Stresses from strains

In this article, Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc at the University of Warwick, UK, talks about the calculation of stress from a history of measured strain in sprayed concrete tunnels.

IT WOULD BE nice to be able to know what the stress in a sprayed concrete lining is, so we know what the actual factor of safety is. This can be done using stress measurement methods, but it would be more convenient to be able to back-calculate the stress from the convergence measurements. However, due to all the other strains going on at the same time such as plasticity, shrinkage, creep and thermal effects, as well as the fact that all these properties are changing as the sprayed concrete ages, this calculation is very complicated and must be done in a stepwise manner calculating increments of stress from increments of strain over small timesteps.

Methods of calculating stress in concrete from a history of measured strain have been around since the 1960's, and for the last 25 years people have been trying to make them work on sprayed concrete tunnel linings. However, full details of the calculation method are not always given, the sources of error or uncertainty are rarely quantified, and the methods rarely compared to actual stress measurements, so in most cases we have no idea how accurate they are.

Recently these back-calculation methods have begun to be used more widely, but there appears to be little appreciation of the assumptions they are based on. This area requires a thorough review of the competing methods, for which there isn't space here, so I am just going to run through the main questions that engineers should be asking of all the methods. A more detailed review can be found in Jones (2007).

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The background

Sir Alan Muir Wood put great emphasis on what he called "overall holistic surveillance" (Muir Wood, 2003). In principle this means that a tunnel project should be approached as a system with a continuous risk management process through all phases of design and construction.

The risk management process for a sprayed concrete lined tunnel was outlined by Powell & Beveridge (1998), who demonstrated the interdependency of prediction and verification with observation and modification. Design must be managed through several phases, from conceptual and detailed design, through construction and into operation.

During conceptual and detailed design, we are in the business of prediction. At the same time, hazards are identified, risks are assessed and the management procedures to control risk during construction are formulated. But design methods for sprayed concrete tunnels are based on assumptions and simplifications that make the design at best semi-empirical (HSE, 1996). Even if the material behaviour of the ground and the sprayed concrete are well-known and a 3D numerical analysis is performed, there are still uncertainties about the true ground mass behaviour and the variability of sprayed concrete to consider.

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It is important to remember that monitoring and associated trigger levels can have different purposes:

1. As a last line of defence to guarantee the safety of the tunnel or nearby structures by allowing the timely implementation of mitigation measures should the tunnel be in danger of collapsing (ultimate limit state).
2. To ensure serviceability limit states are not exceeded, e.g. minor cosmetic damage to buildings or cracking of the lining.
3. Observation followed by modification of the design, i.e. the observational method.
4. For design verification, to provide confidence that the design assumptions are valid.
5. For research purposes, i.e. to compile a case history to use in validation of models for future tunnel designs.
6. For protection against third party legal action.

It is important that the people on site know what the purpose of each instrument is and what the monitoring trigger levels are for. It is no good evacuating the tunnel when the trigger level for settlement is exceeded, when there's not yet a risk of collapse and what you really need to be doing is implementing measures to reduce settlement from within the tunnel or inspecting buildings to ensure the plaster isn't cracked.

In this article, the use of monitoring to ensure safety of the tunnel (point 1 above) will be discussed. This is the most important aspect of monitoring, and it is also the most difficult to get right.

The problem

The simplest and most reliable measurements that can be made in a tunnel are measurements of lining displacements (Clayton et al., 2000). However, there is an inconsistency between the way a tunnel is designed for ultimate limit state stresses and the way its safety is usually monitored during construction by measuring displacements of the tunnel lining. As I have argued in a previous Tunnelling Journal article (Jones, 2012), the fact that the displacements of the tunnel lining or the surrounding ground are similar to those predicted by a numerical model does not necessarily mean that the stresses in the tunnel lining are.

This does not mean that monitoring lining displacements is pointless. Accumulated experience of typical deformation trends in different rock or soil types can be used to assess whether the system is achieving equilibrium (e.g. Müller, 1977). But an entirely observational and empirical approach is unsatisfactory, because the factor of safety of the structural lining is impossible to assess with any degree of confidence unless we have a significant number of case histories of collapse of a similar tunnel lining design in the same geomaterial, which is unlikely.

The answer

The answer is of course to measure lining stresses directly. This has been done in the past using a variety of methods, such as slot-cutting, overcoring, undercoring and embedded pressure cells. According to Negro & de Quieroz (2000), differences between predicted and measured lining stresses are frequently attributed to unrepresentative or erroneous field measurements rather than inadequacy of the numerical model. Due to the complex behaviour of sprayed concrete, especially at early age, it is not clear that this is a reliable assumption. Since these measurement methods are reasonably well-understood, it seems more likely that they represent the real, variable behaviour, and it is the predictions that are inadequate.

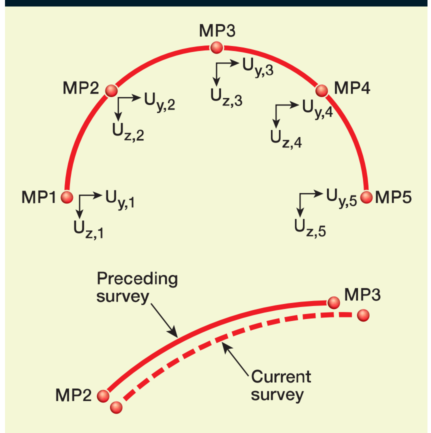
I have many times written of the need for the increased use of stress measurement (Jones et al., 2005; Jones, 2005; Jones, 2007). Stress measurement is needed to estimate the factor of safety of a structural lining, and the current dearth of estimates of stress in sprayed concrete linings with which to validate models also impacts negatively on design by introducing uncertainty.

Another answer?

Another possible solution to this problem is to back-calculate stress from displacement measurements. This method has obvious attractions as we are monitoring lining displacements anyway. However, it is not straightforward, since strains in concrete are dependent on not just elastic deformation but also plastic deformation, thermal expansion/contraction, creep and shrinkage. These strains are all of a similar magnitude to the strain due to loading, so they cannot be ignored.

Back-calculation methods have been around for some time. The majority are rheological models based on the 'rate of flow method' (England & Illston, 1965), which allows the stepwise back-calculation of stress in concrete from a history of measured strain. A generalised Kelvin model is normally used, which accounts for elastic and delayed elastic strain (primary creep) and terms are often added to account for viscous (or secondary) creep, temperature and shrinkage. This was done by researchers at the Montanuniversität Leoben and Geoconsult in Austria, initially by Schubert (1988) and further developed by Golser et al. (1989), Golser & Brandl (1996) and Golser & Kienberger (1997). For an example calculation using this method, see Jones et al. (2005).

Figure 1: Obtaining axial strains from tunnel lining displacements



Usually optical surveying measurements are used with assumptions of constant strain along each arc segment, no bending, and uniaxial sprayed concrete behaviour. This is shown in Figure 1, where displacements in 3D or 2D space may be converted into axial strains in each arc segment of the lining. Sometimes embedded strain gauges or tape extensometers are used, which should be expected to improve accuracy, although some proponents of the back-calculation method insist that optical convergence measurements are accurate enough (e.g. Rokahr & Zachow, 1997). It is possible to take variations of strain and hence bending moments into account by curve-fitting (Macht et al., 2003), but in the case of a closed ring this requires an assumption of curvature at one of the points.

The list of sprayed concrete material parameters required for this kind of model is quite long:

- Age-dependent Young's modulus
- Poisson's ratio
- Stress-strain relationship due to instantaneous loading
- Age-dependent Kelvin spring stiffness and viscosity parameter for primary creep
- A relationship between creep compliance rate (rate of viscous creep deformation per unit stress) and age for secondary creep
- Age-dependent coefficient of thermal expansion
- Age-dependent shrinkage rate

Each of these parameters is inherently variable. A typical value for standard deviation of sprayed concrete compressive strength is 25-30% of the mean strength (Jones, 2007) and there are good reasons to believe that the variability of most of these parameters is similar. Also, the rate that the sprayed concrete 'ages' is also dependent on temperature, accelerator dosage and cement properties. Accuracy can be improved by undertaking tests on the specific mix to be used, but there is still the temperature influence on aging to take into account. This is where a thermochemomechanical model may seem attractive, such as that developed at the Technical University of Vienna by Hellmich et al. (1999a), Hellmich et al. (1999b), Hellmich et al. (2001b), Hellmich et al. (2003) and Macht et al. (2003).

The maturity of concrete can be defined by its 'degree of hydration'. This is the proportion of the cement that is hydrated. Many of the parameters listed above have relatively simple relationships to degree of hydration, and degree of hydration can be determined knowing the thermodynamic properties of the concrete, i.e. the relationship between normalised affinity and degree of hydration, the activation energy, and the temperature history of the concrete. Therefore, although a source of uncertainty is removed (the effect of temperature on the rate of hydration and hence maturity), additional parameters need to be determined in the laboratory, and it is necessary to not just measure strain of the concrete but also its temperature in the field.

The accuracy of all these methods also depends on the timesteps used in the algorithm, and on the time intervals between lining displacement measurements. If thermal effects are to be included, then the average temperature of the sprayed concrete lining across its thickness needs to be measured. The shrinkage rate is also dependent on temperature and relative humidity. The creep parameters need to be calibrated to creep tests and the shrinkage parameters determined from shrinkage tests, both performed on the specific sprayed concrete mix to be used.

Each of the parameters, when measured using laboratory tests, is subject to some scatter. There is also the problem that environmental conditions in the laboratory are not necessarily the same as in the tunnel, and the sample sizes are also different. Therefore, each of the parameters introduces an error to the calculation. Material models used in back-calculation methods are based on uniaxial behaviour, when the sprayed concrete lining is really loaded biaxially or triaxially.

There are also errors introduced by the surveying method. Using best practice optical surveying methods, it may be possible to achieve a repeatability of ± 1mm (Clayton et al., 2000). This will result in an error in stress calculation approximately equal to 10% of the strength in a 10m diameter tunnel or 20% of the strength in a 5m diameter tunnel (Jones, 2007). If the optical surveying has a more standard value of repeatability of ± 2-3mm, then the errors are multiplied by a factor of 2 or 3, and are swamping the calculation. Fluctuations in convergence measurements also cause problems for the stability of the stepwise calculation and I suspect the only way to prevent this is to smooth the curve before putting it into the calculation (although these kinds of details are never published). This means that sudden changes in deformation may not be immediately picked up until several readings show a new trend is developing. The use of strain gauges or a tape extensometer will improve accuracy, but proponents of these methods insist that optical surveying is sufficient (Rokahr & Zachow, 1997; Macht et al., 2003).

Yet another issue is that there is usually a delay before installation of the monitoring points. Clayton et al. (2006) found at Terminal 4 station that targets were normally surveyed within 8 hours of finishing spraying the lining or within 12.5 hours of excavation. Any delay will result in missed strains and hence missed stresses. The use of embedded strain gauges removes this problem, but introduces other issues. For instance, strain gauges measure strains very locally and ideally they need to be placed close to the intrados and extrados to estimate the distribution across the thickness. Strains too close to the intrados may be tensile due to plastic shrinkage or drying shrinkage effects.

Conclusions

It is necessary to measure stress in sprayed concrete linings to know the factor of safety and to verify design models.

Back-calculation methods are appealing because they are cheap and convenient. Although they are becoming increasingly sophisticated and are a promising field of research, more effort needs to be made to compare results to more direct measurements of stress, and to quantify the uncertainties. At present, they have not been demonstrated to be reliable.

Back-calculation methods are only as good as the accuracy of the surveying method and the parameters used to define the relationship between strain and stress. These parameters need to be determined on a site-specific basis and their variability determined.

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