Flexural Deformation Characteristics of Filled Steel Composite Beams Subjected to Pure Bending

Walter O. Oyawa*, Kunitomo Sugiura** and Eiichi Watanabe***

* M.Sc.(Eng.), Graduate Student, Dept. of Civil Engrg., Kyoto University, Kyoto, 606-8501
** Ph.D., Assoc. Professor, Dept. of Civil Engrg. Systems, Kyoto University, Kyoto, 606-8501
*** Dr. Eng., Ph.D., Professor, Dept. of Civil Engrg., Kyoto University, Kyoto, 606-8501

Concrete-filled steel tubular structures are rapidly emerging as one of the inevitable structural systems for earthquake resistance, as they have been known to exploit the best attributes of both steel and concrete, resulting in higher stiffness, strength and ductility. However, despite their proven record, limitations imposed by the brittleness of cement concrete used, its low tensile strength and diminished durability due to porosity is prompting the search for supplementary or alternative fill materials. Studies are presently being conducted on filled steel composite members, employing lighter, high tensile strength and more durable fill materials for the steel tube, in the form of fibre polymer (latex)-cement mortar and epoxy polymers. Findings of these studies relating to elasto-plastic characteristics of filled steel composite beams subjected to uniform bending highlight the enormous increase in stiffness, strength and ductility of the composite beams, over the empty steel tube, as well as the significant effects of fill material properties e.g. bulk modulus and Poisson's ratio.

Keywords: *Filled steel members, Polymers, Polymer concrete, Epoxy, Flexural strength, Ductility*

1. Introduction

Contemporary structural engineering practice mainly employs traditional materials steel and reinforced concrete as the key construction materials. Steel, for example when used in bridge piers, ordinarily ought to be of sufficiently thick plates and of many longitudinal stiffeners to guarantee the safety of the structure against overall and local buckling deformations, especially under severe seismic loads. Likewise, reinforced concrete structures need to be of enormous cross-sectional dimensions or size, massive reinforcement and of complex joint details to resist strong seismic attack. It is apparent in either case that for the structures so designed to satisfy current seismic performance criteria, colossal amount of financial resources will have to be mobilized. Even then, doubts continue to linger as regards the safety and reliability of structures constructed from these traditional materials as imparted by the 1995 Hyogo-ken Nanbu Earthquake in Japan. During this rare occurrence earthquake, even steel structures which had been considered sufficiently safe in the past, unbelievably collapsed.

In the wake of the severe effects of the earthquake, engineers and researchers in Japan have been coerced into regrouping to seek means of providing mankind with safe structures against severe seismic attack. In this regard, the use of concrete-filled composite steel members has already attracted widespread attention[1,2]. Even prior to this earthquake, interest in the use of concrete-filled steel tubular structures had been gaining momentum in the construction and retrofitting of bridge piers and high-rise building columns[3,4]. In addition to providing a better fireproofing and soundproofing property than steel structures, and are even easier, safer, and faster to construct, concrete-filled structures exploit the best attributes of both steel and concrete, thus allowing the engineer to maintain manageable member sizes while obtaining increased stiffness, energy absorption, strength and ductility[5,6,7,8]. The composite action is such that the steel tube, in addition to acting as a reinforcement, confines the concrete resulting in significant increase in concrete compressive strength, while the confined concrete not only relieves the steel tube of some load but also delays and moderates buckling deformations in the steel tube.

However, despite the noted advantages and proven record of concrete-filled structures against seismic attack, they too have their limitations. Cement concrete used in filling the steel tubes, although preferred due to its lower cost and relatively good strength in compression, has marked drawbacks in that it is brittle, reactive, has very low tensile strength, shrinks with time and because of its porous nature allows for the ingress of deleterious substances that significantly compromise the durability of the structure so constructed. Hence, there will always be a persistent endeavour to improve upon the characteristics of cement concrete while retaining its favourable properties, or to even replace it with more advanced materials.

In this venture, interest has been directed towards evaluating the suitability of fibre polymer (latex)-cement mortar, polymer (epoxy)-aggregate concrete, as well as unblended polymers in the form of pure epoxy and rubber pastes, for use as fill materials in filled steel composite members. Polymers or polymer based materials are attracting increased attention in the construction industry due to the supplementary properties to concrete that they posses viz higher tensile capacity and ductility, lower weight, high damping or resilience, and resistance to physical and chemical attack that ensures their longevity or durability[9,10,11,12,13)]. They were first introduced to hydraulic-cement system in 1923 because of an increased need at that time for durable construction materials[14)]. Although the cost of polymers may be comparatively high at present, a situation attributed to their use in other highly lucrative industries such as the defense and aeronautical industries, it is envisaged that continued research directed towards seeking optimal conditions and cheap derivatives e.g. recycled plastic wastes[15,16)] for use specifically in the construction industry will eventually lead to satisfactory cost reduction. Moreover, proposals being made for the evaluation of full life-cycle cost of structures during design to include such parameters as maintenance, repair, demolition and environmental degradation, rewardingly place the durability of polymer based materials at the forefront of cost analysis.

Previous tests have already been conducted concentrating on the behaviour of different types of filled steel composite stub columns subjected to compressive load[17)]. Results obtained indicate the great potential of fiber latex-cement mortar and epoxies as alternative fill materials to cement concrete or which could be combined with cement concrete to form advanced composites for enhanced strength and ductility.

This present study extends on the observations drawn from the aforementioned first phase, and focuses on the flexural behaviour, namely moment-curvature relations as well as cross-sectional strain and stress distributions, of different types of filled steel composite beams.

2. Experimentation

2.1 Outline of experimental program

Circular filled steel composite beams filled with various types of fill materials were gradually subjected to two-point bending load until limiting load or deformation was attained, while recording load, strain and displacement measurements for curvature manipulation, at suitable increments. The variable parameters were the outer radius to thickness ratio of the steel tube expressed as D/2t, where "D" is the outer diameter of the steel tube and "t" is the thickness, and four different types of fill materials. The ratio of effective length to diameter of steel tube (that is the L_b/D ratio) was maintained constant at 3. The four fill materials investigated were either polymers or polymer based materials, and included two epoxy types of high and low stiffness or low and high flexibility (E1 and E2), and fibre reinforced latex-cement mortar at early age and old age (LCM1 and LCM2). All other parameters remained constant during the test.

Fig. 1 shows a typical specimen, while a summary of the testing program and details is presented in Table 1. To facilitate identification, the test specimens for bending test were designated according to material type and the value of radius to thickness ratio of the steel tube as is illustrated in the nomenclature below Table 1.

Preparation of each of the filled steel composite specimens involved mixing of the constituents of the relevant fill material, followed by filling the steel tube with the mixture. The specimens were then left to cure up to the required day of testing. Epoxy-filled steel specimens were tested after about 1 month (epoxies are rapid curing and normally gain 90% of their full strength within 7 days). Latex cement mortar-filled steel specimens were tested at 12 days for early strength and 77 days (2.5 months) for old age. Latex cement mortar, just like epoxies, gains its near full strength within 7 days, having been prepared from Rapid hardening cement, hence 2.5 months age rather than 28 days was preferred for old age assessment.

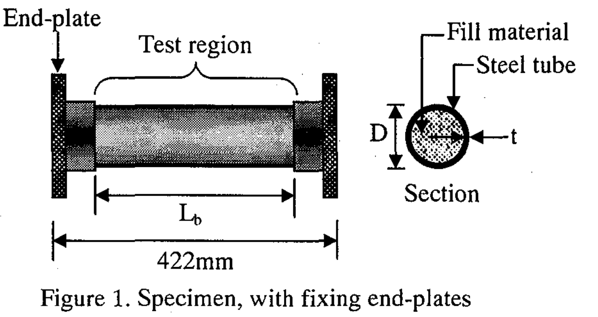


Figure 1. Specimen, with fixing end-plates

Table 1. Beam specimen details (nominal)

Specimen label	Fill material	L_b (mm)	D (mm)	t (mm)	L_b/D	D/2t
S/LCM1-30B	Latex-cement mortar-EA	288	96	1.6	3	30
S/LCM2-30B	Latex-cement mortar-OA	288	96	1.6	3	30
S/E1-30B	Epoxy-HS	288	96	1.6	3	30
S/E2-30B	Epoxy-LS	288	96	1.6	3	30
S-30B	-	288	96	1.6	3	30
S/LCM1-50B	Latex-cement mortar-EA	300	100	1.0	3	50
S/LCM2-50B	Latex-cement mortar-OA	300	100	1.0	3	50
S/E1-50B	Epoxy-HS	300	100	1.0	3	50
S/E2-50B	Epoxy-LS	300	100	1.0	3	50
S-50B	-	300	100	1.0	3	50

Nomenclature: Specimen identification e.g. S/LCM2-50B implies composite beam specimen of steel (S) filled with latex-cement mortar type 2 (LCM2), of D/2t ratio equal to 50 and tested in bending (B).

Abbreviations

EA-Early age (12 days)   OA-Old age (2.5 months)   HS-High stiffness   LS-Low stiffness

2.2 Description of selected fill materials

Fill materials investigated included fibre latex-cement mortar at early age and old age (LCM1 and LCM2), and two epoxies of high and low stiffness or low and high flexibility (E1 and E2), respectively. As previously mentioned, polymers or polymer based materials have supplementary properties lacking in concrete in the form of higher tensile strength and damping or resilience, higher durability and lower weight per unit volume. Moreover, polymers or polymer based materials cure rapidly after only a few days, unlike ordinary concrete.

The fill materials in this phase of study were selected out of a wider range based on previous studies relating to elasto-plastic behaviour of filled steel composite stub columns subjected to compression load[17)]. Findings of the previous study seem to suggest that filling of steel tubular stub columns with latex-cement mortar and epoxy results in considerable increase in strength and ductility over the empty steel tube. However, rubber has negligible effect on the steel tube owing to its very low bulk modulus, and hence has been omitted in this phase of study, while retaining latex-cement mortar and the two types of epoxy.

(1) Fibre latex-cement mortar

In the preparation of fibre latex-cement mortar (LCM), rapid hardening Portland cement is first mixed with fine aggregate of maximum size 2mm, followed by the inclusion of 20mm long carbon fibres. This mixture is then mixed in a ratio of 20:5 with Styrene Butadiene Rubber latex (SBR) in a water/cement ratio of 0.5. Styrene Butadiene Rubber latex (SBR) is an elastomeric polymer and consists of colloidal dispersion of small spherical organic polymer particles in water. On water evaporation the latex particles form a solid matrix that resembles a plastic- or rubber-like material. In fresh cementitious materials, latex particles act as lubricants thereby improving workability. In hardened cementitious matrixes, the sticky latex film interacts with cement paste, generating a double matrix material leading to important gains in impermeability and durability. The fact that the polymer network formation in cementitiuos materials can be accelerated in dry environments makes dry curing after a relatively short period (1 day) of moist curing the suitable curing condition for latex modified cementitious materials[11,12,18)].

Fibre latex-cement mortar is noted for high compressive and flexural strengths, high toughness and impact resistance, as well as low permeability[13)]. On being cast under suitable curing conditions, fibre latex-cement mortar hardens rapidly and is estimated to develop a compressive strength of about 31 N/mm^2 within 7 days; the nominal design strength is about 28 N/mm^2. The inclusion of carbon fibres of low diameter is very effective in arresting microcracks in the cementitious material. However, only fine sand aggregate is recommended for use since coarse aggregate may disturb the fibre distribution in the matrix. In summary, latex modification and carbon fibre reinforcement play complimentary roles in enhancing different aspects of the cementitious material performance. While carbon fibre reinforcement 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 of cementitious materials.

(2) Epoxy

Epoxy resins are a class of organic chemical bonding systems normally used in the preparation of special coatings or adhesives for concrete or as binders in epoxy resin mortars and concretes. They are gradually becoming some of the most important and versatile polymers in modern civil engineering owing to their unique properties such as toughness, versatility of viscosity and curing conditions, good handling characteristics, high adhesive strength, inertness, low shrinkage when compared to most other thermo-setting resins and concrete, and resistance to chemicals. Epoxy resins have found many applications in construction castings, repair materials, bridge deck pavements, coatings, and as structural or nonstructural adhesives[19)]. In these applications, epoxy resins are widely used for polymer concretes, grouting materials, injection glues, and sealants. The most important application of epoxy resins in civil engineering is as structural adhesives for bonding concrete to concrete and concrete to other materials.

The epoxies used in this study are designated E1 and E2. The distinguishing feature between the two epoxies, is their stiffness or flexibility; E1 is characterized as firm or stiff with compressive and tensile strength as high as 61 N/mm^2 and 31 N/mm^2, respectively. E2 on the other hand is relatively flexible, behaving more like a viscous liquid with a tensile strength of about 8.8 N/mm^2. The flowing nature or high flexibility of E2 makes it difficult to assess its ultimate stress-strain conditions, since it deforms well beyond the usual deformation measurements. Preparation of hardened epoxy involves the mixing of the liquid epoxy resin with a chemical hardener or catalyst in the ratio of 2:1 for just a few minutes, after which the mixture is poured into the mould and allowed to cure. In the course of curing, the process of polymerization is initiated consequently resulting in a tough chemical-resistant thermosetting polymer after curing for only a few days[13)].

2.3 Fill material properties

Fundamental properties of the fill materials used in this study were determined from compressive tests conducted on 100mm diameter by 200mm length cylindrical specimens. During the tests, compressive axial load provided by a 1000KN capacity Universal Testing Machine, was applied gradually on the top surface of each specimen which had been suitably capped into a near flat surface by means of fitting steel plates. Data monitored, included longitudinal and horizontal strains through appropriate strain gages for each material, pasted around the middle circumference of each specimen, axial shortening as measured by four Linear Variable Displacement Transducers (LVDTs) between the loading heads and fixed equidistant around the specimen, and the applied load as monitored from the load meter. The data was monitored by a computer via a connection to a data logger. Accordingly, ultimate strength was obtained as the ultimate load per cross-sectional area, Young's modulus (E) as the initial tangent gradient of the load-axial strain curve, and Poisson's ratio (ν) as the ratio of the lateral strain to the longitudinal strain. Bulk modulus (K), regarded as a measure of incompressibility of the fill material, has also been determined from the expression $K = E/3(1\text{-}2\nu)$. Let it be clarified that Young's modulus and Poisson's ratio have been determined using strains measured by the more localized, hence more accurate, strain gages, and not from the average shortening strains measured by LVDTs. Photo 1 shows cylinder specimens of the fill materials after being subjected to compressive load, while Table 2 and Fig. 2 give the properties and characteristics of the fill materials. Further to the mechanical properties of the fill materials, the unit weight defined as the weight of the specimens per unit volume, was determined to illustrate the significant difference in weight between polymers or polymer based materials and ordinary concrete.

A glance at Table 2 presents the varied properties of the different fill materials. It is identified that the two types of latex-cement mortar have properties closer to concrete, since they are actually derivatives of concrete. The difference in strength between LCM1 of 12 days age and LCM2 of 77 days (2.5 months) age is quite small, confirming the rapid hardening nature of latex-cement mortar. Epoxies on the other hand, have much higher Poisson's ratio and much lower Young's modulus than steel. Epoxy E2 has the highest bulk modulus despite its very low Young's modulus, indicating high incompressibility with high capability of outward flow among all the fill materials considered herein. During the compressive tests, ultimate strength of epoxy E2 specimen could not be attained within the usual range of strain measurements, and hence nominal ultimate strength was specified at the very high axial shortening strains of 10%. Upon release of compressive load, the epoxy specimen recovered most of its deformation. Failure of fibre reinforced latex-cement mortar specimens was by formation of longitudinal shear cracks as in the case of concrete (see Photo 1). In contrast, epoxy E1 attained its ultimate load with no visible cracks, suggesting perhaps internal cracking or plastic re-arrangement of molecules. In the previous study relating to compressive tests on filled steel stub columns filled with materials investigated herein, the epoxy E1 at that time failed by formation of a bulging head, which then burst open forming a crack line.

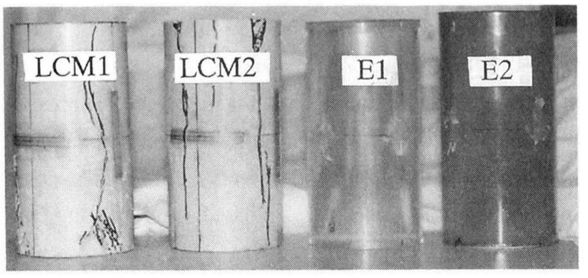


Photo 1. Fill material specimens after compressive test

2.4 Properties of steel

SS400 grade steel was used in this study. Material properties for the two different thickness sizes of steel used were determined from tensile tests on strips cut from steel sheets used to form the tubes. Test strips with a test region of about 15 mm width and 75mm height and grip length of 25mm width and 70mm height at both ends, were each tested by clamping between the heads of the Universal Testing Machine and applying constant load rate while monitoring the axial and lateral strains as well as the applied load through a data logger connected to a computer. Results obtained are shown in Table 3 and Fig. 3. The thinner steel of t=1.0mm is noted to be a little stronger, but less ductile than the steel of t=1.6mm. The yield stress and strain value, determined as the intersection point of the elastic and hardening tangents of the stress-strain curve, are of particular importance in normalizing beam element test results to facilitate comparative evaluation.

Table 2. Properties of the fill materials

Fill material description	Fill material designation	Unit weight (Kg/m^3)	Young's modulus (KN/mm^2)	Poisson's ratio	Ultimate strength (N/mm^2)	Strain at ultimate strength (%)	Bulk modulus (KN/mm^2)
Latex-cement mortar-EA	LCM1	1887	14.5	0.200	26.5	1.04	8.06
Latex-cement mortar-OA	LCM2	1884	17.1	0.220	30.1	0.75	10.18
Epoxy-HS	E1	1153	2.6	0.415	54.5	4.22	5.10
Epoxy-LS	E2	1193	1.12	0.489	>6.1**	-	17.00

**The strength of fill material E2 has been stated at 10 % axial shortening strain, due to its high flexibility

Abbreviations

EA-Early age (12 days)   OA-Old age (2.5 months)   HS-High stiffness   LS-Low stiffness

Table 3. Properties of steel

Thickness (mm)	Young's modulus (KN/mm^2)	Poisson's ratio	Yield stress (N/mm^2)	Yield strain (%)	Ultimate strength (N/mm^2)	Elongation at break (%)	Bulk modulus (KN/mm^2)
1.6	216	0.347	225	0.1042	325	46.9	235
1.0	211	0.337	230	0.1092	340	42.8	216

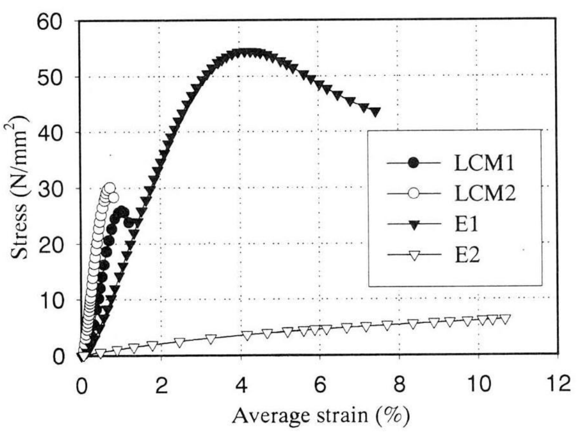


Figure 2. Compressive stress-strain relations for the fill materials (shortening measured by LVDTs)

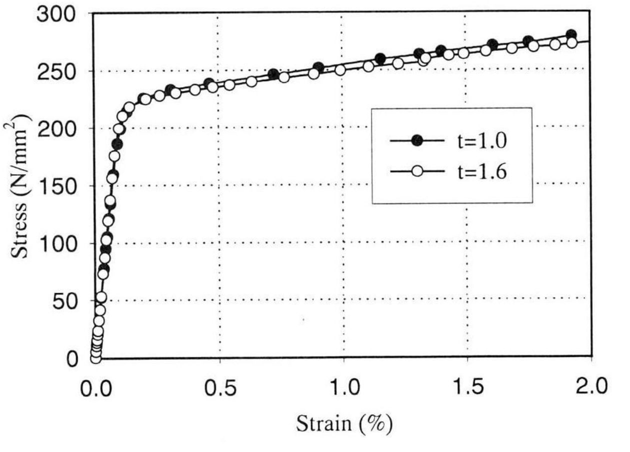


Figure 3. Tensile stress-strain relations of steel strips of different thickness (t)

2.5 Test set-up and loading

It was the objective of this study to assess the flexural behaviour of filled steel composite beam specimens. When a bending moment acts on a composite member, it is hopefully anticipated that perfect composite interaction between the constituent materials will be realized. However, in reality such factors as slippage at interface, local buckling of steel in compression and cracking or compressibility of the fill material will act to defuse or lessen complete composite interaction. In order to quantify such uncertain phenomena, bending tests were carried out on eight filled steel composite beams and two empty steel beams.

The beam tests were in two series formed from tubular steel pipes of radius/thickness ratio, D/2t=30 and 50, and for each of the series several fill materials were involved. A specimen for test was first pasted with seven equally spaced strain gages circumferentially on one side at the mid-span. The circular specimen having rectangular rigid end plates was then firmly bolted to rigid rectangular steel attachments at either end. The whole mass was in turn rested on simple supports fixed to a firm rigid beam base as shown in Fig. 4. The setup was rested and aligned on the bottom platen of 1000KN capacity Universal Testing Machine. Two Linear Variable Displacement Transducers (LVDTs) with magnetic bases were fixed, one at the top and one at the bottom of the beam in such a way as to measure the relative horizontal movement between two known points of gage length=L_b, in order to determine the average curvature. The vertical distance between the LVDTs (S) was recorded for every test.

Load application on the specimen was a two-point load meant to induce a state of pure bending in the test region, and supplied by the Universal Testing Machine through a rigid loading beam as shown in Fig. 4. The loading beam and its attachments had to be securely clamped to prevent possible disastrous consequences. Commencement of the loading process was by slow application so as to avoid abrupt jolting loads. Loading then proceeded gradually and at suitable constant increment, data namely the applied load, displacements of the LVDT heads and strains, as monitored by a computer via a data logger were recorded. The constant incremental load rate was followed until the anticipated yield point of steel, following which the measurement time interval was reduced. For the beam specimens which attained ultimate load, loading was continued beyond the peak load up to a stage where it was judged that no further useful information could be obtained from the test results. Failure load was taken as the peak load after the specimen shed off any additional load increment. However, for the very strong and ductile beams loading was terminated when excessive plastic deformation was evident, particularly when the LVDTs were extended beyond their measuring limit.

3. Results and Discussions

3.1 Moment –curvature relationships

The moment-curvature relationship of a short beam or column is of prime importance in the analysis of any long beam-column, providing required parameters such as the stiffness of a beam-column. The obtained normalized moment-curvature relationships (from idealized representation in Fig. 5) are presented in Fig. 6, the summary of which is given in Table 4. The moment (M) for any applied load (P) can be obtained from the expression;

$$M=PL_a/2 \quad (1),$$

and curvature (ϕ), rotation per unit length, is derived from the expression;

$$\phi = (-U_{top}+U_{bottom})/(S \cdot L_b) \quad (2),$$

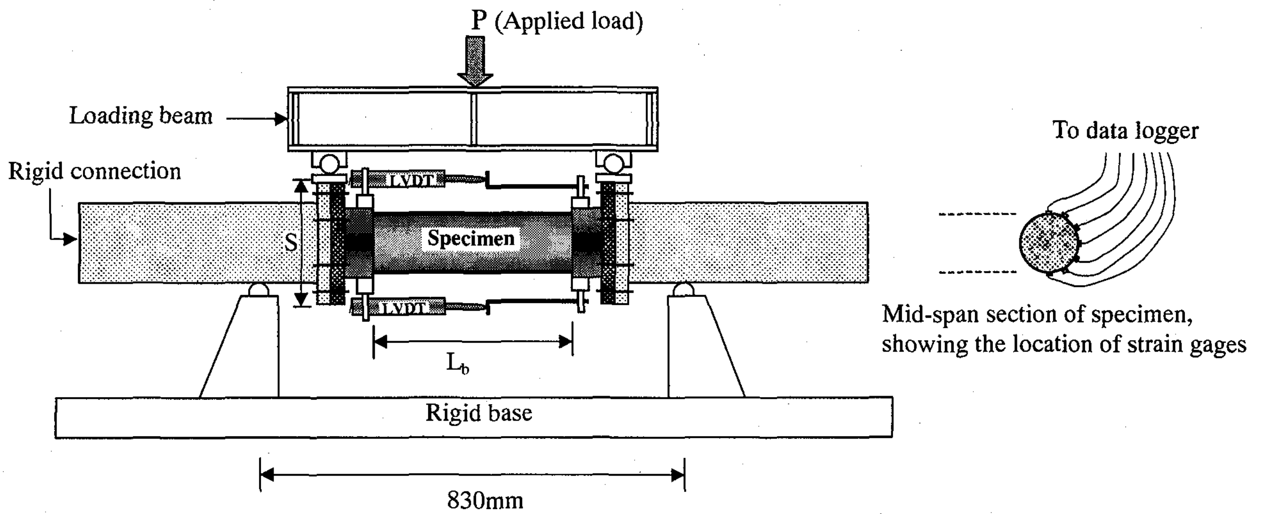


Figure 4. Test set-up before loading

where L_a is the distance from the beam support to the point of load application on the beam assuming symmetry of loading, U_{top} and U_{bottom} are displacements measured by the top and bottom Linear Variable Displacement Transducers, respectively, L_b is test section length, while S is the vertical distance between the two LVDTs.

Schematic representation of the structural and loading conditions as drawn in Fig. 5 implies that the test section should be subjected to a state of pure bending. Accordingly, the assumptions and theories of pure bending may be expected to apply to the elastic structural behaviour of the beam specimens, e.g. plane sections before bending should remain plane even after bending.

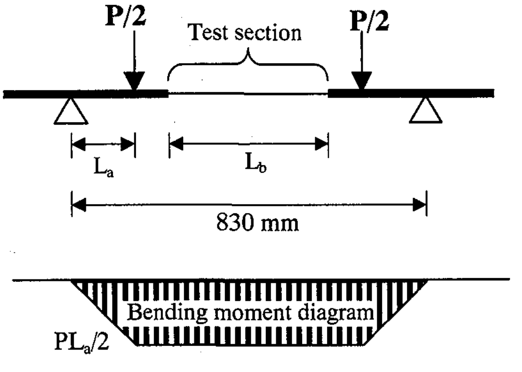


Figure 5. Schematic representation of structural and loading conditions

The yield moment (M_y) and yield curvature (ϕ_y) can be determined from the expressions below.

$$M_y = \frac{\sigma_{sy} I_s}{y_e} \tag{3}$$

$$\phi_y = \frac{\sigma_{sy}}{E_s y_e} \tag{4}$$

where, σ_{sy} : yield strength of steel

I_s :moment of inertia of the empty steel tube

y_e : distance from the elastic neutral axis of the circular cross-section of empty steel tube to the extreme point

E_s :modulus of elasticity of steel

Several distinct features may be observed from the results in Fig. 6. First and foremost, the superior strength and ductility of composite beams vis-à-vis the empty steel tube is evident. This clearly depicts the beneficial interaction between the steel tube and the fill material. The confined fill material considerably delays local buckling of the steel tube on the compression side, only permitting minor outward local deformations in the post-yield response, thereby inducing the extensive exploitation of the bottom tensile yield strength of the steel tube. In other words, although these composite specimens were observed to have undergone considerable plastic deformations in bending, they continued to resist load because local buckling in the steel tube was strictly limited by the presence of the fill material, consequently resulting in increased strength and ductility. Increase in strength and ductility due to the presence of fill material has been recorded for concrete-filled steel beams by other researchers. Particularly, it was recognized that the restriction of longitudinal movement of the fill material by providing end plates or intermediate diaphragms significantly affect ductility[4].

Results of epoxy E2-filled beam specimens (S/E2) are of particular interest in that they show considerable increase in ductility but only nominal increase in strength. This is very desirable in the post Hyogo-ken Nanbu earthquake seismic design method in Japan, because foundation structures of lesser size and cheaper cost can be used[20]. This advantage is most magnified in the retrofitting of structures where modifications in foundations are most unwelcome, necessitating only an increase in ductility and not strength of the retrofitted superstructure. Elsewhere in the world, many design codes now recommend two levels of design seismic force in that structures should be able to resist moderate earthquakes without structural damage, and be able to resist severe earthquakes without collapse but perhaps with some structural and non-structural damage. To satisfy these performance criteria, all structures should be designed to have adequate strength and stiffness to meet the serviceability limit states when responding to moderate earthquakes, and to have adequate strength, stiffness and ductility to satisfy the ultimate limit states when responding to severe earthquakes. Under severe seismic attack, the emphasis seems to be shifting towards high ductility structures, designed employing equal energy (constancy) assumption.

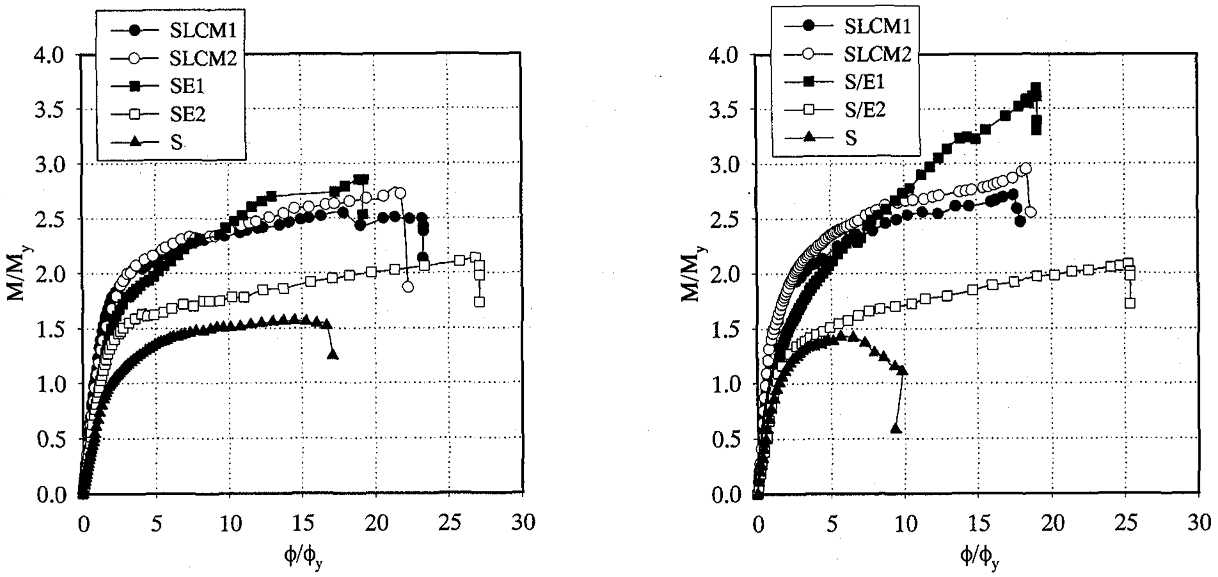
The general shape of the composite beam curves depict an initial elastic linear portion, followed by a bend as the steel yields and transfers some of its load to the fill material in the compression zone. When this transfer stabilizes, the hardening gradient takes a near linear gradient again as the confined fill material in the compression zone takes up most of the load, while the stretched steel in the tension zone resists most of the tensile load. During the tests, some specimens had cracks at the welded connection points, thus leading to an apparently premature attainment of their ultimate state. However, the obtained moment-curvature characteristics show very high ductility and/or strength, thus providing very valuable information required for the understanding of the behaviour of prototype filled steel columns or piers. Further tests will continue, particularly to assess the full potential of these new materials subjected to other forms of loading, e.g. combined loading and cyclic loading.

Table 4 provides a quantified summary of the flexural response of the tested beams, with the outstanding values shown in bold numbers. It confirms the observations noted in Fig. 6, presenting the comparatively higher elastic stiffness of the mortar-filled beams due to the higher Young's modulus of latex-cement mortar, and the much higher hardening stiffness of epoxy E1-filled beams possibly related to the higher tensile and adhesive strength of epoxy E1. In addition, the desirable higher ductility (accompanied with only nominal strength increase) of epoxy E2-filled beams is noted. The composite effect of filled beams is most evident for the thinner steel tube of D/2t=50, where both the elastic and hardening stiffness are higher than that for D/2t=30. Steel tube of D/2t=50 being the thinner steel tube is more susceptible to rapid buckling in the absence of fill material, hence the delay of local buckling by the fill material is more effective. Table 4 further shows a dramatic reduction in hoop/axial strain ratio of mortar-filled beams in the bottom tensile zone. This is thought to be due to the low tensile strength of the stiff mortar, thus initiating early cracking with consequent expansion of the mortar leading to biaxial tension in the bottom tensile zone of the steel tube.

For the empty steel beam specimens, the ultimate normalized moment is about 1.5, this being higher than the shape factor of thin-walled circular sections of about 1.3. The increase is a product of strain hardening of steel, particularly for the thicker steel of D/2t=30.

Photo 2 attempts to show the buckling and plastic bending deformations of some of the specimens. Local buckling on the compression side is clearly visible in the case of empty steel (S-50) and epoxy E1-filled (S/E1-50) beams. Epoxy E1, due to its low bulk modulus permits the buckling of steel in the compression zone. However, for the other composite specimens the fill materials (LCM2 and E2) of higher bulk modulus considerably limit the extent of local buckling and instead a permanent bent shape of the global specimen results.

In general, two modes of deformation are known to manifest themselves in the buckling of empty uniform cylindrical shells acted upon by moments at their extreme ends. The first is the Brazier effect which involves increasing ovalization of the cylindrical cross-section with increasing moment, with the result that the moment-curvature relationship is nonlinear; and the moment eventually reaches a maximum or limit-point value. The second type of deformation is termed the bifurcation buckling whereby axial waves form along the length of the cylinder, having a maximum amplitude at the extreme compression side of the shell and gradually around the circumference[21]. In a real situation, it must be expected that both these effects will be present simultaneously with one or the other dominating, depending on the proportions of the tube and the distribution of initial imperfections. For thicker metal tubes with D/2t<30, there will be more effects of plasticity and less of buckling deformations, just like was observed in this study where the steel tube of D/2t=30 had less buckling deformations in contrast to the tube with D/2t=50.



(a) D/2t=30 (b) D/2t=50

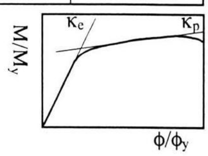
Figure 6. Normalized moment-curvature relationships

Table 4. Summary of bending test results

Specimen label	Elastic stiffness κ_e	Hardening stiffness κ_p	M_{ult}/M_y	ϕ_{ult}/ϕ_y	Hoop/axial strain ratio on beam surface			
					Top of the beam		Bottom of the beam	
					υ_e	υ_p	υ_e	υ_p
S/LCM1-30B	**1.20**	0.0339	2.55*	17.9	0.321	**0.802**	**0.261**	**0.149**
S/LCM2-30B	**1.03**	0.0336	2.74*	22.0	0.360	**0.821**	**0.268**	**0.118**
S/E1-30B	0.817	**0.0938**	2.88*	19.2	0.377	0.689	0.461	0.624
S/E2-30B	0.809	0.0231	2.13	**27.0**	0.379	0.703	0.381	0.603
S-30B	0.645	0.0228	1.57	14.0	0.335	0.563	0.389	0.828
S/LCM1-50B	**1.51**	0.0426	2.71*	17.5	0.315	**0.806**	**0.243**	**0.116**
S/LCM2-50B	**1.73**	0.0459	2.95	18.5	0.351	**0.815**	**0.212**	**0.074**
S/E1-50B	0.848	**0.1337**	3.69*	19.1	0.362	0.643	0.448	0.613
S/E2-50B	0.817	0.0298	2.08	**25.3**	0.355	0.681	0.380	0.592
S-50B	0.807	early buckle	1.43	5.88	0.345	0.690	0.342	0.638

Note: κ_e and κ_p are as defined in the side Fig., while υ_e and υ_p represent the elastic and plastic values of the hoop/axial strain ratio, respectively.

* indicates that the specimen failed at the welded connection point, and not in the anticipated test region. Also, outstanding values are shown in **bold**.



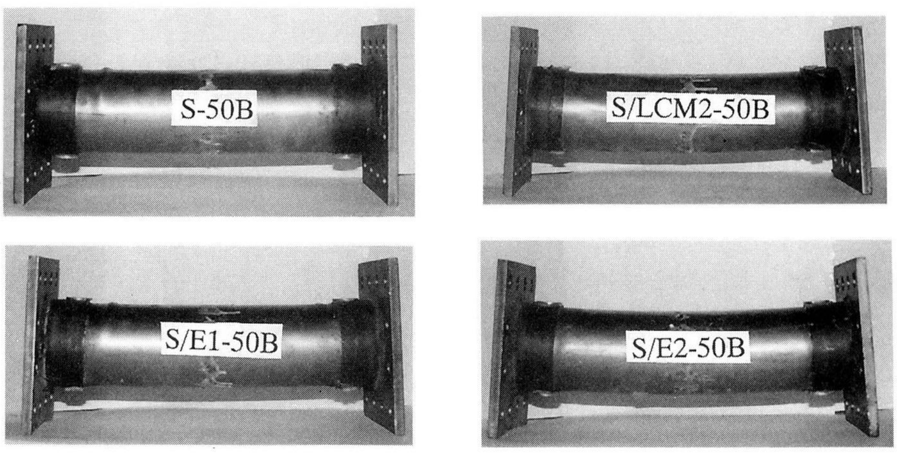


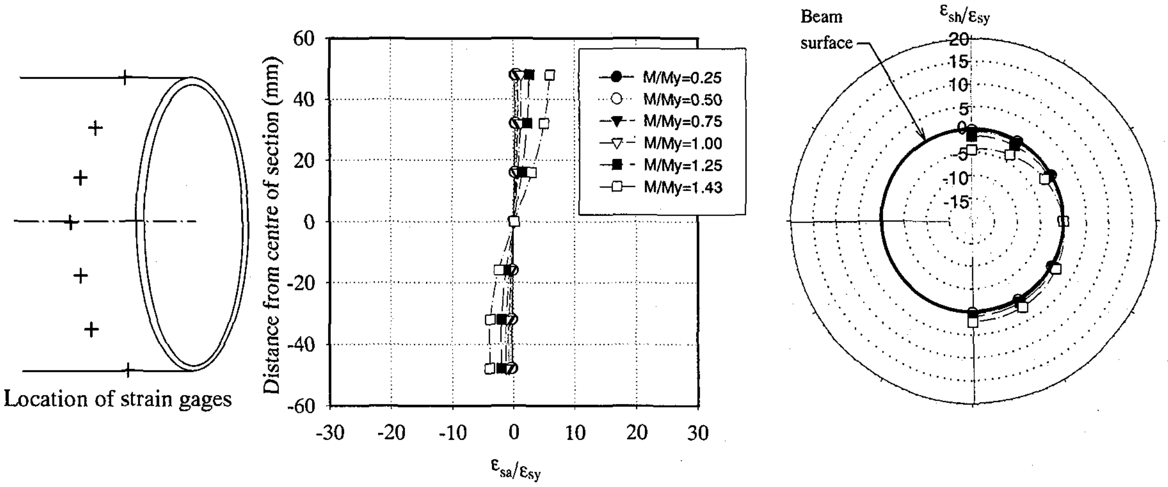
Photo 2. Buckling and plastic bending deformations of some of the beam specimens

3.2 Strain distributions over the cross-section

Figs. 7-10 give the normalized axial (ε_{sa}) and hoop strain (ε_{sh}) distributions over the beam cross-section, normalized by the steel yield stress (ε_{sy}), where compressive strain is taken as positive. A first look of the graphs promptly shows the non-linearity of the strain distribution, even for the empty steel tube. This highlights the unique behaviour of thin-walled circular steel members, inconsistent with the fundamental assumption in the theory of pure bending; i.e. plane sections should remain plane before and after bending. It is further observed that the plastic hoop stresses are quite high, in some instances almost equaling the axial strains. For the case of the empty steel tube, these observations are probably due to bifurcation and/or ovalization of the steel tube as discussed in the previous section, causing cross-sectional instability and complex distribution of stresses.

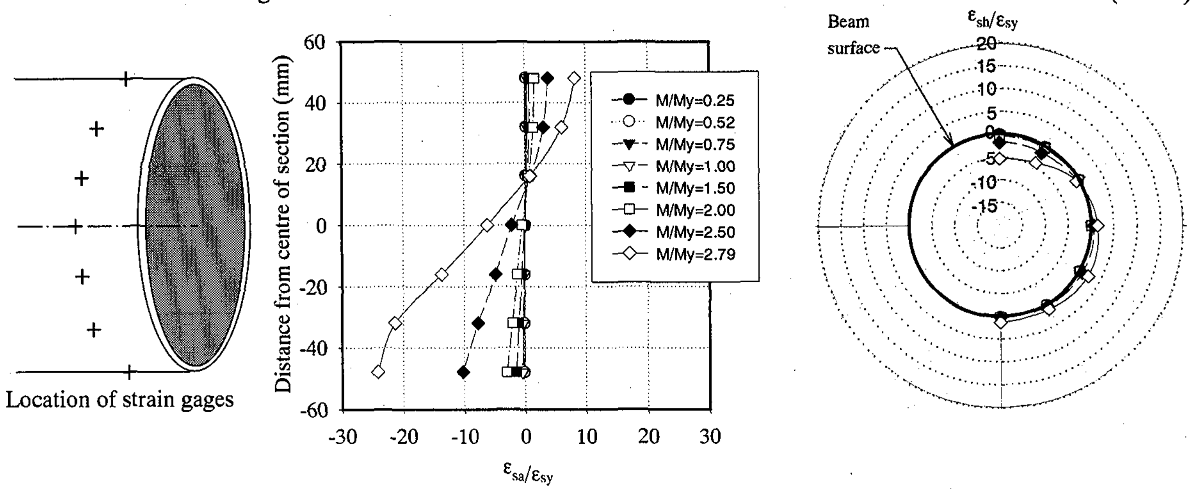
A noteworthy difference in behaviour of the different types of filled steel specimens, is the degree of upward movement of the neutral axis as loading progresses. It is observed that upward movement of the neutral axis is more pronounced for the case of latex-cement mortar filled steel specimens than for the epoxy-filled steel specimens. The explanation of this occurrence lies in the lower tensile strength of concrete or mortar based materials when compared to the much tougher polymer materials. The flexible epoxy types have higher tensile and adhesive strengths, and are thus able to interact effectively with the steel tube both in the compressive and tensile zones. This is a factor of enormous value if one considers that the design of reinforced concrete structures completely neglects the tensile zone of concrete due to excessive cracking. Worse still, it is the tensile cracks in concrete that allow for the ingress of deleterious substances or chemicals that severely compromise the durability of concrete structures.

Generally, the level of confinement for fill material in beam bending is less than that in stub column under compression because of the existence of both compressive and tensile zones in the case of bending. However, for epoxy E2-filled steel beam (S/E2-50B), an approximately equally balanced high axial and hoop strain distribution is detected. As previously stated, Epoxy E2 is an interesting material, owing to its very high bulk modulus and Poisson's ratio, in that it seems to behave somewhere in-between liquids and solids depending on the extent to which it is stressed. Thus, under initial loading, epoxy E2 exerts near equal pressure on the steel tube in all directions just like a liquid, resulting in high level of confinement of E2. This behaviour was also assessed during compressive tests on filled steel stub columns[17].



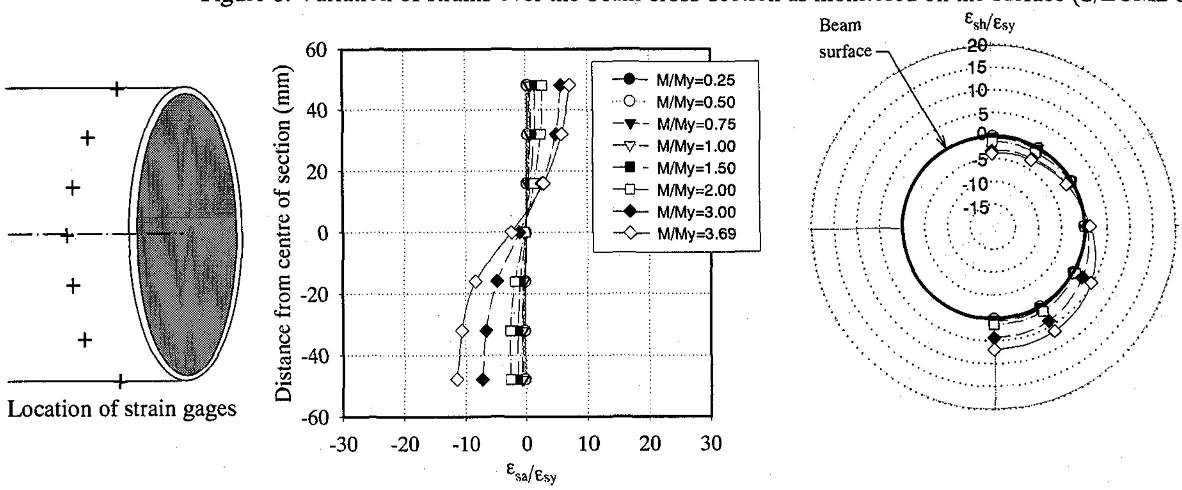
(a) Axial strains (b) Hoop strains over the circumference

Figure 7. Variation of strains over the beam cross-section as monitored on the surface (S-50B)



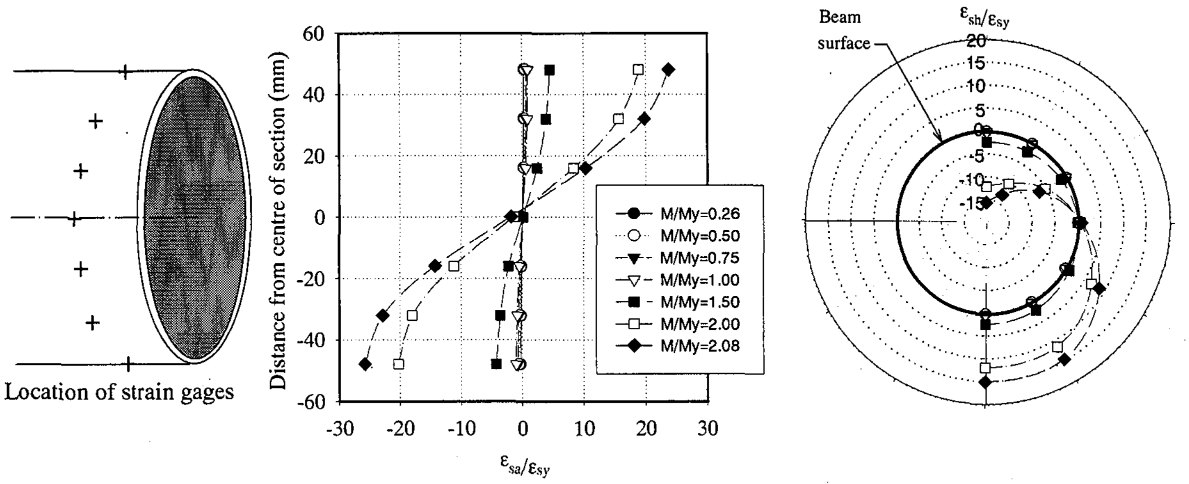
(a) Axial strains (b) Hoop strains over the circumference

Figure 8. Variation of strains over the beam cross-section as monitored on the surface (S/LCM2-50B)



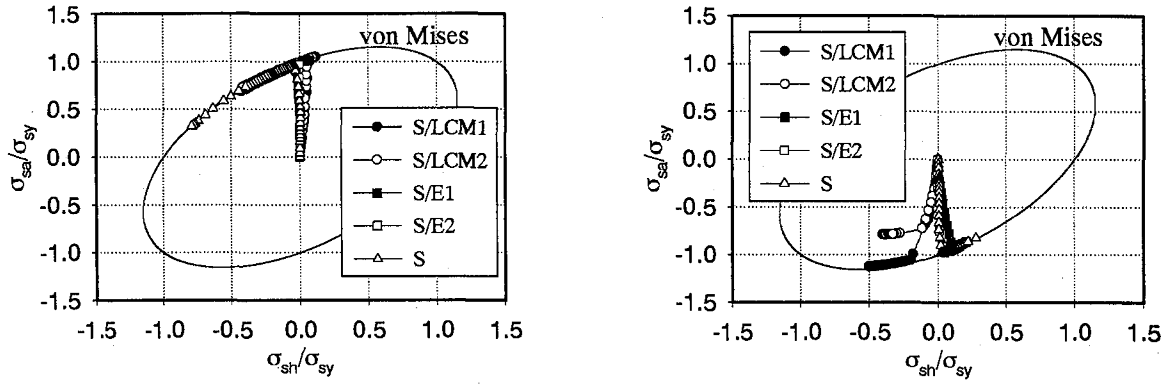
(a) Axial strains (b) Hoop strains over the circumference

Figure 9. Variation of strains over the beam cross-section as monitored on the surface (S/E1-50B)



(a) Axial strains (b) Hoop strains over the circumference

Figure 10. Variation of strains over the beam cross-section as monitored on the surface (S/E2-50B)



(a) Top of the beam (compression) (b) Bottom of the beam (tension)

Figure 11. Elasto-plastic biaxial stress path of the steel component (D/2t=50)

3.3 Biaxial stress path of the steel component

Fig.11 gives the normalized axial stress (σ_{sa}) versus hoop stress (σ_{sh}) at the top and bottom of the various beams with D/2t=50. The stresses have been evaluated from the localized biaxial strain readings employing generalized Hooke's law for the elastic region and Prandtl-Reuss equations associated with elasto-perfectly plastic von Mises' yield function for the elasto-plastic range (see Reference 17 for the equations). It is observed that unlike the stress paths at the top compressive zone of the beams, the stress paths at the bottom tensile zone are more scattered. Particularly, the latex-cement mortar filled steel beams show a sudden increase in hoop tension in the bottom tensile zone. This presents a clear distinction of the tensile properties and behaviour of latex-cement mortar and epoxy. The more flexible and higher tensile/adhesive strength epoxy interacts harmoniously with the encasing steel tube in the bottom tensile zone. On the other hand, latex-cement mortar in the tension zone soon cracks, partially dissociating from the steel tube. The initiation of cracking is accompanied by volumetric expansion of the mortar, inducing biaxial tension in the steel tube in the tensile zone.

4. Conclusions

In close conformity with results from previous compressive tests on stub columns, bending tests have further reaffirmed the immense potential of the much lighter and more durable fibre latex-cement mortar and epoxy as alternative fill materials to cement concrete for enhanced stiffness, strength and ductility. It is presented that:

(a) both fibre latex-cement mortar and epoxy fill materials produce composite steel beams of much increased strength and ductility. The increase in ductility (with only nominal increase in strength) for the case of epoxy E2-filled beams is very desirable in current design recommendations.

(b) epoxy types present varied significant material properties, when compared to concrete or mortar. For example epoxy E2, unlike epoxy E1, has high bulk modulus and Poisson's ratio, which imply incompressibility with the ability to flow outwards when compressed.

(c) epoxy filling of steel tubular beams results in less upward translation of the sectional neutral-axis, since epoxy types unlike concrete, contribute towards moment resistance in both compression and tension zones owing to their high tensile/adhesive strength.

(d) composite interaction between the steel tube and fill material is optimized for thinner-walled steel tubes, which are more susceptible to buckling in the absence of fill material.

Studies are continuing to comprehend the behaviour of these new kinds of materials, and in addition to seek means of cutting down on the high cost of polymers. To this end, the relatively reduced cost of latex-cement mortar when compared to epoxy resin is noteworthy. Further still, it is intended to also investigate epoxy concrete, consisting of the usual aggregates bound together with epoxy resin. However, let it not be forgotten that the high durability of polymeric materials will in due time feature prominently and positively as a cost factor in the emerging new kinds of design methods that involve life cycle costing.

Acknowledgements

This research was financed by Grant-in-Aid for Scientific Research (C) (No. 10650462) from the Ministry of Education, Science, Sports and Culture, and the Kozai club. The authors also wish to express their profound gratitude to Mr. Wakahara, N. of Konishi Bond Co. for his assistance in fabricating the test specimens.

References

1) Tajima, H., Hanno, H. and Kosaka, H., Experimental studies on steel rectangular piers under cyclic loading, *Proc. of the 5th International Colloquium on Stability and ductility of steel structures*, pp. 205-212, 1997.
2) Kawashima, K. and Unjoh, S., Impact of Hanshin/Awaji earthquake on seismic design and seismic strengthening of highway bridges", *J. Struct. Mech.*, JSCE, 1-30, 1997.
3) Bradford, M.A., Design strength of slender concrete-filled rectangular steel tubes, *ACI Struct. J.*, Vol. 93(2), pp. 229-235, 1996.
4) Ohtani, Y. and Matsui, S., Stability problems in steel-concrete composite members and elements, Structural stability design: Steel and composite structures, edited by Fukumoto, Y., *Elsevier Science,* London, pp. 229-251, 1997.
5) Ge, H. and Usami, T., Cyclic tests of concrete-filled steel box columns, *J. Str. Engrg.*, ASCE, Vol. 120(10), pp. 1169-1177, 1996.
6) Usami, T. and Ge, H., Ductility of concrete-filled steel box columns under cyclic loading, *J. Str. Engrg.*, ASCE, Vol. 120(7), pp. 2021-2040, 1994.
7) Elnashai, A.S., Broderick, B.M. and Dowling, P.J., Earthquake-resistant composite steel/concrete structures, *The Structural Engineer*, Vol. 73(8), pp. 121-132, 1995.
8) Shams, M. and Ala, S.M., State-of-the-art of concrete-filled steel tubular columns, *ACI Struct. J.*, Vol. 94(5), pp. 558-571, 1997.
9) Ohama, Y., Principle of latex modification and some typical properties of latex-modified mortars and concretes, *ACI Mat. J.*, Vol. 84(6), pp. 511-518, 1987.
10) Chen, P.W. and Chung, D.D.L., A comparative study of concretes reinforced with carbon, polyethylene, and steel fibers and their improvement by latex addition, *ACI Mat. J.*, Vol. 93(2), pp. 129-133, 1996.
11) Zayat, K. and Bayasi, Z., Effect of latex on the mechanical properties of carbon reinforced cement, *ACI Mat. J.*, Vol. 93(2), pp. 178-181, 1996.
12) Soroushian, P., Aouadi, F. and Nagi, M., Latex-modified carbon fibre reinforced mortar, *ACI Mat. J.*, Vol. 88(1), pp. 11-18, 1991.
13) Kardon, J., Polymer-modified concrete: Review, *J. Mat. Civil Engrg.,* ASCE, Vol. 9(2), pp. 85-92, 1997.
14) Sujjavanich, S. and Lundy, J.R., Development of strength and fracture properties of styrene-butadiene copolymer latex-modified concrete, *ACI Mat. J.*, Vol. 95(2), pp. 131-143, 1998.
15) Rebeiz, K.S. and Fowler, D.W., Flexural strength of reinforced polymer concrete made with recycled plastic waste, *ACI Struct. J.*, Vol. 93(5), pp. 524-530, 1996.
16) Solovjov, G.K., Trambovestky, V.P. and Kruger, D., Furan resin polymer concrete in the commonwealth of independent states (CIS), *ACI Mat. J.*, Vol. 91(2), pp. 158-160, 1994.
17) Oyawa, W.O., Sugiura, K. and Watanabe, E., Elasto-plastic behaviour of axially loaded filled circular steel stub columns, *J. Struct. Engrg.*, JSCE, Vol. 44A, pp. 147-158, 1998.
18) ACI Committee 548, Guide for the use of polymers in concrete, *ACI J.*, Vol. 83(5), pp. 798-829, 1986.
19) Tu, L. and Kruger, D., Engineering properties of epoxy resins used as concrete adhesives, *ACI Mat. J.*, Vol. 93(1), pp. 26-35, 1996.
20) Kitada, T., Ultimate strength and ductility of state-of-the –art concrete-filled steel bridge piers in Japan, *Engineering Structures*, Vol.20(4-6), pp. 347-354, 1998.
21) Reddy, B.D., An experimental study of the plastic buckling of circular cylinders in pure bending, *Int. J. Solids Structures*, Vol. 15, pp. 669-683, 1979.

(Received September 18, 1998)