Original citation:
Su, Jiang and Bloodworth, Alan G. (2014) Experimental and numerical investigation of composite action in composite shell linings. In: 7th International Symposium on Sprayed Concrete, Sandefjord, Norway, 16–19 Jun 2014. Published in: Proceedings 7th International Symposium on Sprayed Concrete ; Modern Use of Wet Mix Sprayed Concrete for Underground Support, Sandefjord, Norway, 16–19 June 2014 pp. 361-374.

[7th] INTERNATIONAL SYMPOSIUM ON SPRAYED CONCRETE – Modern Use of Wet Mix Sprayed Concrete for Underground Support
– Sandefjord, Norway, 16. – 19. June 2014

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF COMPOSITE ACTION IN COMPOSITE SHELL LININGS

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Composite shell linings, consisting of a layer of permanent sprayed concrete primary lining, a layer of spray applied waterproofing membrane and a layer of sprayed or cast secondary lining, represent the latest development in the tunnelling industry. While demand for these linings is increasing, there are still some unknowns associated with their design. One of the biggest areas of uncertainty is the extent of composite action in the interfaces between the waterproofing membrane and the primary and the secondary linings. A research programme is in progress at the University of Southampton, UK, to investigate the behaviour of composite shell tunnels, focusing on the interfaces' properties.

Short-term four-point bending tests have been carried out on beam samples cut from panels built up from a sprayed primary layer, spray applied waterproofing membrane and sprayed secondary layer with different interface finishes. The test results, including vertical displacements, horizontal strains and beam end relative displacements, of composite beams with different interface thickness and roughness are reported and compared. A composite action quantification method has been developed and is applied to the tested beams. The results show that a significant degree of composite action can be achieved by the composite beam with sprayed applied waterproofing membrane.

INTRODUCTION

Sprayed concrete lined (SCL) tunnelling has seen rapid development over the last twenty years in the UK. Two of these developments have been the inclusion of primary linings as part of the long term structural element and the replacement of the traditional sheet membrane with the innovative spray applied waterproofing membrane. Previously, due to lack of understanding of the interface properties, no adhesive and shear bond was assumed at the sprayed concrete-membrane interfaces, for which the design option was called double shell lining [1]. Recently, the tunnelling industry is calling for further investigation into the composite action at the sprayed concrete-membrane interface, which would allow the adhesive and shear bond at the interface to be considered during the SCL tunnel design, leading to a reduced overall lining thickness.

A research programme is in progress at the University of Southampton, UK, to investigate the behaviour of composite shell lined tunnels. As part of a comprehensive testing programme, short-term tension and shear tests were carried out on samples cut from composite shell test panels and the results have been reported previously [2]. Following that, a series of short-term four-point bending tests have been carried out on samples cut from the same composite shell test panels. This paper will report some of the four-point bending test results, referring to the spray applied waterproofing membrane TamSeal 800 supplied by TAM International/Normet UK Ltd. A composite action quantification method will also be introduced and used for the evaluation of four-point bending test results.

TEST SAMPLES

The procurement of testing samples has been introduced in a previous paper [2]. All testing samples were described according to the interface finish and membrane thickness. Thin membrane (2-3mm) with smooth, regulated and as-sprayed interface finishes were designated Type 1, 2 and 3 respectively. Thick membrane (>3mm) with smooth, regulated and as-sprayed interface finishes were designated Type 4, 5 and 6 respectively. Pure sprayed concrete beams without sprayed applied waterproofing membrane were designated Type 7.

A series of beams, consisting of five composite beams and one pure sprayed concrete beam, were tested. The dimensions of each beam are shown in Table 1 below. It should be noted that, while the thicknesses reported for the beams with smoothed interface finishes are the accurate values, the thicknesses for beams with regulated and rough interface finishes are the best approximations from the measurements.

Table 1 Dimension of tested beams

Beam number	Membrane thickness (mm)	Interface type	Thickness of top beam (mm)	Thickness of bottom beam (mm)	Beam width (mm)	Beam length (mm)
1-11	2	smoothed	74	74	150	900
2-11	2	regulated	74	74		
3-11	2	rough	74	74		
4-11	6	smoothed	72	72		
5-11	9	regulated	70.5	70.5		
7-11	N/A	N/A	150			

SHORT-TERM FOUR-POINT BENDING TEST CONFIGURATION

The configuration of the laboratory four-point bending test is shown in Figure 1. Pin supports were positioned 50mm from each end of the beam. Loadings were applied 250mm from each end of the beam, leaving 400mm pure bending area in the centre of the beam span. A potentiometer was positioned at mid span to measure the vertical downward displacement of the top of the beam. The test setup for a typical beam is shown in Figure 2 (a). Machine loading was applied to a yellow crossbeam and then transferred equally to two roller bearings, each embedded in a loading pad to distribute the loads more uniformly to the beam, as shown in Figure 2 (b). Four strain gauges were attached to each beam, two on each side top and bottom, measuring horizontal strain during the test, as shown in Figure 2 (c). Two potentiometers were positioned at the right end of the beam, measuring relative beam end displacement, as shown in

Figure 2 (d). The machine was controlled in stroke mode with a loading rate of 0.1mm every 10s until the beam vertical displacement reached approximately 8mm. No loading-unloading cycles were performed during the short-term four point bending test.

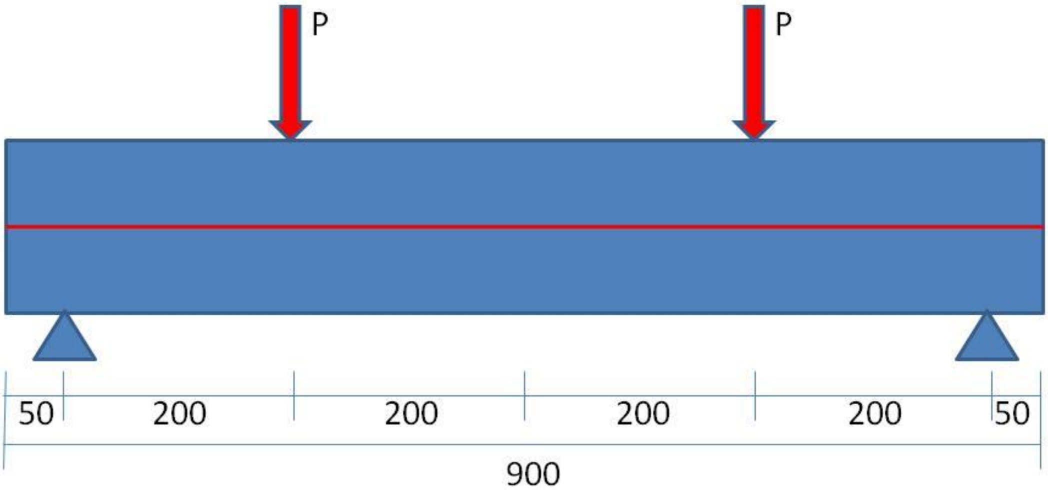
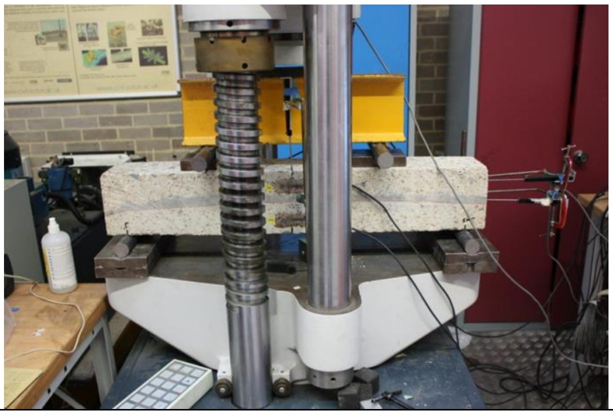
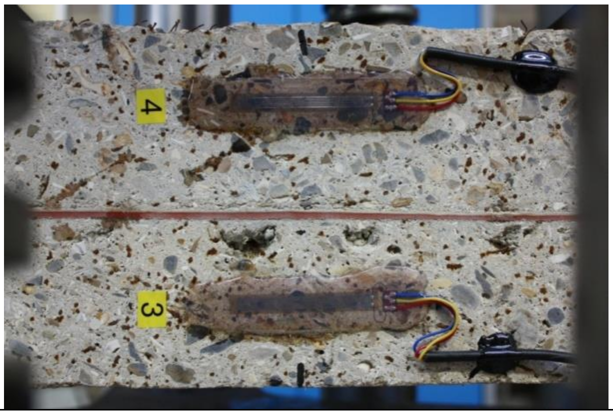


Figure 1 Configuration of four-point bending test

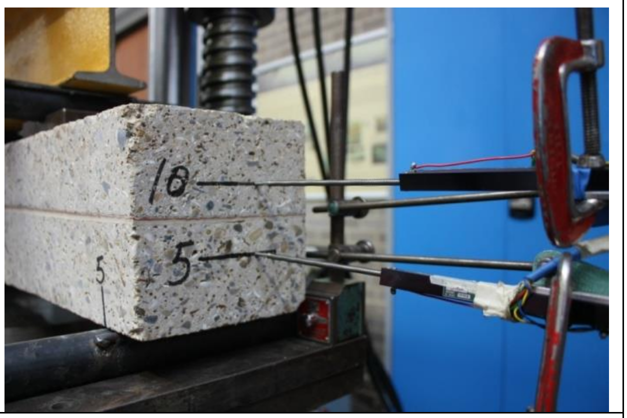


(a) Overall setting

(b) Loading transfer configuration



(c) Strain gauges measuring horizontal strain



(4) Measuring beam end displacement

Figure 2 Setup of four-point bending test

TEST RESULTS

Flexural response

The load-displacement diagram for the beams is shown in Figure 3 and the vertical downward displacement results under 10kN and 20kN total load were s in Table 2 . It was found that:

- The behaviour of pure shotcrete beam 7-11 was generally linear until the peak load was reached
- The behaviour of composite beam 4-11 was firstly linear until 15kN and become slightly nonlinear until the peak load was reached
- The behaviour of composite beam 5-11 was firstly linear until the load reached 11kN. After that, a small "slippage" occurred and the flexural stiffness reduced, leading to a "softer" flexural response up to peak load
- Displacement readings for beams 1-11, 2-11 and 3-11 were unusual because their flexural responses to the loading were stiffer than that of the pure shotcrete beam 7-11
- The load capacity of all beams was reasonable. The pure shotcrete beam has the highest peak load, around 23kN
- This was followed by the beams with 2mm thick membrane (1-11, 2-11 and 3-11), whose peak loads were around 19-21kN,only 10%-20% lower than that of the pure shotcrete beam 7-11
- The peak load of beam 4-11 (6mm membrane thickness) was around 19kN, very close to those 2mm thick membrane beams
- The peak load of beam 5-11 (9mm membrane thickness) was around 16kN, approximately 15% lower than that of beam 4-11

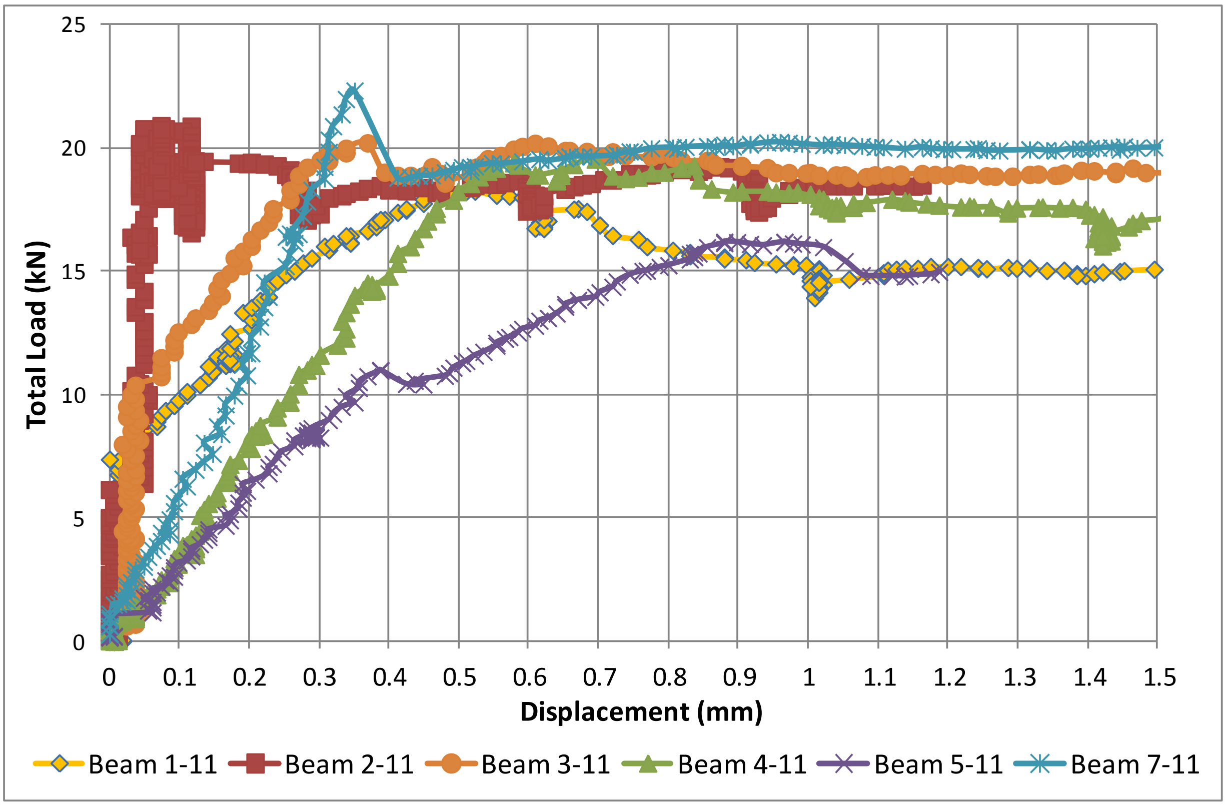


Figure 3 Load-displacement diagram

Table 2 Laboratory tested vertical displacement for beams under different loads

Beam number	Membrane thickness (mm)	Total vertical load (kN)	Laboratory tested vertical displacement (mm)
1-11	2	10	0.111
		18*	0.500
2-11	2	10	0.055
		20	0.043
3-11	2	10	0.031
		20	0.338
4-11	6	10	0.26
		20	0.58
5-11	9	10	0.34
		16*	0.88
7-11	N/A	10	0.178
		20	0.313

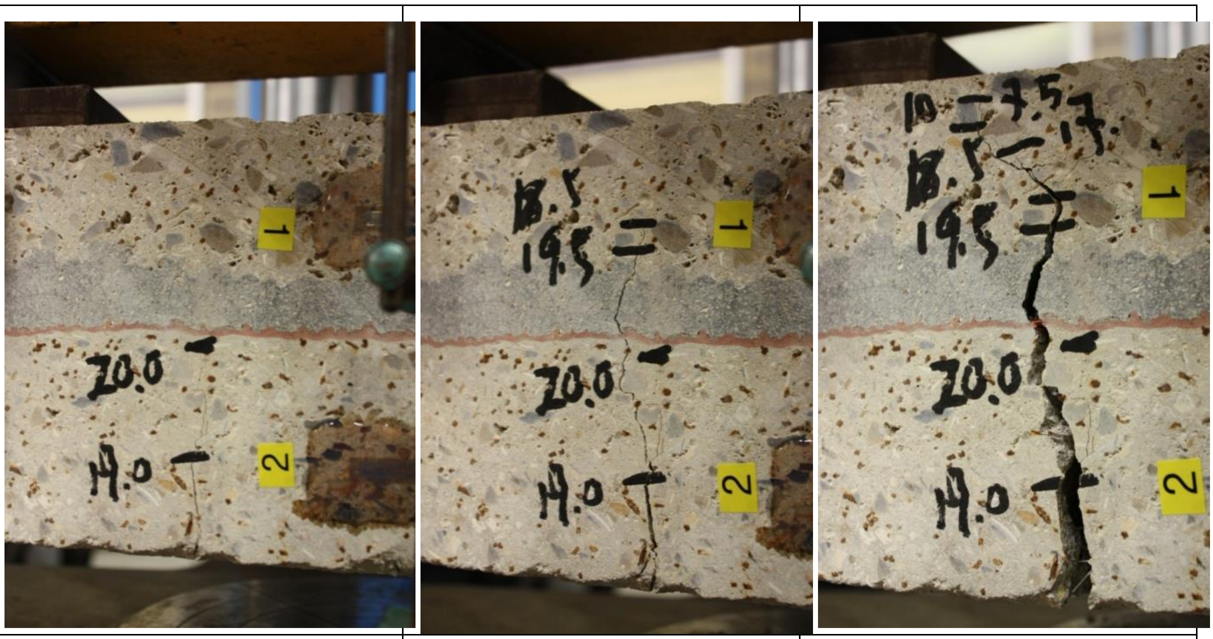
*Peak load for the beam 1-11 was less than 20kN

Crack development

The crack development process was observed to be similar for all beams. Its detailed description is given in Figure 4 below for beam 2-11 as an example.

- The peak load recorded for beam 2-11 was 21kN
- A visible crack was first observed when the load reached 19kN (90% of peak load)
- The crack was developing and approaching the membrane when the peak load was reached.
- When the crack had developed to 3/4 beam depth, the composite beam could still sustain 18.5kN load (88% of peak load).
- When the crack had developed to 4/5 beam depth, the composite beam could still sustain 10kN load (50% of peak load)
- Steel fibres were failed in the desired pull-out mode rather than undesired break-off mode
- A single flexural crack was observed in all the tests

When reviewing the load-displacement diagram and crack development process together, it was found that the tested beams went into nonlinear before visible cracks were observed.



(a) approaching peak load	(b) passing peak load	(c) residual strength

Figure 4 Crack development during the test

Horizontal strains

Four strain gauges were attached to each composite beam, two on each side (Figure 2 (c)). The average of the two strain readings from top and bottom of each composite beam are shown in Figure 5.The average values under 10kN total load for each composite beams are shown in Table 3. It was found that:

- The non-zero strain readings demonstrated that the top and bottom component beams worked compositely
- With the exception of the reading from the top and bottom of beam 3-11, all readings were very similar
- Error readings for beam 5-11 bottom were due to the crack developing through the strain gauge
- Prior to the load reaching 15kN, all strains were increasing linearly with the applied load, in alignment with the observation from the load-displacement diagram
- After the load exceeded 15kN, most readings show some degree of nonlinearity with “softer” response, also in alignment with previous observations

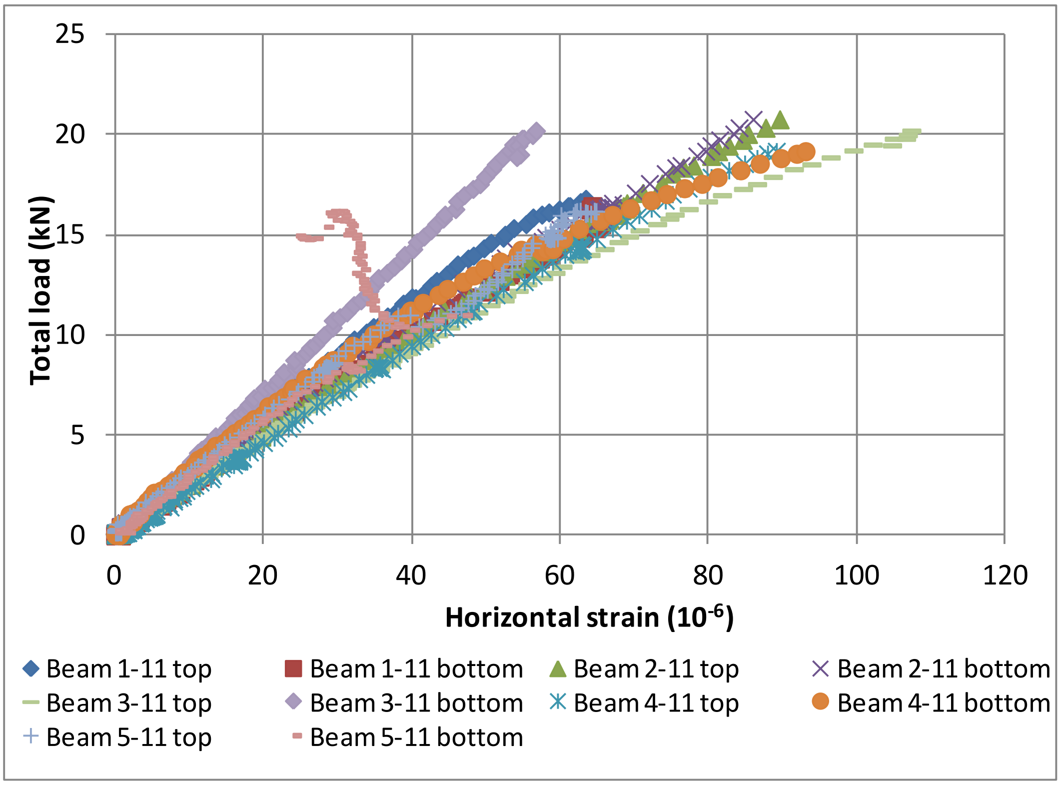


Figure 5 Horizontal strain readings for composite beams

Table 3 Horizontal strain readings for beams under 10kN total load

Beam number	Membrane thickness (mm)	Total vertical load (kN)	Strain gauge position	Strain gauge readings (microstrain)
1-11	2	10	top	33.7
			bottom	39.7
2-11	2		top	39.8
			bottom	36.5
3-11	2		top	43.5
			bottom	28.1
4-11	6		top	42.5
			bottom	34.8
5-11	9		top	35.7
			bottom	39.8

Beam end relative displacements

The beam end relative displacements are shown in Figure 6. It can be seen that the relative displacements were small, between 0-0.2mm, implying a high degree of composite action for all composite beams.

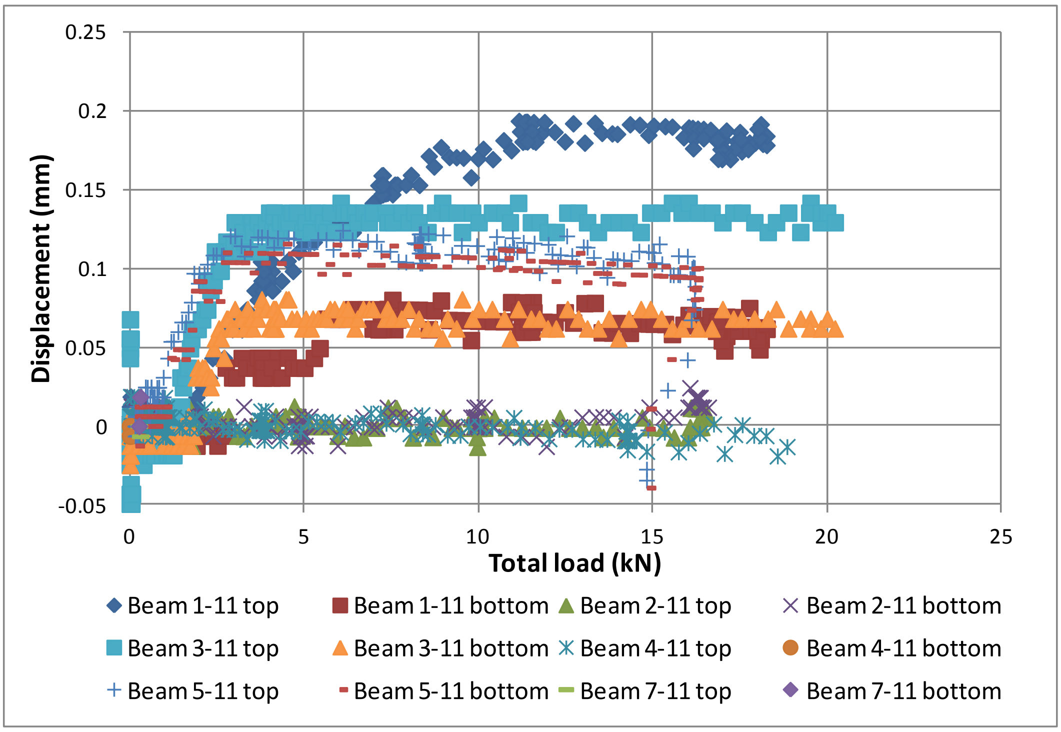


Figure 6 Beam end relative displacement for composite beams

EXAMINATION OF TEST RESULTS

Although the displacement readings for beams 1-11, 2-11 and 3-11 were unusual, the data accuracy of the other two thick membrane composite beams (4-11 and 5-11) were examined based on their load-displacement- strain relationships.

Because the load-displacement relationship became non-linear at higher loads, the load-displacement-strain relationships were examined at a load of 10kN, which was deemed to be still within the elastic region for all samples.

Firstly, the load displacement relationship of the pure shotcrete beam 7-11 was examined based on the theoretical equation:

$w=11PL^3/384EI$ (1)

Where

w: middle span vertical displacement
P: single point loading (50% of total loading)
L: beam span between two supports
E: Young’s modulus
I: Second moment of inertia ($bh^3/12$)
b: beam width
h: beam depth

Back-calculation shows that Young's modulus of the shotcrete for the pure shotcrete beam 7-11 was approximately 10GPa, which was used in the following calculations for beams 4-11 and 5-11. Based on Euler–Bernoulli beam theory, the horizontal strain at half-depth of top and bottom component beams can be calculated using the following equation:

$$\epsilon_x = - zw''(x) \quad (2)$$

Where

ϵ_x: horizontal strain

z: distance from the neutral axis of the separate beams (for composite beams) or the whole beam (for pure shotcrete beam) to a point of interest (top or bottom surface of the beam)

$w''(x)$ second derivative of beam displacement w with respect to distance x along the beam, given by:

$$w''(x)= PL/4EI \quad (3)$$

Therefore, by substituting (3) into (2) and then the result into equation (1), the following relationship can be obtained:

$$w=-11L^2\epsilon_x/96z \quad (4)$$

For the beam 7-11, z calculates to be 75mm, exactly the half-depth of the pure shotcrete beam, complying with the beam theory. For beams 4-11 and 5-11, z calculates to be 48mm and 45mm respectively.

From the beam theory, the z should be the half-depth of the whole beam if the beam is fully composite (75mm as for pure shocrete beam 7-11) or the half-depth of the separate beam if the beam is non composite (e.g. 37.5mm in this study). If the beam is partially composite, the z should be between 37.5mm and 75mm. The calculated z for the beams 4-11 and 5-11 are 48mm and 45mm respectively, falling into the range for partial composite beams. Therefore, the test results for beams 4-11, 5-11 and 7-11 were reasonable and proved to be valid.

ADDITIONAL BEAM TEST

Becasue the vertical displacement readings for the three beams with 2mm thick membrane (1-11, 2-11 and 3-11) were unusual, as shown in Figure 3, one additional beam with 2mm thick membrane (2-12) was tested to investigate the reasons. The dimensions of the additional beam are shown in Figure 7. This time, two potentiometers (rather than one) were positioned one each side of the beam top surface to measure vertical displacement, as shown in Figure 7 . Three longitudinal strain gauges were used; two attached at half-depth of the bottom component beam (one on each side of the beam) and the third on the bottom surface, on the beam centreline.

Table 4 Dimension of additional tested beams

Beam number	Membrane thickness (mm)	Interface type	Thickness of top beam (mm)	Thickness of bottom beam (mm)	Beam width (mm)	Beam length (mm)
2-12	2	regulated	84	64	150	900

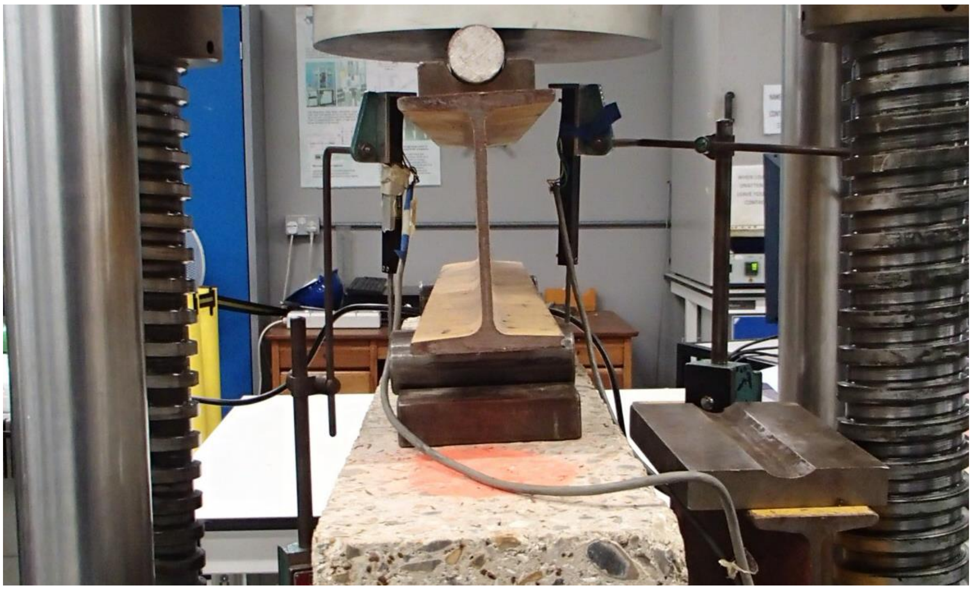


Figure 7 Two potentionmeters were positioned one each side of beam top surface to measure the vertical displacement

Flexural response

It can be seen from **Error! Reference source not found.** that the two vertical displacement readings differed significantly. Gauge 1 (red) curve is very similar to those curves for beams 1-11, 2-11 and 3-11 shown in Figure 3, while Gauge 2 (green) curve showed a clearer and more consistent trend. The average of the readings from Gauges 1 and 2 is also plotted. It was expected that the vertical displacement for beam 2-12, which has 2mm thick membrane with regulated interface, should be between that for the pure sprayed concrete beam 7-11 (0.178mm under 10kN) and the 6mm thick membrane composite beam 4-11 (0.26mm under 10kN). The average value of 0.235mm under 10kN for beam 2-12 indeed falls between these limits and is thus believed to be a reasonable and representative vertical displacement for a beam of this type.

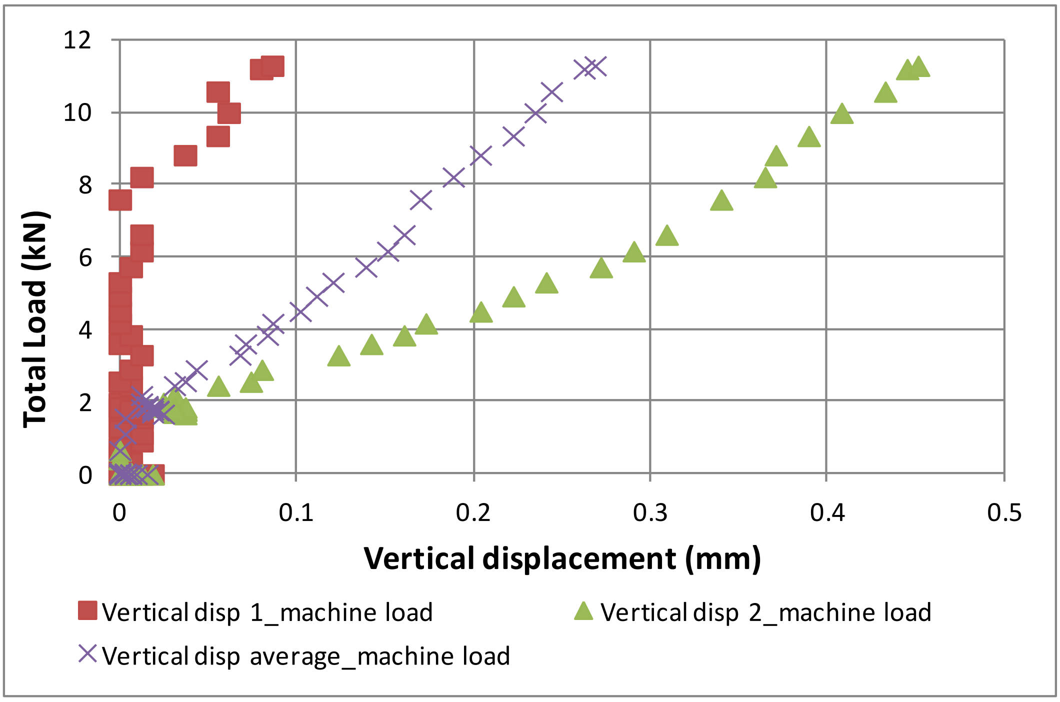


Figure 8 Vertical displacement of beam 2-12

Horizontal strains

It can be seen from Figure 9**Error! Reference source not found.** that the two side and one bottom horizontal strain readings under 10kN total load were 27.3, 34.5 and 71.5 microstrain respectively. The side strain 1 reading (27.3) was lower than all readings and the side strain 2 (34.5) was lower than all readings but beam 1-11 top (33.7) in Figure 5 and Table 3 under the same loading. Considering the thicknesses of the top and bottom component beams of beam 2-12 were unequal, possibly leading to a slightly bigger flexural stiffness than other composite beams with equal thickness component beams and 2mm thick spray applied membrane (beam 1-11 and 2-11), the relatively smaller side strain readings were reasonable. It can also be noted that the bottom strain reading (71.5) was more than twice the side strain readings at half-depth of bottom beam (27.3 & 34.5), proving a degree of composite action between the top and bottom beams.

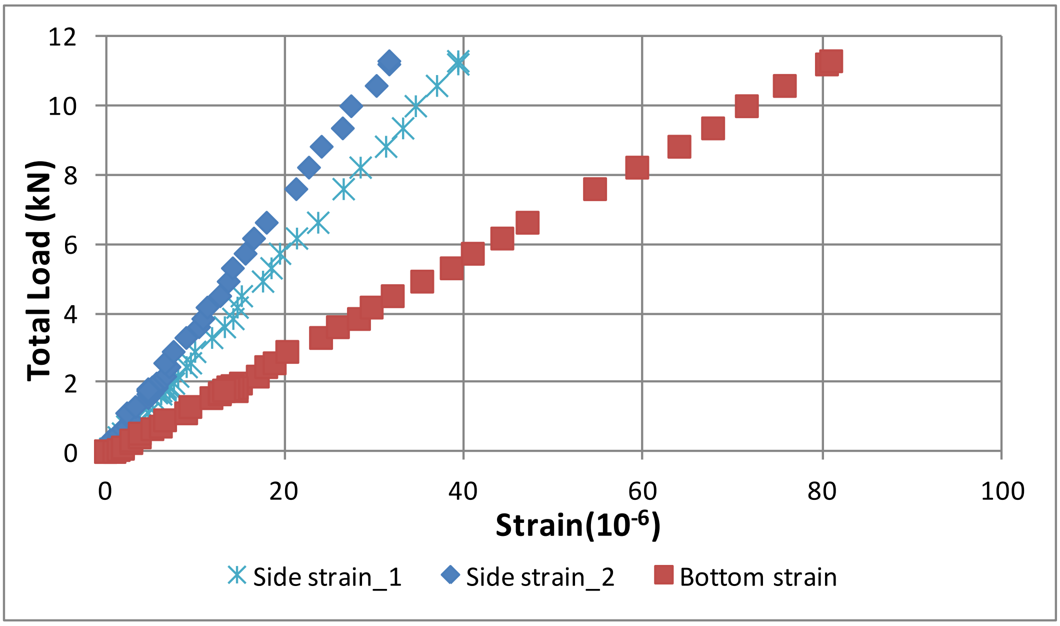


Figure 9 Strain readings of beam 2-12

QUANTIFICATION OF COMPOSITE ACTION

In order to quantify the degree of composite action, two conceptual situations are introduced here. The first is that of a full-composite beam, represented by the pure shotcrete beam 7-11 in this paper. The second is a non-composite beam 8-11, represented by two "conceptual" shotcrete beams each of half thickness (75mm), one on top of the other. It is understood from structural mechanics that if the thickness of the pure shotcrete beam is halved, its flexural stiffness reduces by a factor of 8. Therefore, the total flexural stiffness of the non-composite beam would be 1/4 of the original full thickness beam, and the vertical displacement under the same loading for the non-composite beam would be 4 times as that of a pure shotcrete full thickness beam. Therefore, relative to the full composite beam, the stiffness ratio of the non-composite beam is 25% and the stiffness for any partially composite beam should be between 25%-100%.

The measured stiffness ratios for the tested beams with correct vertical displacement readings are summarized in Table 4. It can be seen from **Error! Reference source not found.** that the stiffness ratios for the three tested composite beams are much higher than for the conceptual non-composite beam, proving a high degree of composite action for all three tested beams. It should be noted that both the pure shotcrete beam and the conceptual non-composite beam have a total thickness of 150mm, while the total shotcrete thickness of the other three composite beams is between 148-141mm, due to the presence of the membrane. It should be noted that the stiffness ratio for composite beams with the top and bottom component beams in equal thickness and 2mm spray applied membrane (beam 1-11 and 2-11) should have a slightly smaller stiffness ratio than that for beam 2-12 (0.76), which may have a slightly bigger flexural stiffness as discussed before, but should have a slightly bigger stiffness ratio than that for a composite beam with the top and bottom component beams in equal thickness and 6mm spray applied membrane (beam 4-11 at 0.68). The load-displacement diagram for the beams listed in Table 5 and up to a total load of 10kN is shown in Figure 10, from which it can be seen that all tested composite beams showed strong degree of composite action at their sprayed concrete-membrane interfaces.

Table 5 Composite action for beams

Beam No.	Membrane thickness (mm)	Interface type	Thickness of top beam (mm)	Thickness of bottom beam (mm)	Vertical displacement (mm)	Stiffness ratio
Beam 7-11	n/a	n/a	150		0.178	1.00
Beam 2-12	2	regulated	84	64	0.235	0.76
Beam 4-11	6	smoothed	72	72	0.26	0.68
Beam 5-11	9	regulated	70.5	70.5	0.34	0.52
Non-composite beam 8-11 (conceptual only, not tested)	n/a	n/a	75	75	0.712 (Theoretical)	0.25

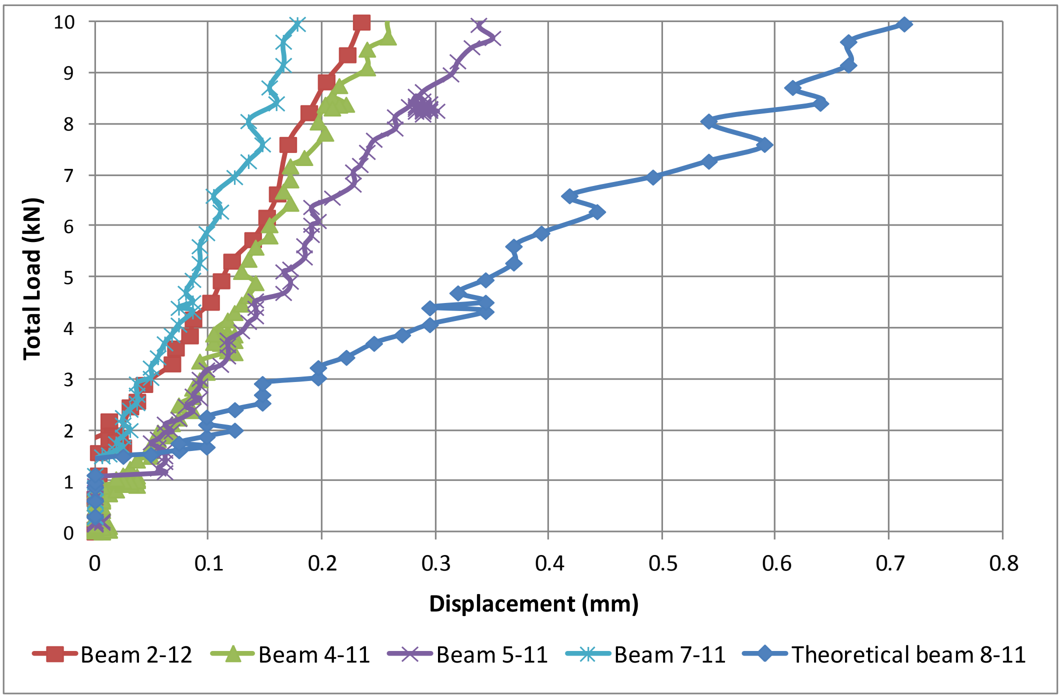


Figure 10 Load-displacement diagram

IMPLICATION FOR INDUSTRY

When comparing the stiffness ratios of the three composite beams, it can be found that the stiffness ratio is relatively insensitive to a change in membrane thickness from 2mm to 6mm, but becomes more sensitive to an increase from 6mm to 9mm. Therefore, by specifying 2-3mm thick membrane in the SCL design, an additional 1-2mm over-spray of the membrane will not have significant impact on the performance of composite sprayed concrete beam (lining).

The high stiffness ratio of the composite beams also means that there is a possibility for the reduction of beam (lining) thickness compared to a design with an assumption of no composite action. Assuming that the flexural stiffness of a 150mm thick full composite (*i.e.* pure shotcrete beam such as 7-11) is A, composite beams with overall thickness of 150mm and with 2mm, 6mm and 9mm thick membranes will have stiffnesses of 0.76A, 0.68A and 0.52A respectively, based on the experimental results. The overall lining thicknesses of these three composite beams at which their stiffnesses are reduced to 0.25A, the same as that of a 150mm thick non-composite beam, may be evaluated in terms of thickness ratios X_1, X_2 and X_3 respectively, calculated as follows:

$$0.76A(X_1)^3 = 0.25A \quad (5)$$
$$0.68A(X_2)^3 = 0.25A \quad (6)$$
$$0.52A(X_3)^3 = 0.25A \quad (7)$$

The thickness ratios X_1, X_2 and X_3 evaluate to be 0.69, 0.72 and 0.78 respectively, representing reduced total thicknesses from 150mm to 104, 108 and 117mm respectively.

CONLCUSION

Short-term four-point bending tests on beam samples cut from panels built up from a sprayed primary layer, spray applied waterproofing membrane and sprayed secondary layer with different interface finishes show that a high degree of composite action exits at the sprayed concrete-membrane interface. This can lead to significant saving in the lining thickness whilst achieving the same lining stiffness relative to a non-composite assumption. Further research is currently in progress to validate a numerical modelling procedure against the tested beam results that can then be used to understand the behaviour of realistic scale composite SCL tunnels in soft ground.

ACKNOWLEDGE

The authors would like to express their thanks to Mott MacDonald and TAM-Normet for their financial support of the research.

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