Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Seismic Collapse Performance of Frames with SRC-RC Columns through Pushover and Non-linear Time History Analysis in OpenSees Software

Abhishek Jain[1], Gautham Anbumani[2] and Dipti Ranjan Sahoo[3*]

[1]PhD Student, Department of Civil Engineering, Indian Institute of Technology, New Delhi, India
[2]Assistant Professor, Department of Civil Engineering, National Institute of Technology, Puducherry, Karaikal, India
[3]Professor, Department of Civil Engineering, Indian Institute of Technology, New Delhi, India
[*] drsahoo@civil.iitd.ac.in (Corresponding Author)

ABSTRACT

Steel reinforced concrete (SRC) columns are used worldwide due to their superior load carrying capacity and swiftness in construction compared to RC columns. There are numerous hybrid structures with RC columns on certain storeys and SRC columns on the rest of the stories. The columns where the cross-section changes from SRC to RC section are termed as SRC-RC columns. In this study, the columns were modelled in OpenSees as fibre elements with a material model considering the typical behaviour of SRC-RC columns and frames. The developed model was used to simulate the behaviour of a five-storey frame with the ground storey having SRC columns and rest with RC columns designed through an energy-based method. The parameter studied was the embedment of the structural steel in the second storey, making it the transfer SRC-RC story. Static pushover analysis was first carried out for the structure studying the base shear- roof displacement response of the structure. Furthermore, non-linear time history analysis was carried out for 22 ground motions scaled to maximum considered earthquake level (MCE) of the design spectrum for the site. It was observed that the frames with the lower embedment of structural steel performed poorly owing to sudden story shear failure. The increase in embedment alleviated this shear failure. The frames with higher embedment achieved close to immediate occupancy performance limit in time history analysis and displayed stable backbone curves.

Keywords: SRC-RC column, Composite column, Pushover analysis, Time history analysis, OpenSees

INTRODUCTION

Steel reinforced concrete (SRC) columns are an efficient load-carrying member with excellent seismic performance and construction speed. Structures with SRC columns can have beams composed of either structural steel members or RC. These frames are well-researched and are utilized worldwide to design structures. However, there are frames where the bottom storeys are SRC and upper stories are RC and vice versa. This combination is generally carried out to suit the project needs concerning speed, economy and ease of construction. In these hybrid frames, the storey where the column changes from SRC to RC is termed SRC-RC storey in this paper and the extent of structural steel in the story's clear length is termed embedment length in this paper.

SRC-RC columns have a higher lateral load-bearing capacity than RC columns but may have reduced ductility and unfavourable failure mechanism if the columns are not detailed adequately [1]. Experimental studies on SRC-RC columns have been carried out [2–4] to study the peculiar failure mechanism of SRC-RC columns. It was observed that the embedment length was one of the most critical factors that affected the structural behaviour, and specimens with higher embedment length performed better than others. A 60% embedment length was recommended by Wu, Xue and Zhao [3] and Wu *et al.* [5], and a 75% embedment length was recommended by Suzuki *et al.* [2]. Finite element study on the SRC-RC columns was carried out by Huang, Zhou and Liu [6] and Zhang *et al.* [7], where the columns were modelled, and embedment length, area of structural steel and axial load ratio were studied. Zhang *et al.*[8] conducted pushover analysis and non-linear time history analysis on buildings with SRC-RC columns. The authors advised a two-step method for designing such hybrid structures.

The research on the applicability of the results of the experimental and analytical studies conducted on isolated SRC-RC members in the global analysis is limited. The buildings with these SRC-RC columns need to be studied to create a complete design guideline for such structures. This research paper will focus on the seismic performance of the multi-storey hybrid building SRC-RC, where the structural steel embedment length is studied as the main parameter. Static pushover analysis and non-linear time history analysis will be carried out on the frames to study the backbone curve, inter storey drift ratio and inter-storey acceleration of the frames.

STUDY FRAMES

A five-storey framed structure having the ground storey columns as SRC members, the first storey column as SRC-RC and the columns in the stories above as RC is chosen from this study. The beams were composed of RC in all the stories. This characteristic frame, shown in Figure 1, is typical for Indian dwellings with a storey height 3 metres and column-to-column span 6 metres. The structure is designed to be located in a zone having the highest seismic intensity in the context of Indian standards , (Zone V) [9], typically located in the Himalayan ranges, its foothills, and the north-eastern states of India. The design carried out by an energy-based design approach [10] is followed to re-design the typical study frame (RC), which was considered in previous studies [10–12]. The live loads considered for roof and floor design are 1kN/m^2 and 3kN/m^2, respectively. The slab thickness considered on all the floors is 150 mm. The yield strength of structural steel was considered as 415 MPa and the compressive strength of concrete was considered 25 MPa. The structural reinforcement of beams and columns are designed to achieve strong column-weak beam elements throughout, as shown in Fig. 1. The structural section encased in concrete for SRC column is an Indian standard heavy beam, ISHB 250, with a cross-section of 150mm x 150 mm 108 flange thickness of 9 mm, and web thickness of 5.4 mm. Four different frames with SRC-RC columns and one control RC frame were researched in this study. The details of the five frames are given in Table 1.

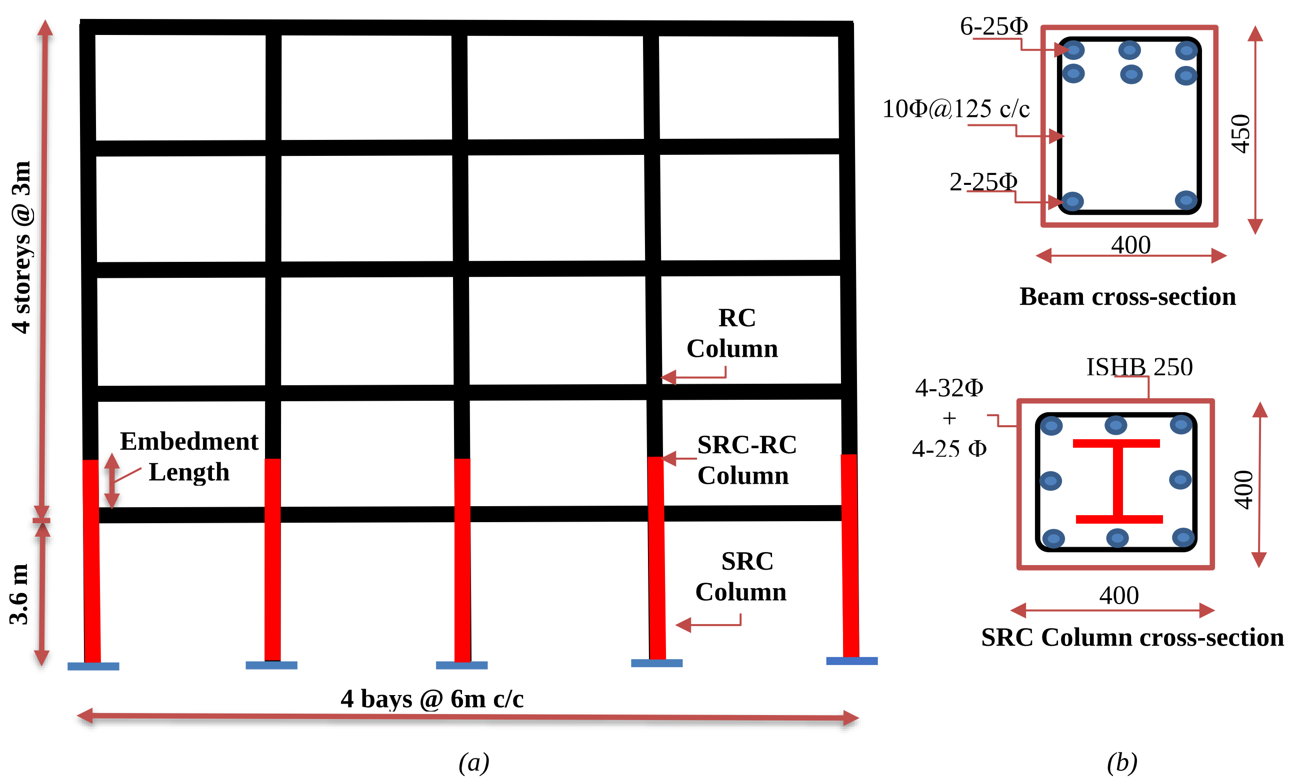

Figure 1. Details of the five storey frame (a) structural elevation of the study frame (b) cross section details of the beam and SRC-RC column in the frame

MODELLING TECHNIQUES

The five-storey structure was modelled in OpenSEES software [13] to incorporate a fibre-based modelling approach so that each fibre in the cross-section contains the material stress-strain model pertaining to either concrete, reinforcement steel or structural steel. The following sections discuss the modelling strategies used in this study.

Table 1. Details of study frame.

Frame Name	Ground Storey Column	First Storey Column	Embedment Length (%)	Direction of Lateral Loading
Hybrid 35% Major	SRC	SRC-RC	35%	Major
Hybrid 70% Major	SRC	SRC-RC	70%	Minor
Hybrid 35% Minor	SRC	SRC-RC	35%	Major
Hybrid 70% Minor	SRC	SRC-RC	70%	Minor
RC	RC	RC	-	-

The fibre-based modelling of RC and SRC elements considered axial force and bending moment interactions implicitly. The non-linear beam-column elements with a maximum of five integration points were considered to model the elements with a plastic hinge zone at the end to record the moment-rotation interaction with the considered loading. The element's shear force versus shear deformation response was modelled separately in OpenSEES and integrated with section aggregator command as a material property. Zero length elements were assigned at either end of each column section. Rotation and shear springs were assigned to capture the bar-slip behaviour and shear force versus shear deformation curves. These springs were assigned between the zero-length element and plastic hinge zone for each vertical member of the five-storey frame. The incorporation of shear force degradation was done with 'RotationShearCurve' material embedded in the OpenSees library [14]. The shear capacity of the RC and he SRC sections were calculated from the American design codes [15,16], respectively. The rotation shear curve lies dormant in the model if the flexural capacity of the column is lesser than the shear capacity; otherwise, the strength and stiffness degradation starts as soon as the limiting shear capacity of the member is reached leading to the section remaining with residual shear capacity. The residual strength of the backbone shear force versus the shear deformation curve was considered as 20% of the shear capacity of the section, which is the default in the material library.

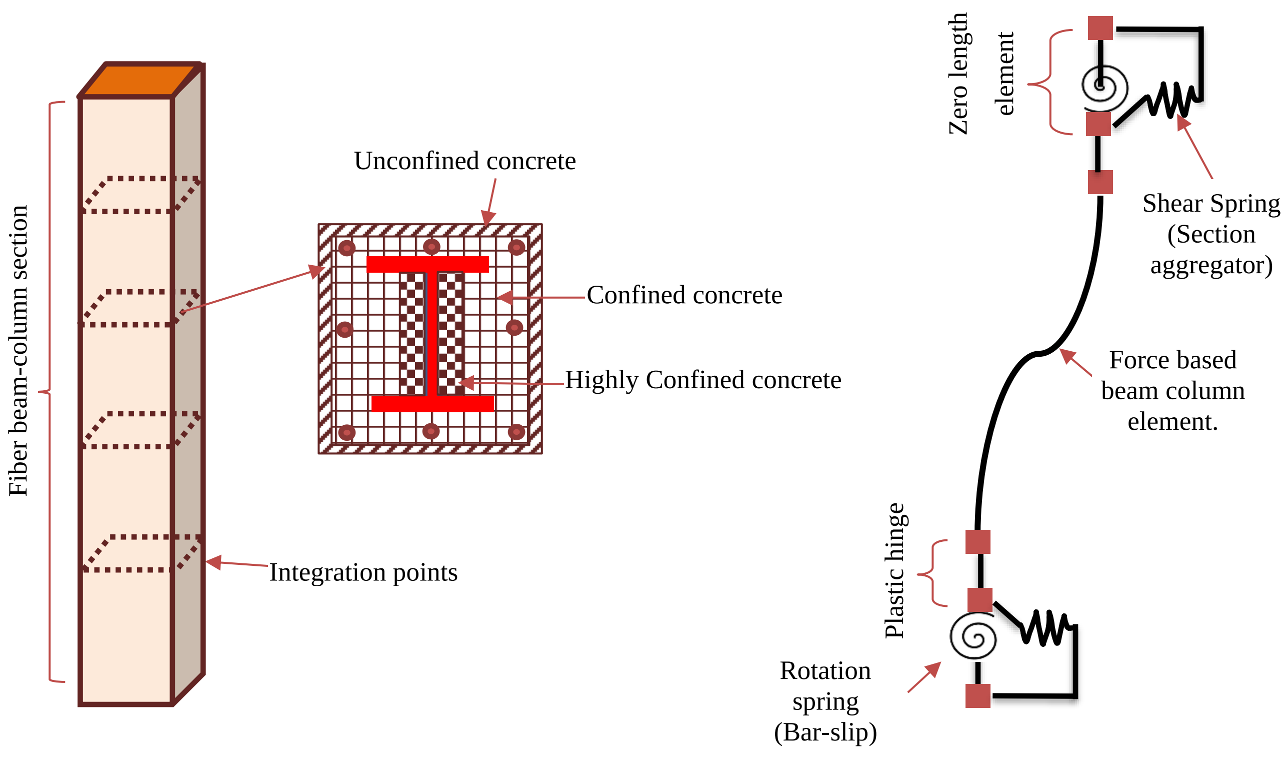

Figure 2. Fiber based modelling of SRC column in OpenSEES and addition of shear and rotation spring in the column element.

The material model considered for concrete was 'Concrete02', which accommodates tensile strength and linear tension softening of concrete. The geometrical fibre patches in the SRC elements were modelled separately for (a) unconfined concrete (b) confined concrete, and (c) highly confined concrete. The cover concrete outside the reinforcement bar cage was modelled as unconfined concrete, the concrete within the cage was modelled as confined concrete, and the concrete patch enclosed by structural steel up to half of its flange width outstand is termed as highly confined concrete. These different concrete patches are integrated with the reinforcement and structural steel layer throughout the member length with integration points. The peak and crushing compressive strength and strain of unconfined, confined, and highly confined concrete were calculated as per Collins, Mitchell and MacGregor [17], Mander, Priestley and Park [18] and Huang, Qian and Zhou [19], respectively. The tensile strength of concrete was taken as 10% of the peak compressive strength Huang, Zhou and Liu [6]. The structural steel was modelled with 'Steel02' material which considered the Giuffre-menegotto-pinto model, and the reinforcement layer was assigned 'Pinching4' material to consider the pinched hysteresis response of concrete members.

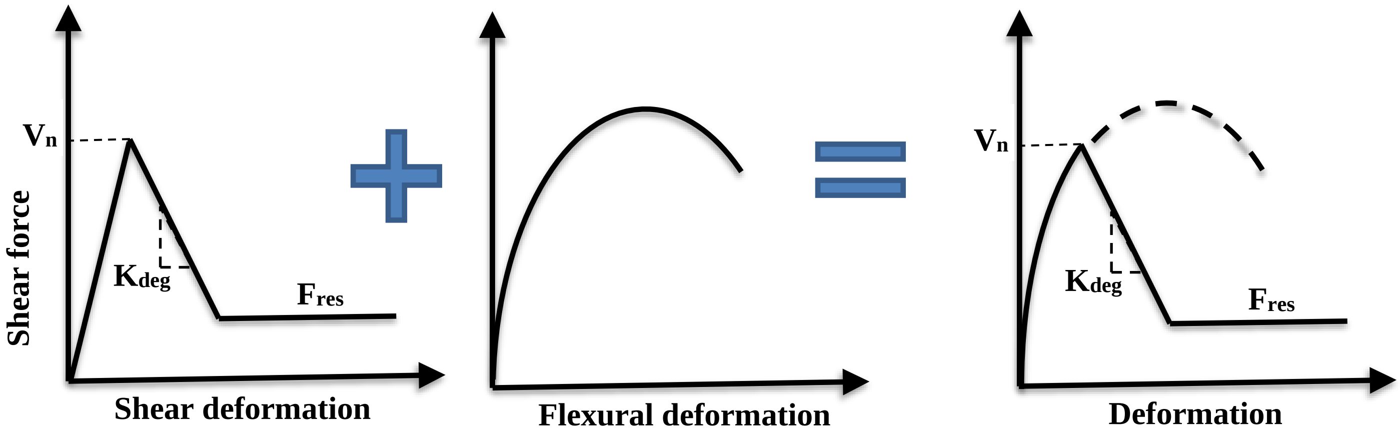

Figure 3. Shear force v/s deformation response of the fiber vertical element: (a) shear response; (b) flexural response; and (c) combined response

PUSHOVER ANALYSIS

The OpenSees model developed in the section was calibrated with the results previously published by [12] and [10]. Static pushover analysis was carried out to obtain the structure's backbone curve as shown in Fig.4 plotted as base shear versus the roof drift percentage. The peak strength of the hybrid 35% major and 70% major frame was the highest (1111 kN) due to the higher stiffness of the SRC column in the major axis. However, a sudden shear failure observed in the frame with lower embedment at 1.6% lateral drift in the SRC-RC storey led to sudden failure and shear degradation in strength with an increasing drift ratio.

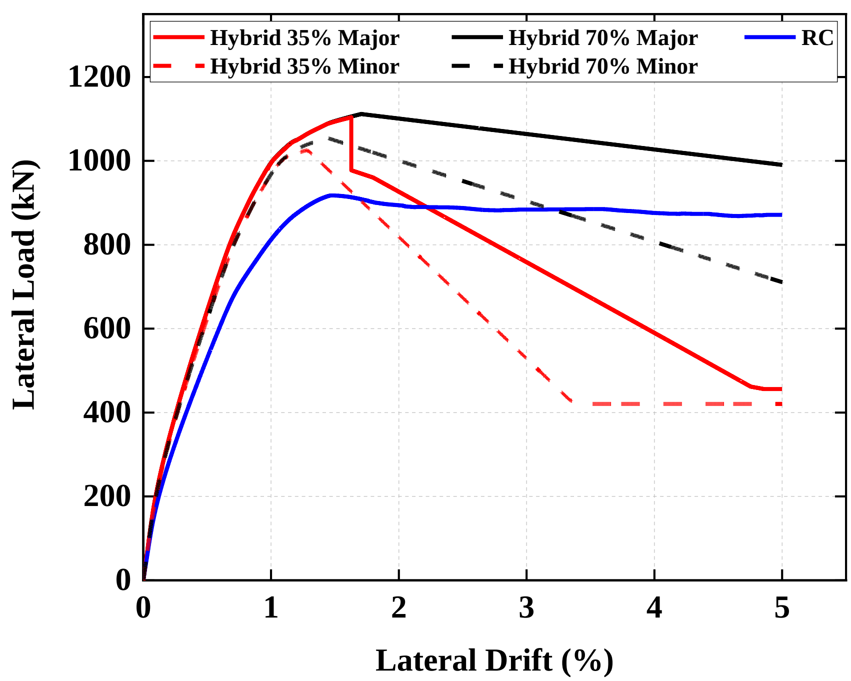

Figure 4. Backbone curve of the study frames with various embedments derived from the pushover analysis.

The peak strength for the minor axis frames was 6% lower (1050 kN) than the hybrid major frames. The failure for hybrid 35% minor frame started at 1.3% lateral drift, while degradation of hybrid 70% minor frame started at 1.4%. The strength degradation slope of the lower embedment specimen was much steeper, leading to quick deterioration of lateral strength. The RC frame had the lowest peak strength (917 kN) but did not have significant strength degradation at higher drifts due to strong column-weak beam detailing and capacity-based design approach.

NON-LINEAR TIME HISTORY ANALYSIS

The non-linear time history analysis is carried out on the frames to assess the seismic performance of the frames. The ground motions are generally scaled to design basis earthquake (DBE), which has a 10% probability of exceedance in 50 years and/or maximum considered earthquake (MCE) demand which has a 2% probability of exceedance in 50 years. This analysis can check the inter-storey drift, floor accelerations and element level demand at each time interval. The most critical data can be reported for all ground motions, and an average value can be established to ascertain that the frame has adequate seismic performance and level of damage.

Selection of ground motions

A group of twenty two ground motions were selected from FEMA P695 [20], compatible with the seismic design demand of the structures being constructed at the required site. The normalisation of the ground motions was done with respect to the peak ground velocity of each ground motion to remove the sensitivity of the data towards earthquake magnitude local soil condition, source distance and direction of motion. The normalised ground motions were scaled to match the design spectrum of the site under consideration. The matching of the design spectrum's spectral acceleration with the median spectral acceleration of the ground motions was done at the fundamental natural translation time period of the frame at 0.81 seconds, as shown in Fig.5

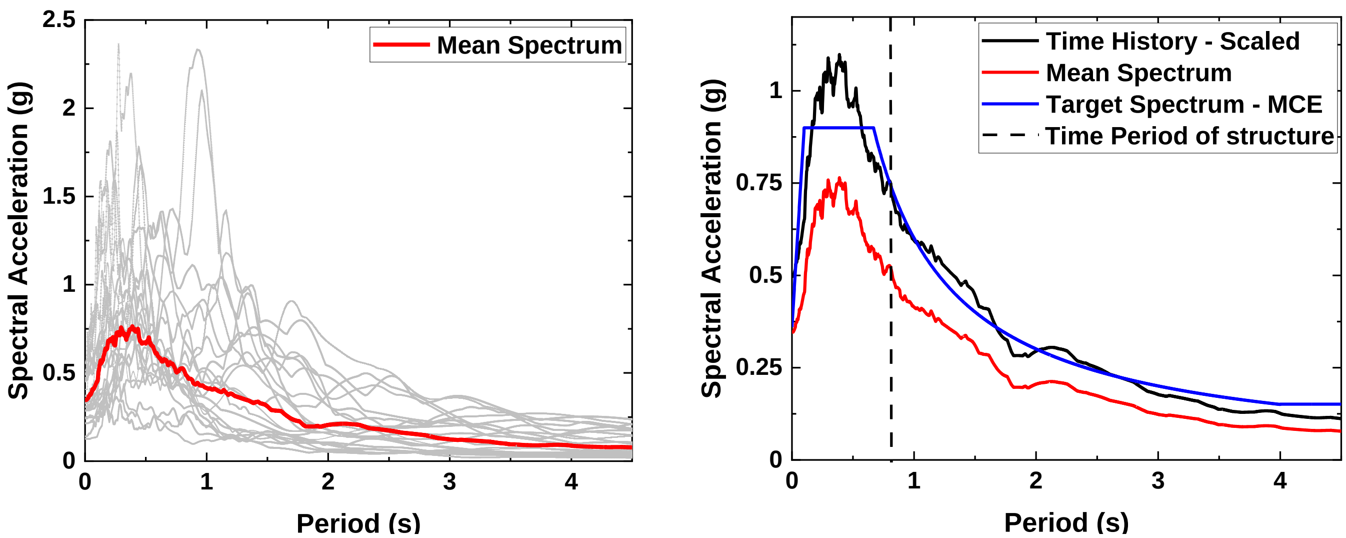

Figure 5. Depiction of (a) mean response spectrum of all time histories; and (b) scaled MCE time history

Results of time history analysis

The collection of ground movements scaled to fit the MCE level spectra for the target location was used in a non-linear time history analysis on the study frames. The inter-story drift ratios (IDRs) for the RC and SRC frames for all the ground motion records are shown in Fig. 5. The figures also display the performance limit levels described in FEMA 356 [21] for collapse prevention (CP), life safety (LS) and immediate occupancy (IO) performance for concrete frames. While collapse prevention performance includes extensive cracking and hinge formation in ductile elements, immediate occupancy performance levels limit the damage of primary frames to minor hairline cracking only.

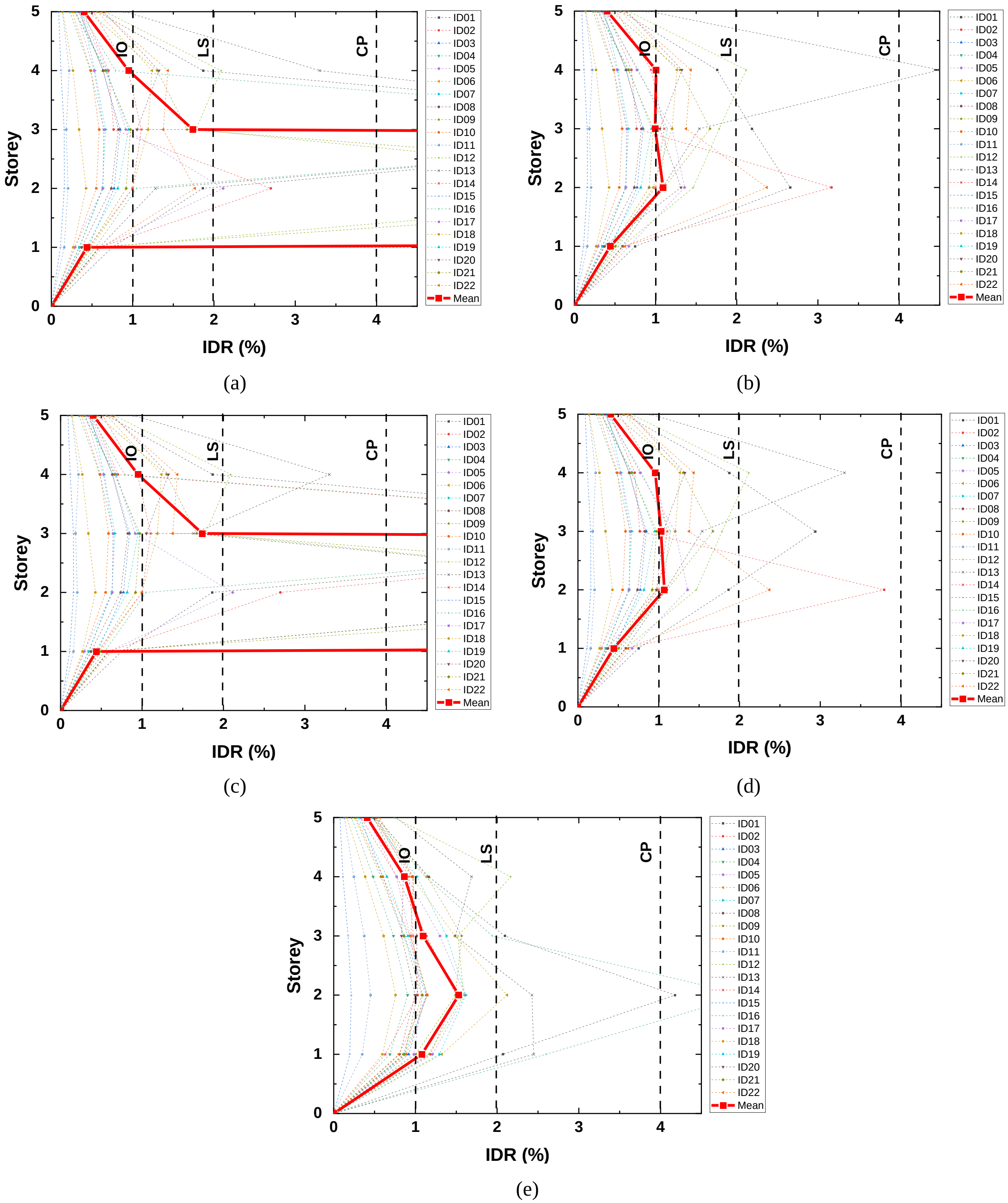

Figure 5. Variation of inter-storey drift with storey height for (a) Hybrid 35% Major (b) Hybrid 70% Major (c) Hybrid 35% Minor (d) Hybrid 70% Minor (e) RC frame

The Hybrid 35% major frame performed well in some ground motions. However, the first and second-storey collapse was observed for the rest of the ground motions. This led to the mean performance levels being below collapse prevention levels. Similar performance was observed for the Hybrid 35% minor frame, except that the number of ground motions triggering the frame's collapse was higher than in the Hybrid 35% major frame. Inter-storey drift ratios for all ground motions were higher for the Hybrid 35% minor frame than the corresponding major frame.

Interestingly, Hybrid 70% major and hybrid 70% minor frame performed exceptionally well for most ground motion by being within the immediate occupancy limit. The mean performance for the 22 ground motions can be said to be nearing IO levels performance. The frame with complete RC columns exhibited acceptable performance, achieving life safety level performance in most ground motions and the mean performance levels lying between the IO and LS levels. This is acceptable level of performance for a RC frame at the MCE level.

CONCLUSIONS

SRC-RC columns are particular elements of the transfer storey susceptible to sudden shear failure in the absence of detailing of the structure. The following conclusions can be drawn from the study:

- The frames with 70% embedment of structural steel in SRC-RC storey had a higher lateral load bearing capacity than those with 35% embedment and RC frames. The lower embedment frames are susceptible to shear failure leading to sudden strength and stiffness degradation, eventually leading to failure at lower drifts.
- The behaviour of the structure varies when the structures are loaded in different axis. The frames with lateral load direction in the minor axis of the SRC-RC column had an inferior performance compared to the major axis loading.
- The frames with 35% embedment in the SRC-RC store had unsatisfactory seismic performance in maximum considered earthquake leading to the complete collapse of the storey. The frames with complete RC columns achieved life safety performance.
- The frames with 70% embedment of I section in the transfer storey achieved immediate occupancy performance in both loading axes. This embedment depth is hence recommended for the SRC-RC column in addition to the ductile detailing of the complete column and the structure as a whole

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of IIT Delhi Laboratory for their experimental and computational support.

REFERENCES

[1] Jain, A., Sahoo, D.R., and Jain, A.K. (2020). "Numerical Investigation of Src-Rc Transfer Columns for Enhanced Seismic Resistance". In *17WCEE, Japan Associaton for Earthquake Engineering*, Sendai, Japanpp.

[2] Suzuki, H., Nishihara, H., Matsuzaki, Y., and Minami, K. (2000). "Structural performance of mixed member composed of steel". In *12WCEE, New Zealand Society for Earthquake Engineering*, Auckland, New Zealand.

[3] Wu, K., Xue, J., and Zhao, H. (2013). "Failure mechanism and bearing capacity of transfer columns in SRC-RC hybrid structures". *European Journal of Environmental and Civil Engineering*. 17 205–228.

[4] Zhang, H., Wu, K., Cao, P., Xu, C., and Ren, L. (2019). "Failure Modes and Damage Processes of Vulnerable Stories in SRC-RC Hybrid Frames". *Journal of Performance of Constructed Facilities*. 33 (5), 04019057, 1–18.

[5] Wu, K., Xue, J., Nan, Y., and Zhao, H. (2018). "Analysis on Extension Length of Shape Steel in Transfer Columns of SRC–RC Hybrid Structures". *International Journal of Steel Structures*. 18 (3), 910–923.

[6] Huang, W., Zhou, Z., and Liu, J. (2017). "Analytical deformation characteristics and shear capacity of SRC-RC transfer columns". *Journal of Constructional Steel Research*. 138 692–700.

[7] Zhang, H., Cao, P., Wu, K., Xu, C., and Ren, L. (2019). "Lateral Bearing Capacity and Stiffness Calculation Method of SRC-RC Columns". *KSCE Journal of Civil Engineering*. 23 2158–2174.

[8] Zhang, H., Cao, P., Wu, K., Ren, L., and Xu, C. (2019). "Two-Step Seismic Calculating Method and Seismic Features of SRC-RC Hybrid Frame Structure". *Journal of Performance of Constructed Facilities*. 33 (5), 1–14.

[9] IS:1893 (2016). Criteria for Earthquake resistant design of structures, Part 1:General Provisions and buildings. Sixth Revi Bureau of Indian Standards, New Delhi-110002.

[10] Gautham, A. and Sahoo, D.R. (2022). "Seismic Collapse Performance of Soft-Story RC Frames with SRC Columns Designed Using the Energy-Based Method". *Journal of Performance of Constructed Facilities*. 36 (6), 1–16.

[11] Sahoo, D.R. and Rai, D.C. (2009). "A novel technique of seismic strengthening of nonductile RC frame using steel caging and aluminum shear yielding damper". *Earthquake Spectra*. 25 (2), 415–437.

[12] Anbumani, G. and Sahoo, D.R. (2020). "Performance-Based Plastic Design of Mid-Rise Soft-Storey Rc Frames With Src Columns". *The 17th World Conference on Earthquake Engineering*. (January 2021), 1–11.

[13] Mazzoni, S., McKenna, F., Scott, M.H., and Fenves, G.L. (2006). OpenSees Command Language Manual. *Pacific Earthquake Engineering Research Center*. 465.

[14] Elwood, K.J. (2004). "Modelling failures in existing reinforced concrete columns". *Canadian Journal of Civil Engineering*. 31 (5), 846–859.

[15] ACI 318 (2019). Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary on Building Code Requirements for Structural Concrete (ACI 318R-19).

[16] AISC 360 (2016) Specification for Structural Steel Buildings, an American National Standard. .

[17] Collins, M.P., Mitchell, D., and MacGregor, J.G. (1993). "Structural Design Considerations for High-Strength Concrete". *Concrete International*. 15 (5),.

[18] Mander, J.B., Priestley, M.J.N., and Park, R. (1989). "Theoretical stress-strain model for confined concrete". *Journal of Structural Engineering*. 114 (8), 1804–1826.

[19] Huang, W., Qian, J., and Zhou, Z. (2016). "Numerical simulation of the seismic performance of steel reinforced concrete columns with various confinement effect". *Gongcheng Lixue/Engineering Mechanics*. 33 (5), 157–165.

[20] FEMA P695 (2009) Quantification of building seismic performance factors. California.

[21] FEMA 356 (2000) Prestandard and Commentary for the Seismic Rehabilitation of Building. Virginia.