3 Dimensional Structural Modelling of Segmental Tunnel Lining Using Finite Element Software

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ABSTRACT

Closed-face shielded TBM driven tunnels are supported using precast concrete segmental linings. In the past these types of lining have been assessed without consideration being given to the coupling action along circumferential joints of adjacent rings or the true behaviour of joints along longitudinal joints, especially where these have a taper. The mechanical and geometrical characteristics of these joints strongly affect the structural behaviour of tunnel lining. The current practice is to use closed form solutions or adopt two-dimensional 'beam-spring' modelling techniques to assess the structural behaviour of segmental linings when loaded. However, it can be argued that this simple two-dimensional approach do not fully take account of the coupling action or joint behaviour and so will not provide accurate results. Particularly with respect to: the structural behaviour of the tunnel lining in longitudinal direction; the deformation of the lining due to the rotation along longitudinal joints; and the relative displacement in the circumferential joints.

It is suggested that a more comprehensive three dimensional finite element method (FEM) is required to more accurately explore the coupling action and joint behaviour. The paper aims to show how the behaviour of the rings and joints can be modelled in an appropriate way. The paper describes an approach that uses the Strand7 structural software to develop a three dimensional model. A description is given of how loading assumptions have been derived. Comparisons are made with the results from traditional two-dimensional beam spring models.

1. Introduction

The behaviour of a segmental tunnel lining under applied loading is very different to that of a monolithic cast-in-place concrete lining. For precast segments, the stiffness and resistance to deformation of rings depends on many factors. These factors include: the number of segments in each ring; anticipated joints rotation under load; the joint profile; the amount of force applied between segments in each ring; the quality of the ring build geometry; and the interaction between the relative rings.

The squatting of precast rings under load is generally a consequence of non-uniform applied ground pressures, where vertical applied pressures are either greater or less than horizontal pressures. This imbalance will cause rings to deform. Depending of the ring rotation of adjacent rings and the staggering of joints, this relative deformation may differ. This change in deformation profile will have an impact on the imposed structural actions on each ring.

Relative ring behaviour is to a large degree dictated by the behaviour of joints, as the segments rotate about these points. Where longitudinal joints are tapered this rotation is complex and requires special attention, given the tendency for local torsional stresses to develop. Therefore, the behaviour of the joints needs to be considered in the design of the segments and in this paper it is shown how these joints can be modelled by using a three dimensional FEM approach.

2. Traditional analysis approaches

Traditional methods of analysis provide a means of determining imposed structural actions on circular tunnel linings at ultimate limit state and lining deformations at serviceability limit state.

Closed form solutions provide a first pass approach to assessing segment behaviour. This approach uses hole-in-a-plate theory and in effect assumes the lining deforms to form an elliptical shape. These solutions are based on the equilibrium equations for a hole in a prestressed plate. The formulae used have been developed from the work of Morgan [1], Muirwood and Curtis [2, 3]. The formulae take into account the resistance of the lining to determine the imposed maximum axial 'hoop' loads and bending moment caused by assumed loading. The equations can also be used to determine lining 'squatting' deformation.

By determining expected lining deformation an assessment of ideal segment behaviour can be undertaken. Employing geometric equations enables longitudinal joint rotation (or bird-mouthing) to be determined. This calculation generally includes allowance for build tolerance. It is typical that precast segmental tunnel lining designs are checked against an absolute deformation value of 1% of the lining radius in combination with worst case ground loading deformation to determine the amount of associated birdmouthing that can be expected. This percentage is a well established figure that complies with the BTS Specification for Tunnelling [4].

Knowledge of joint behaviour provides another approach to understanding imposed structural actions of the tunnel segments, which is different to that assumed by closed form solutions by themselves.

The calculated joint rotation when considered in combination with applied axial forces will cause the development of an asymmetric strain profile across the joint faces, with the greatest strain at the point of rotation. This pressure distribution in turn causes flexural bending within segments. Segments are designed to resist this bending by included reinforcement either in the form of steel fibres or conventional steel reinforcement bars. Segments are also designed to take account of the tensile bursting pressures that accompany these segment-to-segment contact pressures.

More complex structural analysis methods can also be used to assess segmental linings. Following a 'beam-spring' approach provide another approach to determining the structural response of segmental linings to imposed loading, which considers the confinement offered by the surrounding ground. Using this approach requires that a numerical model is created in a structural analysis software program (such as Strand7). The lining is modelled as a series of interconnected beam elements with assumed loads applied at the ends of the beams. These beams are restrained in position by a series of 'compression only spring', whose stiffness is adjusted to replicate the restraint provided by the surrounding annulus comprising grout and rock mass. The stiffness of these springs can be calculated using any one of a number of linear load deformation relationships. A relationship commonly used is that proposed by Duddeck and Erdman [5].

This simplified two dimensional approach is in many respects restrictive in the way it takes into consideration joint behaviour. One approach used to account for joints, is to simply reduce the stiffness of the ring by a linear relationship to the number of longitudinal joints that are present.

To truly understand joint behaviour and its influence on imposed structural actions requires a three dimensional approach to be undertaken. Especially where tapered joints are specified, such as in the case of trapezoidal ring configuration.

3. Case study

A case study is presented where a three dimensional approach has been taken to design lining for water conveyance tunnels, forming part of a major project in Australia. The project involves the construction of 4m internal diameter TBM driven tunnels that are supported using a precast concrete segmental lining system.

These rings have been designed follow a universal lining system, with each ring formed by six segments that are either trapezoidal or parallelogram shaped. These universal rings are tapered for negotiation of the designed alignments.

The lining has been designed to include Ethylene Polythene Diene Monomer (EPDM) compression gaskets for waterproofing of the lining. Longitudinal joints are connected in the short term using spear bolts, whilst rings are secured to one another using dowelled connectors.

4. 3D finite element model

The three dimensional model was developed for the project using the finite element package Strand7 [6]. The finite element model has been created to replicate the tunnel lining. The particular features of the model are described below.

Each segment has been modelled as a discrete structure comprised of a grid of quadrilateral plate elements.

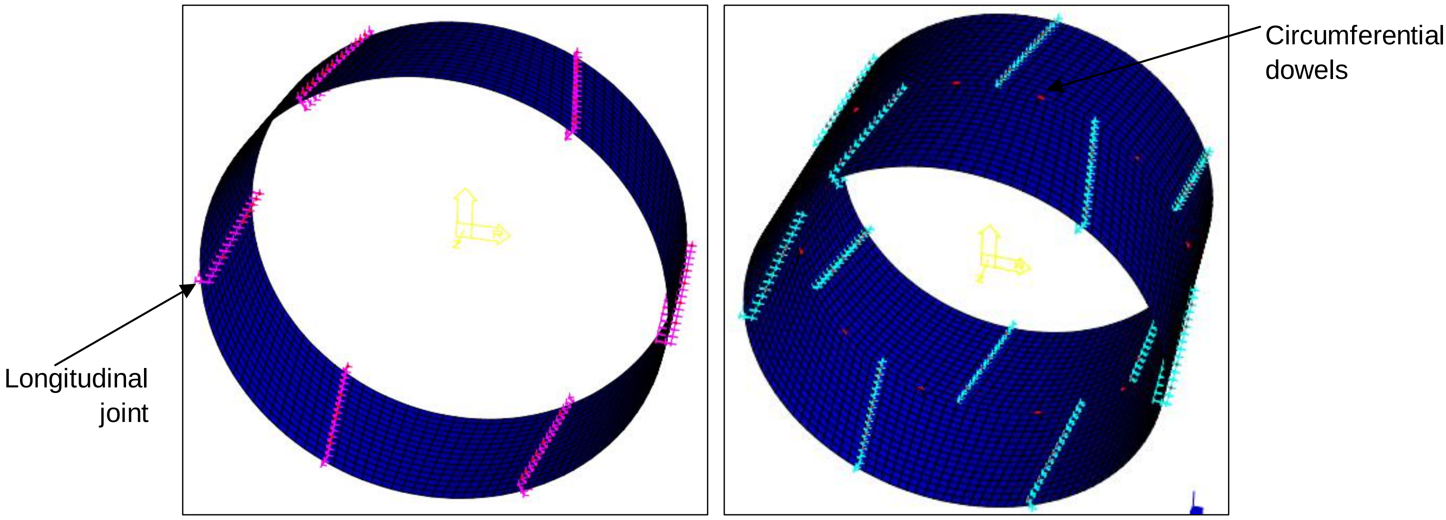

Figure 1 (a) 3D model of tunnel ring with tapered longitudinal joints (b) 3D coupled model

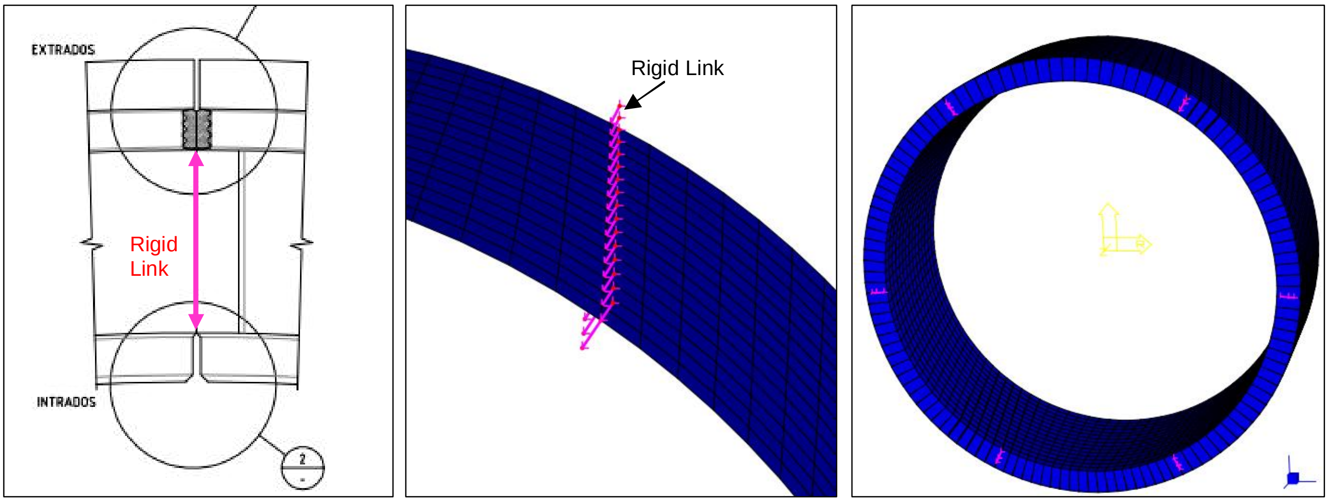

Figure 2 (a) Longitudinal joint (b) Rigid link used to model tapered joint (3) 3D solid model showing joint behaviour

The geometry of these segments incorporates a taper of 10^0 degrees along longitudinal joints. At the interface between adjacent segments, rigid links and contact elements have been used to model the action of joints permitted to pivot about the inner or outer edges of the joint bearing surface. The rigid links along each joint face extend perpendicular to the plate elements to either edge of the bearing surface. The links have been connected with compression-only springs to allow separation to occur and so allow joint rotation. Each compete ring consists of 2400 nodes, 287 beams, 1800 plates and 384 links elements.

The confinement provided by the rock has been modelled using face and edge support of plate elements as shown in Figure 3(a, b). These types of support resist lining movement in direct bearing and tangential shear across the grouted lining annulus. The stiffness of these springs was calculated using linear load deformation relationship according to Duddeck and Erdman [5].

$C_r = \frac{E_c}{R}$ [MN/m^3] and $k = C_r \times A$ [MN/m]

Where the constrained modulus is given by $E_c = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$ [MPa]

E, ν = Young's Modulus and Poisson's Ratio of the ground

R = equivalent tunnel radius

A = area of rock that is to be represented by the equivalent radial spring. This is the distance between adjacent radial springs multiplied by unit length.

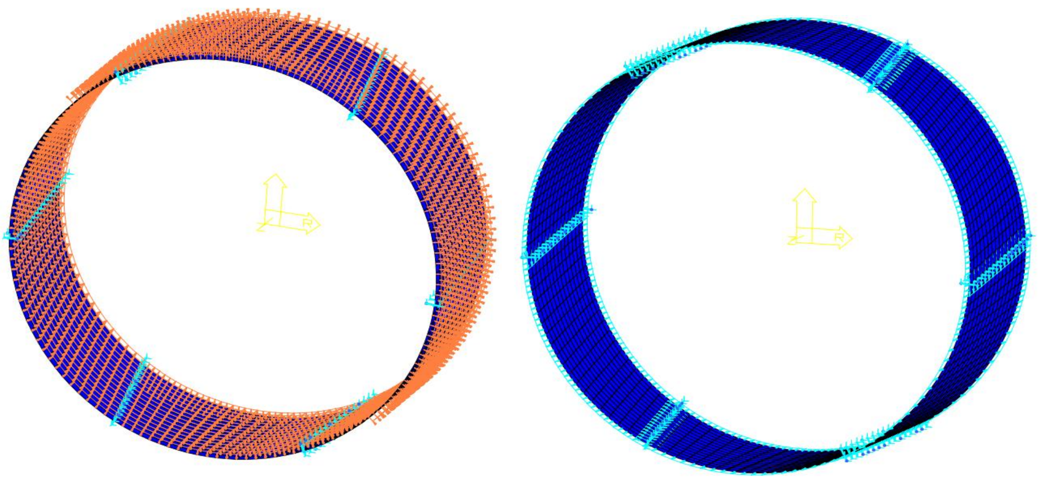

Figure 3 Confinement provided by rock (a) Face support (b) Edge support of plate element

The effect of ring coupling has also been investigated by by the introduction of a second ring which has been rotated by 60 degrees as shown in Figure 1(b). The presence of the circumferential dowels between rings has been included to assess the true interaction of adjacent rings. The dowels are simulated in strand7 by using special connection element, whose properties are provided in terms of translational and rotational stiffness.

5. Loading assessment

The analysis and design of the tunnel linings is driven by the types and combinations of long term loading assumed. These loadings assumed for the design of the segmental lining are described below. Short term loads imposed during construction were assessed during the design, but these and the associated capacity assessments are not discussed in this paper.

Long term loading of the lining, once installed, will come from the weight of any loosened rock that may be present immediately above the tunnels, external pressures imposed by groundwater and the pressures imposed by the injection of grout behind the lining. In the short term, sources of loading that can be applied to the segments during construction will come from their handling, stacking and installation. The following loads have been used to analyse and design the segmental tunnel lining.

5.1 Imposed ground loading

The tunnels are interpreted to align through a varying rock, including sandstone and mudstone/siltstone units. Critical loading was interpreted to be due to rock loosening triggered by deformation of the rock mass around the excavated tunnel opening. Mechanisms for this type of loading are governed by the presence of geological discontinuities, as well as the quality, strength and stiffness of the rock mass along the tunnel alignment. Loosened rock pressures have been determined based on Terzaghi's rock pressure theory. In calculating loosened ground loading, worst credible material parameters have been assumed to generate the highest expected loosened rock loading. This loading is assumed to be uniformly distributed across the full tunnel span

The height of the loosened rock zone as calculated using Terzaghi's rock pressure theory has been compared with the results of FEM modelling using Phase^2 software. Ground reaction curves have also been developed to assess the way in which load is shared between the tunnel lining and the surrounding ground. In the first instance an axis-symmetrical model was created. Figure 4(a) shows this model and the summation of the results from this modelling. From the model it was determined that over 90% of total convergence would occur prior to lining installation. The results from axis-symmetrical modelling results were noted to correlate with methods used to estimate loosened rock loading as described earlier.

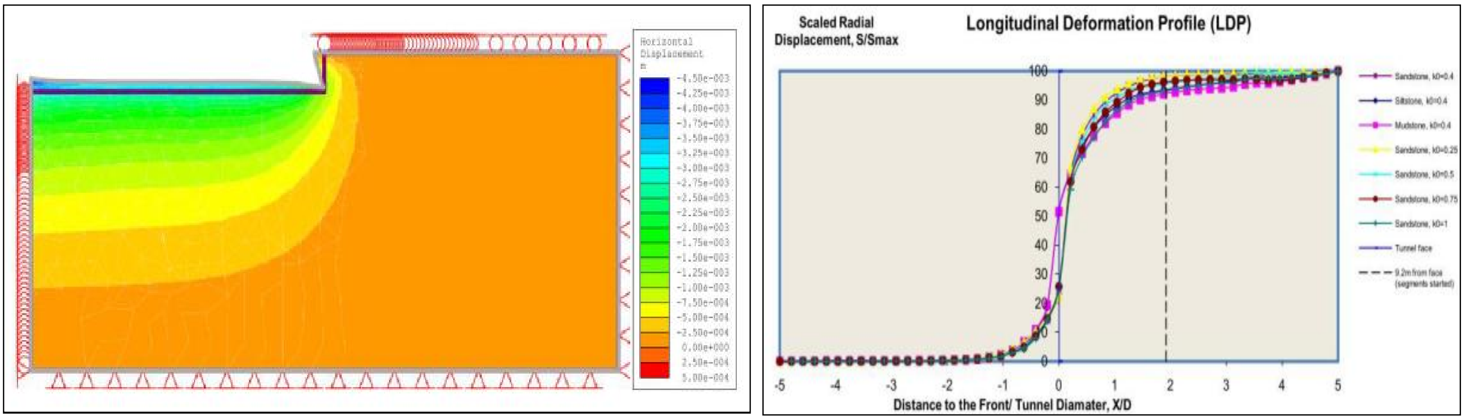

Figure 4 (a) Axisymmetrical modelling using Phase^2 software (b) vertical loading applied in 3D model

5.2 Imposed groundwater pressures

The precast segmental tunnel lining provides a fully tanked tunnel support solution. In this regard the lining has been designed to resist full water pressure. Pressures have been calculated to reflect true as expected conditions.

Uniform groundwater pressures were applied around the circumference of the lining and in all cases (operational and when dewatered) the groundwater exhibits a net external pressure. These pressures have the effect of confining the structural lining and so increases the lining ability to resist induced flexural actions, such as that caused by loosened ground loading. To ensure worst credible conditions have been accounted for, a loading combination reflecting 'dry' conditions was assessed in combination with a full hydrostatic case.

However, there are some loading combinations where the pressure exerted by groundwater has an overall adverse impact, such as when considering high axial loading in combination with the structural effects of tunnel non-circularity (as caused by build tolerances and non-uniform loading) For these cases the design hydrostatic pressure was considered and applied to the three dimensional model developed for the project.

The premise for applying full groundwater pressures is that there will be full hydraulic connectivity through the rock mass, such that water can migrate through geological discontinuities (e.g. jointing and faults) in the rock mass.

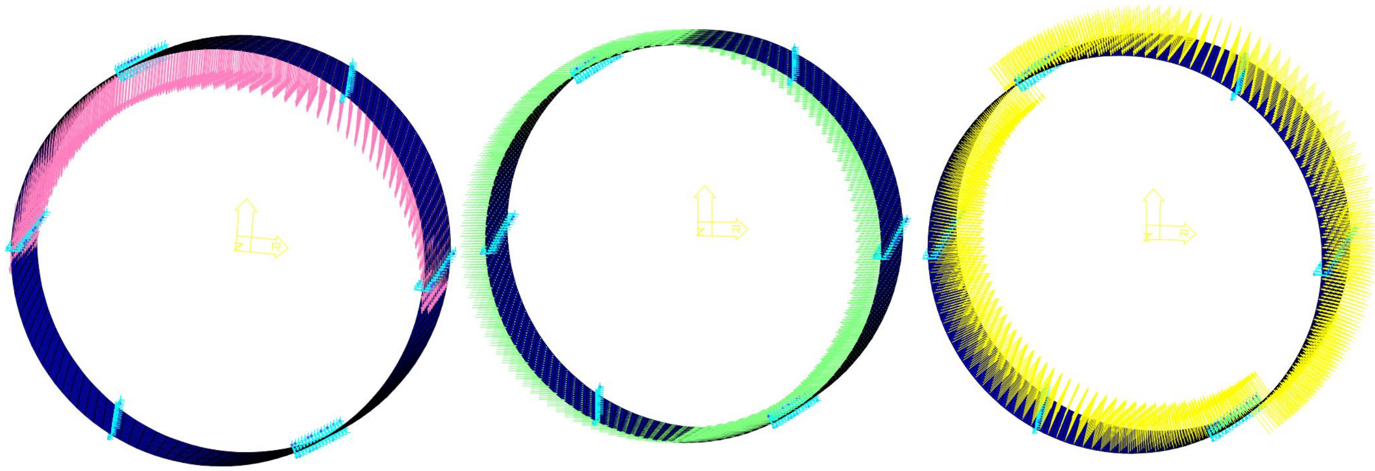

Figure 5 Applied loading in 3D model- (a) Vertical rock loading (b) Lateral pressure (c) Hydrostatic loading

5.3 Grouting pressure

Segmental linings are grouted in place. Grout is injected under pressure into the annulus created between the excavated profile and the outside of the lining.

These pressures can be locked-in with time and so remain around the outside of the lining once the grout has set. Maximum grout pressures are based on the assumption that grout pressures will be limited to 1 bar above prevailing water pressure. This water pressure is assumed to be equal to the full head of water overlying the tunnel alignment. A sensitivity analysis was conducted during the design process to assess the impact of varying the assumed locked in grout pressure

5.4 Loading combination

For the long term loading conditions the tunnel lining has been designed to provide sufficient capacity to resist worst case credible combinations of imposed loading applied along their entire lengths. Loads have been factored in accordance with the principles outlined in AS 1170 and AS 5100.5 to undertake structural assessment at ultimate and serviceability limit states.

6. Summary of results and discussion

Table 1 summarises the results from the three dimensional modelling undertaken. Figure 6 presents some resulting output from Strand7

Table 1 also provides a comparison with the results of various other traditional approaches employed during the design process, such as the use of closed form solutions and the two dimensional beam- spring approach.

In the case of the beam-spring approach, models where created which investigated a single ring (uncoupled) and models that, like the three dimensional approach, included two side-by-side rings (coupled). In the latter case rings were connected to replicate the presence of connecting dowels.

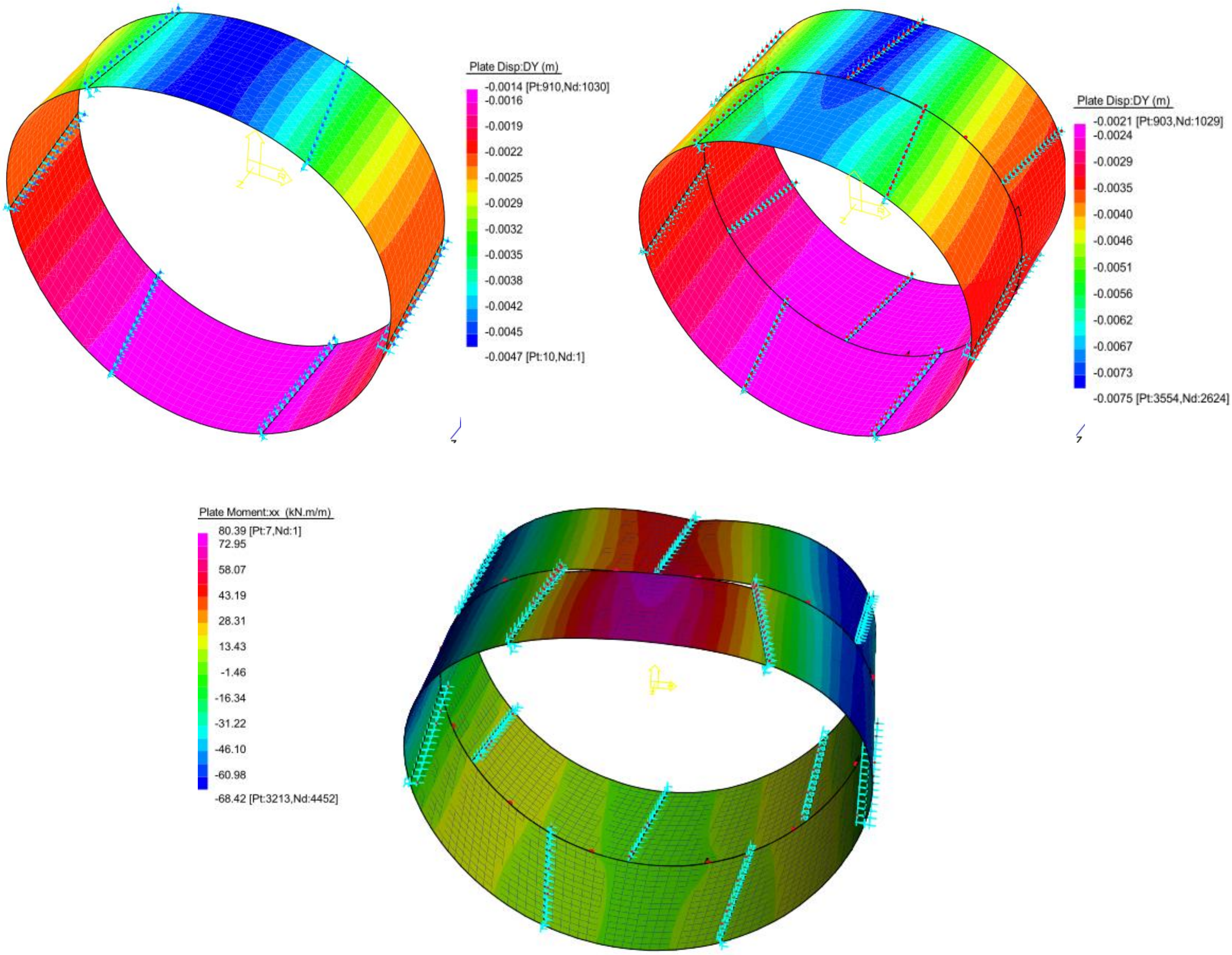

Figure 6 (a) Displacement vector in single ring (b) displacement vectors for coupled ring (c) Bending moment for coupled model [Exaggerated diagram]

Of particular note are the results from the coupled and uncoupled models, which indicates that the three-dimensional model predicts the presence of greater applied bending moments, as compared with the two dimensional approaches. This suggests that conventional analysis approaches underestimate these induced actions.

Also vertical displacement deformation for coupled models is calculated to be greater. This is thought to be due to the 'dragging down' effect of adjacent rings that have a different ring rotation.

Finally, the taper of longitudinal joints has an impact on the bending moments imposed to segments close to joints. The bending moment contours shown on Figure 6 (c) show a complex pattern that cannot be fully appreciated using two dimensional modelling techniques.

Table 1: Summary of results from long term structural modelling of lining

Description of analysis approach	**Bending moment (kNm/m)**	**Axial force (kN/m)**
Closed form solutions	41	775
2D bedded beam model (single uncoupled ring)	51	735
2D bedded beam model (two rings coupled)	62	748
3D plate element mode (single ring)	64	1084
3D plate element model (two rings coupled)	80	1065

7. Conclusions

In this paper a complex three modelling technique is described, which in the author's opinion predicts lining behaviour more accurately than conventional two dimensional methods, especially where tapered longitudinal joints are detailed. It can be seen from the results of analysis that induced bending moments applied close to longitudinal joints are affected by this taper.

Different methods of analysis have been undertaken in order to compare traditional closed form solution and 2D beam spring models with a more complex three dimensional approach. The results show that there are cases where the use of three dimensional methods is warranted to ensure that the segmental linings are designed to have sufficient capacity.

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