CAPACITY PREDICTION OF CONCRETE-FILLED STIFFENED STEEL RIGID-FRAMES

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ABSTRACT

Concrete infilling of hollow stiffened section tubes is a well known technique for improving their ductility and strength. This technique can be used to improve performance of steel rigid frames as well. In this study, pushover analysis using non-linear finite element method is employed to investigate seismic behavior of concrete-filled steel tube (CFST) rigid frames. The ultimate point of CFST frames is determined using a failure criterion that incorporates failure strains of steel and confined concrete. Two frames having stiffened steel sections with different plate thicknesses were designed for the analyses. Each frame was analyzed with and without concrete infilling. Height of the concrete-filled part was selected to be 0.125, 0.25, 0.375 and 0.50 times the total column height. Two indices, namely ductility index (i.e., ratio between ultimate displacement to yield displacement) and strength index (i.e., ratio between ultimate load to yield load), were obtained for all the cases. The results clearly showed that the value of ductility index increased with partial concrete infilling but that of the strength index decreased. For a given plate thickness there is an optimum filled-in height that gives the best ductility. The location of failure point is governed by steel failure or concrete crushing.

***Key words*:** Ductility, pushover analysis, rigid-frames, steel columns, ultimate strength

1. INTRODUCTION

Most commonly found substructure forms in elevated highways are single piers and rigid-frame bridge pier bents. Presently, various techniques are being implemented for seismic resisting performance improvement of steel bridge substructures. Use of partially concrete-filled column is such a widely used technique. Past studies have firmly confirmed that the method is very effective in enhancing the seismic performance of single columns (e.g., Ge and Usami [1], Kitada [2], Susantha *et al.* [3]). The effectiveness of the method is more significant in circular tubes than rectangular-shaped columns. The factors affecting the strength improvement of circular steel columns are column slenderness, diameter-to-thickness ratio, strengths of steel and concrete, loading and boundary conditions, and steel-concrete interface condition (e.g., Schneider [4], Roeder [5], O'Shea and Bridge [6], Chitawadagi *et al.* [7]).

The method of concrete infilling can equally be applied to steel rigid-frames since failure of rigid frames are also usually occur due to excessive inelastic deformations of steel plates at the vicinities of the column base. Excessive inelastic deformation of plates around the base causes severe local bucking deformations which in turn reduce the load carrying capacity. There are two main types of steel sections namely unstiffened and stiffened sections. The performance of concrete-filled stiffened section columns significantly differ from that of unstiffened section columns. Pushover analysis of steel rigid frames having partially concrete-filled unstiffened section columns has been done by an analytical work by Susantha [8]. In the present study, the seismic resisting performance of steel rigid-frames having partially concrete-filled stiffened section columns is presented. Non-linear pushover analysis together with an available failure criterion is employed to determine the failure point of rigid-frames. The effects of concrete filled height on the ultimate strength and ductility are investigated.

2. METHODOLOGY

2.1. Fiber Model for Single Concrete-Filled Steel Column

In order to validate the finite element modeling procedure, a test specimen of partially concrete-filled square-shaped steel column reported in Susantha *et al*. [3] was analyzed. The selected specimen, namely N1, has twelve longitudinal stiffeners as shown in Figure 1, where notations B = width/breadth of the section, t = thickness of outer plates, t_s, b_s = thickness and height of stiffeners, h, h_c = total height and concrete-filled height of the column, and l_d = spacing between lateral diaphragms. The specimen was modeled using beam-column elements by assigning available uniaxial stress-strain relations for steel and concrete. Finite element program *OpenSees* [9] which has been exclusively developed for earthquake analysis was used in the analysis. The cross sections of hollow and composite parts of the column were divided into number of segments (fibers). The element mesh and the fiber sections for composite and hollow parts are shown in Figure 2.

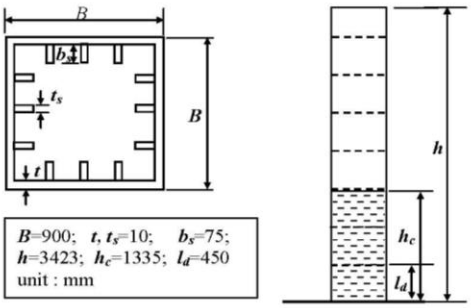

Figure 1: Geometry of test specimen N1 (Amano et al. 1998)

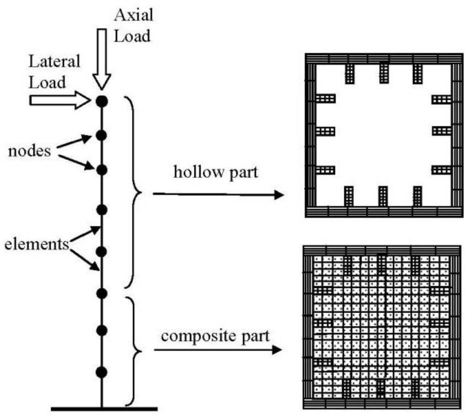

Figure 2: Finite element model of specimen N1

The uniaxial material model assigned for steel consists of Young's modulus, E_s = 206.0 GPa), yield stress, σ_y= 370.0 MPa, and Poisson's ratio, ν = 0.30, yield strain, ε_y=0.0018, and strain at onset of strain hardening, ε_{st}=0.0126. An approximated bilinear stress-strain relationship constructed by the straight line connecting yield point and the stress at the 0.05 strain level at strain hardening range was used [10].

The values of basic material properties of concrete are; Young's modulus, E_c = 19,700 MPa, unconfined compressive strength, f'_c = 22.6 MPa, and Poisson's ratio, μ = 0.153. The confined concrete model explained in Susantha *et al*. [3] was adopted here with a slight modification.

In the test, axial load P (=2475.3 kN) given by $0.15P_y$ ($P_y=A\sigma_y$ where A is the cross sectional area of steel) has applied at the column top. The experimental values of the yield load (H_y) and yield displacement (δ_y) of the specimen were 1831.1 kN and 21.6 mm, respectively. In the fiber model, above axial load was applied at the top node of the model as the first step. Then target lateral displacement of 130 mm (= $6\delta_y$) was applied incrementally at the same node and the lateral load-lateral displacement curve was obtained. It was normalized by yield load and yield displacement and compared with that of the test curve as shown in Figure 3. It is seen here that two curves closely match in the range of 1.5 to 4.5 δ_y but after around 4.5 δ_y displacement level the test curve shows a sudden decrease in load carrying capacity. However, this study concerns on the ductility and ultimate strength which certainly in post peak region hence the modeling can be considered to be reasonable in the context of this study. Therefore, the modeling procedure described in this section was used in the analyses of concrete-filled steel frames as well.

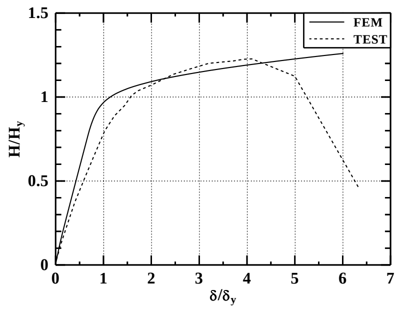

Figure 3: Comparison of test and analytical load-displacement curve for specimen N1

2.2. Fiber Model for Concrete-Filled Steel Rigid Frame

To check the effect of concrete infilling of rigid-frame columns, two frames one having column and beam cross sections similar to that of specimen N1 and the other having the same dimensions of specimen N1 except for thickness of plates (= 12.0mm). Geometrical information of the frame corresponding to h/h_c ratio of 0.375 is shown in Figure 4 where h=l=3,600 mm and l_d=450 mm. The finite element model of the frame is shown in Figure 5 where two types of fiber sections have been defined for the concrete-filled part and the hollow part of the columns and the beam.

Five cases were considered for each model (i.e., t=10.0 mm and t=12.0 mm cases) representing four h/h_c ratios (i.e., 0.125, 0.250, 0.375, 0.50) and a case of hollow section (benchmark case). Axial load given by 0.15 times squash load (i.e., $0.15P_y$) was first applied at the two ends of the beam. Then a target lateral displacement of 190.0 mm was incrementally applied at the top node of the left column. To calculate the yield displacement, strain at the extreme steel fiber at mid height of the first panel of each column, that is $l_d/2$ distance above the base, was plotted against the lateral displacement. When the strain reaches yield strain of steel (ε_y=0.0018) corresponding displacements at each column (δ_{yL} and δ_{yR}) were recorded and the minimum value was taken to be the yield displacement of the frame. The lateral load corresponds to δ_y is taken to be the yield load, H_y. These values will be useful in defining the ductility and strength indices.

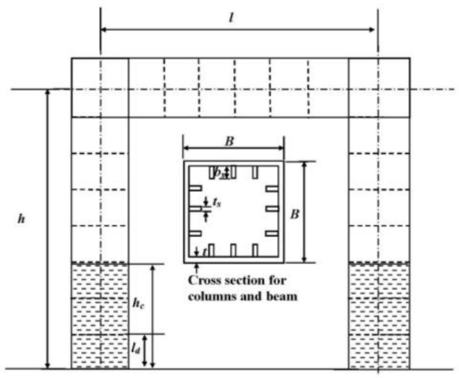

Figure 4: Concrete-filled steel rigid frame model

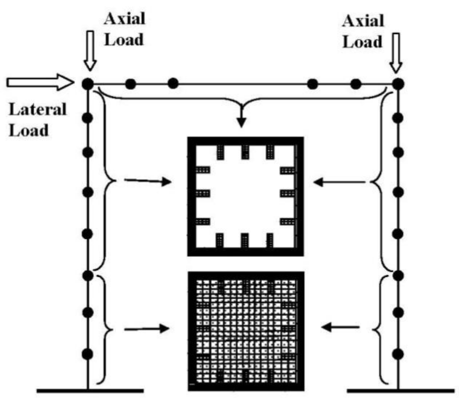

Figure 5: Finite element model

2.3. Failure criterion for rigid frames

Usually a failure criterion is utilized to predict the ultimate point from lateral load-lateral displacement curves obtained using fiber elements. A failure criterion proposed by Susantha *et al.* [3] for partially concrete-filled steel columns was adopted here with a slight modification to incorporate the contribution of two columns in rigid frames. In what follows, strain variation of steel and concrete at three locations are monitored with increasing lateral displacements. They are; outer fibers of steel (point A) and concrete (Point B) at mid height of the first panel and outer fiber of steel (point C) at mid height of the panel just above the top level of the concrete-filled part. Then, compare the corresponding lateral displacements at points A and B at their failure strains and record the maximum value and compare it with that at point C and choose the minimum value. Repeat the procedure for both columns and choose the minimum value as the ultimate displacement (δ_u) and corresponding ultimate load (H_u).

3. RESULTS

The values of ductility index δ_u/δ_y and strength index H_u/H_y were obtained from lateral load-lateral displacement curves (pushover curves) for five cases with t=10.0 mm and five cases with t=12.0 mm. The variation of ductility index and strength index are plotted against h/h_c ratio as shown in Figures 6 and 7, respectively. As per the results shown in Figure 6(a) and (b) ductility increases with concrete infilling. The degree of increase seems very sensitive to plate thickness. The value of strength index decreases with concrete infilling in both plate thicknesses as evident from Figure 7. It seems under present geometrical and loading conditions the optimum filled-in height can be considered as $0.3h/h_c$ which is the value known for single piers.

4. CONCLUSION

Pushover analysis is effective in predicting ultimate strength and ductility of stiffened steel rigid frames having partially concrete-filled steel columns. Available failure criterion that uses failure strains of steel and confined concrete could be modified to locate the failure points of concrete-filled steel rigid frames. It was obvious from the results that the concrete infilling is very effective in increasing ductility performance measured in terms of the ductility index. The ultimate strength represented in terms of the strength index, found to be lower than that of the hollow counterpart. The effect of concrete infilling highly depends on the height of filled-in concrete. There is an optimum filled-in height beyond which the relative increase in ductility becomes insignificant. The optimum height varies with the dimension of frames.

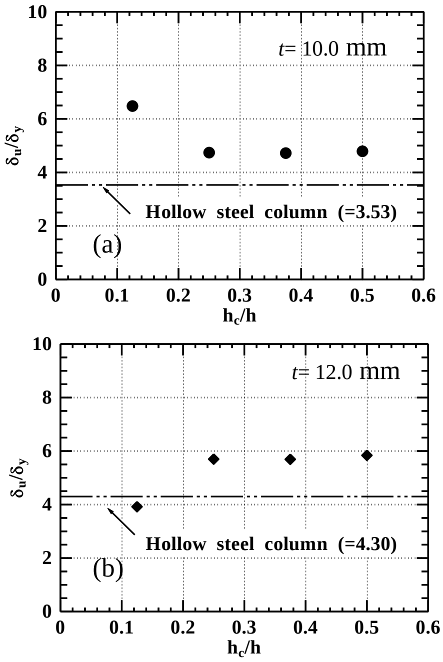

Figure 6: Variation of ductility index with *h/h$_c$* ratio ; (a) *t*=10.0 mm; (b) *t*=12.0 mm

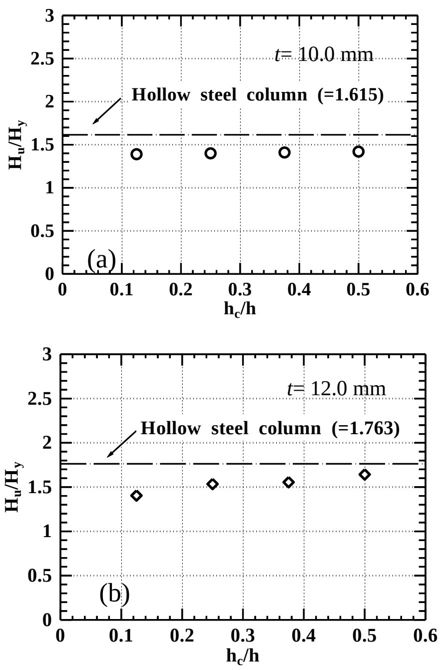

Figure 7: Variation of strength index with *h/h$_c$* ratio; (a) *t*=10.0 mm; (b) t=12.0 mm

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