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Numerical calibration of mechanical behaviour of composite shell tunnel linings

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ABSTRACT

Composite shell linings consist of primary and secondary sprayed concrete linings separated by a layer of spray-applied waterproofing membrane. In order to design such a lining configuration, a calibrated numerical simulation approach is needed and the impact of interface properties on the composite mechanical behaviour should be understood.

A programme of laboratory tests was carried out on beam samples cut from composite shell test panels and subjected to four-point bending under short-term loading. A range of membrane thicknesses and substrate roughness were compared and composite mechanical behaviour quantification methods developed. The behaviour of composite beams was understood and the strain distribution across composite lining cross-section was identified.

A numerical model by the finite difference method was then set up for the beams and verified against the test data. With interface stiffnesses obtained from previous element tests, the composite beam model is capable of predicting the strain distribution across the cross-section and real behaviour of composite beam members to within an acceptable level of accuracy taking into account variations arising from workmanship. Sensitivity studies were carried out to understand the impact of interface properties and membrane interface position on the degree of composite action.

1. Introduction

Sprayed concrete lined (SCL) tunnel has seen rapid development over the last twenty years in the UK (Su, 2013). Three of these developments have been the inclusion of wet-mix sprayed concrete primary lining as part of the permanent load-bearing structure, the replacement of the traditional sheet membrane between the primary and secondary linings with a double bonded spray-applied waterproofing membrane and use of a wet-mix sprayed or cast in-situ concrete secondary lining. This innovative configuration is called a *composite shell lining* (CSL) and has recently been adopted in projects in the UK and other European countries (Pickett, 2013; Holter et al., 2010; Hasik et al., 2015) in soft ground of low permeability.

While the design of traditional SCL tunnels, consisting of sacrificial sprayed concrete primary lining, sheet waterproofing membrane and permanent cast in-situ concrete secondary lining, has become relatively mature and is backed with many successful case histories, the design of CSL is still at its infant stage. In most cases the CSL tunnels are designed as the *double shell lining* (DSL) tunnels, which is a similar lining configuration to CSL but assuming an unbonded (i.e. no tension nor shear but only compressive stiffness assumed) waterproofing interface sandwiched between the two layers of linings (Pickett, 2013). It has been claimed that, if composite action is considered in the design, the CSL could achieve 20–30% overall lining thickness reduction when compared with traditional SCL tunnels under the same ground conditions (Pickett and Thomas, 2011).

In order to achieve an efficient design for CSL tunnels, two issues need to be resolved: (1) understanding of the mechanical properties of the spray-applied membrane interface under realistic humidity conditions, and (2) a calibrated modelling methodology for simulating the composite mechanical behaviour of composite shell linings.

Research on the membrane interface material has been gradually providing understanding of its function and mechanical properties (Verani and Aldrian, 2010; Thomas, 2010; Nakashima et al., 2015; Su and Bloodworth, 2016; Holter and Geving, 2015; Holter, 2016), and its main findings will be discussed in the following section. This paper

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Abbreviations: SCL, sprayed concrete lined; CSL, composite shell lining; DCA, degree of composite action; DSL, double shell lining; EVA, ethylene vinyl acetate; FE, finite element; FD, finite difference

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focuses on the second issue on modelling methodology. Once the modelling methodology is validated, it can then be applied to a full CSL tunnel, with considerations of factors that are essential to CSL tunnel design such as soil-structure interaction, stage construction, *etc*. By doing so, it is expected that the general behaviour of CSL tunnels may be understood, a set of design principles derived and the CSL tunnel proved to be an efficient lining form.

In this paper, a set of laboratory flexural tests on CSL beams is presented and a numerical analysis methodology for simulating the composite mechanical behaviour of CSL is developed and calibrated against the flexural test results. A sensitivity study on the spray-applied membrane interface properties is undertaken to evaluate the impact of varying interface stiffness (caused by for example different types of membrane, impact of different temperature or humidity conditions, or long-term creep effects) and membrane interface position on the composite mechanical behaviour of CSL beams. A unified parameter, 'degree of composite action' (*DCA*), is developed to quantify the composite mechanical behaviour of laboratory tested and numerically modelled CSL beams.

2. Technical background

For tunnelling waterproofing purposes, there are currently two types of spray-applied membrane: Ethylene-Vinyl-Acetate copolymer (EVA) based products and methyl methacrylate resin based products. The membranes discussed in this section, used in the following described laboratory composite beam tests and to calibrate the numerical model, are all EVA-based products.

Until now there has been limited literature published on the laboratory testing or numerical analysis of composite mechanical behaviour for CSL tunnels.

Verani and Aldrian (2010) reported three-point bending tests on a pure sprayed concrete and a composite beam with spray-applied waterproofing membrane sandwiched half-depth under ambient laboratory climate conditions (e.g. 15–20° in temperature and 40–60% relative humidity), showing the composite beam had 50% of the peak flexural strength of the pure sprayed concrete beam, but greater residual flexural strength. Thomas (2010) analysed a CSL tunnel to obtain load-sharing ratios between the linings with interface shear stiffness varied between a full-slip (non-composite action) to a non-slip (fully-composite action) case, and pointed out that the CSL tunnel lining should be partially composite if realistic membrane interface stiffnesses are used. Nakashima et al. (2015) presented flexural test results on two CSL beams with and without axial force again under ambient laboratory climate conditions. For a beam tested without axial force, although the strains and midspan deflections did not match theoretical values for a fully-composite beam, the authors nevertheless concluded that the CSL beams were fully composite and that there was a problem with the strain measurement. In fact, the CSL beams were only partially composite and would be expected to have larger deflections and different strain distributions compared to sprayed concrete beams under the same loading.

Su and Bloodworth (2016) carried out a comprehensive laboratory testing programme on element specimens cut from CSL sprayed panels with different primary lining substrate surface preparations and membrane thicknesses, loaded in compression, tension and shear under ambient laboratory climate conditions. The impacts of substrate surface preparation and membrane thickness on the interface parameters were investigated.

All the above reported laboratory tests were carried out on samples that were essentially 'dry', i.e. were being tested under ambient laboratory conditions without the samples being in contact with or immersed in water such as might be the case if a crack in a primary lining in water-bearing ground led to water contacting the extrados of the membrane. Field measurements by Holter and Geving (2015) on a rock SCL tunnel with spray-applied waterproofing found the moisture content of the membrane to vary between 30% and 40%, determined by the moisture properties of the concrete and the membrane, as well as the interfaces between the two materials. Further research by Holter (2016) suggested that high moisture content in the EVA-based polymer membrane may affect its mechanical properties, e.g. reduce its tensile strength. More research is needed on this topic, particularly to quantify the membrane moisture content in soft ground applications of CSL and then to go on to obtain the membrane mechanical properties under those conditions. In the meantime, the main purpose of this paper is to provide a calibrated numerical modelling methodology for simulating the composite mechanical behaviour of CSL tunnels. The calibration of the model is from laboratory tests in ambient conditions, which is understood do not relate to completely realistic in-situ conditions. However, once the calibration of the model is done, the model is used in a parametric study to investigate the effect on the behaviour of composite beams of varying of interface parameters such as membrane stiffness that are known from the research carried out by Holter (2016) to be a function of membrane saturation.

3. Composite mechanical behaviour

CSL beams consist of two layers of component beams, representing the primary and secondary linings, and a sandwiched layer of membrane interface. The stress and strain distributions through the cross-section will depend on the degree of composite action, as shown in Fig. 1. As this reduces from fully-composite to non-composite, neutral axes for each component beam move away from the membrane until they reach half-depth of each component. Applying Euler-Bernoulli beam theory with an assumption of linear elastic behaviour, the lower the degree of composite action, the lower the moment (calculated from the stress blocks) for a given deformation (curvature), and hence the lower the flexural stiffness of the lining.

The *DCA* may be quantified based on beam deflection as follows (Frankl et al. 2011):

$$DCA = \frac{k_{comp} - k_{non}}{k_{full} - k_{non}} \tag{1}$$

where k_{comp}, k_{non} and k_{full} are equivalent flexural stiffness of the composite, non-composite and fully-composite beam respectively under

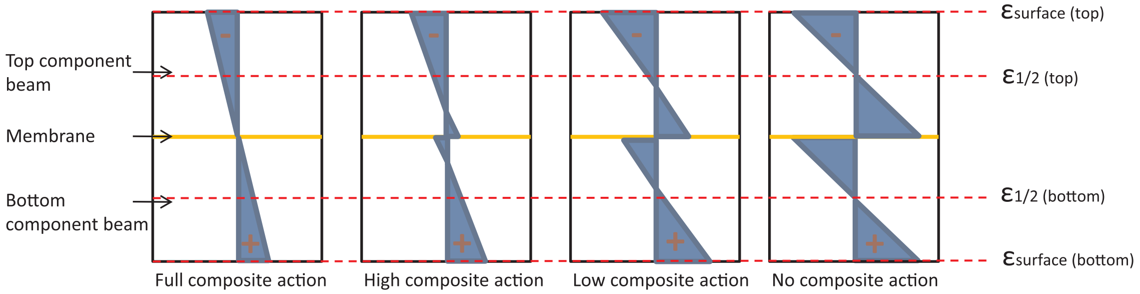

Fig. 1. Stress and strain distributions through linings for different degrees of composite action assuming linear elastic behavior.