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Seismic Performance of SRC Column and Steel Beam Hybrid Frame Based on Pushover Method

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Abstract: Hybrid structures combine different materials to achieve architectural and economic benefits. This study investigates the seismic performance of a steel–reinforced concrete (SRC) column and steel beam hybrid frame using the pushover method, a nonlinear static analysis approach. The structural analysis was conducted with the finite element program SAP2000 to evaluate the frame's response to various loads, including seismic actions. A baseline model was developed as a reference, and key parameters—such as beam-to-column stiffness ratio, and frame height—were systematically varied to assess their influence on seismic performance. The results show that generally the hybrid frame demonstrates satisfactory resistance to seismic loads. Stiffness ratio parameter affect structural performance positively for model 1 to 5 but for model 6 to 9 the structure collapse first. While frame height parameter until 10 story height doesn't significally impact the performance. These findings provide useful insights for optimizing the design of hybrid frames in seismic regions.

Keywords: hybrid frame, nonlinear static analysis, pushover analysis, SRC column

INTRODUCTION

Currently in the construction technology, concrete and steel are the most famous materials. Those two are also most frequently encountered combination materials to be used as construction materials to be applied to the buildings or factories, as well as bridges, towers, or other constructions. These materials can be used together to form structural members such as reinforced concrete (RC), steel-section reinforced concrete (SRC), or concrete-filled steel tube (CFST). As well as to be used in hybrid structure where the members consist of concrete and steel can work together.

The steel reinforced concrete column-steel beam (SRC column-S beam) hybrid frame structure is one of the steel-concrete composite structures. The most common form of composite element in construction is the steel-concrete composite (Yu et al., 2024). Compared with ordinary reinforced concrete frame structure, it has better integrity and seismic performance. The steel reinforced concrete column-steel beam composite frame structure system can effectively meet the reasonable coordination of functions and economy of office buildings and small high-rise residential buildings, and can also exhibit better performance advantages and economic benefits in other important projects, especially in high-rise buildings. SRC structure are also proven to have a good resistance against fire (Guangyong & Dongming, 2017). Therefore, hybrid structure has notable advantage in decreasing self-weight, reducing section size of structural members, and accelerating construction progress (Jiang et al., 2008). In hybrid construction, the different materials may work together or independently, but will always provide advantages over the use of a single material (Nieri et al., 2023).

A building is objected to carry its own weight, its lateral load, and also to stand against seismic load. In countries that are in the area of "Ring of Fire" or other seismic area such as Japan and Indonesia, it is the ultimate thing to avoid life loss and material loss. A lot of seismic design methods are used around the world. Each of them has their strengths and weaknesses. One of the most suitable approach is performing a damage-controlled design by using nonlinear static procedures (Jaiswal & Jain, 2004). In this paper, Nonlinear Static Procedure (NSP) is used as a tool to verify the design and also to asses performance of structural system. This method is also known as pushover method. Pushover method is an essential simplified static nonlinear procedure used for estimating structural deformations (Kuria & Kegyes-Brassai, 2024).

One of the way to analyze the characteristics of this composite structure is by using the modeling from Finite Element Method program such as SAP2000, ANSYS, and so on (Lai et al., 2021). Using computing software make the calculation and analysis easier and faster.

RESEARCH METHOD

This research used quantitative methods, with the creation of an analytical model as the initial basis. The model was designed based on the 2009 International Building Code (IBC) and the American Society of Civil Engineers (ASCE), and was designed to meet FEMA seismic requirements. Building performance in this standard is expressed in terms of target building performance levels. These include the ability to resume normal functions within the building, the advisability of post-earthquake occupancy, and the risk to life safety (FEMA 356, 2011).

The designed baseline model must then be tested using the pushover method. Pushover method is non-linear static seismic analysis. According to FEMA 440, Nonlinear static procedures are one type of inelastic analysis that can be used to estimate the response of structures to seismic ground shaking. The differences between the various approaches relate to the level of detail of the structural model and the characterization of the seismic ground shaking (FEMA 440, 2005). If the model meets the basic structural performance requirements, it can be used as a basis for analyzing factors that may affect the structural performance, which will also be tested using the pushover method.

Basic Model

Structure that represented in this design as the basic model structure is hybrid frame structure. Structure is designed based on International Building Code (IBC) 2009 and American Society of Civil Engineers (ASCE) 7-05. This model also uses Federal Emergency Management Agency (FEMA) 356, FEMA 440, Applied Technology Council (ATC) 40 as the reference for its seismic design. The sample structure used in this paper is described as follows:

1. Frame building with three floors and 2 spans.
2. The floor height is 3 m each.
3. Hybrid frame consists of steel reinforced concrete (SRC) column and steel beam.
4. The material used for concrete member is concrete C35 and the material used for steel member is Q345 according to Chinese code.
5. The SRC column dimension for first floor is 55 x 55 cm rectangular concrete with H-shaped steel section reinforcement and also 10 bars of 1-inch longitudinal bars. H-shaped steel section attributes are mentioned:

Tabel 1. Steel Section for First Floor Column

Height (mm)	Flange Width (mm)	Web Thickness (mm)	Flange Thickness (mm)
400	400	28	28

6. The SRC column dimension for second and third floor is 50 x 50 cm with H-shaped steel section reinforcement and also 10 bars of 1-inch longitudinal bars. H-shaped steel section attributes are mentioned:

Table 2. Steel Section for Second and Third Floor Column

Height (mm)	Flange Width (mm)	Web Thickness (mm)	Flange Thickness (mm)
350	350	28	28

7. The steel beam is also using H-shaped steel section W16 x 26 with dimension specification as follows:

Table 3. Steel Section for The Beams

Height (mm)	Flange Width (mm)	Web Thickness (mm)	Flange Thickness (mm)
398,78	139,7	6,35	8,763

8. The model is applied distributed rectangular live load 2 kN/m^2.
9. The model is applied seismic load response spectrum according to IBC 2009.
10. Standard hinges from ASCE 41-13 are added to both columns and beams with relative distance 0,1 and 0,9.

Figure 1 will represent the frame model from 3D perspective mode in SAP2000 software program.

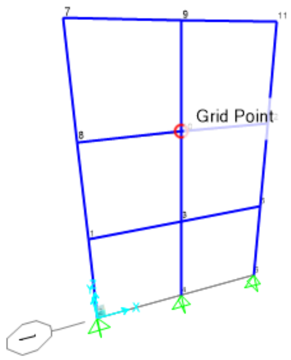


Figure 1. Basic Model Frame

Figure 2 will represent SRC column section which has concrete, steel profile, and rebar component and Figure 3 will represent beam steel section together with its dimension explanation.

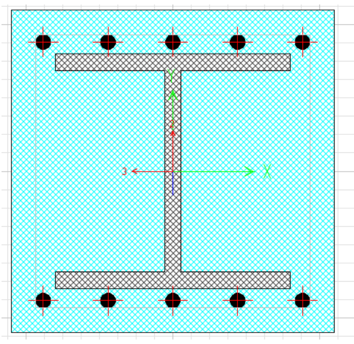


Figure 2. SRC Column Section

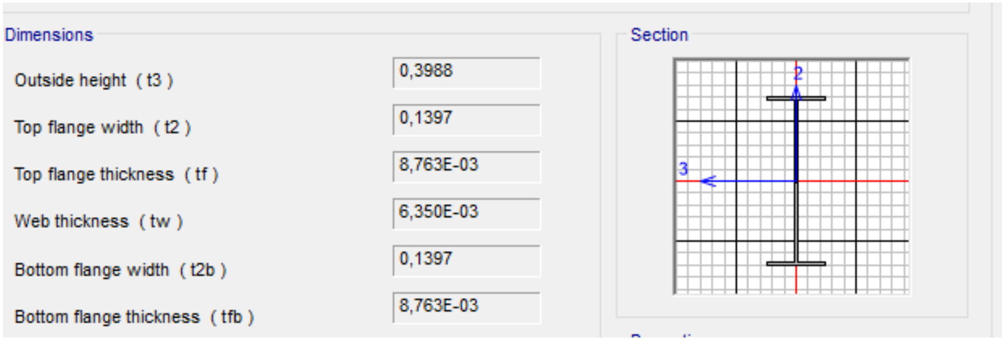


Figure 3. Steel Beam Section

Influencing Factors

There are many influencing factors that could be tested in the pushover analysis of composite steel-concrete column-steel beam hybrid frames. This paper only discusses some of them such as beam-column stiffness ratio and frame height. Those influencing factors will be the measuring parameters on how the basic model frame structure reacts to the seismic analysis.

Beam-Column Stiffness Ratio

The stiffness ratio of beam-column line of the composite steel-concrete column-steel beam composite frame is a very important factor in determining the overall performance of the frame. The frame structure is a statically indeterminate structure, and the interaction between the stiffness of the beam and column is obvious.

It affects the anti-seismic performance of the frame structure such as the overall resistance to lateral stiffness, internal force distribution, ductility, deformation ability, and energy dissipation capacity. The linear stiffness ratio of the beam column directly determines the internal force distribution of the beam column structure in the frame structure. Therefore, under the premise of satisfying the seismic requirements of structural bearing capacity, deformation, and strong columns and weak beams, it is very important to find the optimal stiffness ratio of the column and column according to the use environment of the structure, the purpose of use, and its own characteristics (Feng, 2014).

In this paper, the stiffness ratio of beam-column is changed by adjusting the beam size. Beam-column stiffness ratio is calculated by dividing beam inertia moment and column inertia moment ratio (Chun & Hur, 2015).

$$I = {}^{I_b}/_{I_c} \tag{1}$$

$$I_c = \frac{bh^3}{12} \tag{2}$$

$$I_b = \left[\frac{t_w(H-2t_f)^3}{12}\right] + \left[\frac{Bt_f}{6}\left\{{t_f}^2 + 3(H-t_f)^2\right\}\right] \tag{3}$$

There are total of 9 models including the basic model that will be presented in table 4.6. below. The table has included beam-column stiffness ratio. For further information, the column is bottom 550 x 550 column and above 500 x 500 column.

Table 4. Beam-Column Ratio Model Parameter

Model	**Beam Dimension/mm**	**Bottom Stiffness Ratio**	**Above Stiffness Ratio**
Basic Model	399×140×6,35×8,76	0,0020126	0,0029467
Model 1	300×160×12×16	0,0020097	0,0029424
Model 2	352×160×16×16	0,0030868	0,0045194
Model 3	350×180×16×18	0,0036066	0,0052804
Model 4	350×250×16×20	0,0051194	0,0074953
Model 5	350×250×14×20	0,0050380	0,0073762
Model 6	400×300×18×20	0,0082549	0,0120860
Model 7	500×400×20×26	0,0216271	0,0316643
Model 8	600×450×22×28	0,0386540	0,0565933

Frame Height

Another parameter to explore the seismic performance of hybrid frame is the frame height. Along with ground motion characteristics, building height to a degree is influencing seismic performance especially in buckling (Tirca & Tremblay, 2004). In order to know the influence of the frame height, this paper will include 3 models that are 5-story frame and 10-story frame and the basic model 3-story frame, with each story is 3 m height. The models have same section dimension size, only vary on frame height selection. Table 4.7 will represent the model's height parameter.

Table 5. Frame Height Parameter for Hybrid Frame

Models	Number of Story
Basic Model	3-story
Model 1	5-story
Model 2	10-story

RESULT AND DISCUSSION

Seismic Performance of Basic Model

As pushover analysis has many advantages over the elastic examination (Sharma, 2022), after running the pushover analysis in the SAP2000 program, the generalized load-deformation curve is obtained, as shown in Figure 4 below. Figure 4 is described by a linear response from A (unloaded component) to an effective yield B, a linear response at reduced stiffness from point B to C, a sudden reduction in lateral load resistance to point D, a response at reduced resistance to E, and final loss of resistance thereafter (Sujani et al., 2012).

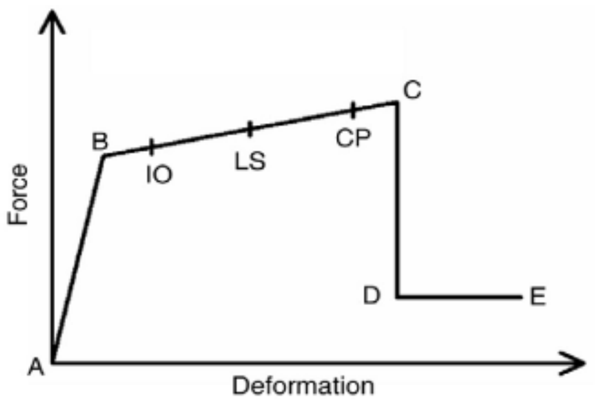


Figure 4. Generalized Load-Deformation Curve (FEMA 356)

The pushover curve is also known as the capacity curve, which is a plot of base shear versus displacement of the roof of the structure. From the pushover curve, the maximum displacement at the roof and base reaction of the structure during displacement-controlled analysis can be obtained. The pushover curve is a good indicator of the inelastic behaviour of the structure beyond the elastic stage (A, Kadid and A, 2009).

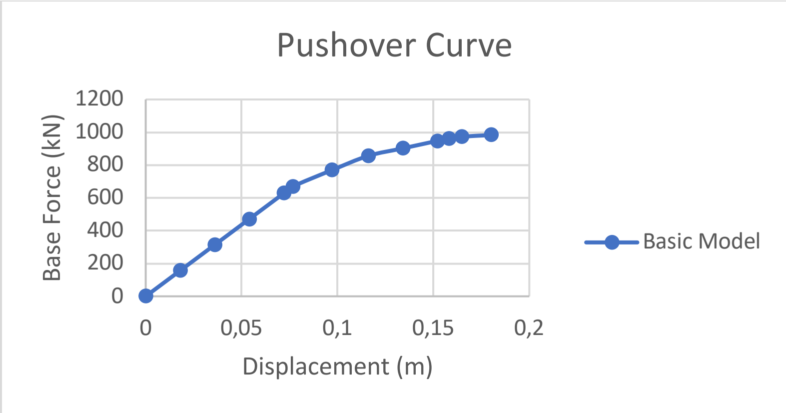


Figure 5. Pushover Curve for Basic Model

It can be seen from the curve that the structure has experienced several stages:

1) A to B area is the elastic stage. Therefore, before the structure reaches about 76 mm in displacement, the frame structure is always an elastic stage. The base reaction force increases linearly with the increase in displacement value, and the structure has a small overall stress.
2) After the displacement value is greater than 76 mm, with the continued loading, the velocity of the structural base reaction force increases with the increase of the loading displacement, and the slope of the curve gradually decreases. In the compressed area of the frame structure, part of the concrete has been crushed, and the stress of the steel in the SRC column has increased significantly. At this point, the plastic hinges appear to be more in the entire structure, mainly in the vicinity of the beam-column nodes, indirectly indicating that the cracks are concentrated in the vicinity of the beam-column nodes.

Analysis Result of Influencing Factors on the Hybrid Frame

Beam-Column Stiffness Ratio

Analysis of the beam-column stiffness ratio was used in a total of 9 models, as mentioned in Table 4. Table 6 shows the comparison of maximum capacity, maximum displacement, and the number of steps for the beam column stiffness ratio factor.

Table 6. Table of Beam-Column Stiffness Ratio Parameter Models Comparison

	Maximum Capacity (kN)	Maximum Displacement (mm)	Number of Steps
Basic Model	982,752	180	12
Model 1	1176,278	180	11

	Maximum Capacity (kN)	Maximum Displacement (mm)	Number of Steps
Model 2	1545,892	180	10
Model 3	1738,541	180	11
Model 4	2274,275	180	10
Model 5	2230,736	180	10
Model 6	2675,55	144,285	12
Model 7	2508,584	61,108	6
Model 8	2546,408	48,602	6

Figure 6 shows the pushover curve for beam-column stiffness ratio parameter models. A total of 9 models are compared based on their base force and displacement curve that can be seen below:

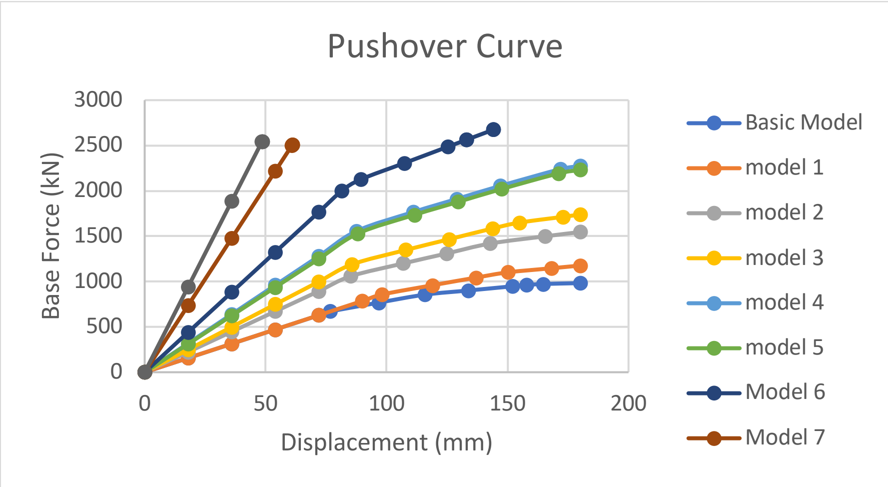
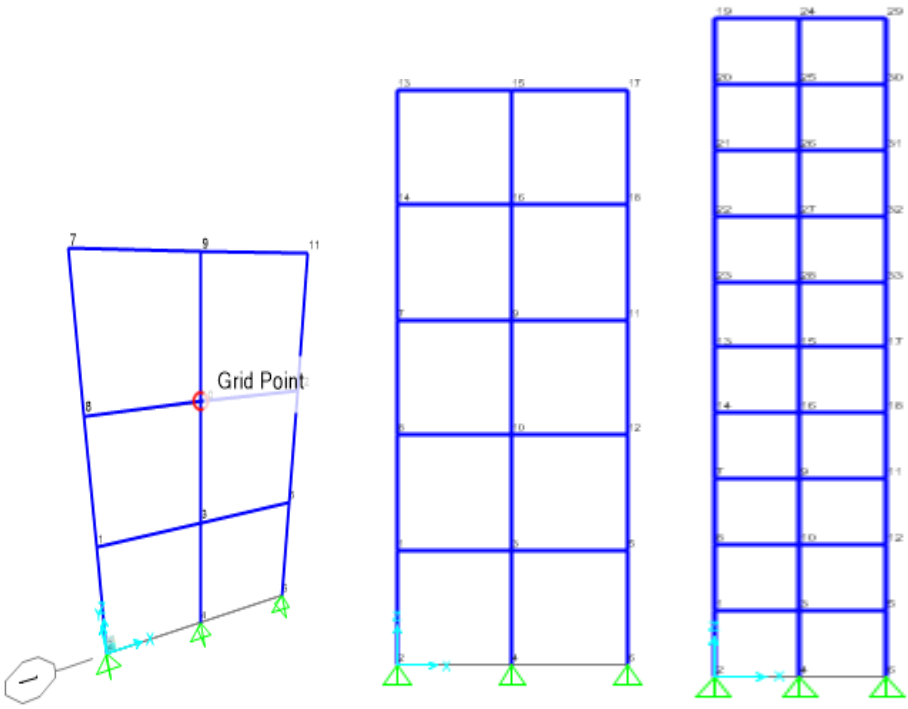


Figure 6. Pushover Curve of Beam-Colum Stiffness Ratio Parameter Models

From Table 4, Table 6, and Figure 6, it can be concluded that an increase in the beam-column ratio will increase the maximum capacity as well. As the ratio is increasing, the maximum capacity in the elastic stage is also increasing. However, for the maximum displacement, especially for models 6, 7, and 8, the maximum displacement decreases obviously. The reason for this could be that the beam-column stiffness ratio is obtained by adjusting the beam size only without changing the column size. Thus, for models 6, 7, and 8, the beam-column stiffness ratio is very high, and the column collapses first. This is not good for the concept of "weak beam strong column". It can be concluded that too high a beam-column ratio is not good for the structure. Hence, we have to make some adjustments to the column size to make them balance.

Frame Height

The frame height parameter only adjusts the frame story without changing the column and beam dimensions or even each floor's height. This parameter is used to determine the effect of total height differences. The models of the frame height parameter can be seen in Figure 7 below:



a). 3-story b). 5-story c). 10-story

Figure 7. Frame Height Parameter Models

The result of the pushover analysis of the frame height parameter is shown in Figure 8. The maximum capacity decreases as the frame height increases. It should be highlighted that the models do not have member size adjustment. The displacements of the three models do not differ significantly. They have the same maximum displacement, even though the displacement for every step is slightly different.

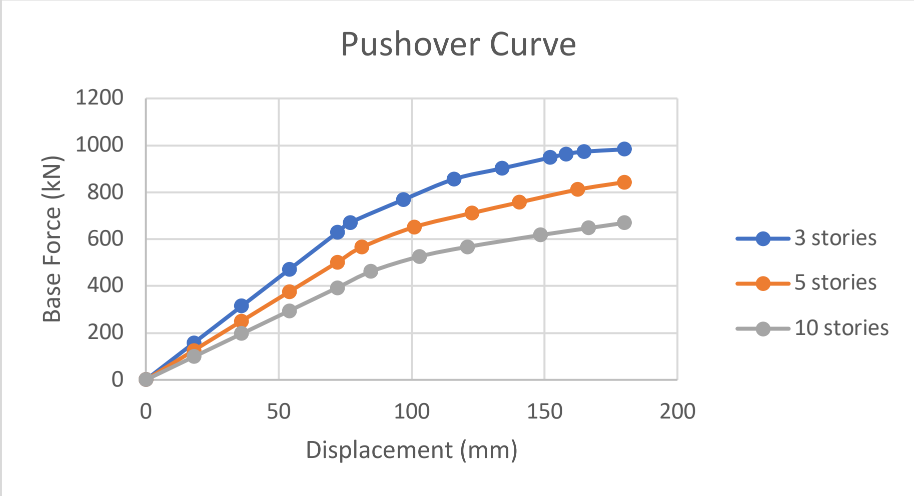


Figure 8. Pushover Curve for Frame Height Parameter Models

Table 7 shows the differences in the maximum capacity, maximum displacement, and number of pushover steps from the frame height parameter models. For the models with the same dimension members but different frame heights, the maximum capacity decreases as the frame height increases, as shown in Table 7 below:

Table 7. Table of Frame Height Parameter Models Comparison

	Maximum Capacity (kN)	**Maximum Displacement (mm)**	**Number of Steps**
3-story	982,752	180	12
5-story	842,922	180	10
10-story	669,218	180	10

CONCLUSION

In this paper, the SAP2000 program is used to establish the SRC column-steel beam hybrid frame model, of which the seismic performance is studied by nonlinear static analysis or pushover analysis. For the overall result, the hybrid frame is a good prospective structural form. Pushover analysis is one of the easiest ways to assess seismic performance. The pushover analysis used in this thesis is the performance-based method that relies on the displacement-force curve or also called the pushover curve. This paper examines the influence of some factors, that are beam-column stiffness ratio and the frame height, on the seismic performance of the SRC column and steel beam hybrid frame. After conducting the analysis, the following conclusions can be drawn from this investigation:

1. For the basic model case, which has a 3-story frame and C35 and Q345 material, the seismic performance is pretty good. The frame has resulted in a typical pushover curve and has good capacity. This basic model can be the basis for involvement to other influencing factors.
2. For the beam-column stiffness ratio influencing factor case, this thesis adjusts the beam size. The higher the stiffness ratio is, the bigger the capacity. This study used 9 models, including the basic model. As the ratio increases, the maximum capacity in the elastic stage also increases. Basic model, model 1, model 2, model 3, model 4, and model 5 show a pretty good pushover curve. Good maximum displacement and increasing capacity. However, for models 6, 7, and 8, the maximum displacement decreases even though the capacity increases. From the curve, we know that the frame collapses in a brittle manner. Those three models will collapse from the column first. Thus, it is not good for the concept "weak beam strong column". This is because the beam is too big for the current size of the column, since for this variable, the only thing to adjust is the beam size.
3. In the case of the frame height influencing factor, the maximum capacity decreases as the frame height increases for the same dimension members but varying frame height. Based on the plastic hinges' status and condition, it can be concluded that the frame height does not significantly impact the seismic performance.

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