

DUCTILITY OF PARTIALLY-FILLED SANDWICH BOX COLUMNS UNDER CYCLIC LOADING

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ABSTRACT

Bridge piers with adequate seismic capacities are considered vital to bridge construction in countries with potential earthquake threats. In order to improve bridge-pier efficiency, the authors here developed a new design concept that integrates double steel tubes with tie rods filled in to various heights with concrete to form partially-filled sandwich box columns. This study is focused on evaluating the ductility of such members. Sixteen specimens with various tube width/thickness ratios and in-filled concrete heights were tested under combined cyclic loading. Test results showed that the ductility ratios of partially-filled sandwich box columns fell between 5 and 11, greater than that required by design codes. Experimental information was also used to determine optimal concrete in-fill heights and to establish design guidelines.

KEYWORDS: Sandwich Box Columns, In-Filled Concrete, Ductility

INTRODUCTION

Bridge piers with adequate seismic capacity are considered vital to bridge construction in countries with potential earthquake threats. Since bridge systems are usually designed with less structural redundancy than buildings, bridge piers must possess sufficient strength and ductility to enable the bridge systems to sustain major earthquake damage without failure. Hollow steel box piers possess high strength and significant ductility and are frequently used in bridge constructions in urban areas and in areas of high seismic activity. However, the large width/thickness ratios of steel box pier wall plates make them susceptible to local buckling which hampers the members' performance when subjected to major earthquake stresses. Buckled steel box piers exhibit significant deteriorations in strength, stiffness and energy dissipation capacity during post-buckling stages. In order to improve the seismic performance of such designs, the steel box piers are usually fully or partially filled with concrete, to form new structural systems called concrete-filled tubes (CFTs).

CFTs have been recognized as efficient structural forms for earthquake-resistant designs (Ge and Usami, 1992; Usami and Ge, 1994) because they provide sufficient strength with comparatively small dimensions, which reduces the structural weight required to support superstructures while simultaneously maintaining significant ductility. The CFT design concept can be justified by its ductility performance and efficient strength/mass ratio. However, when CFT designs are used in constructions with extremely heavy loads and in high-elevation bridge constructions, the pier columns must be extremely heavy thus diminishing the efficiency of the design. In order to maintain design integrity, the authors (Hsu and Lin, 1999) have proposed a new design concept that integrates double steel tubes and concrete with tie rods to form hollow sandwich box columns. This study demonstrates that the proposed sandwich box columns are stronger and possess higher strength/mass ratios than the traditional CFT members with similar dimensions. Test results also show that the failure mechanisms of the sandwich box columns are composed of plastic hinges due to bending moments at the bottoms of the columns while the remaining column lengths are undamaged throughout the loading process.

Considering the ratios between member strength and the bending moment due to lateral forces along the members, as shown in Figure 1, the upper portions of the piers are actually over-strong. Therefore, the pier column designs will be more efficient if the section rigidities of the piers can be adjusted according to the magnitudes of expected earthquake-induced moments. However, for practical purposes, the section rigidities along the pier columns cannot be continuous; therefore, filling for various heights with concrete between the double steel tubes to form partially-filled sandwich box columns to achieve greater design efficiency is more desirable. A further benefit is that using partially-filled sandwich box columns can be

justified by their higher member flexibility over fully filled ones, which gives the members higher deformation capacities. This study is focused on evaluating the ductility of partially-filled sandwich box columns under cyclic loading. Experimental information is also used to establish design guidelines.

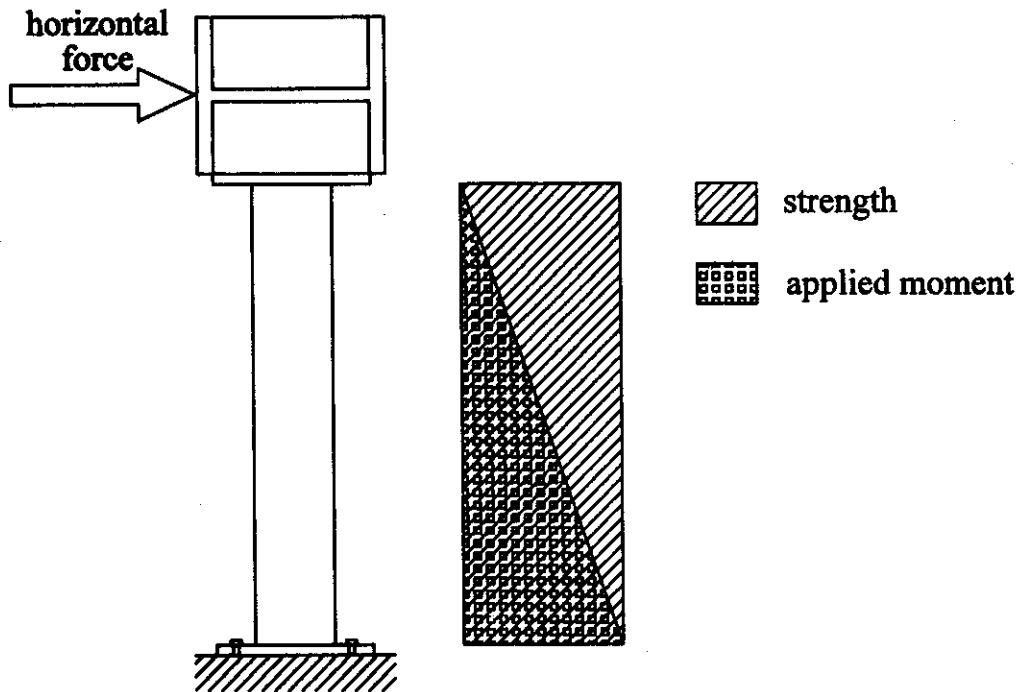


Fig. 1 Ratio between member strength and bending moment

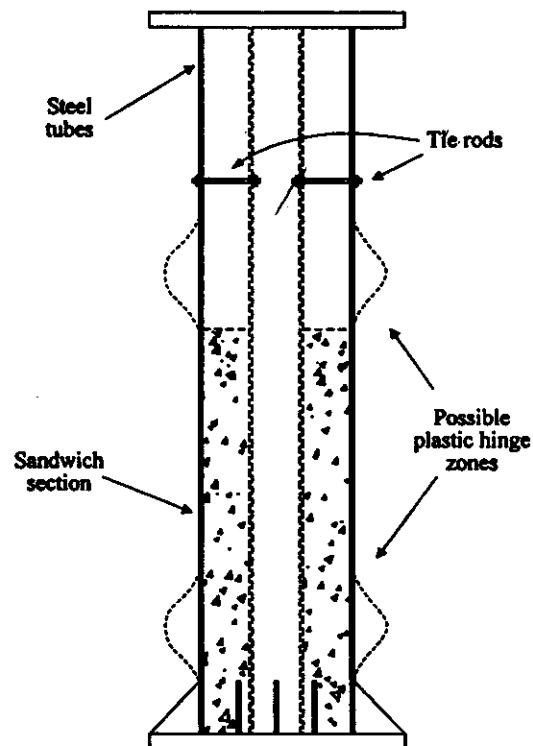


Fig. 2 Possible plastic hinge locations

ANALYSES

1. Determination of Concrete In-Fill Height

Failure of bridge piers during earthquake motion usually starts with the formation of plastic hinges. Plastic hinges in members subjected to lateral forces can occur in the sections subjected to maximum bending moment, sections sustaining the highest stress concentrations, or at locations subjected to sudden section changes, as shown in Figure 2. As stated above, when plastic hinges form in thin-walled steel tubes, members' seismic performances become questionable because the deterioration in section integrity is significant due to large plate width/thickness ratios. In order to guarantee member performance, formation of plastic hinges must be made to occur in sandwich sections because the steel-concrete interaction in such locations significantly enhances the stability of the tubes and reduces the rates of deterioration in strength and stiffness after the occurrence of local buckling (Boyd et al., 1995; Chiew et al., 1987; Taylor et al., 1995).

According to the simple plastic analysis theorem, the following equilibrium equations can be established if plastic hinges form in steel tubes:

$$M_{ps} \times \theta_p = P_{u1} \times L_s \times \theta_p \quad (1)$$

or,

$$P_{u1} = \frac{M_{ps}}{L_s} \quad (2)$$

in which M_{ps} is the plastic moment strength of the steel tubes in a partially-filled sandwich box column, L_s is the length of the steel tubes and P_{u1} is the lateral force causing the plastic hinges to form in the steel tubes, as shown in Figure 3.

Similarly, the relationship between plastic moment and plastic rotation must also be established for plastic hinges occurring at the bottom of members containing sandwich sections:

$$M_{pc} \times \theta_p = P_{u1} \times (L_s + L_c) \times \theta_p \quad (3)$$

or,

$$P_{u2} = \frac{M_{pc}}{(L_s + L_c)} \quad (4)$$

in which M_{pc} is the plastic moment capacity of the sandwich section, L_c is the length of the sandwich part, and P_{u2} is the lateral force causing the plastic hinge to form in the sandwich section.

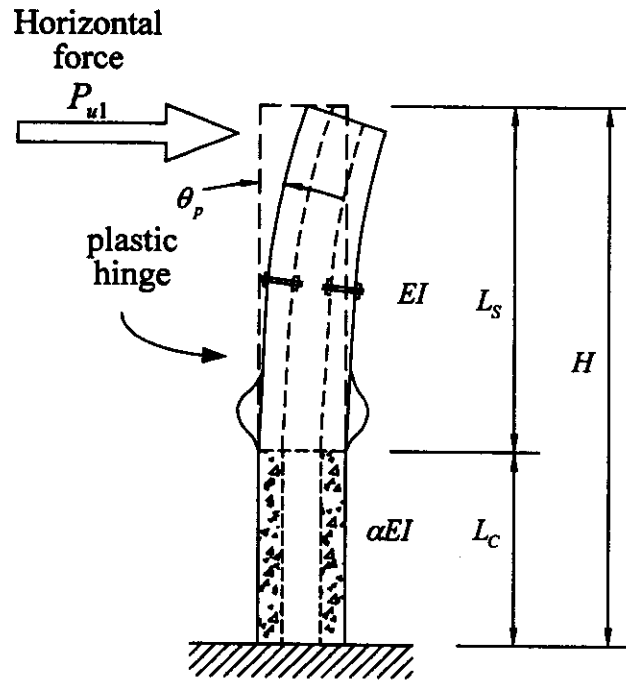
In order to guarantee the occurrence of plastic hinges in sandwich sections, the relative strength between steel tubes and sandwich sections and the height of in-fill concrete must be as described in the following equations:

$$P_{u2} < P_{u1} \quad (5)$$

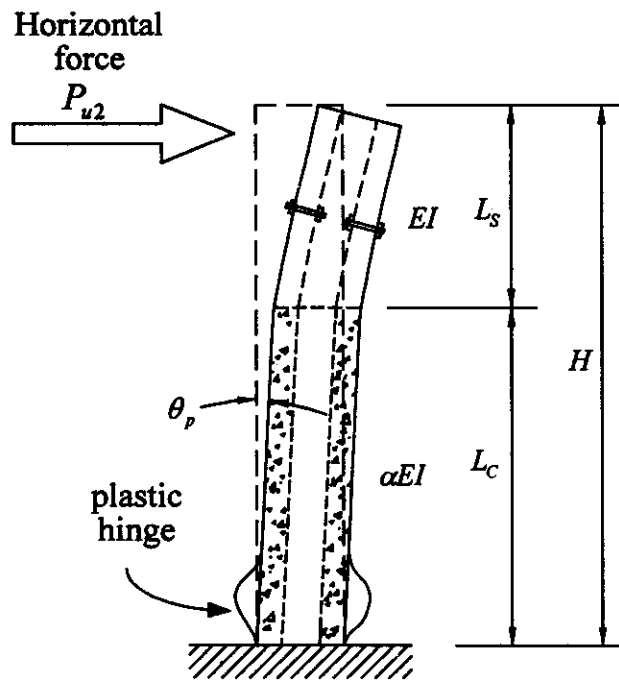
or,

$$\frac{M_{pc}}{H} < \frac{M_{ps}}{L_s} \quad (6)$$

if H represents the member length and is equal to the sum of L_s and L_c .



(a) Plastic hinge at steel tubes



(b) Plastic hinge at sandwich section

Fig. 3 Equilibrium relationships

2. Flexibility of Partially-Filled Sandwich Members

Consider the partially-filled sandwich box column shown in Figure 3 and assume the flexural rigidity of the sandwich section to be α times the rigidity of the steel tubes, EI . The relationship between displacement of the cantilevered tip, Δ , and the lateral force, P , can be derived from the theorem of conjugate beam as follows:

$$\Delta = \frac{PH^3}{3EI} \left[\left(\frac{\alpha - 1}{\alpha} \right) \times \left[1 - \left(\frac{L_c}{H} \right) \right]^3 + \frac{1}{\alpha} \right] \quad (7)$$

Therefore, the flexibility of a partially-filled sandwich box column, f , can be defined as:

$$f = \frac{H^3}{3EI} \left[\left(\frac{\alpha - 1}{\alpha} \right) \times \left[1 - \left(\frac{L_c}{H} \right) \right]^3 + \frac{1}{\alpha} \right] \quad (8)$$

Equation (8) shows that member flexibility is a function of the ratio of flexural rigidities between sandwich section and the steel tubes, and the ratio between in-fill concrete and member height.

Specimens were designed according to the preceding discussions, such that structural parameters, such as width/thickness ratios and heights of in-fill concrete, could be adjusted to study the effects of these parameters on the performance of partially-filled sandwich box columns. The following sections discuss the experimental program and test results.

EXPERIMENTS

1. Specimens

The test program was conducted in the Structural Laboratory of the National Central University, Taiwan. Sixteen specimens composed of double JIS-SS41-grade steel tubes concrete-filled to different heights were fabricated for testing. Yield stress for JIS-SS41 steel was 240 MPa. Average compressive strength for the concrete was 43.3 MPa. Slump and maximum aggregate size for the concrete were 100 mm and 25 mm, respectively. Two types of inner tube: 150 mm (width) x 150 mm (depth) x 4 mm (thickness) and 100 mm x 100 mm x 4 mm with width/thickness ratios equaling to 37.5 and 25, respectively, were used. These ratios were selected so that premature local buckling of inner tubes could be prevented to enhance member efficiencies. Outer tubes, 280 mm x 280 mm, were made by fillet-welding four thin plates to form box sections. 4.5 mm- and 6 mm-thick plates were used to fabricate the outer tubes so that the tube width/thickness ratios could be set to 62 and 46.67, which represent non-compact and compact plate elements as specified in design codes (AISC, 1994), to study their effects on member behavior. All specimens were 1800 mm long.

Table 1: Test Specimen Dimensions

Test series	b ₁ (mm)	d ₁ (mm)	t ₁ (mm)	b ₂ (mm)	d ₂ (mm)	t ₂ (mm)	A _s /A
T5-BH	280	280	6.0	150	150	4.0	0.16
T5-SH	280	280	6.0	100	100	4.0	0.12
T6-BH	280	280	4.5	150	150	4.0	0.13
T6-SH	280	280	4.5	100	100	4.0	0.10

Note : A_s indicates cross-sectional area of double steel tubes.
A indicates cross-sectional area of sandwich section.

Specimens were categorized according to inner tube size, outer tube width/thickness ratio, and concrete in-fill height and were designated as T5SH, T5BH, T6SH and T6BH test specimens. Specimen details and dimensions are listed in Table 1 and shown in Figure 4. The test specimens were in-filled with concrete to 30, 45, 60 and 100 percent of specimen length. A diaphragm was placed at the top of the filled-in concrete so that effective concrete confinement could be achieved. Tie rods were placed at the middle of the bare double-steel-tube portion of the member to prevent tube instability. Both inner and

outer tubes were welded to 30 mm-thick end plates at the top and bottom; so the specimens could be mounted on a rigid test platform and a stiffened loading beam could be attached to the top to apply lateral forces.

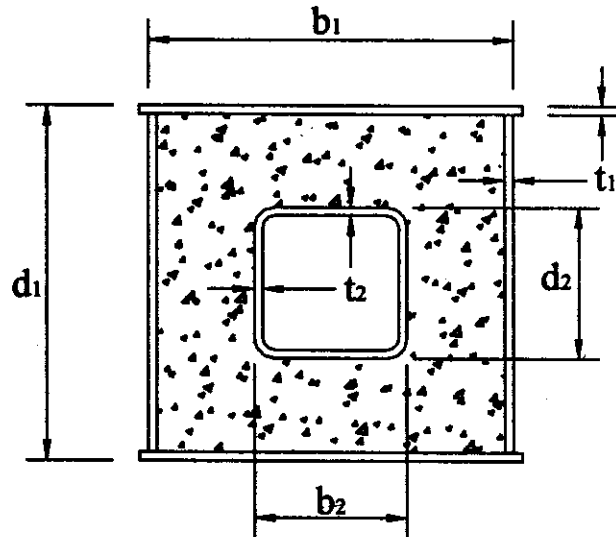
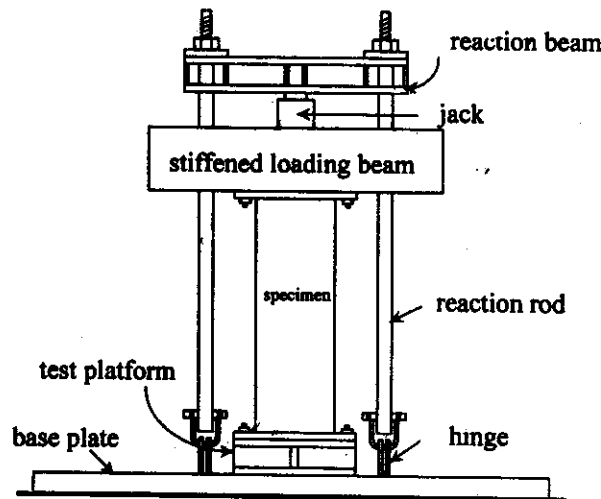
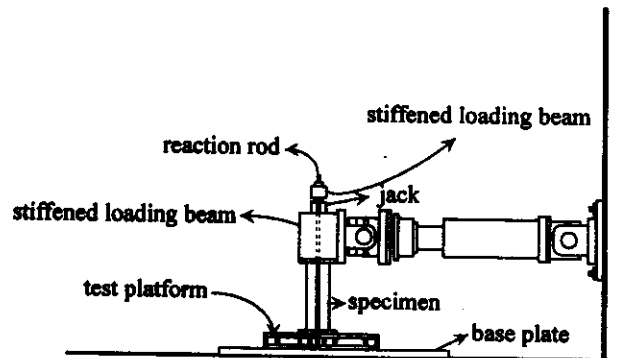


Fig. 4 Definition of cross section



(a) Front view



(b) Side view

Fig. 5 Test set-up

The surfaces of the specimens were white-washed to aid in visual observation during testing. Strain gauges attached to the flanges of the outer tubes were used to measure strain variations during loading processes and to determine the degrees of specimen yielding. The rigid test platform was welded to a 100 mm-thick base plate fastened to a strong floor. The stiffened loading beam linked specimen tops to a servo-controlled hydraulic actuator. Axial forces were generated by the combination of a hydraulic jack atop the loading beam pushing against a reaction beam which was constrained by a pair of reaction rods hinged to the strong floor. A relief valve was used to adjust the pressure on the hydraulic jack so that constant axial loading could be maintained. The test setup is shown in Figure 5.

2. Test Procedures

The specimens were tested under combined axial loading and cyclic lateral forces. An axial force equaling to 200 kN for all specimens was applied so that a comparison basis could be set. In each test, the prescribed axial force to specimen was first applied and held constant, while lateral force was applied by driving the actuator according to a set of prescribed increasing displacement commands so that yielding and ultimate stages could be defined. Each displacement amplitude was repeated three times. The loading history is shown in Figure 6. Displacements at the specimen top and the corresponding lateral forces were measured using a linear variable differential transformer (LVDT) and load cell mounted inside the actuator. Strains on the steel tubes were first amplified by a signal conditioner and then sent to a personal computer for later analyses. Member yielding was defined when the outer tube reached the yielding stage. Yielding displacement Δ_y and corresponding yielding strength P_y were experimentally determined from the test information.

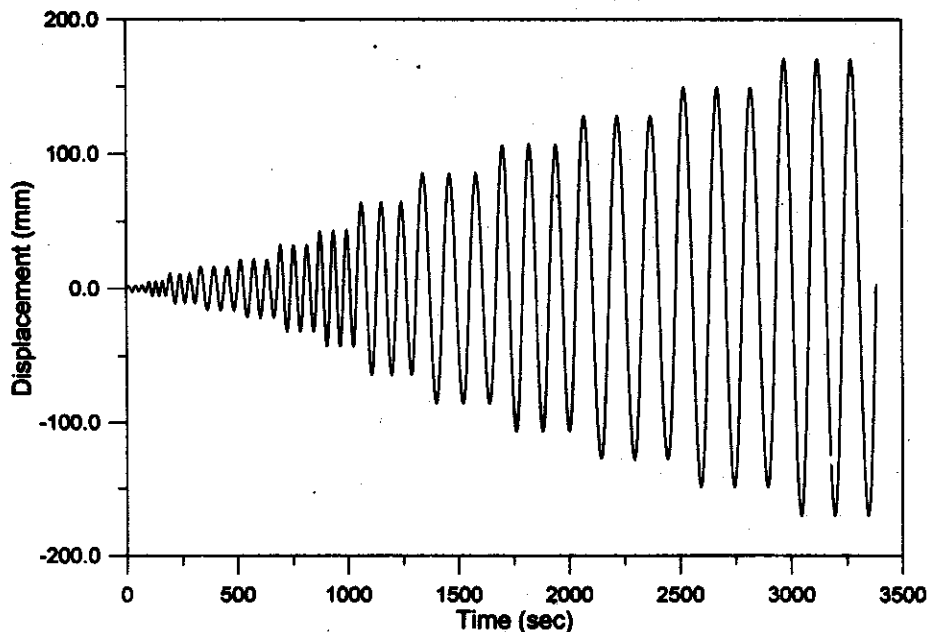


Fig. 6 Loading history

TEST RESULTS

1. Observation

Test specimen failure mechanisms can be generally divided into two categories: plastic hinges at the steel tubes and plastic hinges at the sandwich sections. Members filled with concrete height to 30 percent of their length exhibited plastic hinges in the steel tubes near the boundaries between the tubes and the sandwich sections. Other members, either fully or partially-filled with concrete, failed due to plastic hinges in the sandwich sections at the bottoms of the members. When failure occurred at the sandwich sections, local buckling was first observed at the flanges of the outer tubes. These buckling zones expanded when lateral force was increased. Members retained strength until tube plates fractured due to

repeated inelastic deformation at the buckling zone causing leakage of crushed powdery concrete. This phenomenon could be attributed to the small concrete thickness, because the concrete sustained higher level of stress than in the traditional CFT design. Significant deterioration in member strength was observed at this stage.

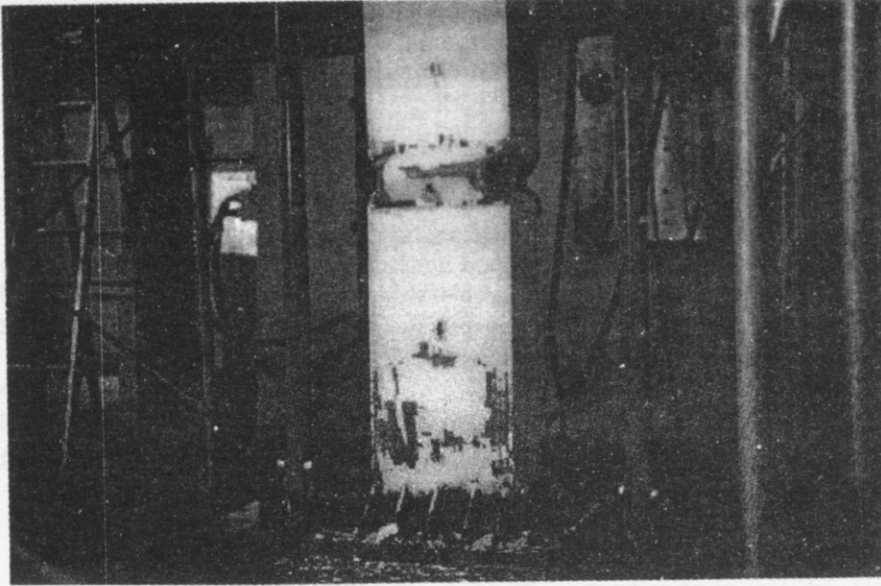


Fig. 7 Failure mode of partially-filled sandwich box member

When plastic hinges occurred at the steel tubes, member performance was governed by the tube width/thickness (b/t) ratios. Members with smaller tube b/t ratios exhibited lower rates of deterioration in strength and stiffness than those with larger b/t ratios. In general, the deteriorations in performance for members buckling at the steel tubes were of greater magnitude than for those buckling at the sandwich sections. The member failure mechanisms are shown in Figure 7.

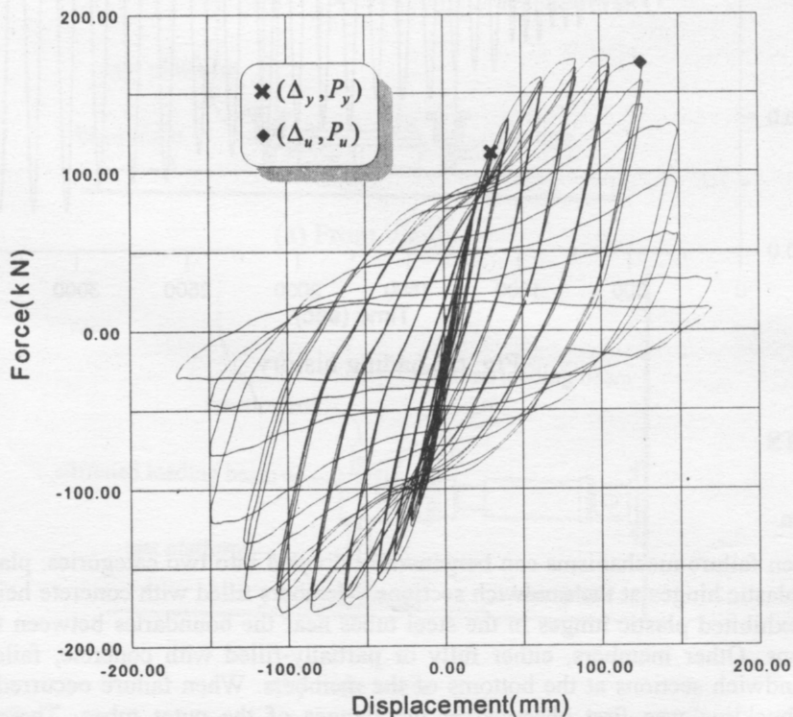


Fig. 8 Hysteretic loop and definitions of yielding and ultimate displacements

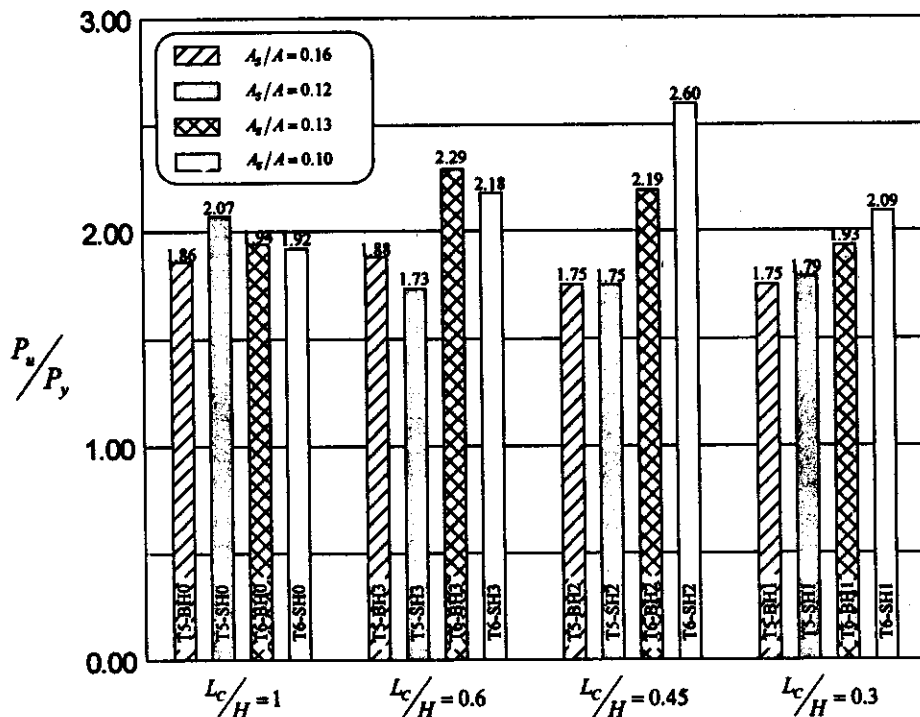


Fig. 9 P_u/P_y ratios for test specimens

2. Strength

In order to be effective in resisting earthquake-induced loading, members must possess sufficient reserve strength beyond their yielding stage. Therefore, the ratio between maximum strength P_u and yielding strength P_y is a useful index in predicting members' seismic performances. Figure 8 shows a typical hysteretic curve for a member tested under cyclic loading, and the definitions of its P_y and P_u . Table 2 lists the P_u/P_y ratios for all members tested. In order to determine member efficiency normalized member weights are also included in Table 2.

Figure 9 shows the relative magnitudes of P_u/P_y for all test specimens. Note that the P_u/P_y ratios for partially-filled sandwich box columns are close to those of fully-filled ones; however, the former are much lighter than the latter. Further investigation of the effect of tube width/thickness ratios on strength performance showed that members with higher width/thickness ratios tended to exhibit higher P_u/P_y ratios, ranged from 1.9 to 2.6, than members with lower width/thickness ratios, ranged from 1.7 to 2.1, because they originally possessed lower yielding strengths. This strength efficiency initially validates the applicability of partially-filled sandwich box columns.

3. Ductility

Besides sufficient reserve strength beyond yielding points, the capacity to withstand inelastic deformation is also vital for members designed to be earthquake-resistant because local buckling causing occurrence of plastic hinges is usually attributed to a lack of deformation capacity. Therefore, an indicator: member rotational ductility, was studied.

Member rotational ductility μ is denoted as follows:

$$\mu = \Delta_u / \Delta_y \tag{9}$$

in which Δ_u is the displacement at which member attains its maximum strength. The member ductilities of all test specimens are listed in Table 2 for comparison. Figure 10 shows that the ductility

ratios for sandwich box members, either partially- or fully-filled fell mostly between 5 and 11. These values are much greater than the ductility ratio required by design codes (JRA, 1990), which is 5, for concrete-filled tubes which are currently considered efficient seismic-resistant design components. Considering member weight further demonstrates the efficiencies of sandwich box columns, thus further validating their applicability to earthquake-resistant designs.

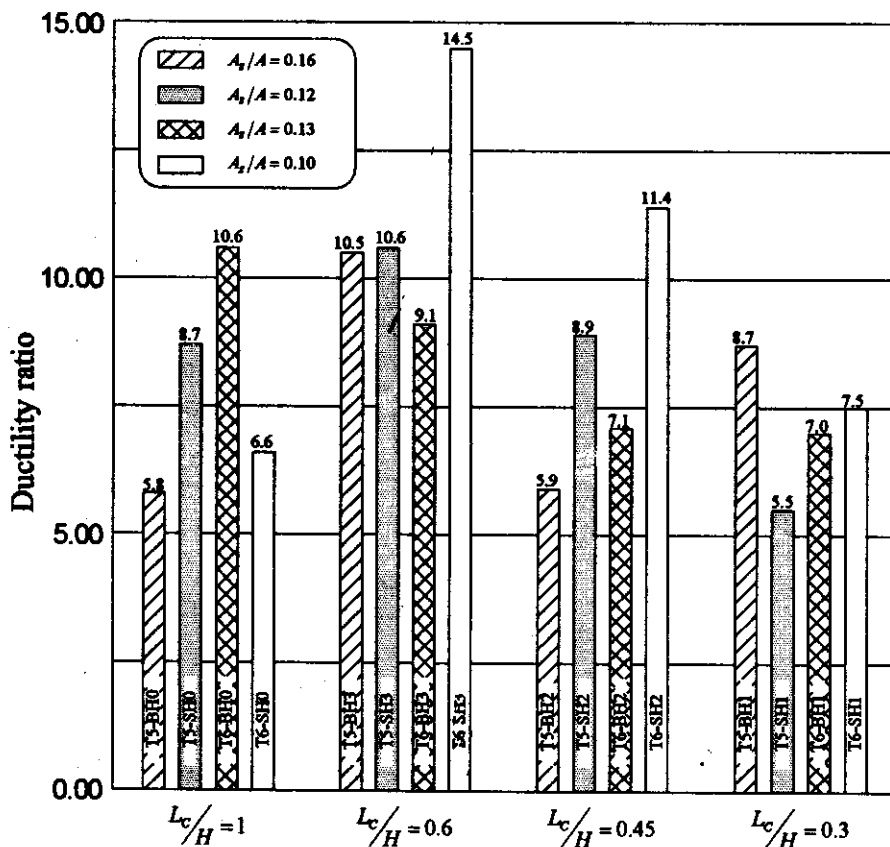


Fig 10 Ductilities for test specimens

The relationship between member deformation ductility and the height of in-fill concrete is shown in Figure 11. It was found that the fully-filled sandwich box columns did not necessarily exhibit the greatest ductility. Instead, members in the T5SH, T5BH, and T6SH test series, 45 and 60 percent in-filled with concrete showed higher ductility ratios than the fully-filled ones. Only fully-filled member in the T6BH test series exhibited higher ductility ratio, 10.1. However, this is only slightly higher than that exhibited by members 60 percent in-filled with concrete, i.e. 9.1. This is attributable to the flexibility of the steel tubes and the locations of the plastic hinges. When the height of the concrete in-fill decreases, the member flexibility increases. Furthermore, when plastic hinges occur at the sandwich sections, deterioration in section integrities is controlled by the steel-concrete interaction, and the flexibilities of the partially-filled sandwich members are increased to higher levels than those of fully-filled members due to contribution of the steel tubes. Therefore, partially-filled members can sustain greater deformations without losing their strength, thus enhancing the members' ductilities.

Considering the effect of tube width/thickness ratios, we find that it does not change ductility significantly. This can be explained by the nature of the sandwich-section design. Because the concrete in-fill functions as full lateral support for the tube walls, the effect of width/thickness ratios is not obvious and the members can thus sustain large deformations without local tube buckling. It can thus be preliminarily concluded that the height of concrete in-fill rather than the tube width/thickness ratio is the major parameter governing member ductility for members with width/thickness ratios ranging from 46 to 62. By correlating member performance in strength and ductility discussed above, it can also be concluded that the optimal height of concrete in-fill for sandwich-member design should be set at 60 percent of member length.

Table 2: Comparisons of Test Specimen Strength Performance and Ductility

Specimen	Concrete height	Width/thickness ratio	P_u/P_y	Δ_u/Δ_y	Normalized member weight
T5-SH0	H	46.6	2.07	8.7	1
T5-SH1	0.3H	46.6	1.79	5.5	0.515
T5-SH2	0.45H	46.6	2.10	8.9	0.619
T5-SH3	0.6H	46.6	1.73	10.6	0.723
T5-BH0	H	46.6	1.86	5.8	1
T5-BH1	0.3H	46.6	1.75	8.7	0.565
T5-BH2	0.45H	46.6	1.75	5.9	0.658
T5-BH3	0.6H	46.6	1.88	10.5	0.751
T6-SH0	H	66.7	1.92	6.6	1
T6-SH1	0.3H	66.7	2.09	7.5	0.480
T6-SH2	0.45H	66.7	2.60	11.4	0.591
T6-SH3	0.6H	66.7	2.18	14.5	0.703
T6-BH0	H	66.7	1.94	10.6	1
T6-BH1	0.3H	66.7	1.93	7.0	0.527
T6-BH2	0.45H	66.7	2.19	7.1	0.629
T6-BH3	0.6H	66.7	2.29	9.1	0.730

Note: H indicates the height of the specimens.

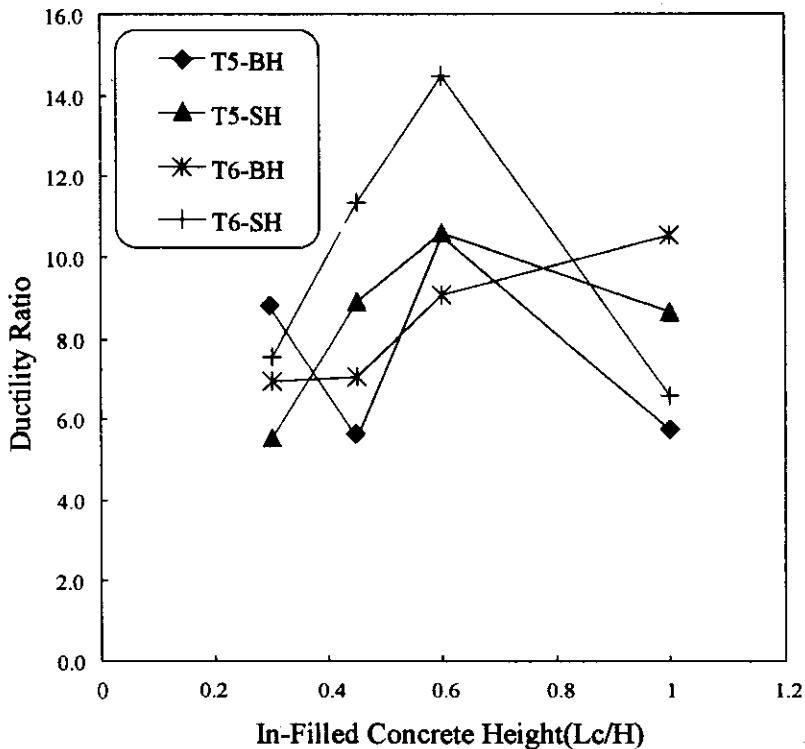


Fig. 11 Relationship between ductility and height of in-filled concrete

CONCLUSIONS

This paper has examined the performance of partially-filled sandwich box columns subjected to combined axial and cyclic lateral loading. Test results show that members performed better when plastic hinges occurred at composite sandwich sections. Test results also show that the strength efficiency of partially-filled sandwich box columns is at the same level as that of fully-filled sandwich members; however, their rotational ductilities are much larger than those of the fully-filled ones. It can also be concluded that height of concrete in-fill rather than the tube width/thickness ratio, is the major parameter governing member performance, and that the optimal concrete in-fill height for sandwich-member design is 60 percent of member length for members with width/thickness ratios ranging from 46 to 62.

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