Experimental and Analytical Modeling of Interface Interaction in Composite Flexural Members

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In view of the mounting cost of maintaining or rehabilitating deteriorating infrastructure or reconstructing the collapsed ones, the application of advanced composite materials in the construction industry employing polymer-based materials is now considered a necessity for sustainable economy. Polymer-based materials have both complementary and supplementary properties to cement concrete that include high durability, fatigue resistance, strength, ductility and energy absorption, and are hence presently being assessed for suitability as alternative fill materials to concrete in filled steel tubular members (FST). This study is a continuation of previous work and is aimed at quantifying the steel-polymeric material interface interaction, as simulated by open sandwich beams subjected to flexure, for future use in the analyisis of filled steel tubular members. Experimental results confirm the very high level of composite interaction between steel and polymeric materials as promoted by the high adhesive, tensile, and compressive strengths of polymeric materials. Through finite element analytical modeling, the interface force-slip response is sufficiently quantified, and is to be used in the analysis of filled steel composite tubular members (FST) in a future study.

Keywords: *Filled steel members, Finite element modeling, Flexural test, Interface interaction, Polymers*

1. Introduction

Experience gained over the last few decades in Europe, USA and Japan reveal that existing construction technology has not delivered the reliability needed, as is evidenced by the severely deteriorated infrastructure and inability to guarantee safety against natural hazards. In consequence, governments are now investing heavily in harness with private industry to develop high performance construction materials and systems[1], with special interest being directed towards filled steel tubular members (FST) e.g. the presently popular concrete filled tubular members (CFT) [2-4]. Lately, studies are also exploring the use of alternative polymer based fill materials to replace cement concrete in FST to alleviate several drawbacks inherent of ordinary cement concrete e.g. high shrinkage and creep, and low tensile strength, fatigue resistance and durability[5,6].

Polymers or polymer based materials posses complementary and supplementary properties to concrete viz higher tensile and adhesion capacity, lower weight and shrinkage, high ductility and resilience, and resistance to physical and chemical attack[7-13]. Although the cost of polymers may be comparatively high at present, it is envisaged that continued promotion of their unconventional advantages e.g. as repair materials[7] and research directed towards seeking optimally cheap derivatives e.g. recycled plastic wastes[14], will eventually lead to a satisfactory cost.

Studies already conducted by the authors concentrating on filled steel tubular stub columns and beams reveal colossal increase in strength and/or ductility of polymeric material-filled steel tubular members[5,6]. A most unique feature realized was the wide array of properties presented by polymer-based materials, making them amenable or versatile to meet specific requirements of any desired construction e.g.

high ductility with only nominal increase in strength for strength design or high strength for strength design.

This study is motivated by the observed vast potential of polymer based materials in FST, and is focussed on highlighting and quantifying the superior composite interaction between polymer based materials and steel, as promoted by the superbly interlocked and bonded interface in the absence of shear connectors. Although conventional design of composite members assumes either full interaction for strong bond or no interaction for weak bond at the interface, the reality is that there is a partial interaction, the extent of which depends largely on the interface bond behavior. In acknowledgement of the importance of interface bond characteristic, attempts have been made in the construction of CFTs to enhance the weak natural bond between steel and concrete by empirically relying on either shear connectors as in the USA, or ribs and diaphragms as in Japan[15,16,17)]. However, the actual contribution of these interface conditions on stress transfer mechanism remains uncertain and hence not adequately quantified for engineering applications[16,18)]. Even for the weak natural bond between steel and concrete, questions exist regarding the effect of bond strength induced by frictional forces, on both ductility and strength of the composite member, particularly the stress transfer mechanism from steel beam to a concrete-filled steel column[3,17,18)]. The importance of interface interaction is even more emphasized in the case of filled steel members filled with polymeric materials such as epoxies, which are noted for their high adhesive/tensile strengths as well as flexibility. Assuming no connection at the interface between the epoxy and steel components is very conservative, while on the other hand assuming a perfect connection in the analysis overestimates their strength and stiffness properties.

It was the objective of this study to experimentally and analytically simulate composite interaction in FST through flexural tests on open sandwich beams, and more specifically quantify the interface force-slip characteristics, with the intention of using the determined interface relations, in place of unreliable assumptions, in the analytical modeling of filled steel tubular members (FST) in a future study.

2. Experimental program

2.1 Outline

Since there is not yet a universally accepted test method for the determination of interface interaction or bond slip characteristics of composite filled steel members, researchers have used a variety of test methods. These include push-out tests on CFT, pure flexure tests and tests on I-girders framing into CFTs using simple shear-tab connectors[16,18,19)]. In this study, the interface interaction in filled steel members was simulated through flexural tests on open sandwich beams, since flexural bending is more closer to FST beam columns than push-out loading. Additionally, it was possible to have direct access on both the fill material and steel components enabling the measurement of sectional strains and interface slip for detailed understanding of composite interaction. The only feature in FST which could not be captured by the sandwich beams is the effect of confinement. However, confinement is less pronounced in interface interaction, but mainly increases fill material strength.

A total of 16 open sandwich beam specimens comprising a nonmetallic material-steel combination were tested in flexure under a central point load. Each of the open sandwich beam specimens had a breadth (b) of 40mm, a total height (h) of 120mm and a span length (L) of 800mm as shown in Fig. 1. Since the primary objective was to assess interface behaviour, the breadth of the specimens was decided so as to ensure that failure occurred at the interface and that the specimens were light enough to be handled by the staff.

The variables selected for investigation included (a) the type of nonmetallic material namely, latex cement mortar-steel (LCM/S), epoxy-steel (E/S) and ordinary cement mortar-steel (OM/S) combinations compared to steel-steel (S/S) combinations, (b) the nature of the nonmetallic material-steel interface which was varied by either allowing for natural bond at the interface or gluing the interface using an epoxy adhesive of 50 and 20 N/mm^2 compressive and tensile strengths, respectively, and (c) the ratio of height of fill material component to steel component (h_f/h_s). In addition, some combinations were subjected to opposite loading by having a replicate specimen turned upside down i.e. inverted and tested in flexure, so as to asses the interface characteristics under both compressive and tensile regimes of stress. Table 1 gives the summary of experimental program.

A specimen for test had uni-directional strain gages for strain measurement pasted transversely at four sections within the half-span, namely at the mid-span (7 gages), quarter-span section (7 gages) and the two 1/8th span sections (3 gages each) as illustrated in Fig. 1. On placement upon the end supports spanning 800m, Linear Variable Displacement Transducers (LVDTs) for deflection measurement were fixed in vertical alignment; one at the centre and one each at the end supports. In order to measure slip at the interface, semi-circular type displacement transducers were attached at four locations within the half-span (i.e. the two 1/8th points, quarter point and the support) using fixed metal plugs. A central point load (P) was then applied gradually on the specimen through a 1000 KN capacity TKS Universal Testing Machine, during which load, deflection, interface slip and strain data were monitored and recorded by a computer at suitable intervals, via a data logger.

2.2 Material properties

Each composite beam specimen consisted of a steel component and a non-metallic component (either latex cement mortar or epoxy or ordinary cement mortar). The selection of the non-metallic materials was pre-determined by previous investigations on filled steel composite stub columns and beams[5,6]. In brief, latex cement mortar is a polymer based or modified material prepared from rapid hardening Portland cement, fine aggregate of maximum 2mm size and 20mm long carbon fibres, which is then mixed in a ratio of 20:5 with Styrene Butadiene Rubber latex (SBR) in a water/cement ratio of 0.5. Epoxy, on the other hand, is a commercial preparation, usually formed by condensation of epichlorhydrin and polyhydroxy, and supplied as a liquid epoxy resin together with a chemical hardener or catalyst, to be mixed just before casting[20]. The ordinary cement mortar, which represented ordinary cement concrete, was prepared from cement, sand and water in a ratio of 1:2:0.65, in that order. Material properties for these non-metallic materials were determined from compressive tests on 100x200mm cylinders, the results of which are given in Table 2. For the steel, basic material properties were obtained from coupon tensile test, and are also given in Table 2.

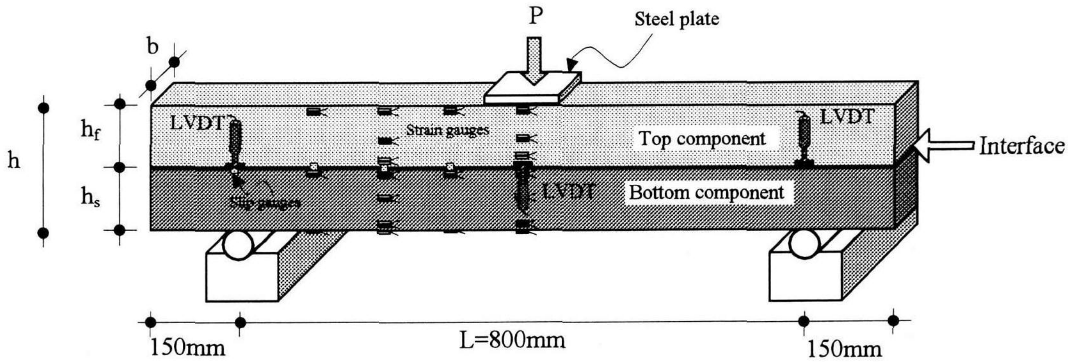


Figure 1. Open sandwich beam specimen under flexural loading
(Simulating the interface between the components in filled steel members)

Table 1. Experimental details of the testing program

Specimen label	No. of specimens	b (mm)	h_f (mm)	h_s (mm)	h_f/h_s (mm)	b/h_s (mm)
LCM/S -1ns, LCM/S-1gs	2	40	60	60	1	0.667
E/S-1ns, S/E-1ns	2	40	60	60	1	0.667
OM/S-1ns, OM/S-1gs, S/OM-1gs	3	40	60	60	1	0.667
S/S-1ns, S/S-1gs	2	40	60	60	1	0.667
LCM/S-11ns, LCM/S-11gs	2	40	110	10	11	4.0
OM/S-11ns, OM/S-11gs, S/OM-11gs	3	40	110	10	11	4.0
E/S-3ns, S/E-3ns	2	40	90	30	3	1.333

Nomenclature: Specimen identification; gs and ns in the labels represent glued surface and natural surface respectively e.g. OM/S-1ns represents ordinary cement mortar-steel open sandwich beam (with steel at the bottom) of h_f/h_s=1 and of natural sandwich interface.

Table 2. Material properties of the nonmetallic materials and steel

Material	Young's Modulus (KN/mm^2)	Poisson's ratio	Strain at ultimate (%)	Yield stress (N/mm^2)	Yield strain (%)	Ultimate strength (N/mm^2)	Elongation at break (%)
Latex cement mortar (LCM)	14.7	0.200	0.481	-	-	16.8	-
Epoxy (E)	2.81	0.418	4.76	-	-	71.2	-
Ordinary mortar (OM)	21.7	0.194	0.315	-	-	32.0	-
Steel (S); case for h_s=10mm	209	0.276	-	646	0.3112	661	19.9
Steel (S); case for h_s=60 and 30mm	205	0.303	-	254	0.1920	430	57.4

3. Experimental results and discussions

3.1 Load-deflection characteristics

Fig. 2 presents the recorded load-deflection response for some of the beam specimens tested. In addition, theoretical response obtained using the fundamental theory of beam deflection is also given for two cases i.e. complete interaction with no slip (Eq. 1), and no interface interaction with full slippage allowed (Eq. 2). For the case of full interface interaction;

$$y_m = \frac{PL^3}{48E_{fill}I_{tfill}} \qquad (1)$$

while for the case of no interface interaction, it is assumed that the deflection of the two components remains the same, giving the expression;

$$y_m = \frac{PL^3}{48(E_{fill}I_{fill} + E_sI_s)} \qquad (2)$$

where, y_m is the deflection at the mid-span

E_{fill} and I_{fill} are the Young's modulus and moment of inertia of the top fill material component

E_s and I_s are the Young's modulus and moment of inertia of the bottom steel component

$I_{tfill} = (n_s-1)bh_s^3/12+(n_s-1)bh_s(d_{na}-0.5h_s)^2 +bh^3/12+bh(0.5h-d_{na})$

$n_s= E_s/E_{fill}$

d_{na} is the neutral axis of the transformed section

A glance at Fig.2(a) promptly reveals the high adhesive property of epoxy resin when the glued steel specimen (S/S-1gs) is compared to the independent steel beam specimen (S/S-1ns). It is observed that the stiffness and strength of S/S-1gs are much higher than that of S/S-1ns, tending towards the full interaction obtained from beam theory. The superior composite interaction of S/S-1gs is attributed to the high adhesive and tensile strengths of the epoxy glue. However, it is noted that even though epoxy glue considerably improves the interface bond, it does not provide a perfect one implying a case of partial interaction until debonding occurs. During the tests, the debonding point was characterized with a loud sound, after which extensive slip was observed at the beam-ends while the load drastically dropped. In order to understand the nature of the interface bond after the debonding, the displacement transducers were reset and loading commenced from zero. As is seen in Fig.2 (a), the nature of the interface after debonding (S/S-1gs; debonded) approximates that of the unbonded beam specimen (S/S-1ns), but with a little lower stiffness possibly due to the previous yielding of steel. The unbonded steel gradually shifts away from the theoretical no interaction curve, perhaps due to the introduction of unequal bending deformations at the interface. Using the formula τ_{max} =1.5F/(bh), where F is the debonding shear force, the debonding shear strength (τ_{max}) of S/S-1gs has been calculated to be 24.3 N/mm^2, equivalent to the design epoxy shear strength.

In the case of latex cement mortar-steel (LCM/S) beams specimens, the difference between the natural interface and glued interface seems to be negligible, and both curves are initially more aligned towards the theoretical full interface interaction response, and are stiffer than the approximated response of steel only. The closeness between the glued and unbonded specimens exemplifies the dominant adhesive effect of the latex in the mortar, as well as the enhanced tensile strength due to the presence of fibres. Latex modification and carbon fibre reinforcement play complimentary roles in enhancing different aspects of the cementitious material performance. While carbon fibre is capable of significantly improving the tensile and flexural strength, toughness, and impact resistance of cement, latex modification results in major gains in the impermeability, durability and adhesion capacity[25)]. The sudden drops and overall change in gradient of the curves indicate partial debonding and the formation of tensile cracks in the latex-cement mortar. After this state, the response approaches that of steel only.

The epoxy-steel specimen (E/S-1ns) presents dual nature in that the interface condition can be considered to be both natural and glued because epoxy is in itself a glue. It is seen that the theoretical full interaction and no interaction curves are very close, due to the low modulus of elasticity of epoxy. In addition, it is observed that the experimental curve aligns with theory only on the very early stages of loading, soon deviating as loading progresses. Possible cause of this deviation is thought to be due to the low modulus of elasticity, resulting in earlier yielding of steel beam. When a replicate specimen is inverted so that the epoxy component is at the bottom tensile region (S/E-1ns), a similar composite interaction as for E/S-1ns is observed, albeit with a lower ultimate strength. This clearly shows the isotropic nature of epoxy i.e. similar material properties in tension and compression, unlike ordinary concrete or mortar. The post-elastic response is significantly above that of steel only.

Ordinary mortar-steel beams present the least scenario of interface interaction, for both glued and unbonded specimens, which deviate from the theoretical curves just after the initial loading. The glued beam has an initial linear portion which follows the theoretical no interaction curve, but soon a sudden change of gradient occurs possibly due to the failure of the mortar, consequently transferring all the applied loads to the steel component. Generally the OM/S beams manifest a case of low tensile strength of mortar compounded by low bond or adhesive strength. After the failure of the mortar the response of the beam moves closer and closer to that of the steel only. When a replicate specimen is inverted so that the mortar component is at the bottom tensile region (S/OM-1gs), the mortar cracks and debonds almost immediately and as the cracks widen most of the applied load is resisted by the top steel component. This explains why in CFTs subjected to cyclic bending loads, the concrete has to be confined by a diaphragm to prevent widening of the cracks and slippage for the benefits of composite interaction to be realized[15,21,22]. In this study, the open sandwich beams could not model the confinement effect normally found in FSTs. However, the chemical and mechanical interface characteristics determined in this study are deemed adequate for application in the modeling of FSTs by ABAQUS program, since the extra benefits of confinement will be catered for in the actual FST model by specifying a rigid plate at the fill material ends. The plates in the model reduce slippage very much like the confinement induced by actual diaphragms or end plates, and if necessary ordinary frictional coefficient between concrete and steel may be used.

In generalization, it may be stated that the high adhesive and tensile strengths of polymers or polymer based materials promotes composite interaction over a much wider load range with consequent increase in strength, stiffness and ductility. Cement mortar, on the other hand, presents low interface interaction attributable to its low tensile and adhesive strengths. The low tensile strength of ordinary cement mortar or concrete has been of serious concern to engineers for many years since it creates a wasteful non-structural and porous tensile region.

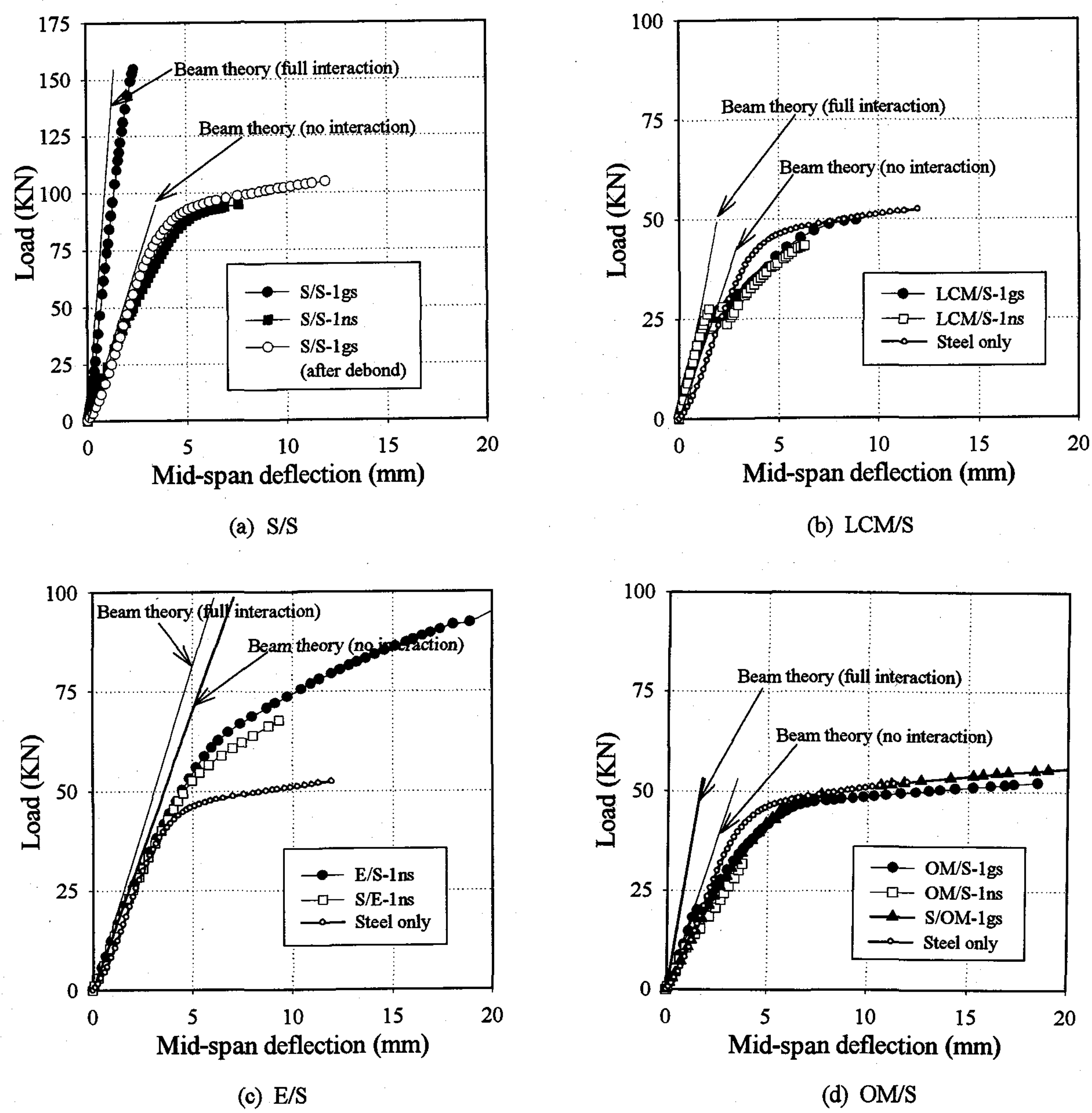


Figure 2. Load-deflection response of some of the tested beam specimens (h_f/h_s=1)

3.2 Strain distribution over the cross section

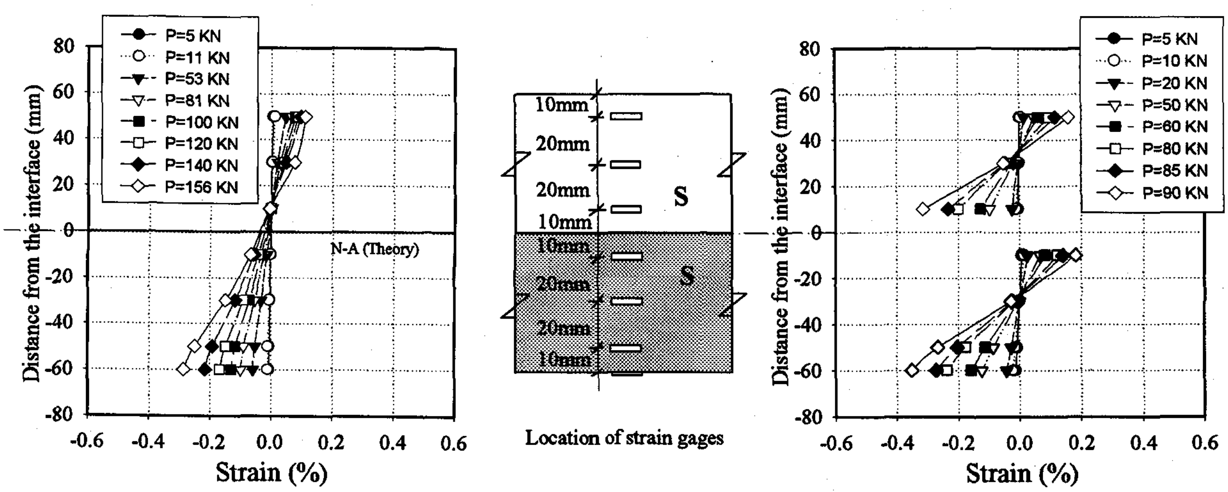
Sectional strain distribution provides fundamental beam behaviour, particularly the extent of strain linearity that is usually assumed in beam theory as well as degree of partial interaction at the interface of composite beams. Figs. 3–6 give the strain distribution at mid-length for some of the tested beams, and in addition shows the severe effect of localized strains at the load application point for E/S beam, due to the low modulus of elasticity of epoxy. Compressive strains are taken as positive and tensile strains as negative.

The glued steel beam (S/S-1gs) in Fig. 3(a) shows a fairly homogenous composite behaviour, with the nearly linear strain distributions, indicative of the high adhesive and shear strength of epoxy resin. The neutral axis is constant at a point slightly above the expected interface line, suggesting that the bond is not a perfect one. The unglued beam specimen (S/S-1ns) depicts a perfect case of independent response for each of the components, implying a smooth interface.

The strain distributions for the LCM/S beams are quite similar for the two cases of glued and natural interface beams, further confirming the adhesive nature of latex cement mortar. Debonding occurs at strains below the yield strain of steel.

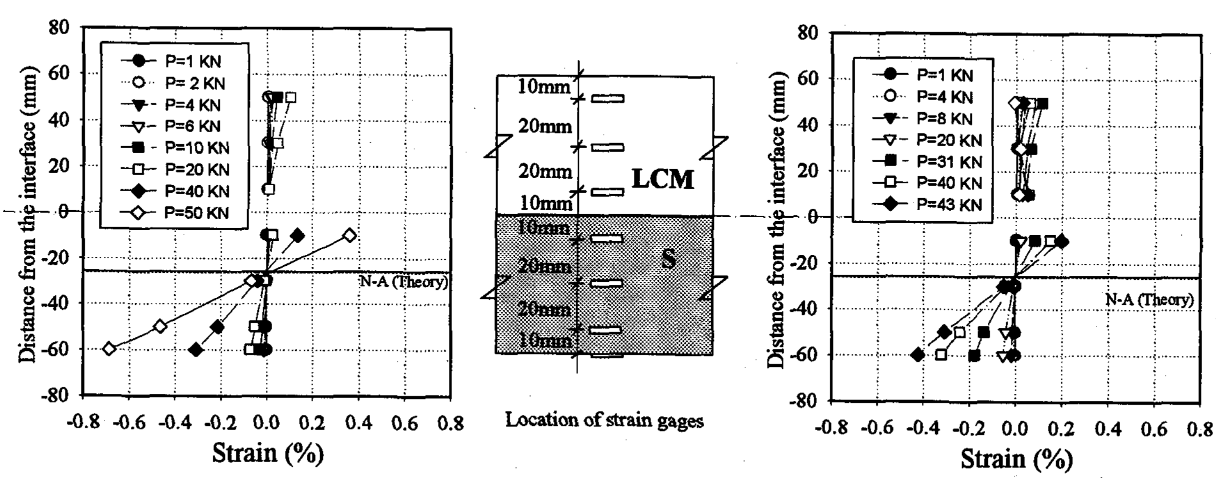
E/S-1ns beam presents extensive composite interaction up to the very high compressive strains of about 0.8% in the epoxy. It is evident that the high flexibility of epoxy, coupled with its high tensile, shear and adhesive strengths promotes composite action with steel in the elasto-plastic range. The experimental neutral axis is very close to the theoretical full interaction prediction.

Finally, mortar-steel sandwich beams (OM/S) show minimal composite interaction, attributable to the very low tensile, shear and adhesive strengths of mortar. Even the use of adhesive at the interface seems to have insignificant enhancement on the composite interaction, making it clear that very low tensile strength of ordinary mortar overrides the gluing at the interface.



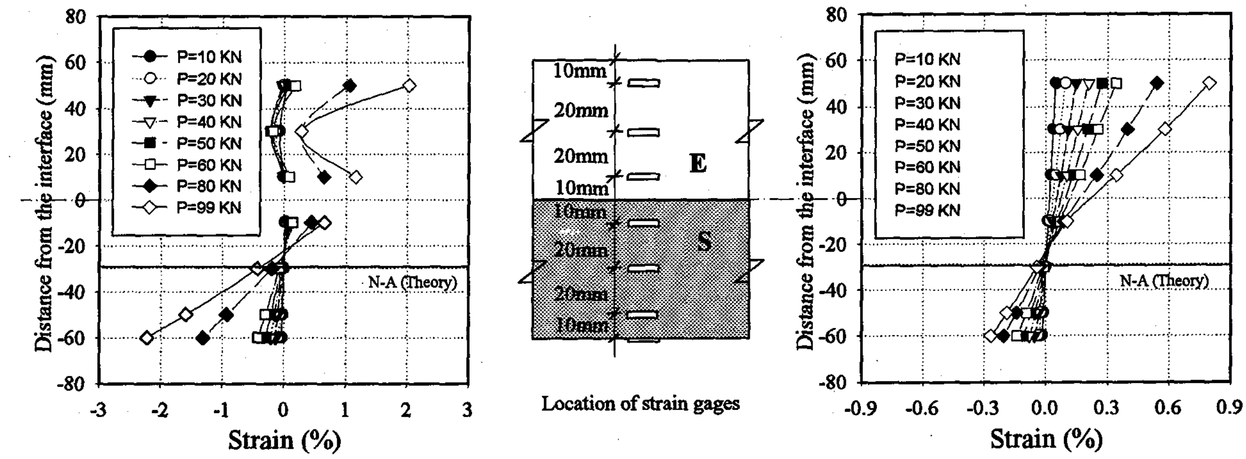
(a) S/S-1gs (b) S/S-1ns

Figure 3. Strain distribution at the mid-span for S/S beams



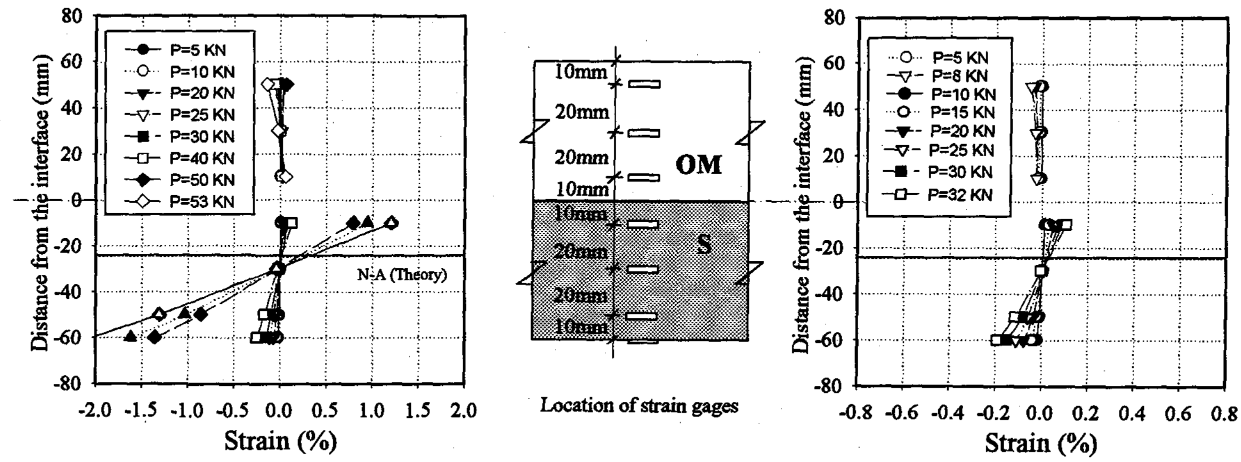
(a) LCM/S-1gs (b) LCM/S-1ns

Figure 4. Strain distribution at the mid-span for LCM/S beams



(a) Mid-length (b) Quarter-span

Figure 5. Strain distribution at the quarter-span for E/S beam



(a) OM/S-1gs (b) OM/S-1ns

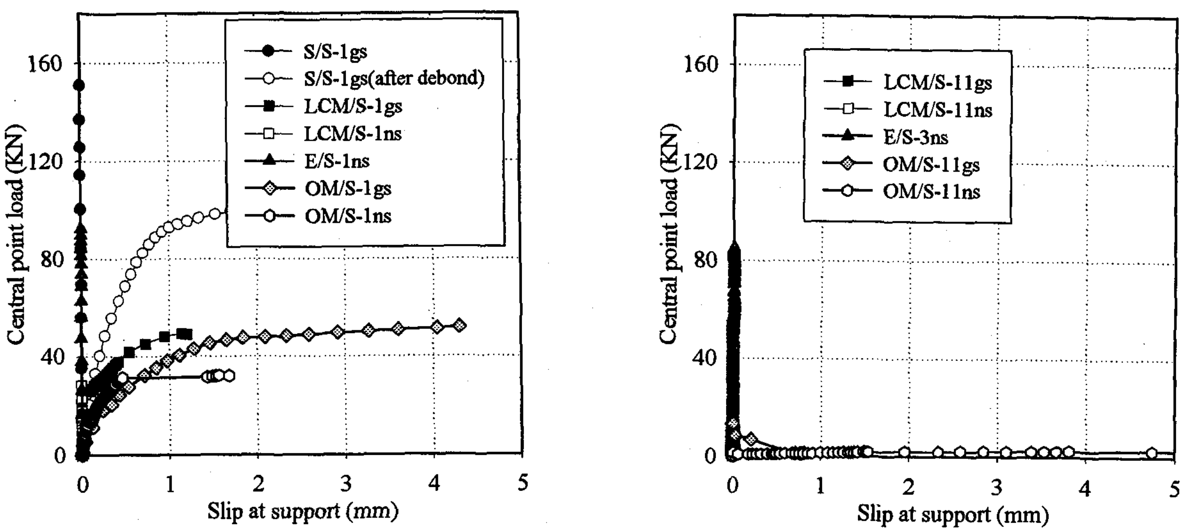
Figure 6. Strain distribution at the mid-span for OM/S beams

3.3 Mid-span point load versus slip at the support

The mid-span load-slip behaviour shown in Fig. 7 gives a localized approximation of the relative movement at the support between the two components of any beam, and generally gives an idea of the extent of interaction at the interface. However, the experimental force at the interface causing the slip is unknown, and will hence be determined by use of finite element modeling in the next section.

The observed slip characteristics in Fig. 7 largely accounts for the behaviour observed in the load-deflection curves. The high bond strength until debonding in specimens S/S-1gs and E/S-ns is vividly presented attesting to the high adhesive and shear strength of epoxy resin. When specimens debond, the sudden release of energy results in the flying off of slip measurement stoppers as well as pieces of the nonmetallic material, preventing any further measurement of slip. Similarly, the insignificant difference in debonding load between LCM/S-1ns and LCM/S-1gs also confirms the adhesive nature of latex-cement mortar, further enhanced by the mechanical bond at the interface caused by the surface roughness even after cracking has occurred. On the contrary, the high slip of OM/S and OM/S specimens commencing quite early in loading show their poor adhesive bond characteristics as well as low tensile strength. The cement mortar cracks and as the cracks widen increasingly high slip is recorded at very low central point load. The severe effect of cracking is visible in Fig. 7 (b) where the increased relative height of mortar component results in rapid cracking followed by high slip deformations. In the post-cracking response, frictional resistance provides mechanical bond at the interface preventing the total failure of bond. This is different from E/S beams, which mainly rely on chemical bond of epoxy until the attainment of sudden failure.

Other researchers have also highlighted the superior bond characteristics of polymer-based materials; for example recent studies by Ali et al.[23] reaffirmed that epoxy has excellent bonding property and the bond is not weakened by fatigue loading. Polymer modified cement mortar (modified



(a) h_f/h_s=1

(b) h_f/h_s=11 or 3

Figure 7. Central point load-slip characteristic of some of the tested beams

by Styrene Butadiene Rubber latex) was also found to have good bonding property almost as high as epoxy specimens. Fresh concrete with no bonding agent and cement mortar as the bonding material did not have good bonding property. They depended largely on surface roughness to achieve a better bonding strength. He concluded that surface roughness has a great influence on the bonding shear strength when no bonding agent is used.

4. Finite element analytical modeling

To supplement the experimental data particularly in the determination of interface force causing slip, an analytical model using ABAQUS finite element analysis[24] was developed. This process, conducted in conjunction with the experimental data, was particularly important as it enabled the quantification of force-slip response at the interface, which may be used in the analysis of filled steel tubular members (FST).

4.1 Geometric and structural modeling

An elasto-plastic three-dimensional nonlinear finite element modeling and analysis of composite open sandwich beams subjected to flexure was conducted by employing the commercial finite element code ABAQUS[24], in conjunction with experimental results. The composite beam was modeled by 20-node quadratic brick (hexahedral) elements of reduced integration (C3D20R), all included in the ABAQUS software. Quadratic (second-order) elements are known to provide higher accuracy than linear (first-order) elements, and capture stress concentrations more effectively. They are very effective in bending dominated problems. The reduced integration is adopted as means of reducing the running time. To account for the interface interaction between the top and bottom components of the beam, spring elements oriented in the X, Y, and Z Cartesian coordinate system were deployed at each of the interface nodes. The complete model had supports at the two lines near the ends, as shown in Fig.8.

Load application was achieved by imposing incremental axial displacements through a rigid plate at the mid-span top location of beam. ABAQUS identifies any rigid body through a reference node by which the actions on the rigid body are defined.

4.2 Material models

The primary material properties required for analysis were from tensile coupon tests and cylinder compressive tests on steel and fill material, respectively (see Table 2).

In modeling the steel material behaviour, an elastic-plastic constitutive model incorporating flow rule, von Mises yield surface and isotropic strain hardening were adopted. For the nonmetallic materials, extended Drucker Prager model with an exponential yield surface relating equivalent pressure stress $p=(\sigma_z+2\sigma_l)/3$ to Mises equivalent stress $q=\sigma_z-\sigma_l$ was used. σ_z and σ_l are the axial and lateral stresses on the nonmetallic material, respectively. The yield function is written as;

$$F=aq^b-p-p_t=0 \quad (3)$$

where, $p_t=a\sigma_c-\sigma_c/3$ and σ_c is the yield stress. The material parameters a, b, and p_t can be given directly or can be calculated by ABAQUS (as is the case for this study) from input experimental data of lateral confining stress versus axial confined strength.

Modeling the interface interaction between the steel component and the nonmetallic material was by means of nonlinear springs aligned in each of the three Cartesian axes. This was of prime importance in this study because it enabled the quantification of interface behaviour for the different types of composite beams, which could not be easily obtained through loading tests. ABAQUS program provides three types of spring elements (which can be linear or non-linear), namely axial spring between nodes, spring between a node and ground and a spring between two nodes, acting in a fixed direction. The spring type selected for each of the X, Y, and Z directions was a non-linear spring connecting two nodes and acting in a fixed given direction. Obtaining a force-slip relation for the spring commensurate with overall experimental load-deflection response was the target of this modelling, and this was achieved by adjustments after several trials. The process entailed approximating the initial average force-slip relationship of the spring from experimental data, subsequent to which the relationship was suitably modified as dictated by the comparison between experimental and analytical results of the overall load-deflection curves.

4.3 Comparison with experimental results

Since the stiffness and yield/failure characteristics of the interface is unknown, the simulation of the load-deflection curves are simulated repeatedly until the satisfactory results are obtained. A comparison between the experimental and best simulated load-deflection curves is given in Fig. 9. The almost perfect alignment between analytical and experimental results is obtained for S/S-1gs and E/S-1gs beams. However, for the latex cement and ordinary mortar composite beams, initial elastic range is well predicted by the model, but after the commencement of cracking or debonding at spontaneous locations on the interface, the model is unable to adequately capture the sudden drops in force. Nonetheless, the model predicts average gradient through these drops.

Additionally, a typical analytical strain distribution is also given by Fig. 10, illustrating the continuity of strains through the interface, before debonding occurs.

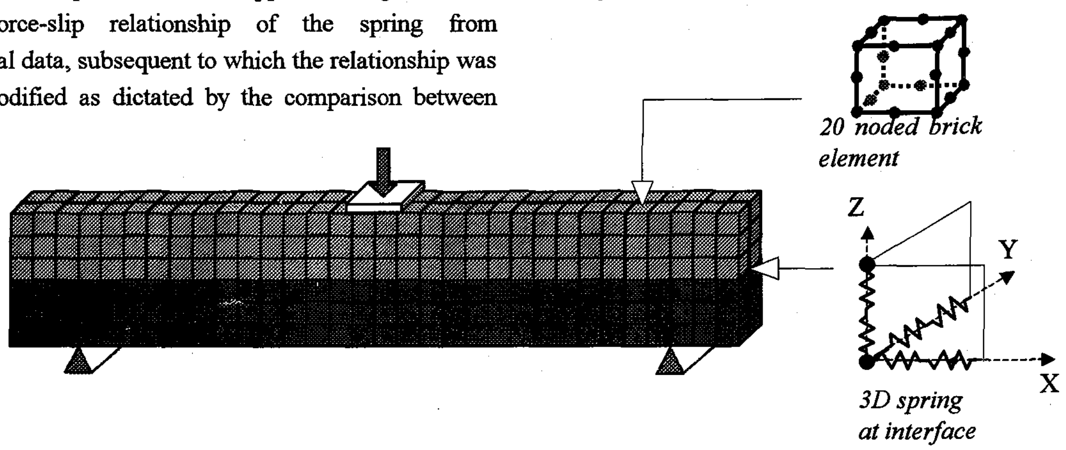


Figure 8. Finite element modeling of open sandwich beams in flexure

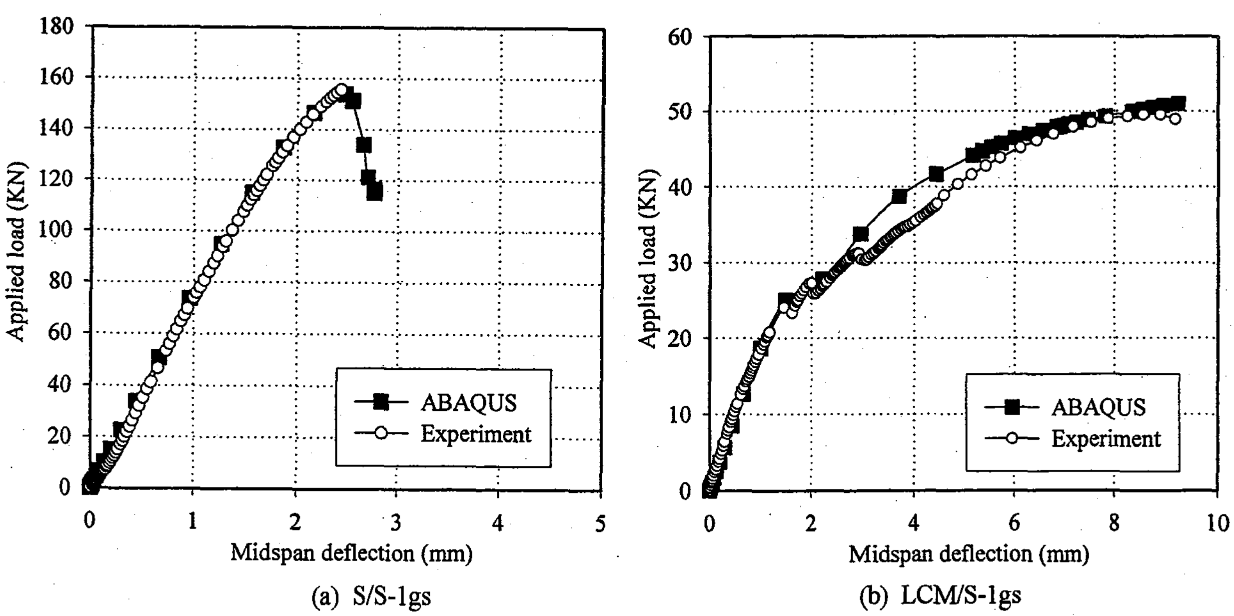
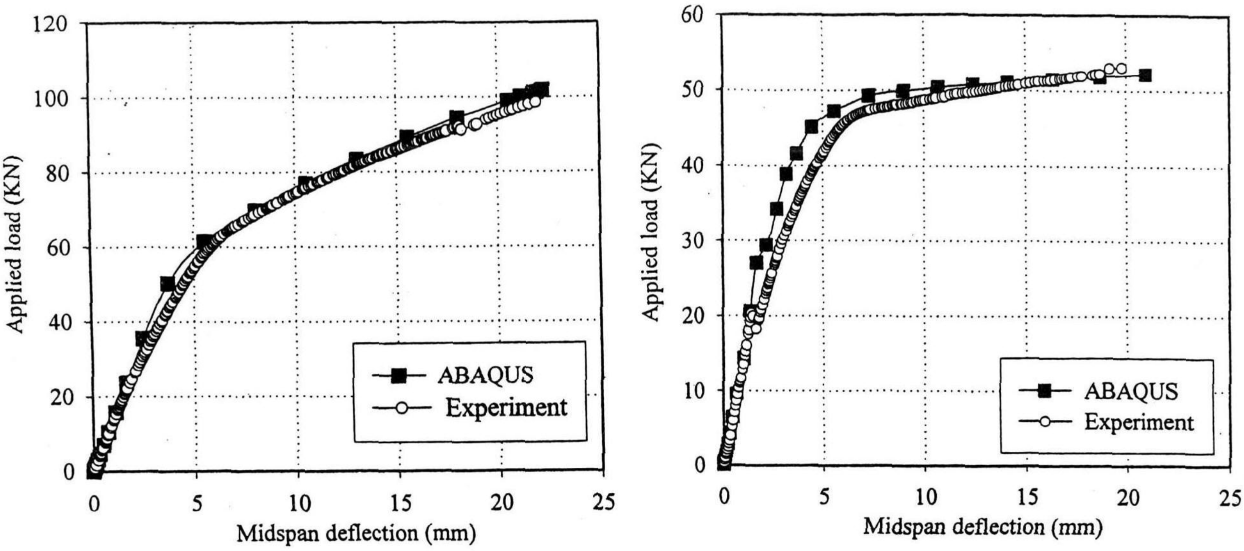


Figure 9. Comparison of simulated load-deflection response to experimental results



(c) E/S-1gs (d) OM/S-1gs

Figure 9 (Contd.). Comparison of simulated load-deflection response to experimental results

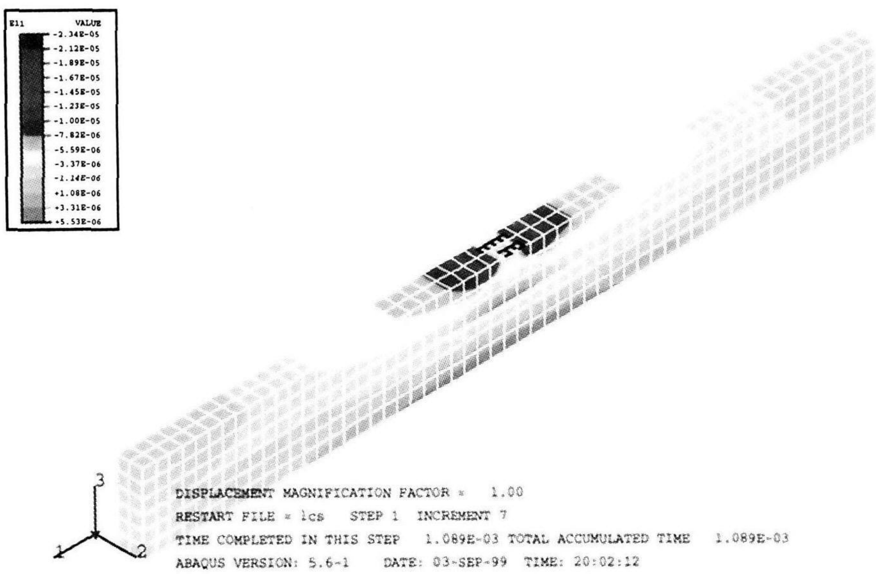


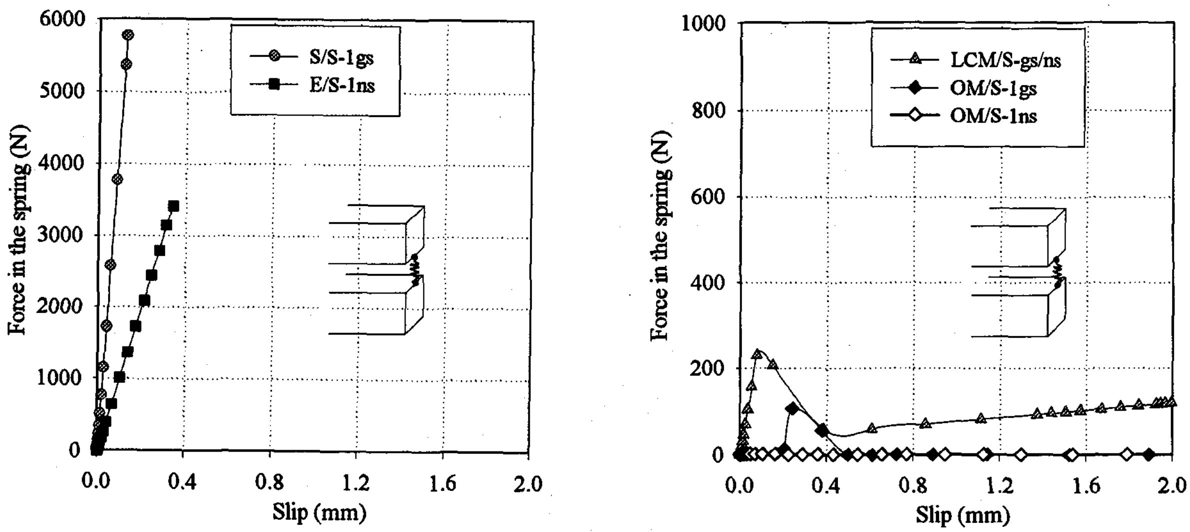
Figure 10. Strain distribution contours

The distribution also depicts strain concentration at the loading point, as was recorded experimentally. Thus, the model is considered verified and sufficient for further study on the behaviour of composite members. However, the sudden drop of load after debonding like the explosion is very difficult to be simulated and also to be provided with reliable observation. Furthermore, the normal stress exists on the interface due to the confinement from the steel tube in the case of filled steel members, so that the modeling taking into account such an effect also should be developed in the future.

4.4 Predicted interface shear stress-slip relation

Prediction of the interface force-slip characteristics for the different material combinations was the main objective of this investigation, with the hope of using the predicted values in the analytical modeling of filled steel tubular members. The prediction was achieved by directing ABAQUS program to specify the force-displacement results of a spring at any required location. Thus, interface characteristics have been obtained for springs located at the beam quarter-span section; quarter-span section had the highest slip compared to the center-span and support sections. In fact Chapman[25] has suggested that slip in composite beams begins around the quarter-span. Fig. 11 illustrates the interface force-slip response, where typical values have been specified for the inner-springs.

A comparison of the different composite beam combinations reveals the very superior interface strength and stiffness for beams S/S and E/S due to high adhesive and tensile strengths of epoxy. The two beams have no post-peak interface response since the beams failed by abrupt



(a) S/S-1gs and E/S-1ns beams (b) LCM/S-1gs/ns, OM/S-1gs and OM/S-1ns beams

Fig. 11 Interface force-slip relation at quarter-span, by ABAQUS

simultaneous debonding at the interface and bursting of the epoxy component into small pieces. On the other hand, the OM/S and LCM/S beams have a post-peak or softening response since failure at the interface is accompanied by gradual formation of cracks in the mortar component. It is also observed that after debonding, the curve for LCM/S does not immediately drop to zero perhaps due to the frictional and stiffening effect of the carbon fibres in the latex cement mortar, which enable the transfer of load across the cracks. Generally, the use of short, randomly distributed fibers in cementitious materials results in the arrest of microcracks by the fibers, and also the restraint against widening of cracks provided by the fibers bridging these cracks[10).

OM/S-1ns interface is seen to give the poorest interface characteristics, presenting a case of almost zero bond attributable to the very low tensile and adhesive strengths of ordinary cement mortar. The low tensile and adhesive strengths, compounded by shrinkage strains of cement mortar induce microcracks (a common occurrence in cement concrete) and may result in early or premature propagation of cracks in the mortar during the fabrication or curing process. This hypothesis is put forward as the reason for the abnormal response of the OM/S-1gs interface, which has an initial near zero bond strength then a sudden rise followed by a drop back to zero bond. It is inferred that the preloading cracks open up in the initial stages of loading relieving the springs at the interface of any load as is depicted by the near zero portion of the curve, and then the cracks stabilize at some point permitting shear load to be transferred to the glued interface as is depicted by the sudden rise of the curve. When the glued interface debonds accompanied by further cracking of the mortar, the curve drops back to the zero line. ABAQUS modeling is seen here to shed more light on the interface behaviour than could be obtained experimentally.

An additional characteristic obtained from ABAQUS was the similarity in stiffness between the inner springs and the edge springs. However, some difference is noted for the peak values of E/S beam, where the peak load and slip are higher for the inner springs than for the edge springs. In the case of LCM/S and OM/S beams, the peak loads for the inner and edge springs are quite similar. In implementing the results obtained in this study for the analytical modeling of filled steel tubular members, average values of force-slip for the entire interface area will be used, and it is also intended to investigate further the edge effect on slip.

5. Conclusions

(1) The very high adhesive and/or shear strengths of epoxy resin have been demonstrated by means of steel-epoxy-steel interface, resulting in increased stiffness and strength of the sandwich beams compared to unglued sandwich beams. However, bond failure is abrupt and with no residual strength.

(2) It is also noted that the natural bond in latex cement mortar-steel interface approximates the glued interface, thus presenting the potentially high adhesive nature of fibre latex-cement mortar.

(3) The main objective of quantifying the average interface load-slip response for the different composite sections was achieved by the use of non-linear spring model.

In summary, the test results present a rational assessment of interface bond behaviour for the various composite sections, which may be useful for the assessment of existing composite beam theory as well as reliable modeling of filled steel tubular members.

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