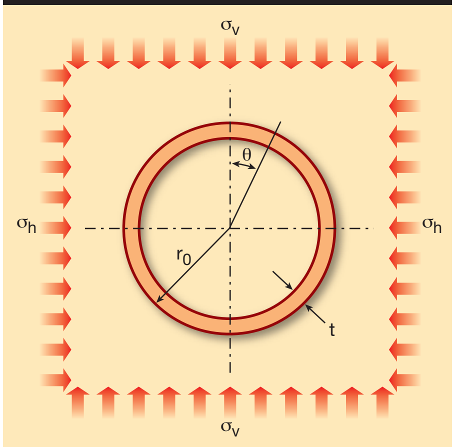
Segmental lining joints

In this article, Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc at the University of Warwick, UK, looks at recent developments in the design of segmental lining joints.

THERE HAVE BEEN SIGNIFICANT ADVANCES in our understanding of segmental lining behaviour in the last 15 years from instrumented rings in actual tunnels, full scale or reduced scale laboratory tests and 3D numerical modelling. This article will attempt to summarise this work, with particular reference to the behaviour of the joints in a segmental lining.

Segmental tunnel linings have traditionally been designed in two dimensions using quite simple models. For instance, the International Tunnelling Association's Working Group No.2 Report in 2000 (ITA, 2000) recommended the use of analytical solutions, such as the Curtis-Muir Wood solution (Curtis, 1974; Muir Wood, 1975), or bedded beam models, where each segment is modelled by a 1D beam element and the ground is modelled by springs. In addition, simple methods were used to estimate construction loads due to handling, storage, ringbuilding and jacking forces, and these were performed as a separate check from the service loads. But recent studies have found that ringbuilding and jacking loads remain in the lining permanently.

Figure 1: Curtis-Muir Wood solution boundary conditions



Virtually all the cracking and damage to segmental linings occurs during construction. Once the rings are in place and the grout has hardened, it is rare for them to experience any further distress. This should indicate to us that although we are probably quite good at designing for the earth and water pressures in service, the worst design loads occur during construction and we need to improve our methods of estimating them.

Introduction – previous state of the art circa 2000

In the case of the continuum analytical solutions, which are referred to in ITA (2000) as the 'elastic equation method', the material properties of the lining and the ground are assumed elastic and the effect of joints is 'smeared' by reducing the moment of inertia of the whole lining. The boundary conditions are shown in Figure 1.

Muir Wood (1975) proposed the following equation to reduce the moment of inertia of a ring to take account of joints:

$$I_e = I\left(\frac{4}{n}\right)^2, I_e \ngtr I, n > 4$$

This 'smears' the effect of joints by reducing the moment of inertia of the whole ring. The equation is based on the assumption that there is no resistance to rotation at the joints, except that provided by ground reaction to the ring's ellipsoidal deformation. The equation is only valid if there are more than 4 joints. In reality a ring can deform with 4 joints if the joints are aligned with the principal stress directions in the ground, i.e. joints at 12, 3, 6 and 9 o'clock positions in Figure 1. But if they were rotated 45°, then the joints would have no effect. When a ring has 4 joints, the orientation of the joints makes a huge difference, but this effect decreases as the number of joints increases. Hefny & Chua (2006) compared Muir Wood's equation to analyses using continuum finite element models and found that as the number of joints increases beyond 6 joints, the influence of joint orientation becomes negligible.

Muir Wood's equation also assumes that an individual ring's deformation is unimpeded by the adjacent rings, which would only be the case if the circumferential joint had no shear keys, dowels or friction, or if the radial joints were all aligned down the length of the tunnel (Klappers et al., 2006). Usual practice, however, is to stagger joints and to encourage shear resistance, so this assumption is unrealistic.

Another problem with continuum analytical solutions is that the smearing of the effect of the joints allows calculation of 'average' bending moments, but in reality, bending moments near to the joints will have a different value (usually higher) than bending moments mid-segment and will depend on the joint geometry, bolt details, packer and gasket. One way to 'fudge' this is to assume a

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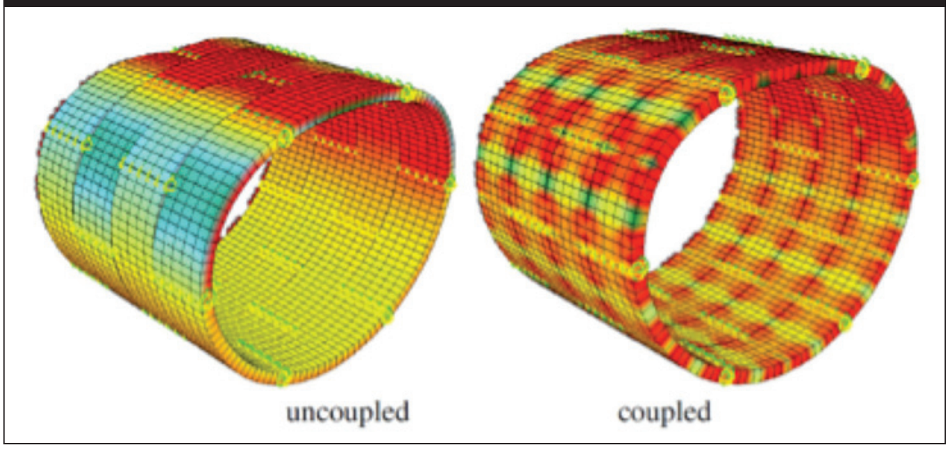
Figure 2: From left to right: aligned radial joints, staggered radial joints, monolithic rings (from Fei et al., 2014).

Figure 3: Effect of ignoring circumferential joint shear resistance ('uncoupled', left) and modelling circumferential joint shear resistance ('coupled', right) (from Klappers et al., 2006)

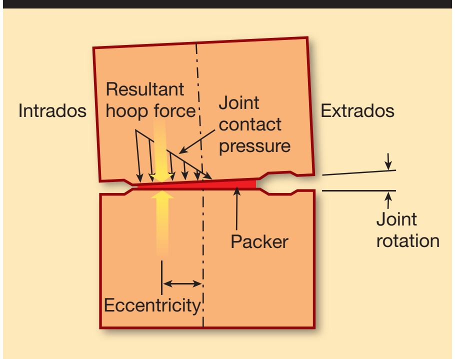


joint rotation based on the maximum specified ovalisation and then to use the joint geometry and packer properties to calculate the eccentricity of the hoop force and hence a bending moment. The designer can then use the greater of the 'average' and this local value for design, and this approach should be conservative. From experience I know that this approach is not commonplace and often only the 'average' values are used for design.

When a bedded beam model is used, the radial joints may be modelled by rotational hinges, which is a slight improvement on the continuum analytical solutions. If a finite element or frame analysis program is used, then these hinges can be assigned a rotational stiffness. However, knowing what this rotational stiffness should be is not straightforward. De Waal (2000) showed that the results will always be between the two limiting situations of a monolithic ring with no joints and a ring with free (or pin) joints. Lee et al. (2001) estimated that it is between 1/10 and 1/4 of the segment stiffness.

The bedded beam models and analytical solutions, prevalent circa 2000, usually ignored the following factors or dealt with them in a very simplistic way (Blom et al., 1999; Molins & Arnau, 2011):

Figure 4: Eccentricity of hoop thrust caused by joint rotation



- Staggering of joints in adjacent rings
- Packing material in the joints
- Grout pressure and grout hardening
- The type of joints and their rotational stiffness
- Redistribution of moments via shear stress across the circumferential joint to adjacent rings
- The effect of longitudinal compression in the tunnel caused by the TBM jacks
- Restraint from the shield, and in particular the tailseal brushes
- What happens when radial joints are not parallel to the axis of the tunnel, e.g. when trapezoidal or hexagonal segments are used.

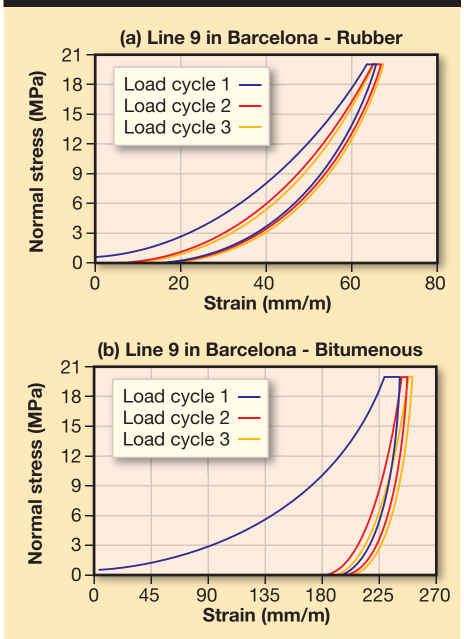
In this article I will discuss staggered radial joints, packers, joint geometry, rotation and misalignment of joints. Next issue I will discuss jacking forces, grout pressures and longitudinal effects.

Staggering of radial joints

Staggering the radial joints has the effect of reducing deformations and increasing bending stiffness of the rings. Fei et al. (2014) used small scale physical models (Figure 2) to show that by staggering the joints an overall stiffness is achieved that is somewhere between that of aligned radial joints and that of monolithic rings (with no radial joints).

By increasing the circumferential joint bolt forces in their model, Fei et al. (2014) also showed that a higher longitudinal axial force across the circumferential joints increases bending rigidity. This is illustrated by the exaggerated deformed mesh plots from a 3D numerical analysis by Klappers et al. (2006), showing how 'coupling' of rings by introducing longitudinal axial force and shear resistance in the circumferential joint 'harmonises' deformations. This effect was found to occur even at quite low values of longitudinal axial force, so it is likely that even residual axial forces left behind by the TBM shove rams would be sufficient.

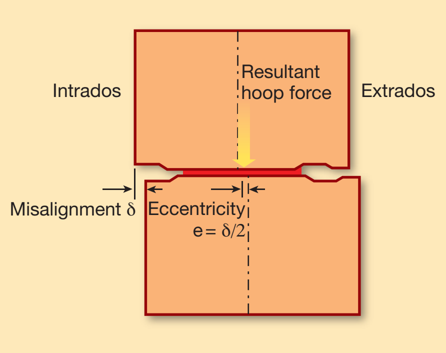
Figure 5: Behaviour of elastomeric and bituminous packers - 3 loading cycles under simple compression (from Cavalaro & Aguado, 2012)



Joint geometry and packers

In reality, bending moments at the joints depend on the geometry of the joint and the properties of any packer. As joints rotate, the line of thrust across the joint moves and this eccentricity of the thrust transfers moment to the adjacent segment (Figure 4). The moment is equal to the hoop force multiplied by the eccentricity. In addition, as eccentricity increases and the hoop force gets closer to the edge, the shearing resistance of the corner reduces as the potential shear plane reduces in length. This could result in damage to the edges of the joints. If this occurs on the intrados, it will require repair. If a shear failure occurs on the extrados it cannot be repaired, and it may also compromise the watertightness of the gasket. Therefore, designing to minimise eccentricity is important.

Figure 6: Effect of misalignment on eccentricity



The properties of the packer have a big influence on the eccentricity of the hoop force. A packer that is too thin or too compressible will result in a concrete to concrete contact and a high stress concentration. A packer that is too stiff will also generate a large eccentricity as stress is mobilised at the edge of the packer first. Understanding the stress-strain behaviour of a packer and how it interacts with joint rotation is absolutely essential.

Cavalaro & Aguado (2012) performed simple compression and simultaneous compression and shear tests on elastomeric and bituminous packers for several tunnelling projects in Spain, testing the packer between both concrete blocks and steel plates. Using steel plates resulted in a more repeatable test, because even concrete cast to tight tolerances has small asperities that can cause stress concentrations. Bituminous packers were found to have a softer response than elastomeric packers, but both have an exponential behaviour; they become stiffer as strain increases, due to densification (Cavalaro & Aguado, 2012). Two of their tests are shown in Figure 5. The first loading cycle also shows a much softer response – this is known as the 'Mullins effect'.

Joint geometry and packer properties are crucial to the design of a segmental lining, because the eccentricity of the hoop force across the joint determines the bending moment induced, the bursting stress and the shear capacity.

Sometimes radial joints are designed with curved surfaces, and in theory curved joints have a lower rotational stiffness than flat joints. This is because when flat joint surfaces rotate relative to each other, they will quickly generate a larger eccentricity by tending to hinge about the edge of the contact area. As curved joints rotate, the line of thrust stays closer to the centreline of the segment. Another feature is that as flat joints in a ring rotate, the perimeter of the ring increases. As far as I know, no-one has researched this effect, but it should be expected to slightly increase the hoop force. If curved joints have a radius approximately equal to one half the arc length of a segment, then the perimeter does not change.

Eccentricity in radial joints is also caused by lipping, where segments are misaligned and have a step between them. In this case the eccentricity is equal to half the misalignment, as shown in Figure 6.

Conclusions

Virtually all the cracking and damage to segmental linings occurs during construction. Once the rings are in place and the grout has hardened, it is rare for them to experience any further distress. This should indicate to us that although we are probably quite good at designing for the earth and water pressures in service, the worst design loads occur during construction and we need to improve our methods of estimating them.

Continuum analytical solutions smear the effect of joints and therefore provide 'average' bending moments. In reality, bending moments vary a lot within each segment.

Where staggered radial joints are used, it is important to model more than one ring. In the simplest possible model, 3 rings need to be modelled in 3D.

Joint geometry and packer properties are crucial to the design of a segmental lining, because the eccentricity of the hoop force across the joint determines the bending moment induced, the bursting stress and the shear capacity.

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