature of the line of thrust in the initial modelling. The application of the creep model to the initial state brought about a change of stress which was entirely beneficial. This change in stress was achieved regardless of the type of masonry model adopted and the universal outcome was a tunnel ring entirely in compression.

This is only an initial study and there are significant omissions and areas for improvement in the work undertaken. It may also be true, to a certain extent, that common sense would have indicated the outcome predicted. That said, the authors are aware that this issue is a real and present concern for a number of assessment engineers and that this work, however limited, does provide some evidence of a possible way forward for this.

There are a number of research themes that flow from this initial work. One clear area to progress this work is to develop a more robust model of the likely creep behaviour of old clay brickwork and then to look at the sensitivity of the outcomes to different material and geometric properties. It is also likely that there are insufficient flatjack tests to form a priori an assessment of the insitu stress and the development of its use in tunnel assessment needs to be progressed.

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