Assessment on Non-Concrete Filled Steel Bridge Piers Subjected to Cyclic Loading

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In view of the enormous cost of maintaining or rehabilitating deteriorating infrastructure, the application of advanced composite structural systems as well as new materials in the construction industry is now considered a necessity for sustainable economy. Polymers are now considered to be both complementary and supplementary to cement concrete owing to their vast potential that include high durability, fatigue resistance, strength and deformability. Particularly, the versatility and wide variation of material properties is attractivein design. In this study, attempts are made to assess the effectiveness of filling polymer based materials into steel bridge piers especially on their strength and ductility improvement. This study is a continuation of previous experimental and analytical works on composite stub columb compression test, beam bending test, interface slip test and corresponding FEM analysis. It is confirmed that the epoxy filling can improve ductility and make strength degradation less significant, without overstrength and weight increse not like ordinary concrete filling.
***Keywords**: Filled steel tube, Latex modified mortar, Epoxy, Cyclic Loading, Buckling, Fill materials*

1. Introduction

Prior to the 1995 Hyogoken-Nanbu Earthquake, the Japanese bridge design specifications did not include any requirements to ensure ductile response of steel piers, even though ductile detailing was mandated for reinforced concrete piers; implicitly, reliance on the inherent ductility of the steel material was deemed to be likely sufficient[1)]. In consequence and most surprisingly, steel piers were significantly damaged due to the Hyogoken-Nanbu Earthquake. In the aftermath of the earthquake, worldwide consensus for aseismic design of structures is centred on providing increased structural deformability and energy absorption capacity[1),2),3),4)]. Use of fill materials such as concrete inside the hollow steel tube is seen as the most obvious economic possibility of achieving this feat, hence precise tools or methods are required to predict the cyclic behavior of filled steel tubular members.

Nakai et al. in an experimental attempt to evaluate the strength and ductility of concrete filled thin walled steel box columns after receiving seismic loading concluded that the composite columns are much superior than the empty steel columns[5)]. They also determined that shear connections greatly enhanced ductility of the filled box columns. In order to establish the rational seismic design method for concrete-filled steel pipe bridge piers, Koeda et al. conducted cyclic loading tests on circular concrete-filled steel pipes under constant axial force[6)]. They confirmed that the strength and ductility of the composite pipes were considerably increased over the empty pipe, which degree increased as the fill length increased. Most recently, Nakanishi et al. conducted an experimental study on ultimate strength and ductility of concrete filled steel columns under strong earthquakes, following which they proposed composite sections that enable the enhancement of ductility of columns, but with only nominal increase in strength, thus saving on foundation retrofitting costs[7)]. Such composite section could be of low strength fill material e.g. concrete of 12 N/mm^2 strength, or have a hollow small diameter steel or plastic tube inserted in the middle core, in addition to the encasing outer steel tube as a means of reducing self weight. Usami and his co-workers also have conducted the cyclic loading tests on concrete-filled steel bridge piers and concluded the effectiveness of concrete filling on strength and ductility[8),9)].

This study is concerned with the cyclic behavior of non-concrete filled steel composite columns based on experimental and analytical works with the main variable being the type of fill material, to complement the heavy weight and low bond strength of concrete. The work herein is a sequel to the previous research by the authors referred to Refs[10,11,12,13,14]. By filling suitable materials into steel tubes, not like brittle materials of concrete but elastic materials of polymers, it is anticipated that even the severe effects of complex multi-directional loads[15)] can be mitigated through enhanced ductility, energy absorption capacity and less weight increase by filling.

2. Experimental Procedure of Cyclic Loading Test

2.1 Outline of experimental program

Studies were conducted on six filled steel box columns and two hollow steel box columns modeling bridge piers, tested as cantilever columns under constant axial load and each subjected to cyclic lateral load in either a designated X or Y direction. For the filled steel box columns (Fig. 1), the steel tubes were first fabricated as thin-walled rectangular hollow steel box columns with rounded corners and of size B=150mm, D=100mm, t=4.21mm, length L=881mm and effective height h=853mm. To prevent cross-sectional distortions during tests, diaphragms of about 6.3mm thickness were welded at three spaced locations along the length of the specimens, on the outside since it was not practically possible to weld on the inside. The steel top end plate had two small holes of about 50mm diameter each, to allow for the injection of the fill material. Relevant fill material type after being prepared was then injected into the entire box tube through one small hole, while the other hole allowed for the release of air. The specimens were then allowed to cure until the required testing date. No surface treatment such as sand brust to improve bond strength was made.

The main test variable investigated was the type of fill material inside the steel tube, and these were compared to hollow steel columns under the same loading condition. In testing, each column specimen was subjected to a constant axial load simulating the weight of superstructure of magnitude $P=0.2P_y$ where P_y is the axial yield load of the steel section, and lateral cyclic loads in the desired direction. The displacement paths were of incremental amplitudes namely fractions and multiples of the predicted uniaxial yield displacement δ_{y0} caused by lateral load in the respective X, Y directions, and for each displacement amplitude three cycle tests i.e. three cycles of gradual loading and unloading were conducted. Table 1 gives details of the test program.

The uniaxial yield displacement (δ_{y0}) of the empty steel column for the case of zero axial load was predicted from the equation below, for each of the respective X, Y directions;

$$\delta_{y0} = \frac{H_{y0} \cdot h^3}{3E_s I} \tag{1}$$

where the corresponding yield load (H_{y0}) is given as

$$H_{y0} = \frac{M_{y0}}{h} = \frac{\sigma_{sy} \cdot I}{Z_t \cdot h} \tag{2}$$

and M_{y0} = yield moment due to lateral load, I = sectional moment of inertia, Z_t = distance to extreme fibre from the centre of gravity, h = effective height of specimen, σ_{sy} = yield stress of steel, and E_s = modulus of elasticity of steel. Calculated values were as follows: $(\delta_{y0})_X$=5.73mm, $(H_{y0})_X$=38kN, $(\delta_{y0})_Y$=8.58mm and $(H_{y0})_Y$ =30kN. In addition, the plate slenderness parameter for the rectangular box section is R = 0.53 and 0.79 for the narrow and wide plates respectively. Furthermore, the column slenderness is also $\bar{\lambda}$=0.555 and 0.405 for the weak and strong axis respectively.

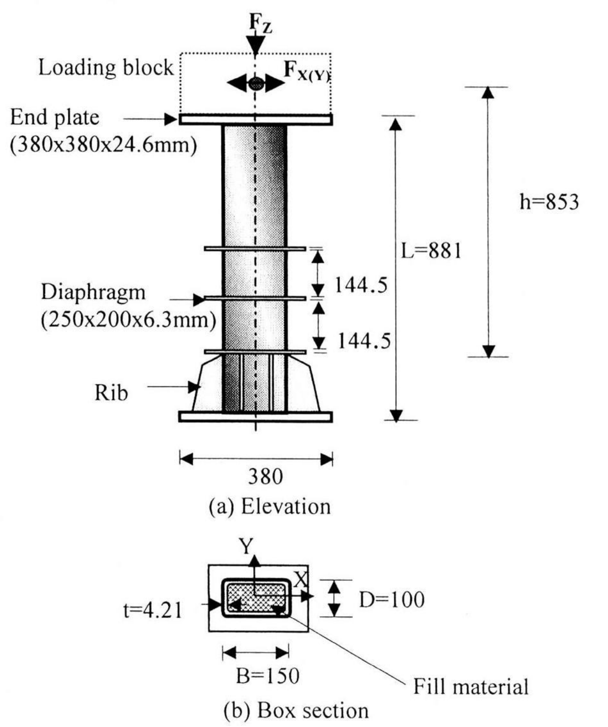


Fig. 1 Filled steel box test specimen(nominal)

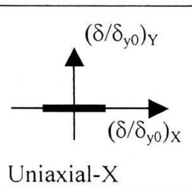
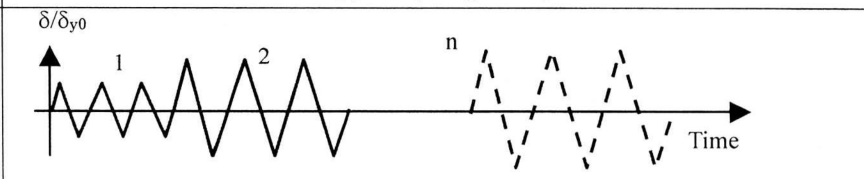
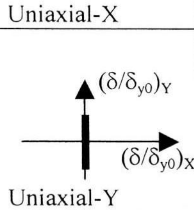
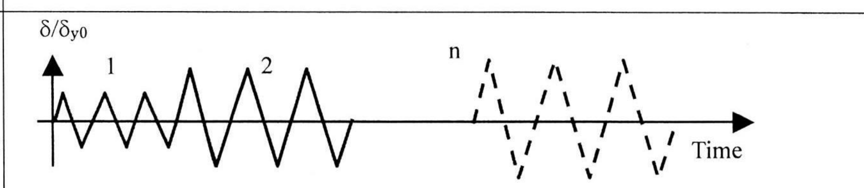
2.2 Test setup and loading program

The newly developed multi-directional structure testing system at Kyoto University (referred to Fig. 2) was used in this study. A specimen for test, having four strain gages pasted at the corners of each of the plates forming the box, was securely clamped within the loading head and reaction frame of the testing system by bolting on to the end plates. Angle plates for holding external linear variable displacement transducers (LVDTs) were then securely fixed at appropriate rigid parts of the specimen, subsequent to which a total of six LVDTs were fixed and aligned accordingly. Out the six LVDTs, two were for displacement measurement in the lateral X and Y directions, and the remaining four were for the determination of curvature in the most stressed bottom portion of the specimen. Prior check-up tests on the system indicated that in-built transducers in the actuators had accrued errors emanating from gaps and rotations in machine joints, hence the external LVDTs gave the required displacements.

After fixing and setting the specimen in the testing machine, lateral cyclic loads in the relevant displacement direction, under constant axial force, was applied quasi-statically through displacement control as ordered by computer. In each cycle, the load was applied gradually until the pre-determined maximum displacement and then unloaded, followed by a similar process in the opposite direction. As testing progressed, load and displacement readings were intermittently recorded using a computer, and testing ended when load resistance of the specimen deteriorated to a level almost near zero, as indicated by on-line computer monitoring, and further confirmed by the observed damage on the specimen.

Steel material properties were determined from tensile coupon tests on strips cut from the three plates of the steel rectangular one seam tube(STK400)[15]. In addition, the stub column compressive test was carried out to evaluate buckling strength of plate elements of the box section. Fill material properties were determined from cylinder compression tests. Table 2 presents the obtained material properties, in which e.g. the ultimate strength, yield strain of steel, unit weight, Young's modulus, the ultimate strength of fill materials are compared. Compared to an ordinary mortar(referred to concrete), the Latex cement mortar with ultimate strain improvement and the epoxy with elastic material characteristics are taken into consideration. The significance of Epoxy is its low unit weight, just half of ordinary mortar. Details of these material properties and process can be referred to the previous studies[10),13)].

Table 1 Loading and cycling histories

Specimens	Load path	Typical cycling history
S/LCM-UX S/OM-UX S/E-UX S-UX		
S/LCM-UY S/OM-UY S/E-UY S-UY		

(Note) LCM: Latex Cement Morotar, OM: Ordinary Mortar, and E: Epoxy used as fill materials.
UX: Loading in X-direction, and UY: Loading in Y-direction are used.

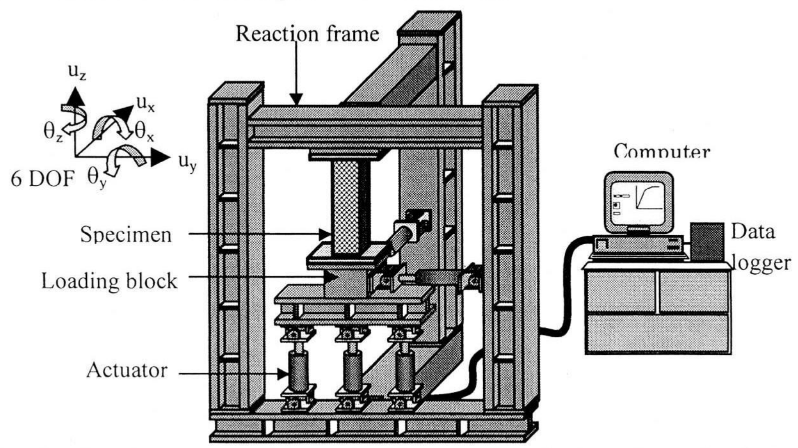


Fig. 2 Multi-directional testing system, with a total of 9 actuators (only 5 are shown for clarity)[15)]

Table 2 Material properties of the fill materials and steel

Material	Unit weight (kg/m³)	Young's modulus (kN/mm²)	Poisson's ratio	Strain at ultimate (%)	Yield stress (N/mm²)	Yield strain (%)	Ultimate strength (N/mm²)	Elongation at break (%)
Latex cement mortar (LCM)	1840	17.2	0.205	0.554	-	-	31.1	-
Epoxy (E)	1210	2.78	0.406	4.760	-	-	71.2	-
Ordinary mortar (OM)	2330	20.7	0.186	0.291	-	-	30.3	-
Steel (tensile coupon test)	-	211	0.283	-	374	0.174	459	42.5
Steel (stub column test)	-	206	-	-	275	0.146	386	0.48*

*Strain at the peak

3. Test results and discussions

3.1 Lateral load-displacement hysteretic response

The normalized load-displacement curves of the tested columns, normalized with lateral yield load (H_{y0}) and displacement at yield (δ_{y0}) calculated from Eq.3 and Eq.4, are presented in Figs. 4 to 7. The arrow mark pinpoints the ultimate normalized horizontal load. In addition, a summary of the hysteretic response is given in Table 3, which shows the ultimate strength as well as ductility measure (μ) defined as;

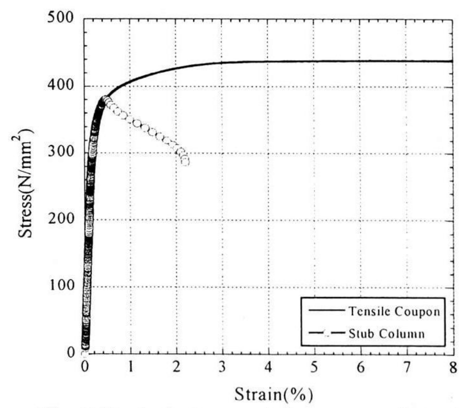


Fig. 3 Typical strress-strain curves of steel

$$\mu_m = \frac{\delta_m}{\delta_{y0}} \quad (3)$$

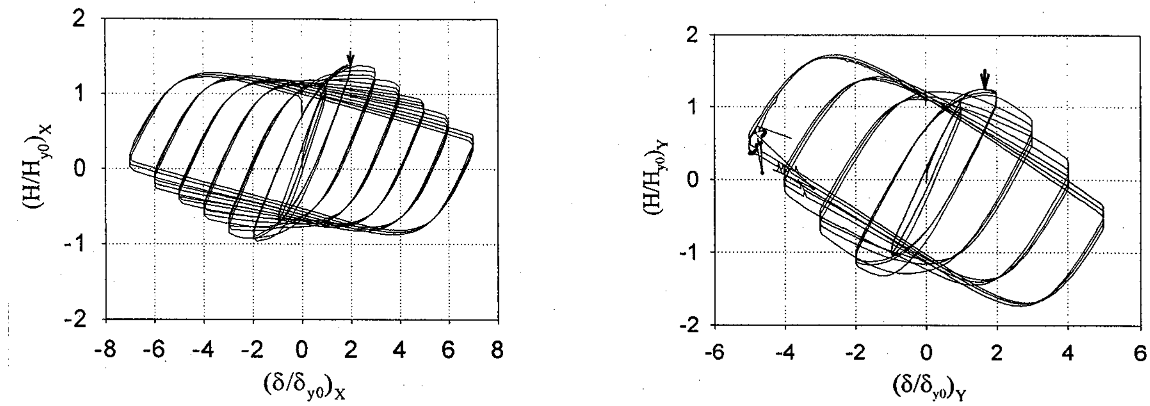
$$\mu_a = \frac{\delta_a}{\delta_{y0}} \quad (4)$$

where δ_m and δ_a are the displacement corresponding to the maximum lateral load and its displacement amplitude respectively.

A glance at the Figs. 4 to 7 promptly shows the superior strength and softening gradient of filled steel columns over the hollow steel box columns, especially for the columns tested in the X-direction. The per amplitude characteristics are also different in that at any post-ultimate amplitude, the hollow steel specimens have cycles which degrade more rapidly than the case of filled steel columns as is indicated by the deviating lines, whereas the curves for filled steel columns are more compact together at each cycling amplitude. However, it is to be said the effects of composite interaction are not well illustrated perhaps due to the specimen size or shape or buckling mode of steel; the width/thickness ratio of the encasing rectangular steel tube (B/t=35.6 and D/t= 23.8) was low implying a relatively thick plate, the aspect ratio (B/D=1.5) was high causing one of the axes to be very weak and independent and lastly, the initiation of buckling in the steel tube was observed to be outward in the direction of loading making the fill material to be less effective in supporting the steel tube. The outward buckling mode loses the opportunity for the fill material to support the steel tube as well as creating enough room for the fill material to easily fail as if under uniaxial compression without any confinement. This situation is most evident for specimens loaded in the Y direction about the weaker axis, where only a little difference is noted between filled steel members and the hollow steel member. It would seem that in the Y direction, the response of columns is mainly dictated by the behaviour of the perpendicular steel plates, which may be acting independent of the other orthogonal plates. Columns loaded in the X direction about the stronger axis probably had better interaction between orthogonal plates as illustrated by the propagation of buckling deformations. These columns loaded in the X direction displayed significant increase in strength and ductility, as well as post ultimate state deformability. The filled steel columns loaded in this direction also showed different shape characteristics amongst themselves. The curves for latex cement mortar filled steel columns and for ordinary mortar filled steel columns are seen to form into portions on either side of the vertical axis, with the negative and positive displacement parts somehow separated with a ridge. On the other hand, the epoxy filled steel column S/E-UX shows a smooth transition from the negative displacement part to the positive displacement part. It would seem that damage in the encased latex cement mortar or ordinary mortar increases progressively with each cycling amplitude, due to their lower tensile strength, while the higher tensile strength of epoxy moderates and delays damage after each successive cycle.

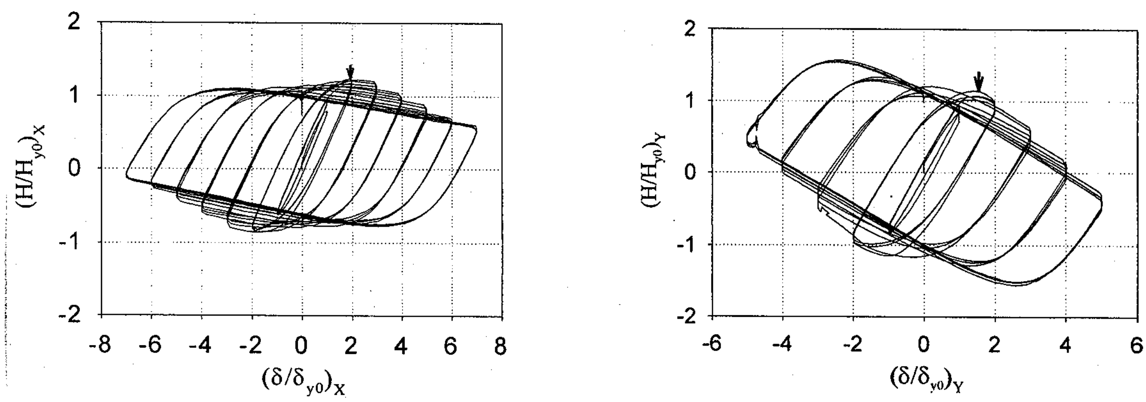
The effects of cyclic loading are summarized in Fig. 8, in the form of envelope curves of the hysteretic response at the peak points for each cycling amplitude, and Table 3 which has the ultimate strength and ductility of the tested columns. Increase in strength and ductility due to filling of the steel tube is higher for the columns loaded about the stronger axis than for those loaded about the weaker axis.

Generally, rectangular sections have been reported to have very little confinement of the fill material because the wall of the rectangular tube resists fill material pressure by plate bending, instead of membrane type hoop stresses developed in the case of circular tubes[16]. Further to this, if



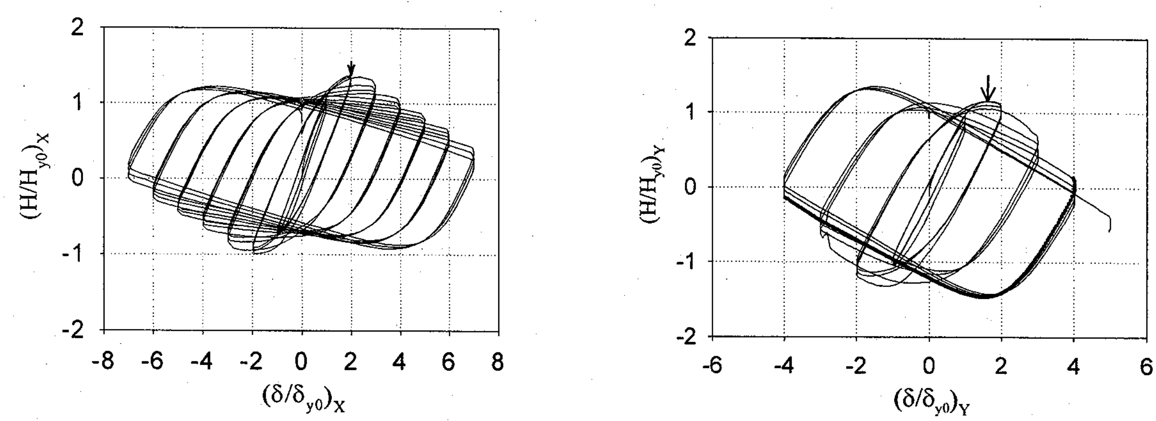
(a) X-direction (b) Y-direction

Fig. 4 Nondimensional lateral load-displacement curves(S/LCM)



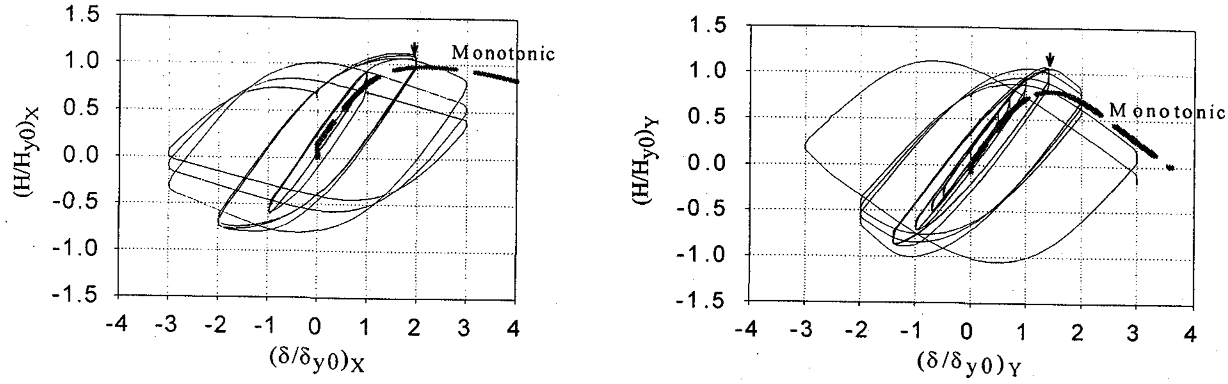
(a) X-direction (b) Y-direction

Fig. 5 Nondimensional lateral load-displacement curves(S/E)



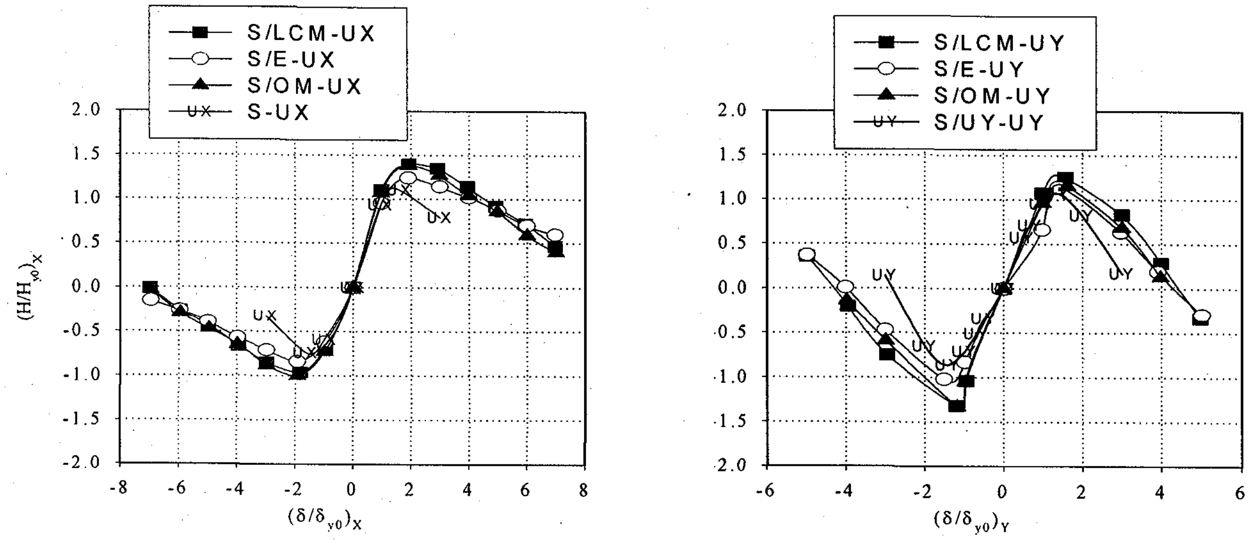
(a) X-direction (b) Y-direction

Fig. 6 Nondimensional lateral load-displacement curves(S/OM)



(a) X-direction (b) Y-direction

Fig. 7 Nondimensional lateral load-displacement curves(S)



(a) X-direction (b) Y-direction

Fig. 8 Envelop curves

Table 3 Strength and ductility of the test columns

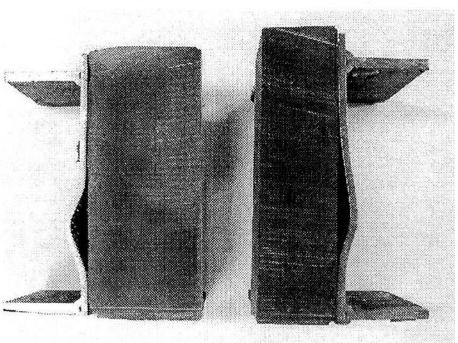
Loading directions	Specimen Type	H_{max}/H_{y0}	μ_m	μ_a
X	S/LCM-UX	1.40	1.93	2.00
	S/E-UX	1.24	1.90	2.00
	S/OM-UX	1.38	1.92	2.00
	S-UX	1.10	1.62	2.00
Y	S/LCM-UY	1.25	1.56	2.00
	S/E-UY	1.14	1.39	2.00
	S/OM-UY	1.15	1.61	2.00
	S-UY	1.07	1.37	1.41

μ = Ductility Measure

the steel tube is thick and aspect (B/D) ratio high, then failure is likely to be dominated by the plastic characteristics of the material and deformations of the weaker plate panel as opposed to the case of thin-walled circular steel tubes which have bifurcation-type local instabilities better suited for fill material complementary action[17),18)]. This viewpoint is supported by experimental studies on circular filled steel pipes by Koeda et al. who obtained considerable increase in strength and ductility of circular filled steel pipes over empty steel pipes[6)]. Hence, these experimental results have to be best inferred in conjunction with analytical parametric studies considering varied steel dimensions and shape.

3.2 Buckling deformations

The buckling deformations for the filled steel columns were all outside buckling, confirming that fill material in the tube prevents and moderates local buckling deformations. Extensive outward buckling in all the box plates was observed for the filled steel specimens loaded in the X direction, while for the filled steel specimens loaded in the Y direction, extensive buckling was observed only in the plates perpendicular to the Y direction. It may be said that the steel box plates aligned with the weaker axis were too weak to interact with the orthogonal plates, and hence were independent in resisting the loads, without the support of the orthogonal plates. In other words, loading about the weaker axis resulted in less propagation of buckling deformations to the neighbouring orthogonal plates. On the other hand, orthogonal plates for specimens loaded about the stronger axis seemed to have some supplementary interaction leading to propagation of buckling deformations circumferentially. Buckling in hollow steel specimens was both inward and outward; outward buckling occurring in the flange plates perpendicular to the direction of loading, accompanied by inward buckling of the orthogonal plates. That is, S-UX had extensive outward buckling in the narrower plates perpendicular to the loading direction and hence acting as flange plates, and extensive inward buckling of the wider plates acting as the web plates. On the other hand, S-UY had moderate outward buckling in the wider plates acting as flange plates, and moderate inward buckling of the narrower plates acting as the web plates. Typical buckling shape with the state of Epoxy fill material after tests is shown in Photo 1, after cutting the section at the bottom of the column into four pieces. It is observed that Epoxy fill material has no damage because of its elastic recovery even though the steel plates have the siginificant local buckling.



(a) Narrower plate (b) Wider plate

Photo 1 Bucking deformation and Epoxy(S/E-UX, UY)

3.3 Energy Absorption capacity

The energy absorption is interpreted in the form of the normalized cumulative energy absorption per cycle, E, defined as;

$$E = \frac{E_k}{E_\ell} = \frac{\int H \cdot d\delta}{E_\ell} \tag{5}$$

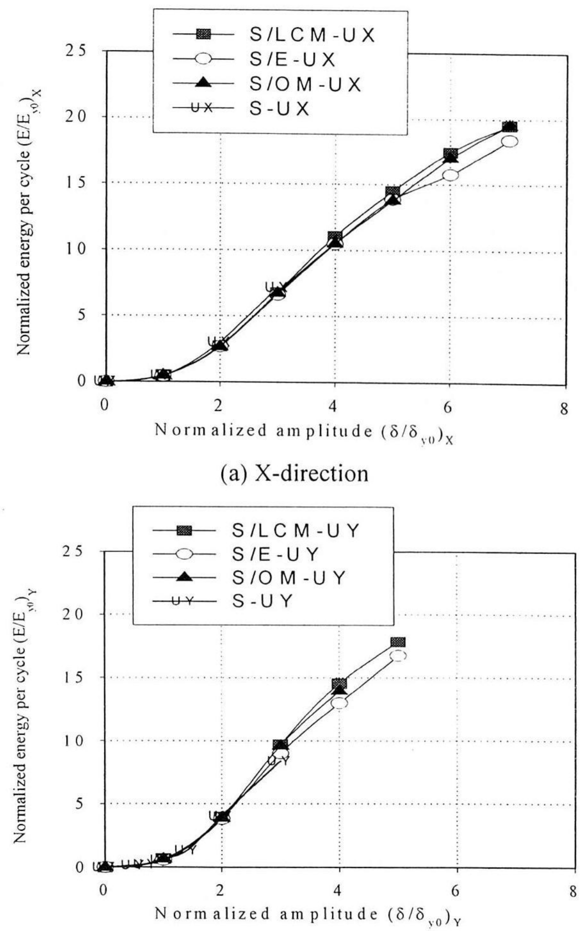
where $E_\ell = \frac{1}{2} H_{y0} \cdot \delta_{y0}$,

and E_k = energy absorption in cycle "k" of a test.

The normalized energy absorption per cycle at the each of the cycling amplitudes have been evaluated and presented in Fig. 9. The energy absorption curves show that the different specimens are very close in their energy absorption. As mentioned previously, it would seem that the response for this particular shape and dimension is mainly dominated by the behaviour of the encasing steel tube. For example studies by Koeda et al. on cyclic behaviour of circular concrete-filled steel pipe piers showed a colossal increase in energy absorption capacity of circular concrete-filled steel pipe piers over the empty steel pipe piers[6].

3.4 Simple strength prediction

The strength of the rectangular filled steel columns have been predicted using a method recommended by the Hanshin Expressway Public Corporation[19], and a proposed method whose approach is similar to the fiber stress method, namely RC section method. The approach by the Hanshin Expressway Public Corporation (HEPC) assumes full plasticity in both the steel tube and the fill material (Fig. 10) and is therefore similar to the Architectural Institute of Japan's stipulations[20], while the proposed method considers the compatibility of strains.



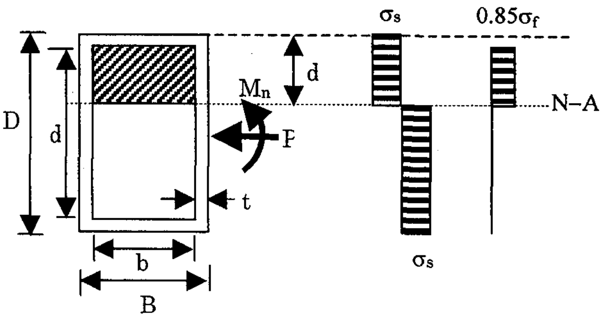
(a) X-direction

(b) Y-direction

Fig. 9 Normalized energy absorption per cycle

(1)HEPC approach:

By considering equilibrium of axial force and bending moment, the ultimate bendin moment (M_u) is determined as given by the expressions below.



(a) Section (b) Stress distribution

Fig. 10 Sectional stress distribution by Hanshin Expressway Public Corporation

$$M_u = M_{u0}\left(1.0-(1+\beta)\left(\frac{P_n}{P_u}\right)^2+\beta\left(\frac{P_n}{P_u}\right)\right) \qquad (6)$$

where the ultimate flexural capacity with no axial load (M_{u0}) is given by;

$$M_{u0} = \sigma_{sy}\left[d_i t(d_i - d_n) + \beta t(d_i + t)\right]$$

and position of the neutral axis (d_n) is derived as

$$d_n = \frac{2d_i t}{4t + b_i\dfrac{0.85\sigma_f}{\sigma_{sy}}}$$

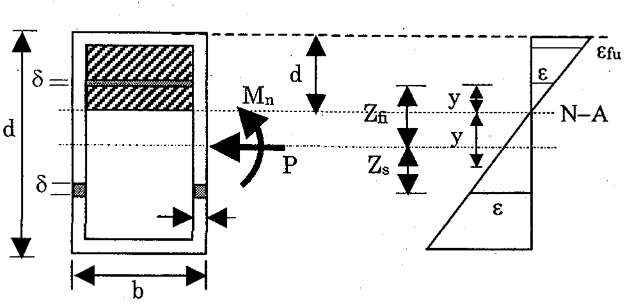
$$\beta = 9.17\gamma^2 - 13.75\gamma + 4.63$$

$$\gamma = \frac{\sigma_{sy}A_s}{\sigma_{sy}A_s + 0.85\sigma_f A_f}$$

(2)Proposed formulation:

In the proposed formulation (Fig. 11), the good bond of fill materials to steel is considered, and it is also assumed that;

a) Plane sections before bending remain plane after bending, implying that the strain in the fill material and the steel tube are linearly proportional to the perpendicular distance from the neutral axis.
b) Failure occurs when the extreme compressive strain in the fill material reaches a limiting value ε_{fu} which is known from material property tests.
c) Good bond exists between steel and concrete.



(a) Section (b) Strains

Fig. 11 Sectional strain distribution

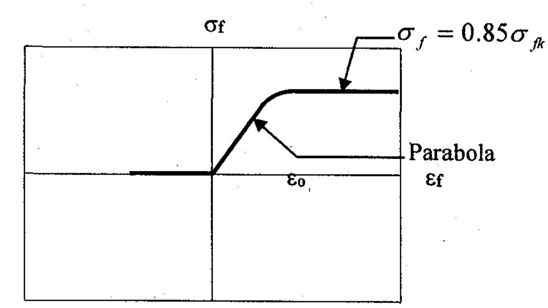
For equilibrium,

$$P_n = \int_{A_f}\sigma_f(\varepsilon_f)dA_f + \int_{A_s}\sigma_s(\varepsilon_s)dA_s = 0 \quad \text{(locate the N - A)} \qquad (7a)$$

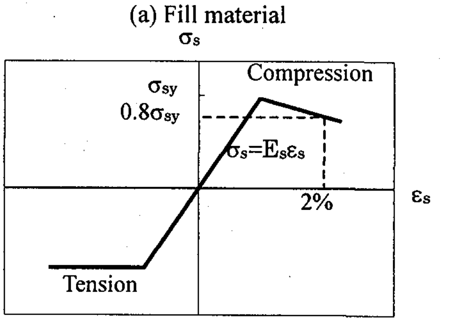
$$M_u = \int_{A_f}\sigma_f(\varepsilon_f)Z_{fi}dA_f + \int_{A_s}\sigma_s(\varepsilon_s)Z_{si}dA_s \qquad (7b)$$

where Z_{fi} and Z_{si} are elemental lever arms of forces measured from the center of section. The stress-strain relation for the fill material (see Fig. 12(a)) is assumed to be defined by Hogenstad's parabola i.e.

$$\sigma_f = 0.85\sigma_{fk}\left[2\left(\frac{\varepsilon_f}{\varepsilon_o}\right)-\left(\frac{\varepsilon_f}{\varepsilon_o}\right)^2\right] \qquad (8)$$



(a) Fill material



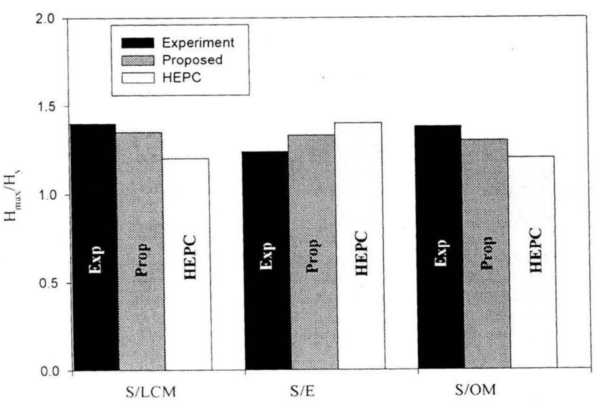
(b) Steel

Fig. 12 Stress-strain relationships

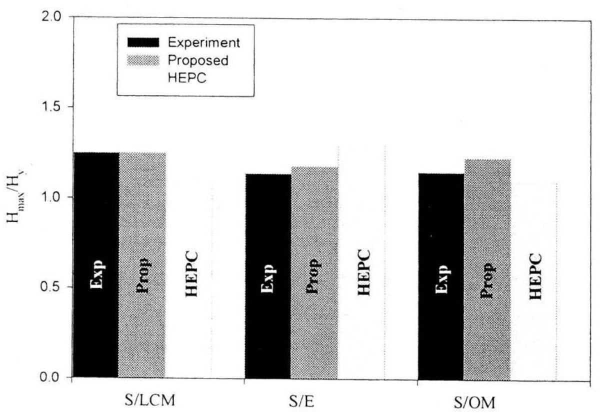
where ε_o is unique for each material and is obtained from the experimental stress-strain curve. In the case of steel in tension, an elasto-perfectly plastic response is assumed while for steel under compression buckling is taken into consideration by employing the stub column test results (see Figs. 3 and 12 b).

The suitability of the analytical predictions is assessed as shown in Histogram charts in Fig. 13. The proposed formulation generally gives the best strength prediction for columns loaded about either of the axes, i.e. for lateral load in either X or Y direction. In the weaker Y direction there is a slight over-estimation of the ultimate strength. The experimental resistance in the weaker Y direction was recorded to be exceptionally low, perhaps due to the high aspect ratio (B/D ratio), which might have instigated concentration of stresses in the flange plates, hence independent action of these plates. Visual observation of buckling deformations indicated that for lateral load in the Y direction, outward buckling mainly occurred in the flange plates, with very little propagation in the other two orthogonal web plates. In contrast, for lateral load in the stronger X direction, extensive outward buckling occurred in both the flange plates and the orthogonal web plates. The Hanshin Expressway Public Corporation's (HEPC) formulation also seems to adequately predict the column strengths.

For both methods, the strength of epoxy filled steel column is overestimated, and could perhaps be attributed to the lack of consideration of the effect of lateral pressure exerted on the steel tube by the epoxy fill material. Epoxy has high deformation capacity, whereby the ultimate state is attained at very high strains when the steel tube might have seriously buckled due to the combined effect of applied load and the lateral pressure of the confined epoxy.



(a) X-direction



(b) Y-direction

Fig. 13 Ultimate strength of rectangular filled steel columns

4. Conclusions

The main conclusion drawn from this study is that filled steel composite members filled with either latex cement mortar, epoxy or ordinary cement mortar result in increased strength, ductility and energy absorption capacity of the column, when compared to the hollow steel columns. By employing simple analytical formulations, the ultimate strength and ductility of the composite members were reasonably predicted.

Since the versatile material properties of polymer based materials can be designed, further study should be made on the guideline of fill materials design among wide range of properties which can provide the corresponding various options of rehabilitation of existing steel bridge piers, such as only ductility improvement, not strength increase in order not to overload the foundation, or both strength and ductility are improved. Particularly, the less unit weight of polymer based materials can be contributed to reducing seismic force as well. Even though the cost of Epoxy is still high, the cost can be reduced by mixing with low cost materials such as sands, industrial wastes, while keeping the suitable material properties. In addition,this part of the study only investigated rectangular sections subjected to cyclic loading, hence further study is recommended on circular filled steel sections since the beneficial effects of composite interaction may be more pronounced for circular sections. Studies are also required for composite columns subjected to multi-directional loads. It is thought that the severe effects of biaxial loading may be mitigated by polymer based material filled composite columns because cumulative damage of concrete with cracking is more profound under biaxial bending, but the polymer can remain in the elastic state even under severe biaxial stressing.

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