Sprayed concrete composite tunnel lining – load sharing between the primary and secondary lining, and its benefit in reducing the structural thickness of the lining.

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ABSTRACT: Compression core tests and flexural beam tests have been carried out using sprayed waterproof membrane sandwiched samples to obtain shear strength parameters at the sprayed waterproof membrane interface. These are inputted into LS-DYNA software to model realistic load sharing behaviour of a composite lining structure. This paper presents the findings and observations in load sharing between the primary and the secondary lining when composite action is considered in lining design.

1 INTRODUCTION

Traditionally, when sheet membranes are used, no bond has been assumed across waterproof membranes installed between tunnel primary and secondary linings, and any structural benefit of the primary lining has been ignored for the design of the secondary lining.

Spray-applied membranes offer the opportunity to take into account some bond between the two linings, producing a composite action. The composite action allows the designer to consider the primary and secondary lining as a single composite structure, meaning the structural benefit from the primary lining is no longer ignored. There is a possibility to reduce the secondary lining thickness, which can lead to thinner total lining thicknesses, with associated benefits for settlement, cost and programme. This composite lining design concept has been discussed and agreed in the tunneling industry throughout the last couple of decades, but there is not enough published technical information which designers can reference, especially that which quantifies the lining thickness reduction potential.

This paper first presents details of how the shear strength parameters at the waterproof membrane interface were interpreted and calibrated from a series of core and beam tests, and then goes on to show observations in load sharing between the primary and secondary linings from LS-DYNA finite element analysis results when composite action is considered in lining design.

2 TEST SAMPLE FABRICATION

2.1 Lining configurations

Two types of laboratory tests were carried out to investigate the failure behaviour of a composite lining at the waterproof membrane interface. These were:

- Cylindrical cores with the waterproof membrane orientated at various angles to the vertical (45°, 55° and 70°) to test in compression to understand shear failure behaviour;
• Beam samples with the waterproof membrane layer at the mid-depth of the beam to test in bending to understand flexural failure behaviour.

All samples were prepared in a laboratory from bespoke test panels with the waterproof membrane sandwiched between layers of steel fibre reinforced concrete. One of the aims of the testing was to understand the effect that different lining configurations could have on lining structural behaviour as a composite, therefore different configurations were prepared and tested; these are detailed in Table 1.

Table 1. Lining configuration details for testing

<table>
<thead>
<tr>
<th>Lining Configuration</th>
<th>Details *</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>P-S</td>
</tr>
<tr>
<td>C2</td>
<td>P-R-M-S</td>
</tr>
<tr>
<td>C3</td>
<td>P-M-S</td>
</tr>
<tr>
<td>C4</td>
<td>P(cast in-situ)-M-S(cast in-situ)</td>
</tr>
</tbody>
</table>

* P: Primary lining, R: Regulating layer (a layer of sprayed concrete which does not have steel fibre reinforcement), M: MasterSeal 345, S: Secondary lining

The testing of both sprayed and cast primary and secondary linings was carried out to determine the effect that the lining installation method could have on the composite action.

2.2 Materials

2.2.1 Concrete mix
The sprayed concrete mix used for this research is summarized in Table 2. Special hydration control admixtures and superplasticizers were used to get the required open time for the mix. An alkali free accelerator MasterRoc SA160 was used at the nozzle during spraying of the panels.

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity kg per m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I</td>
<td>455</td>
</tr>
<tr>
<td>Limestone 0-4mm</td>
<td>1226</td>
</tr>
<tr>
<td>Limestone 2-6mm</td>
<td>238</td>
</tr>
<tr>
<td>Filler</td>
<td>28.5</td>
</tr>
<tr>
<td>Microsilica</td>
<td>30</td>
</tr>
<tr>
<td>Steel fibre</td>
<td>45</td>
</tr>
<tr>
<td>MasterRoc HCA</td>
<td>1.4</td>
</tr>
<tr>
<td>MasterRheobuild</td>
<td>8.4</td>
</tr>
<tr>
<td>Water</td>
<td>205</td>
</tr>
</tbody>
</table>

2.2.2 Regulating layer
The regulating layer used was the MasterRoc STS 112 with a thickness between 10-20mm. It is a polymer-modified fine concrete and it contains fumed silica, high range water reducing admixtures and carefully graded aggregates.

2.2.3 Sprayed waterproofing system
The sprayed waterproofing system used for this testing is MasterSeal 345. The basic raw material of sprayed waterproofing system is a re-dispersible EVA (Ethylene Vinyl Acetate) polymer. An EVA is an organic polymer and contains selected fillers which contribute to the long term behavior and curing mechanism. The MasterSeal 345 is vapour permeable and typical material properties are: a) bond strength to concrete approx. 1.2 MPa, b) tensile strength 1.5~3.5 MPa, and c) elongation 100%.

2.3 Test panel fabrication and curing
The test panels were sprayed at the Tunneling and Underground Construction Academy in London using various Meyco robotic pump systems. The waterproof membrane was sprayed using a dry mix pump. Quality control measures were carried out on the concrete and the waterproof membrane including slump and curing testing. The thickness of the waterproof membrane was ensured to be 3-4mm coverage.

For cast concrete, a timber board was used to screed off the top of the concrete and the temperature of the concrete ranged from 19°C to 28°C (temperature range quite high due to casting at different times of the year). The cast samples were tamped rather than vibrated.

After production of sprayed and cast panels, the panels were not moved or disturbed in the first 24 hours and they were stored at a temperature of +20°C (±5°C), were covered by a polythene sheet and were not exposed to direct sunlight until the time of coring.

The test sample preparation programme was defined to leave 14 day lapses between spraying layers, and 28 day or 90 day curing times following the last concrete layer covering the waterproof membrane.

2.4 Test sample preparation

2.4.1 Core sample preparation
The core samples were obtained from the cured test panels using a coring rig which could be
orientated at various angles to the vertical. The core samples were 116mm long and 58mm diameter, giving a 2:1 ratio. Once cored, the cores were stored immersed in water with tape around the waterproof membrane. The cores were packed to reduce moisture loss in transit to the laboratory in Switzerland. The cores were squared off in the laboratory and were capped with a compound based on a Sulphur cement in order to have the surfaces flat and parallel to each other. The test samples ready for testing were stored in 20°C and 65% relative humidity, with the extremity of the primary lining immersed in water to simulate saturation due to ground contact to emulate a tunnel environment.

2.4.2 Beam sample preparation
The beam test samples were cut from the panels to be 150x150x560 mm. This was done using a digitally controlled diamond beam saw. The cut beams were then stored in water at 20°C +/- 2°C before being tested.

3 TESTING

3.1 Core testing
A strain controlled compression test was adopted to obtain a full stress-strain relationship beyond the failure point. The core testing was specified to be carried out at a slower test speed than the standard compression core test developed for hardened concrete cores such as BS EN 12390-3:2009. This is due to the fact that in reality, when a tunnel lining is subject to a change in loading condition, the lining will deform over a time scale of hours or days. A standard concrete core test would last only for a few minutes so would not be able to represent the correct shear failure behaviour at the concrete and membrane interface.

A rate of 0.005mm/minute was specified and a maximum test time of 18 hours (for practicality); this gave a limit to displacement of 6mm, which was judged to be sufficient to capture the peak and post-peak stress-strain behaviour of the samples.

A machine with an electric spindle drive was used for the compression testing and the force-deflection curve was measured throughout the test. The displacement was measured indirectly in the force load cell of the machine and therefore post processing of the force-deflection data was done to remove deflection considered to be due to the testing equipment.

3.2 Beam testing
The beam samples were tested according to the European standard EN 14651. A notch of 25 ± 1 mm, with a thickness ≤ 5 mm, was created in the middle of every water proof membrane sandwiched beam. Around the notch a CMOD (crack mouth opening displacement) gauge was installed to check the widening of the notch and to obtain data during the test.

The flexural tensile strength values determined from the load-CMOD curve were obtained by applying a centre-point load on a simply supported notched beam. The CMOD was measured by the transducer installed on the beam subjected to the centre-point load.

4 CORE TEST RESULTS ANALYSIS

4.1 Failure Zone concept
In modern SCL lining design, the design verification is now widely carried out using commercial FE analysis. Thus, developing a simple and easy FE modelling technique that can reflect actual composite action between the primary and secondary lining interface (interface hereafter) is important for the advance of composite shell lining design practice. However, there are many individual factors that affect the failure behaviour at the concrete and the sprayed waterproof membrane interface such as direct bond strength between concrete and waterproof membrane, surface undulation of concrete, and tensile strength of the waterproof membrane itself. It would be very challenging to model all those factors separately at the concrete-membrane interface. And, even if an interface model is developed that considers all those factors, it would be too complicated to be used by the tunnel designer in tunnel lining design practice.

The core tests presented in this paper showed typical strain softening behaviour which indicates that the sprayed waterproof membrane interface’s strength parameters may be able to be represented as a simple constitutive model.
Thus, a failure ‘zone’ concept is introduced (see Figure 1) which makes modelling the concrete-membrane interface simple and straightforward. The results of the compression core testing were therefore interpreted to determine shear strength parameters of the failure ‘zone’.

The key engineering characteristics that govern the failure zone’s behaviour are considered to be bond and roughness at the interface. Thus, the Mohr-Coulomb constitutive model – which is represented by cohesion and friction – is adopted to model the failure zone.

### 4.2 Mohr-Coulomb strength parameters of the failure zone

The force-deflection data was processed to determine the normal and shear stresses on the failure zone, depending on the angle to the vertical of the test sample. A typical stress-strain graph is shown in Figure 2 for C2 with the membrane interface at 45° to the vertical.

<table>
<thead>
<tr>
<th>Peak angle of friction, φ°</th>
<th>Cohesion, c, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>11.6</td>
</tr>
<tr>
<td>All JRC &lt;12</td>
<td>10.4</td>
</tr>
<tr>
<td>All JRC &gt;12</td>
<td>11.7</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>11.0</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>13.7</td>
</tr>
<tr>
<td>Sprayed Cores only</td>
<td>12.1</td>
</tr>
<tr>
<td>Configuration 4 (Cast Cores)</td>
<td>11.4</td>
</tr>
</tbody>
</table>

The plot in Figure 3 shows the Mohr-Coulomb parameters obtained from the core test results with comparing the joint roughness coefficient (JRC) ‘high’ (≥ 12) to ‘low’ (<12). The ‘high’ JRC results give slightly higher peak φ’ and c’ values, as expected.

The plot in Figure 4 shows the Mohr-Coulomb parameters comparing the cast to sprayed sample.

This typical stress-strain curve indicates post peak strain softening behavior. As the failure zone is not homogenous, the typical stress-strain curves of core samples didn’t show clear peak failure points. Thus the ‘peak’ normal and shear stresses were determined based on where the stress-strain graphs showed a change in gradient which is considered as an initial failure point.
sprayed sample results. The cast results show slightly lower peak angle of friction and cohesion results, due to the smooth interface achievable when the concrete is cast. The difference is small, however, indicating that the construction method does not largely affect the strength parameters of the interface zone.

The Mohr-Coulomb strength parameters of the interface zone found are summarized in Table 3. The result for C2, sprayed with a regulating layer, are slightly lower than that for C3 without. This indicates that the regulating layer may have a smoothing effect to the interface, reducing the friction angle values.

The average parameters for the sprayed samples are selected for use in the numerical modelling, since the primary lining is sprayed in real tunnels.

4.3 Shear modulus

The values of pre-failure shear modulus, G, obtained from the core tests were plotted on a histogram of values across the results, this is shown in Figure 5. The data is shown to follow an F-distribution.

To calculate an average value of pre-failure G, the ‘reliable’ data limit was set to 15MPa, by engineering judgment not to overestimate the G value at the interface. This gave a result of average G=7.0MPA which was adopted for the numerical modelling work.

5 NUMERICAL MODELLING

5.1 Software and model set up general

LS-DYNA software was selected for the numerical analysis in this study. LS-DYNA can model the steel fibre reinforced concrete (SFRC) material using the Winfrith non-linear...
constitutive model (Broadhouse, 1995), and it is also capable of modelling very fine meshes (3-5mm thick mesh) that are required to model the membrane interface element of the failure zone. The membrane interface was modelled with a modified Mohr-Coulomb constitutive model in which post peak softening behavior was accounted for by allowing the $\varphi'$ and $c'$ to change with plastic strain.

The constitutive models used for the numerical analysis are summarized in Table 4.

Table 4. Constitutive models used for analysis

<table>
<thead>
<tr>
<th>Elements</th>
<th>Constitutive models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel lining (SFRC)</td>
<td>Winfrith non-linear</td>
</tr>
<tr>
<td>Interface element between primary and secondary lining</td>
<td>Mohr-Coulomb with strain softening</td>
</tr>
<tr>
<td>Ground</td>
<td>London Clay - BRICK soil model</td>
</tr>
<tr>
<td>Others - Mohr-Coulomb</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Model calibration analysis

5.2.1 Core test calibration
To verify the adequacy of the interface modelling, laboratory core tests carried out for the waterproof membrane sandwiched cores were repeated for three different interface angles 45°, 55° and 70° using LS-DYNA with the use of the interpreted Mohr-Coulomb strength parameters of the interface (model shown in Figure 6). The calibration analysis results are superimposed over the core test data in Figures 7 to 9.

5.2.2 Beam test calibration
As deformation in a tunnel lining is dominated by flexural bending, additional calibration analyses were performed using the notched beam test results earlier mentioned. Similar to the core calibration analysis, an SFRC-only beam model was calibrated to verify the SFRC constitutive model inputs, and then the main calibration analysis for the spray waterproof membrane sandwiched beam was performed.

Figure 10 illustrates the beam analysis model developed for this analysis, and Figure 11 shows the calibration analysis results of SFRC-only beams which confirms a good match to the beam test data.

Figure 12 shows the calibration analysis results of the waterproof sprayed membrane sandwiched beams which give a good match with the test results. The calibration analysis
results indicate that the interface model used in the numerical analysis is valid.

One important observation from the beam test results is that the waterproof sprayed membrane bond is bridging the crack, so the post peak failure behaviour of the SFRC beam changes from strain-softening to strain-hardening as can be seen by comparison between Figure 11 and Figure 12.

### 5.2.3 Tunnel section analysis

A series of numerical analyses were carried out using a real 10m diameter railway platform tunnel section profile constructed in London. Ground conditions were assumed as London Clay overlain by Terrace Gravel and Made Ground. Figure 13 shows the tunnel analysis model with the interface detail between the primary and secondary linings. The primary and secondary lining thickness are 260mm and 280mm respectively.

The analysis stages were simplified to help straight forward interpretation of the results in respect of load sharing between the primary and secondary linings. To eliminate the complexity that would be caused from divided excavation (e.g. top heading, bench and invert division), a full face excavation is also assumed for this study.

Both ground and hydrostatic water pressures have been modelled as permanent loading. It is assumed that the groundwater pressure is always applied to the extrados of primary lining because the tight bond between the primary lining and the waterproofing layer will limit the water pressure development through the interface layer.

The analysis stages applied to the numerical analysis are summarized in Table 5 and Figure 14. \( \lambda_1 \) is the stress relaxation ratio to the ‘full undrained ground loading’ at each stage of the analysis until the primary lining is constructed. In this paper, \( \lambda_1 \) is assumed as a constant value of 40%.

The stress relaxation ratio for Stage 4, is set as \( \lambda_2 \). \( \lambda_2 \) is influenced by many factors such as ground conditions, time interval between the construction of primary and secondary lining, etc. Thus, a series of analyses were carried out varying \( \lambda_2 \) to see the influence of \( \lambda_2 \) on the load sharing characteristics between the primary and secondary linings. \( \lambda_2 \) could be in the range between zero and \((1-\lambda_1)\) in theory. If \( \lambda_2=1-\lambda_1 \), then it means 100% of ground load is released before the secondary lining is installed.

The tunnel section numerical analysis was carried out for three different interface conditions between the primary and secondary

<table>
<thead>
<tr>
<th>Analysis stages</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initialization</td>
</tr>
<tr>
<td>2a</td>
<td>Dummy stage to obtain forces (F) from tunnel void nodes</td>
</tr>
<tr>
<td>2</td>
<td>Apply force relaxation by 0.4F (( \lambda_1 ))</td>
</tr>
<tr>
<td>3</td>
<td>Install primary lining</td>
</tr>
<tr>
<td>4</td>
<td>Apply force relaxation further by 0F, 0.2F and 0.4F (( \lambda_2 ))</td>
</tr>
<tr>
<td>5</td>
<td>Install secondary lining</td>
</tr>
<tr>
<td>6</td>
<td>Remove all remaining forces</td>
</tr>
<tr>
<td>7</td>
<td>Long term</td>
</tr>
</tbody>
</table>

Figure 13. Tunnel analysis model

![Figure 13. Tunnel analysis model](image)

Figure 14. Numerical analysis stages with stress relaxation
linings; these were a) full slip, b) composite, and c) full bond. The analysis cases are summarized in Table 6.

<table>
<thead>
<tr>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>Interface condition between linings*</th>
</tr>
</thead>
<tbody>
<tr>
<td>40%</td>
<td>0%</td>
<td>FB, C, FS</td>
</tr>
<tr>
<td>20%</td>
<td></td>
<td>FB, C, FS</td>
</tr>
<tr>
<td>40%</td>
<td></td>
<td>FB, C, FS</td>
</tr>
</tbody>
</table>

* FB: Full Bond at the interface (virtual condition)
  C: Composite represents sprayed membrane interface
  FS: Full Slip represent sheets membrane interface

6 ANALYSIS RESULTS AND OBSERVATIONS

6.1 Structural integrity at the interface
To allow designers to adopt the composite action theory for tunnel lining design in the permanent condition, it is crucial to demonstrate that the bond created by the sprayed waterproof membrane at the interface between the primary and secondary linings does not damage under the permanent loading condition. When the tunnel is loaded, the primary and secondary lining would deform together, but the relative normal and shear displacement of the two lining layers at the interface would not be exactly the same as the interface is bonded by a thin sprayed waterproof layer. The likely failure mode at the interface when the tunnel is being loaded is assumed as a shear or tension failure. As noted earlier, the interface is modelled as a Mohr-Coulomb element with the input strength parameters interpreted from the lab core tests.

Analyses indicate that the maximum shear stress developed in the sprayed membrane in all cases is less than 105kPa which is much smaller than the shear capacity of the membrane. Thus it can be concluded that the sprayed waterproof layer is unlikely to be damaged from the differential movement (normal and/or shear) between the primary and secondary lining.

Durability such as degradation of materials over time is outside of this study’s objectives, so no special considerations are made as a part of this study.

6.2 Load sharing from composite action
The comparison of the calculated bending moment of the primary and secondary linings for $\lambda_2$=zero and 40% cases outlined in Table 6 are presented in Figures 15 and 16. As expected, in all three load cases, with the full slip the bending moment in the primary lining is much higher than the cases with full bond and
comprise. This is because the secondary lining shares some load with primary lining for composite and full bond case.

It was expected, in the composite lining, that the calculated bending moment in the primary lining had to be somewhere between the predictions with the full slip and the full bond linings. The analysis correctly predicted this for the primary lining as can be seen from Figures 15 and 16.

For further review of the load sharing trend, Figure 17 is drawn by extracting the maximum bending moment value at the knee location of the lining (i.e. approximately 135deg to 140deg location from the crown) from the analysis results.

In the full slip case, analysis result show that primary lining is taking all the load and not sharing any meaningful load with the secondary lining. This is because the secondary lining is detached from the primary lining thus the secondary lining is in a situation like ‘floating’ inside of the primary lining. So no further detailed review of the full slip analysis case has been carried out.

On the contrary, for both the composite and full bond cases, the load sharing mechanism is clearly observed from Figure 17. The primary lining bending moment is significantly reduced from the full slip case, because the secondary lining is contributing as a structural member by sharing load with the primary lining. It can be seen from Figure 17 that the secondary lining’s bending moment is approximately 50% level of primary lining’s bending moment as a minimum for the composite and full bond cases.

When the primary lining bending moment is compared between the composite and full bond cases, it can be seen that the composite cases’ bending moment is always greater than the full bond case. This is because the load sharing contribution of the secondary lining is different - full bonded secondary lining shares more load than the composite case, thus it leaves less load on the primary lining.

![Figure 16.Bending moment in tunnel lining from LS-DYNA analysis results, When \( \lambda_1=40\% \), \( \lambda_2=40\% \)](image)

![Figure 17. Load sharing comparison chart](image)
It is interesting to see the secondary lining bending moment between the composite and full bond cases. As mentioned earlier, since the full bond case is more capable to transfer load to the secondary lining, it is expected to have higher bending moment in the full bond case. However, the result shows that the bending moment of the composite case is greater than the full bond case. The reason for this requires further study, but one of the possible reasons currently being considered is due to the radial compression of the waterproof membrane layer which may allow the secondary lining to bend slightly more than the full bond case where there is no compressible material between the two lining layers.

Another interesting finding on the load sharing trend is from the change of $\lambda_2$ value. It is important to highlight the meaning of the $\lambda_2$ factor. When $\lambda_2=0$, it represents a case where no relaxation of ground load is occurring between the primary and secondary lining construction, i.e. the secondary lining is installed immediately after the primary lining construction. Thus, when the $\lambda_2$ value increases, it means that the time delay between the primary lining construction and the secondary lining construction is increasing.

From Figure 17, it can be seen that the secondary lining is sharing more load when $\lambda_2$ value is smaller – i.e. when the secondary lining is installed at earlier stage. This trend is repeated for the full bond case. This indicates that the earlier construction of the secondary lining would increase the utilisation of the secondary lining’s load sharing capability.

7 CONCLUSION

Uniaxial compressive stress tests performed on cores of SFRC with sprayed waterproof membrane showed a strain softening behaviour. The membrane interface is modelled using a Mohr-Coulomb model with conventional shear stiffness parameter such as $G$. The failure behaviour of the membrane interface was reasonably reproduced in the LS-DYNA finite element model.

From the core test results, it is observed that the construction method of lining gives little impact to the membrane interface’s strength parameters. However, the authors found that the size of samples used in this study may be not large enough to represent the scale effects – such as the relative size of the sample to the undulation of the spayed surface. A further study on this subject will be required.

From the beam tests, it is found that the waterproof sprayed membrane bond bridges the cracks developing in the concrete, so the post peak failure behaviour of the SFRC beam changes from strain-softening to strain-hardening.

Numerical analyses results indicate the maximum shear stress developed in the membrane interface is much smaller than the shear capacity of the membrane interface. Thus it can be concluded that the sprayed waterproof layer is unlikely to be damaged from the differential movement between the primary and secondary lining.

This study revealed that the use of sprayed water proof membrane makes the primary and the secondary lining work as a composite lining, and the load sharing between the primary and the secondary lining is achieved effectively. The parametric study showed that the magnitude of load transfer to the secondary lining becomes greater when the time interval between the construction of the primary lining and the secondary lining decreases.

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REFERENCE


European Standards 2005. Test Method for Metallic Fibre Concrete, Measuring the Flexural Tensile Strength (Limit of Proportionality (LoP), Residual). CSN UNI EN 14651