ULTIMATE STRENGTH AND DUCTILITY OF PARTIALLY CONCRETE-FILLED STEEL RIGID-FRAME BRIDGE PIERS

K.A. Saman Susantha
Department of Engineering Mathematics, Faculty of Engineering, University of Peradeniya
email: samans@pdn.ac.lk

Abstract

Concrete-filled steel tubes have wide range of applications in building and civil engineering structures due to their excellent earthquake resisting characteristics. In this study effectiveness of partially concrete-filled steel tubes (CFST) in rigid-frame bridge pier bents is examined in terms of their ultimate strength and ductility performances. The columns and beam of frames consist of an un-stiffened rectangular-shaped steel section. Pushover analyses of single columns and rigid-frames were carried out using beam-column elements associated with nonlinear stress-strain relations for both concrete and steel. The effect of filled-in height of single columns was first examined by comparing the ultimate displacement and the ultimate strength determined using an available failure criterion established for cantilever type concrete-filled steel columns. The optimum concrete-filled height of the single columns was found to be around 0.30 times the column height. The pushover analyses were carried out for three rigid-frames having different filled-in heights. The ultimate displacement and the ultimate strength of concrete-filled rigid-frame were significantly higher than those of the hollow section frame. The optimum filled-in height of rigid-frames was found to be around 0.15 times the total height of the frame.

Key words: concrete-filled steel tubes, ductility, steel columns, steel frames, ultimate strength.

1. Introduction

Elevated highways are the most preferred option in road infrastructure developments in rapidly developing countries as it pays way to pass through highly congested areas. Most commonly found structural forms in elevated highways are single piers and rigid-frame bridge pier bents. Presently, various methods are being used to enhance the seismic resisting performance of steel bridge substructures. Most often seismic performance of bridge substructures is measured in terms of ductility, ultimate strength and energy absorption capacities. One of an attractive technique introduced for improving ultimate strength and ductility of steel bridge piers is partial concrete infilling of columns. Past studies have extensively confirmed that the method is very effective in enhancing the seismic performance of single columns (e.g., Ge and Usami 1992; 1994; 1996, Watanabe *et al*. 1997, Kitada 1998, Susantha *et al*. 2001). The above studies which involved numerous experimental and analytical investigations have revealed that the increase in ultimate strength and ductility are the main advantages of CFST columns over hollow steel tubes.

The strength characteristics of concrete-filled steel tubes (CFST) have been widely studies in the past. The strength of concrete-filled steel tubes is higher than the sum of individual strengths of steel tube and concrete core because of the enhancement of concrete strength due to the confinement provided by the surrounding steel plates. The method is more effective in circular tubes than rectangular-shaped columns. The main factors affecting the strength of concrete-filled 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 1998, Roeder *et al*. 1999, O'Shea and Bridge 2000, Johansson and Gylltoft 2002, Zeghiche and Chaoui 2005, Chitawadagi *et al*. 2010).

Rigid-frame steel bridge piers subjected to severe earthquakes usually fail due to excessive inelastic deformations of steel plates near the base and/or connection between column and beam. Inelastic deformation causes local buckling of plates and eventually the load carrying capacity decreases with increasing lateral deformation. The local buckling can be prevented or delayed by introducing longitudinal stiffeners, having closely spaced lateral diaphragms, using linearly tapered steel plates, etc. (e.g., Fukumoto *et al*. 2005, Aoki *et al*. 2008). Use of concrete-filled steel columns is another attractive method. In this study, at first, the optimum filled-in height of partially concrete-filled steel columns is investigated considering the seismic resisting performance. Secondly, the investigations of rigid-frames having partially concrete-filled steel columns are carried out to determine the failure points and the effect of concrete-filled height on the ultimate displacement and strength. Only the un-stiffened sections are considered throughout the study. A kind of pushover analysis together with a failure criterion previously proposed by author is employed in all the analyses.

2. Methodology

Determination of lateral load-lateral deformation relation of rigid-frames can be obtained using the pushover analysis with the help of beam-column elements, shell elements, or combination of beam-column and shell elements. In this study, only beam-column elements (fiber elements) were utilized for modeling. Since beam-column elements are involved in the present analysis, post-peak strength degradation due to local buckling of steel plates cannot be expected. Therefore, a kind of failure criterion is required to determine the ultimate point of the frame. A failure criterion governed by failure strains of steel and concrete was adopted here.

2.1 Fiber model for CFST single column

For the model validation, a partially concrete-filled test specimen, namely UU5, reported in Usami *et al.* 1995 was selected. The dimension of the specimen is shown in Figure 1, where notations B = width of the flange, D = width of the web, b = center to center distance between webs, t = thickness of plates, 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. Nonlinear uniaxial stress-strain relations were assigned for steel and concrete. Finite element program called *OpenSees* which has been exclusively developed for earthquake analysis was employed for 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 division of sections for composite and hollow parts are shown in Figure 2.

A bilinear stress-strain relationship having strain hardening ratio, $E_s^{'}/E_s$, of 0.01 (i.e., ratio between post-yield tangent and initial elastic tangent) was assumed for steel as shown in Figure 3(a). Material parameters of the model are; Young's modulus, E_s = 197.0 GPa), yield stress, σ_y= 266.0 MPa, and Poisson's ratio, ν = 0.269, and yield strain, ε_y=0.0013.

The values of basic material properties of concrete are; Young's modulus, E_c = 28700 MPa, unconfined compressive strength, f'_c = 40.8 MPa, and Poisson's ratio, μ= 0.157. The confined concrete model adopted here is shown in Figure 3(b). Parameters f'_{cc}, ε_{cc}, ε_{cu} and f_{cu} (□ □= 0.2f'_{cc}) shown in the figure were calculated using equations given in Susantha *et al.* (2001). The values of these parameters depend on the geometric and material parameters of the section. The values thus calculated were; f'_{cc}= 41.97 MPa; ε_{cc}=0.0023, ε_{cu}=0.0169 and f_{cu}=8.4 MPa.

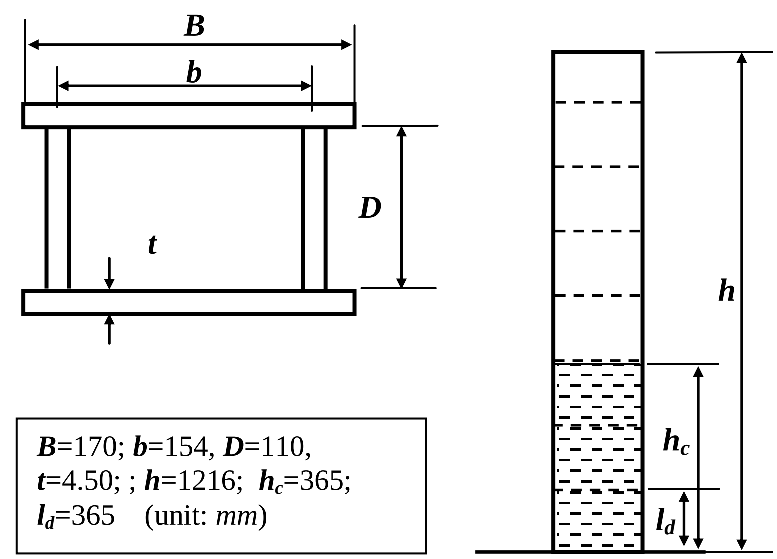


Figure 1: Geometry of test specimen UU5

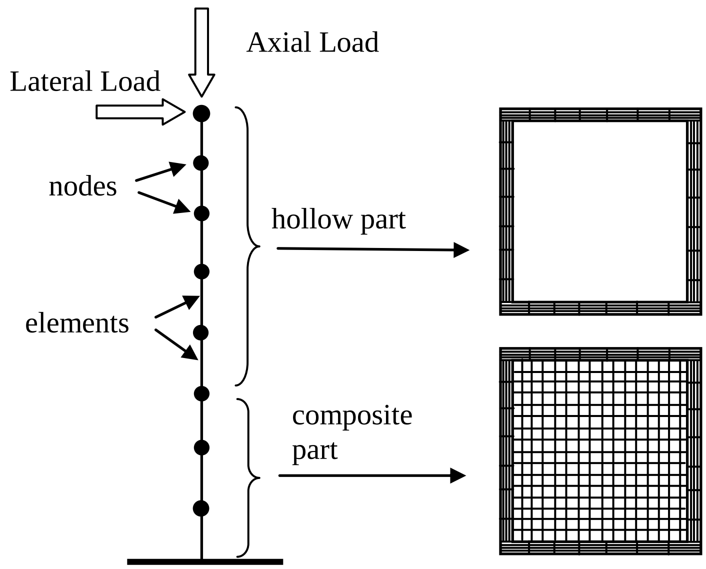
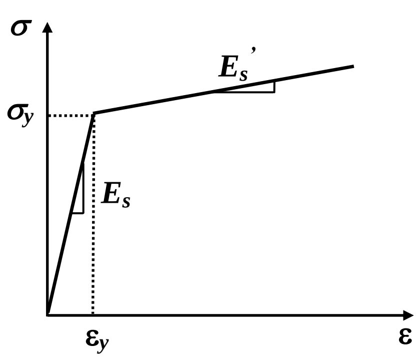
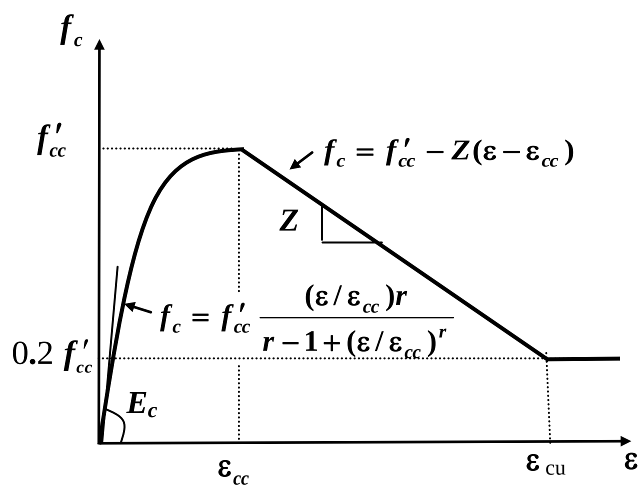


Figure 2: Finite element model of specimen UU5



(a)



(b)

Figure 3: Uniaxial material models; (a) Steel, (b) Confined concrete

In the test, axial load P (=134.36 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 26.2 kN and 12.5 mm, respectively. In the fiber model, first, this axial load was applied at the top node of the model. Then, target lateral displacement of 100 mm (= $8\delta_y$) was incrementally applied and the lateral load-lateral displacement curve was obtained. The curve was normalized by the yield load and the yield displacement and compared with that of the test curve as shown in Figure 4. It is seen here that two curves closely match up to $2\delta_y$ but beyond that the test curve shows a sudden decrease in load carrying capacity. This is because the present analysis does not incorporate possible outward local buckling of steel plates and any sudden crushing of concrete. However, this study mainly concerns on the ultimate point which is to be decided using a failure criterion involving failure strains of materials. Therefore, the modeling procedure can be accepted for the intended use of this study. Also, it can be adopted in the analyses of concrete-filled steel rigid-frames as well.

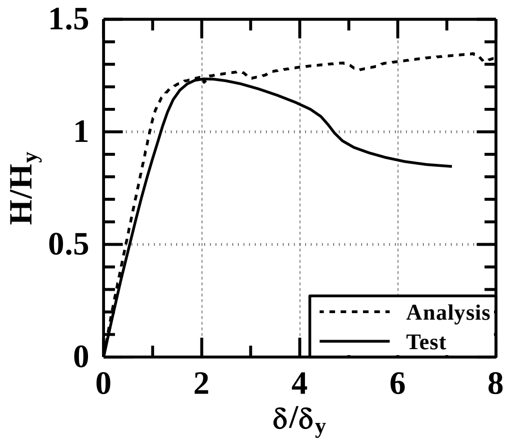


Figure 4: Comparison of test and analytical load-displacement curves of specimen UU5

2.2 Failure criterion

In this study the yield load and the yield displacement were found using the pushover curve. To decide the yield displacement, strain in extreme steel fiber at the mid height of the first panel ($\varepsilon_{\mathrm{a,bs}}$) of each column ($l_d/2$ distance above the base) was plotted against the lateral displacement. When the strain reaches the yield strain of steel (ε_{y}=0.0013) corresponding displacement and load were taken to be the yield displacement and the yield load, respectively. It is important to define a suitable failure criterion to predict the failure load using the pushover curves of fiber models. Fiber elements do not treat local buckling effects of steel plates hence strength reduction beyond the peak load cannot be expected from the pushover curves unless damaged based material models are utilized. Therefore, it is essential that a kind of failure criterion be used here to predict the failure point. As such, a failure criterion proposed by Susantha *et al*. (2001) for partially concrete-filled steel columns was adopted here with a slight modification to incorporate frames. The procedure is explained below (see Figure 5 for points ***A***, ***B***, and ***C*** and displacements $\boldsymbol{\delta}_{\mathbf{A}}$, $\boldsymbol{\delta}_{\mathbf{B}}$ and $\boldsymbol{\delta}_{\mathbf{C}}$).

Step-1: Plot displacement versus steel strains at points ***A*** ($\varepsilon_{\mathrm{a,bs}}$) and ***B*** ($\varepsilon_{\mathrm{a,bc}}$) which is on the extreme steel and concrete fibers at the mid height of the first panel ($0.5l_e$ above the base).

Step-2: Plot displacement versus steel strain at point ***C*** ($\varepsilon_{\mathrm{a,s}}$) which is on the extreme steel fiber at the mid height of the panel just above the filled-in concrete level ($0.5l_e$ above the top level of concrete).

Step-3: Obtain corresponding displacements ($\boldsymbol{\delta}_{\boldsymbol{A}}$ and $\boldsymbol{\delta}_{\boldsymbol{C}}$) when steel strains at point ***A*** and ***C*** reach steel failure strain $\varepsilon_{u,s}$ (=0.0053).

Step-4: Obtain displacement ($\boldsymbol{\delta}_{\boldsymbol{B}}$) when concrete strain at point ***B*** reaches confined concrete failure strain $\varepsilon_{u,c}$ (=0.0059).

Step-5: Select the maximum of $\boldsymbol{\delta}_{\boldsymbol{A}}$ and $\boldsymbol{\delta}_{\boldsymbol{B}}$ and compare it with $\boldsymbol{\delta}_{\boldsymbol{C}}$ and select the minimum value as the ultimate displacement $\boldsymbol{\delta}_{\boldsymbol{u}}$ and corresponding load as the ultimate load $\boldsymbol{H}_{\boldsymbol{u}}$.

The above process should be repeated for both left and right side columns and select the minimum value as the ultimate displacement δ_u of the frame. The value of $\varepsilon_{u,s}$ and $\varepsilon_{u,c}$ are to be calculated using relevant equations reported in Susantha *et al*. (2001). The effective length l_e is given by minimum of 0.7*B* or l_d.

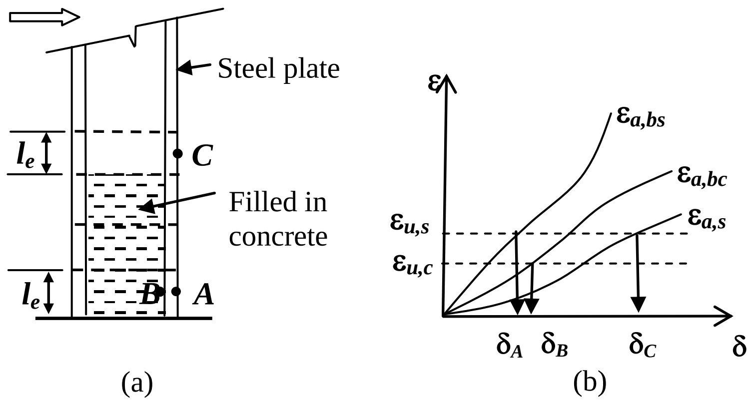


Figure 5: Failure criterion; (a) Locations of strain outputs, (b) Displacements at failure strains

2.3 Effects of concrete-filled height of single column

Parametric analysis was carried out for single column to check the optimum concrete-filled height that gives the best performance. For this purpose, five cases of filled-in heights given by h_c/h ratios of 0.1 to 0.5 were selected. The dimensions and material properties similar to the test specimen were used in the parametric analyses as well. Pushover analyses were performed for each case and ultimate point was determined using the failure criterion described earlier. The results of load-displacement curves of all the cases together with the hollow column are shown in Figure 6. It is evident from the figure that the effect of h_c/h ratios on load-deformation relation becomes insignificant after h_c/h ratio of around 0.3. The values of ultimate displacement, δ_u, and ultimate load, H_u, were calculated and plotted as shown in Figures 7. The figure clearly showed that the value of around 0.3 is the optimum concrete-filled height.

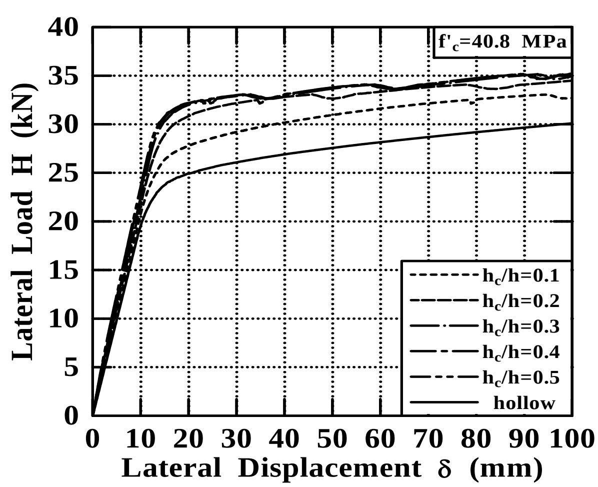


Figure 6: Load-displacement curves for different concrete-filled heights

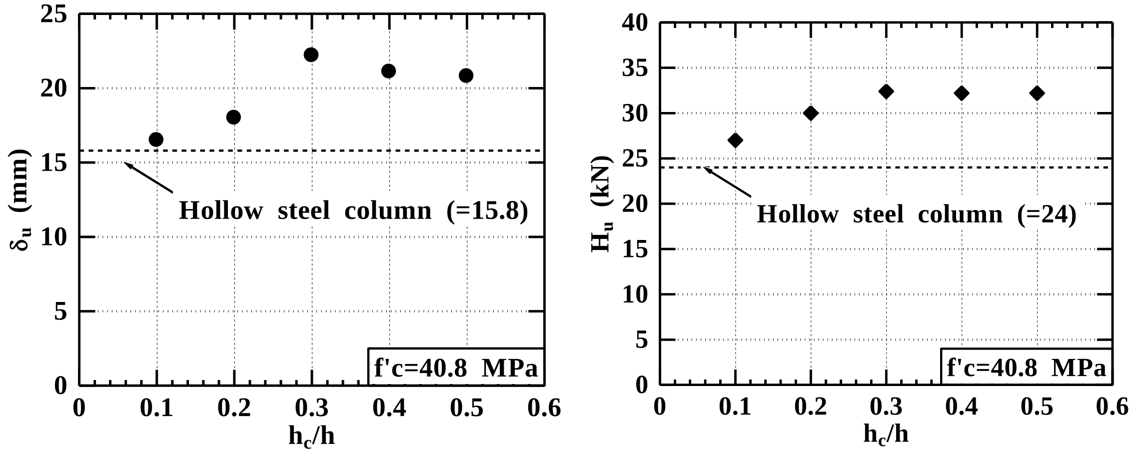


Figure 7: Ultimate points for different h_c/h ratios; (a) Ultimate displacement; (b) Ultimate load

2.4 Fiber model for CFST rigid-frame

A steel rigid-frame, as shown in Figure 8, was designed to check the effect of concrete infilling. Both columns and the beam consist of a square cross section having side length (B) equal to 300.0 mm. The columns were partially filled with concrete. The material properties are similar to those of specimen UU5. The height of the frame (h) and the span of the beam (l) equal to 2000.0 mm. The spacing of lateral diaphragms (l_d) is 300.0 mm. The finite element model is shown in Figure 9. Two types of fiber sections are defined for the concrete-filled part and the hollow part. Four cases were considered in the analysis representing h/h_c ratios of 0.15, 0.30, 0.45 and 0.55. In addition, a frame without concrete-filled columns is also considered. Axial load of 478.8 kN (=0.15 P_y) was first applied at the top of the columns. Target displacement of 200 mm was incrementally applied at the top node of the left column.

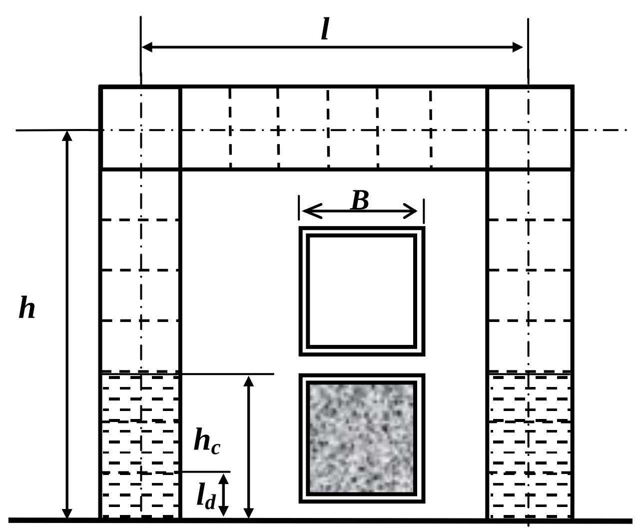


Figure 8: Geometric details of CFST rigid-frame

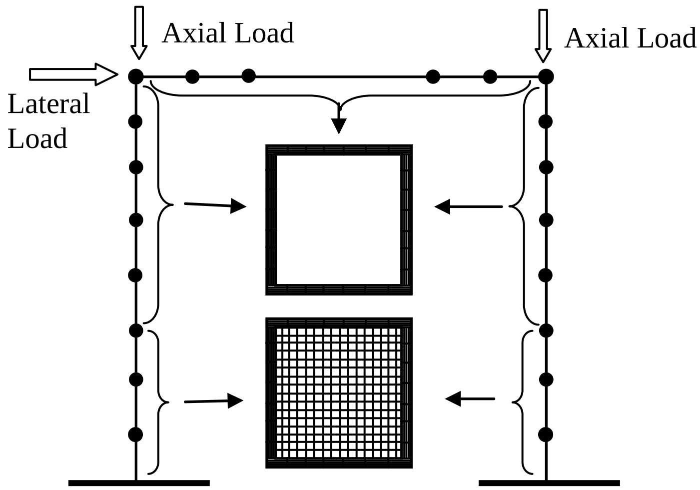


Figure 9: Fiber model of CFST rigid-frame

3. Results and Discussion

Lateral load-lateral displacement curves obtained using the pushover analysis are shown in Figure 10. The solid line represents the frame with hollow steel columns and the other four curves represent frames with partially concrete-filled columns having different h_c/h ratios. As expected, lateral load carrying capacity increased with concrete infilling but the increase is insignificant when h_c/h ratio is increased beyond around 0.15. For single CFST columns the optimum h_c/h ratio has been found to be 0.30. Thus, under the present geometrical and loading conditions the optimum filled-in height of frames is half of the optimum height of single columns. This fact needs to be further verified considering the effects of other parameters such as different cross sections, material strengths, frame dimensions, etc.

The ultimate strength H_u and ultimate displacement δ_u of all four frames were calculated using the procedure explained in section 2.2. The values of δ_u and H_u for each case are given in Table 1 and graphically shown in Figures 11(a) and (b). The concrete infilling has caused a significant increase in δ_u and H_u as seen in Figure 11. However, noticeable increase in the values of δ_u is not observed when h_c/h ratio increases beyond 0.15. Therefore it is essential that concrete infilling should be done only up to the optimum height in order to avoid unnecessary overload due to extra concrete infilling.

Table 1: Ductility and strength indices of frames

Case	h/h_c	δ_u /mm	H_u/ kN
Frame-1	*0.15*	*42.0*	*2392.0*
Frame-2	*0.30*	*40.0*	*2417.0*
Frame-3	*0.45*	*40.0*	*2417.0*
Frame-4	*0.55*	*40.8*	*2423.0*
Frame-0	*-*	*23.0*	*2100.0*

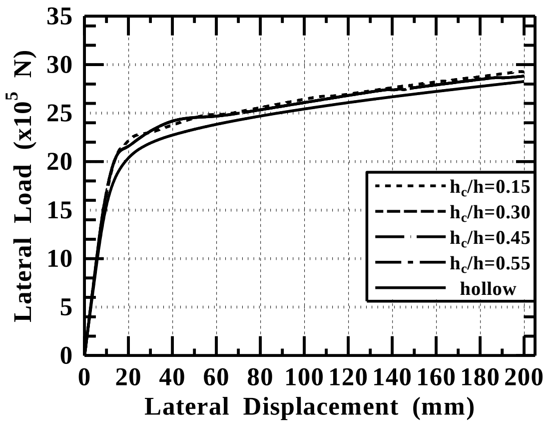


Figure 10: Lateral load-lateral displacement curves for steel rigid-frames

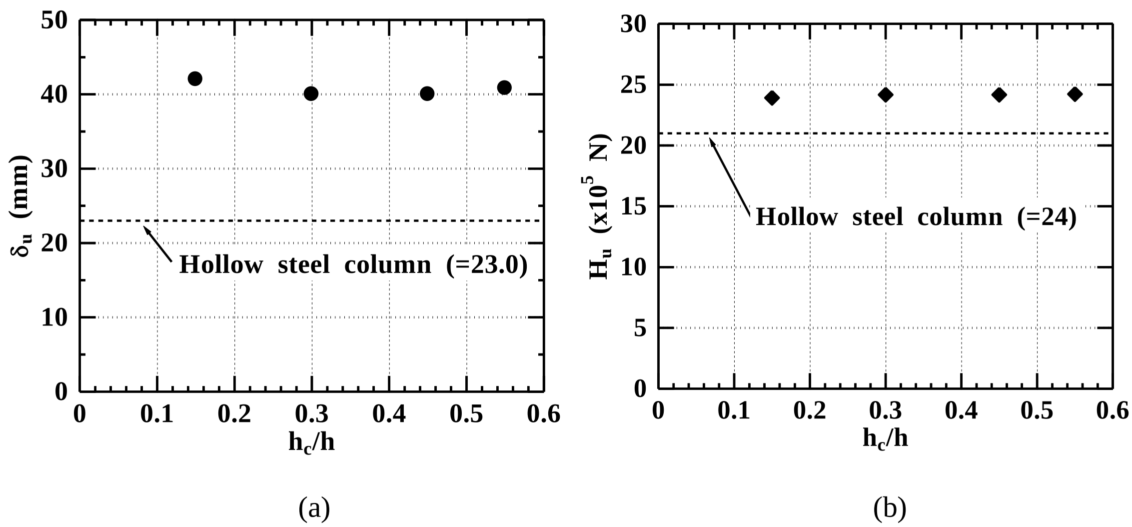


Figure 11:Ultimate points for different concrete filled-in heights; (a) Displacement, (b) Strength

4. Conclusions

Ultimate displacement and ultimate strength of partially concrete-filled steel columns and steel rigid-frames having partially concrete-filled steel columns were studied using the pushover analysis. The fiber model with nonlinear stress-strain relations of concrete and steel were used in the analyses. The ultimate points were decided using a failure criterion involving failure strains of materials. The main findings of the study can be summarized as follows:

1. Failure criterion developed using failure strains of steel and confined concrete can be effectively used to predict ultimate state of concrete-filled steel rigid-frames.

2. Concrete infilling significantly increased the ultimate displacement and ultimate load of steel frames.
3. The effect of concrete infilling depends on the height of filled-in concrete. There is an optimum filled-in height beyond which further increase in ductility would not be achieved.
4. The optimum filled-in height of single columns was found to be 0.30 times the total height of the column.
5. The optimum filled-in height of rigid-frames was found to be around 0.15 times the total height of the frame.
6. Further study is required to quantify the effect of various parameters on ductility and strength indices. Variables such as cross sectional dimensions, material strengths, axial load ratio, and geometry of frame could be considered in a study.

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