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Seismic Behavior of an Inter-story Hinged Lateral Resistance Braced Frame

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ABSTRACT

Based on the deflection behavior of structural components occurring at the lateral deformation of moment frames, a new lateral force-resisting system, the R-BRACE Frame (RBF) system, was proposed. This system is capable of effectively limiting the inter-story drift response of tall buildings. An evaluation was conducted using the finite element method program SAP2000 to simulate the internal force distribution and deformation of the system. The equivalent lateral force procedure (ELFP), the capacity spectrum method (CSM), a linear time-history analysis and the pushover method were applied to assess the yielding mechanism of the structure under different earthquake intensity levels. The findings revealed that the sub-unit, referred to as an R-BRACE, had a major impact on improving a structure's lateral stiffness. The placement of R-BRACE units could guarantee controllable stiffness degradation and enhanced seismic ductility, but would not alter the vertical load transfer path of the initial structure, which makes the RBF system an ideal option for seismic retrofitting.

KEYWORDS: Lateral force-resisting system, R-BRACE frame, Enhanced lateral stiffness resistance, Seismic ductility.

INTRODUCTION

Seismic and wind loads play controlling roles in the structural designs of high-rise buildings in seismically active regions. The center braced frame (CBF) and eccentrically braced frame (EBF) systems, both of which employ arrangements of diagonal bracing, are extensively employed in seismic designs to improve the lateral stiffness of steel structures. For these systems, local bracing (especially at the bottom of a structure) is prone to failure during long-duration moderate-or high-intensity earthquakes due to the large seismic forces that the structure passively endures. The shear stiffness of the floor on which the bracing buckling or yielding is located will be greatly reduced once the bracing is damaged, increasing the risk of an overall collapse of the structure.

Recently, scholars have extensively researched design methods for enhancing the seismic ductility of high-rise frames and some studies on new lateral force-resisting systems have been performed. Several design concepts have been proposed in previous research to limit inter-story drift concentration. The Strongback system (SBS) was developed as a new lateral system dependent on the elastic response of a strengthened vertical steel truss spine to limit the inter-story drift ratio distribution of a frame (Lai and Mahin, 2015). The yield frequency spectra (YFS) process was proposed as an accurate design process for the SBS, where it was demonstrated that the SBS had a better ductility than conventional bracing systems and a lower probability of the soft-story mechanism occurring during earthquake excitation (Salek Faramarzi and Taghikhany, 2020). Beyond this, there have been several interesting investigations and the proposal of a primarily conceptual design, like a segmented elastic spine truss labeled SESBF, for which the vertical truss spines were segmented along the frame height and which was designed to uniformly distribute story drifts by restricting inertia forces inside each trussed segment (Chen, Tremblay and Tirca, 2019). Some scholars proposed the use of a stiff rocking core (SRC), which consisted of a reaction steel column and an elastic vertical truss connected to the existing framing *via* pin-

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pin-ended steel links to achieve the desirable response and redistribution of the lateral demands (Pollino et al., 2017). A seismic resisting system, referred to as the curved damper truss moment frame (CDTMF) system, was developed that utilized curved dampers as energy-dissipating elements that could be easily repaired or replaced (Fathizadeh et al., 2020). Additionally, researchers are working to prevent beam and column connections from breaking by controlling the formation of plastic hinges at non-critical points and producing moment-resisting frames with better energy absorption capacities. Studies were conducted to determine the most suitable length for a reduced knee brace that absorbs a large amount of seismic energy through plastic deformation during cyclic loading, avoiding the formation of plastic hinges on the main frame structure (Majid et al., 2020).

After investigating the working mechanisms of the existing lateral force-resistance systems, the authors of the current paper developed and proposed an inter-story hinged lateral force-resisting braced frame system (referred to as the R-BRACE Frame [RBF] system) with significant stiffness and ductility enhancements (Ren yu, 2022). Figure 1 shows a sub-unit (referred to as an R-BRACE) that provides lateral-force resistance. It consists of upper and lower trusses formed by lateral bracing located in the plane of the frame, with the ends of the trusses joined by a horizontal steel link hinged at both ends (designed as a "two-force member"). This design resulted in a configuration that resembles the letter "R." The design method for R-BRACE units must follow the following principles. First, the upper and lower trusses must equally divide the floor height. Secondly, in the span direction of the beam, the truss should be arranged in the middle and the opening angle should be selected according to the function and traffic conditions. Usually, in the case of there being no function limit, it is suggested that the truss divides the frame beam into thirds. Finally, according to the yield force under the design level, the size of the horizontal connecting links and the inclined rod of the truss can be designed.

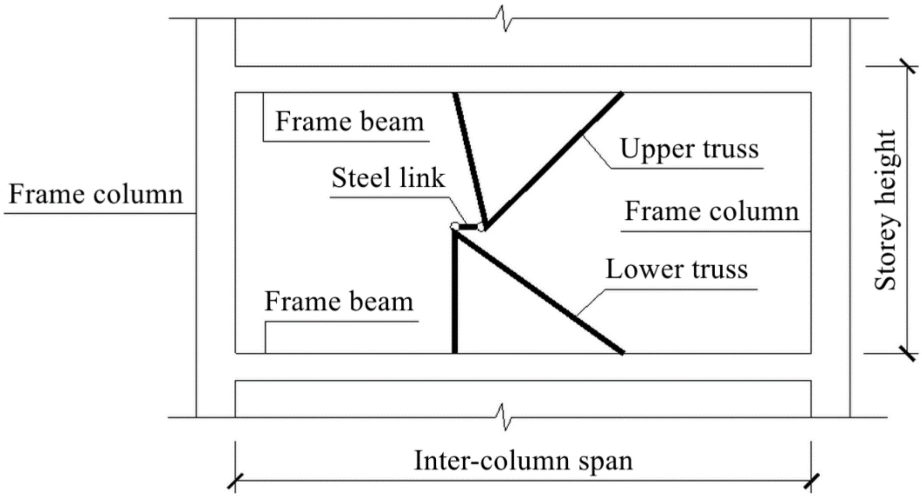


Figure (1): Configuration of the R-BRACE unit for structural frames

Inter-story Displacement-restraint Mechanism of the RBF System

Figure 2 shows schematically the lateral deformation process that would occur in a typical floor in the RBF system. A qualitative analysis was performed to identify its displacement-restraint mechanism. First, under the lateral force F_x, the beam and column would undergo an overall lateral displacement combined with local flexural bending, generating a rotation angle, θ, at the frame's ends. Second, the lateral shift of the frame beams with rotation at adjacent floors would primarily induce a horizontal relative displacement, Δx_i, and an additional torsional deformation, θ, of the associated upper and lower trusses. Since the upper and lower trusses are on both sides of the frame beam, when the frame beam bends, the adjacent-story trusses would be displaced in opposite directions, resulting in a reverse dislocation trend. Finally, the steel links would act to prevent the trusses from separating. By deriving the force equilibrium relationship for the system, the axial force, F_i, acting in the steel links was determined to be proportional to the designed tensile line stiffness, E_A/l_0, the floor height, h_0 and the magnitude of the elastic inter-story response. Taking the frame beam located on a single story as the object of study, the force acting through the nodes of connecting steel links would form a reverse force couple in the mid-span of the frame beams. The reverse deformation compensation caused by this force couple would balance out the elastic inter-story drift produced by the lateral force, F_x.

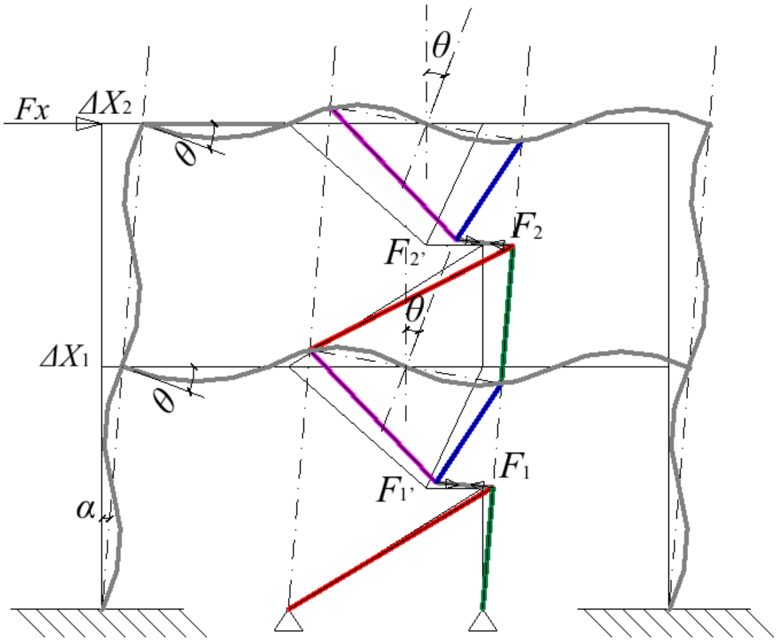


Figure (2): Schematic of the inter-story shift-restraint mechanism of the RBF system

Mechanics Characteristic of the RBF System under a Static-load Case

Computational Conditions

By selecting section properties from the AISC Steel Construction Manual, two frame configurations with identical geometries were modeled for comparison. An eight-story conventional moment-resisting frame with a typical floor height of 3 m was compared with a steel braced frame with additional hinged lateral force-resistant trusses, as illustrated in Figure 3. The two configurations' frame beams and columns were of the same size. The dimensional details for the hinged trusses' braces are listed in Table 1.

Calculation Results

The SAP2000 finite element analysis program was used to estimate the internal force distribution for the RBF system. Vertical distributed loads applied along the spans of the beams and horizontal forces applied to the roof were chosen for the load assignments. They were used to compare the differences between the working behaviors of the two analytical models under static conditions.

The axial force distribution diagrams when only a vertical load was applied (Figure 4) revealed that there was almost no difference between the results of the analyses of the two models. According to the force transmission principle, the horizontal steel links, designed as two-force members, that were hinged at both ends, would not transfer vertical loads between stories for cases of slight deformation, implying that the addition of the R-BRACE system would not modify the original transfer path of the vertical force in an existing building system.

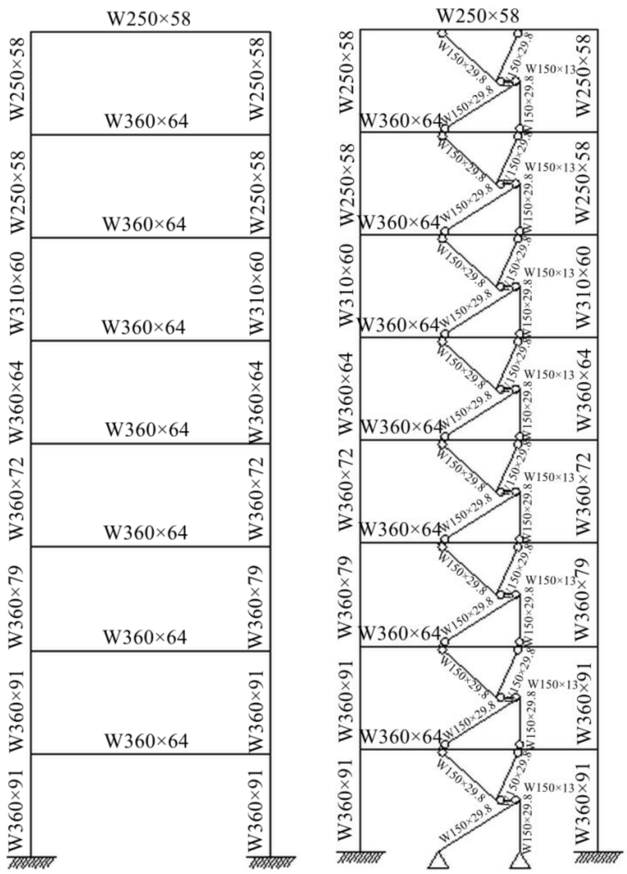
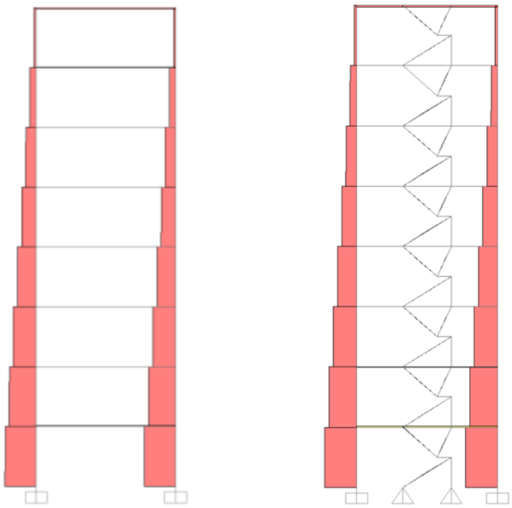


Figure (3): Two configurations used for comparison

Table 1. Cross-sectional characteristics

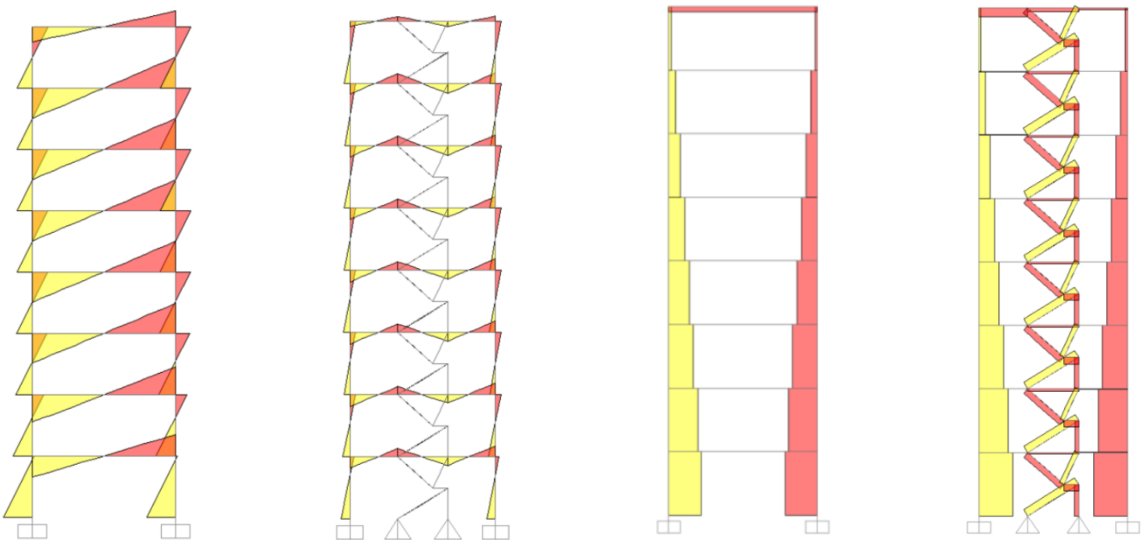
	Section Name	**Material**	**Shape**
		Column	
Floors 1–2	W360X91	ASME A572	I/Wide Flange
Floor 3	W360X79	ASME A572	I/Wide Flange
Floor 4	W360X72	ASME A572	I/Wide Flange
Floor 5	W360X64	ASME A572	I/Wide Flange
Floor 6	W310X60	ASME A572	I/Wide Flange
Floors 7–8	W250X58	ASME A572	I/Wide Flange
		Beam	
Floors 1–7	W360X64	ASME A572	I/Wide Flange
Floor 8	W250X58	ASTM A36	I/Wide Flange
		Lateral bracing	
Steel links	W150X13	ASTM A36	I/Wide Flange
Diagonal braces	W150X29.8	ASTM A36	I/Wide Flange



Conventional frame RBF system

Figure (4): Internal force distributions for the systems experiencing a vertical load

A comparison of the diagrams for the two configurations when only a horizontal force was applied (Figure 5.a) shows that the RBF system exhibited a uniform trend in the distribution of the bending moment. Unlike the moment-resisting frame, which relied entirely on the flexure strength of its mainframe components and the rigidity of the beam-column joints to resist the lateral force, the R-BRACE units increased the points of contra-flexure along the beam span, causing the bending moments at the beam-column connections to be reduced accordingly. Additionally, the analysis results for the systems experiencing a horizontal force show that all components of the R-BRACE units were resistant to axial forces (Figure 5.b). The axial forces in the R-BRACE units also did not vary significantly between adjacent floors and did not exhibit superimposed effects as the frame columns did.



Conventional frame RBF system

a. Moment bending diagrams

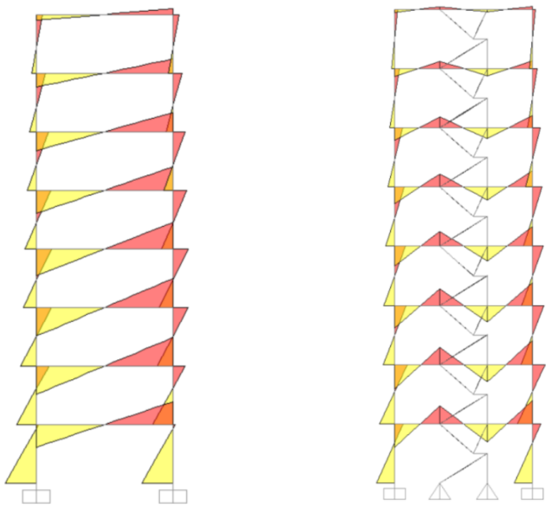
Conventional frame RBF system

b. Internal force distributions

Figure (5): Graphic simulation results for the systems experiencing a horizontal force

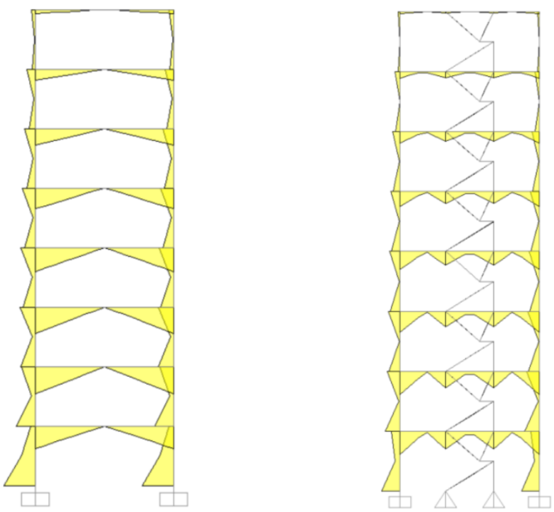
Mechanics Characteristics of the RBF System Subjected to a Moderate Earthquake

For the structural response evaluation in the design stages, a static seismic response was performed, using the lateral force procedure and the response spectrum analysis that adopted the complete quadratic combination (CQC) as the combination method of modes, to investigate the deformation behavior of the two configurations experiencing moderate seismic motion. The seismic coefficients, Ca = 0.042 and Cv = 0.037, which were defined in UBC97, were chosen for simulating a moderate earthquake. A damping ratio of 2% was assumed for the steel buildings. As shown in Figure 6, the overall bending moment distribution for the RBF system was more uniform than that for the conventional frame system. The number of points of contraflexure in the frame beams increased from one to three and the concentration of bending moments at the nodes of the beams and columns was significantly reduced. The RBF system had a lower bending moment at the bottom of the frame column, which was only 58% of the bending moment calculated for the frame system and the maximum inter-story drift ratio of the RBF system was reduced by 52%–61% when compared with the conventional frame system (Figure 7).



Conventional frame RBF system

a. Results for the lateral force procedure



Conventional frame RBF system

b. Results for the response spectrum analysis

Figure (6): Moment bending diagrams for the systems

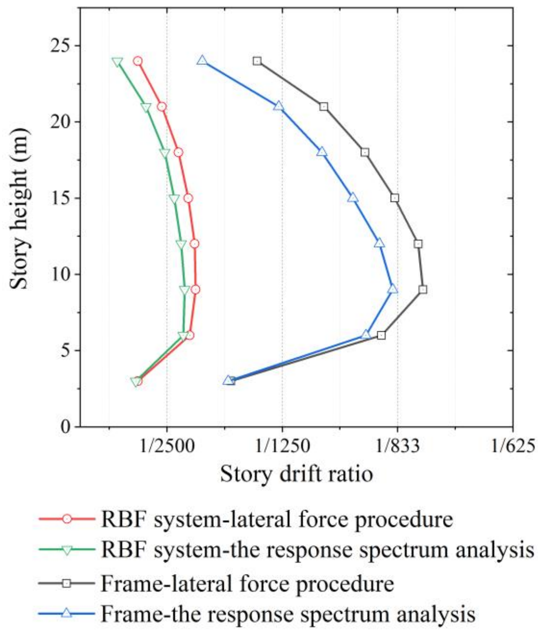
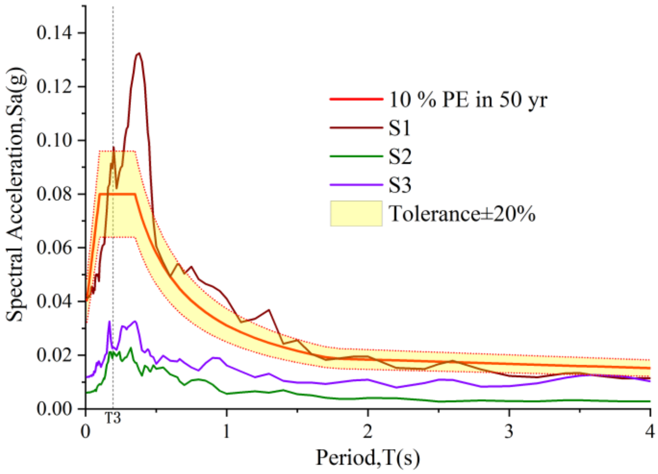
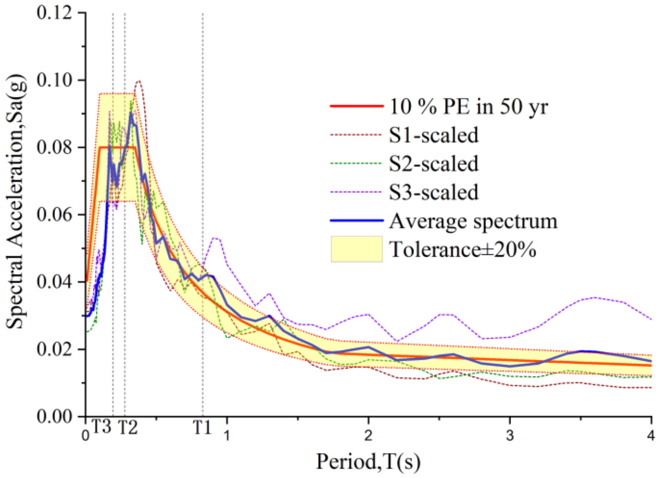


Figure (7): Maximum inter-story drift ratio obtained by the static seismic response analysis

As an option amongst the seismic methods of analysis and some indications provided for design, time-history analysis was proposed as a supplement to the CQC modal combination rules for obtaining the internal force variation and dynamic deformation response with transient moderate earthquake ground motion with a 10% probability of exceedance of 50 years (return period, TR=475 years). Three earthquake accelerogram records were selected from the Pacific Earthquake Engineering Research Center's Next Generation Attenuation (NGA) database and were spectrum compatible with the proposed site-specific target response spectrum (elastic 2% damped response spectra). The ground motions were scaled such that the average value of the elastic response spectra matched a tolerance range of ±20% with respect to the target spectrum at the corresponding structure's main vibration period points [T_1,T_2,T_3]. The yellow area in Figure 8 corresponds to the above-mentioned limits. In addition, the selection rules recommended by FEMA P-1050/2015 provisions were referred to. The average spectrum was not less than 90% of the design response spectrum over the period range from $0.8T_{lower}$ to $1.2T_{upper}$. Figure 8 compares the peak ground acceleration before and after amplitude modulation.



(a) Before amplitude modulation



(b) After amplitude modulation

Figure (8): Matching of the response spectra for the code-based design spectrum

The overall bending moment distributions indicated that the internal force and deformation response results for the two configurations obtained from the time-history analysis were similar to the results from the response spectrum method. The bending moment at the bottom of the frame column for the RBF system was only 45% of the bending moment calculated for the frame system and the inter-story drift ratio of the RBF system was 53%-70% less than that of the frame system, as determined by the average response spectra of the three selected seismic records (Figure 9). Additionally, the roof displacement for the RBF system was only 36% of that for the conventional frame system (Figure 10). As a result, installing the R-BRACE units would significantly improve the stiffness of a structure and ensure the desired seismic performance.

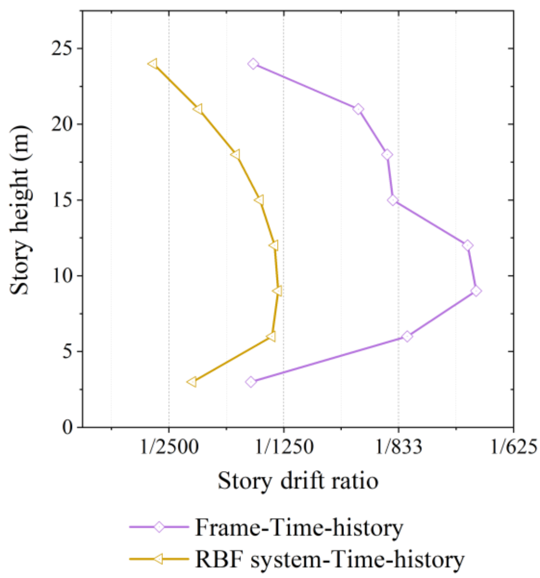


Figure 9. Maximum inter-story drift ratio obtained from the time-history analysis

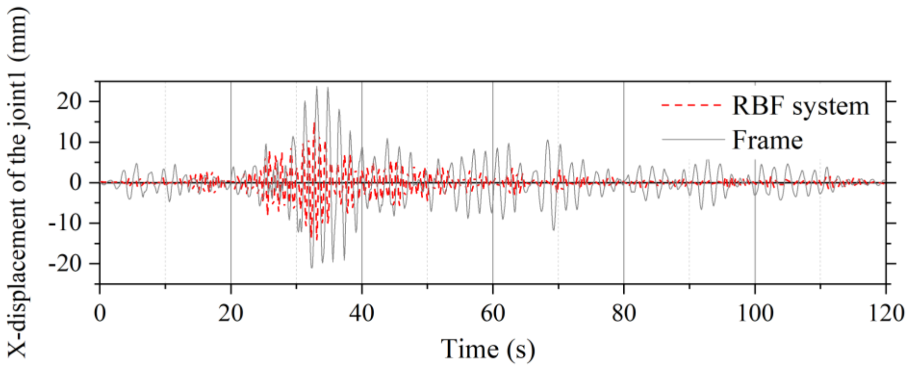


Figure (10): Roof displacement obtained from the time-history analysis

Working Behavior of the RBF System during a Major Earthquake Excitation

To evaluate the ductile performance of the RBF system, a pushover analysis was performed to calculate the plastic hinge distribution and deformation response under a major earthquake.

The plastic hinges were defined as coupled P-M2-M3 hinges for steel beams and columns and appeared in the conventional frame system as well as in the RBF system. The plastic hinges for R-BRACE elements are defined as axial force hinges. An inverted triangular distribution of lateral forces was applied as the load assignment for the pushover loading process. The seismic coefficients, Ca = 0.26 and Cv = 0.23, were chosen for simulating a major earthquake (2%–3% probability of exceedance in 50 years); then, the results were evaluated using the FEMA440 equivalent linearization method. To examine the development of plastic hinges in the members of the RBF system throughout the pushover process, a conjugate displacement loading control was employed to monitor the load increment required for the structure to reach the target displacement.

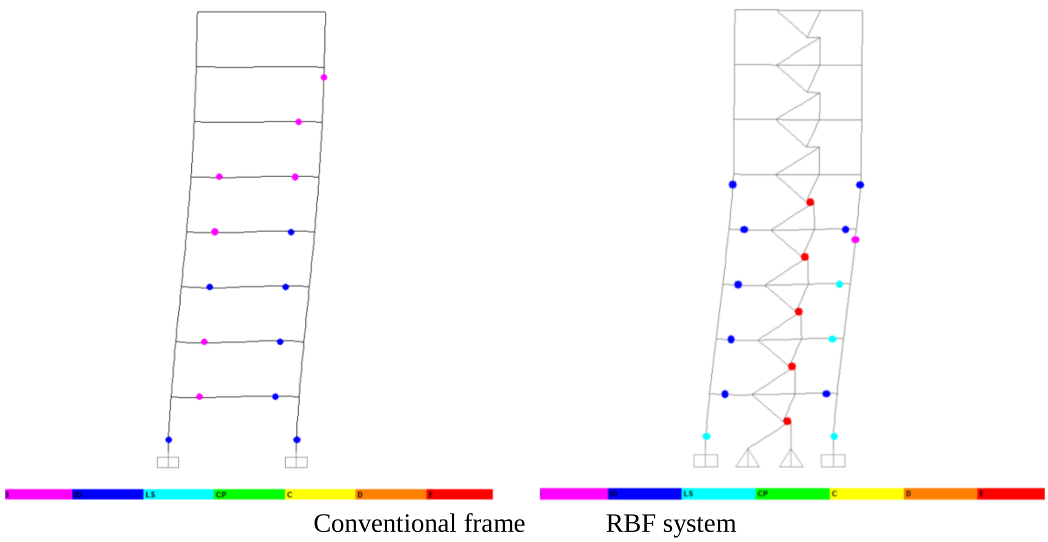


Figure (11): Plastic hinge distribution for the pushover analysis

According to the distribution of the plastic hinges shown in Figure 11, the R-BRACE system and the conventional frame system had remarkable differences during the development of plastic hinges. The plastic hinges in the RBF system appeared first on the horizontal steel links from the bottom to the top, then developed on the ends of the beams at each floor and eventually reached the collapse mechanism when the steel column base on the first floor yielded.

Observations of the capacity-demand spectrum curves for the two configurations (Figure 12) indicated that the RBF system had a higher stiffness than that of the conventional frame system in the elastic phase. The capacity curve shows several stepped descent phases appearing as strengthening mechanisms during plastic deformation, indicating that the buckling of the horizontal steel links from bottom to top caused the structural stiffness to degrade in a controlled and tunable manner, effectively ensuring a high seismic ductility. As indicated by the trends of the curves, the earthquake resistance behavior of the RBF system was significantly better in all phases than that of the conventional frame system under major seismic activity.

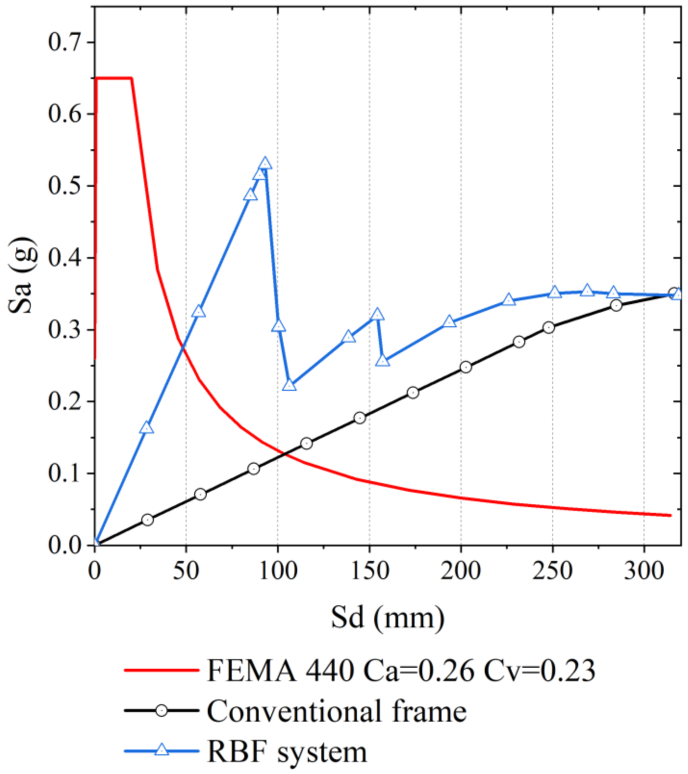
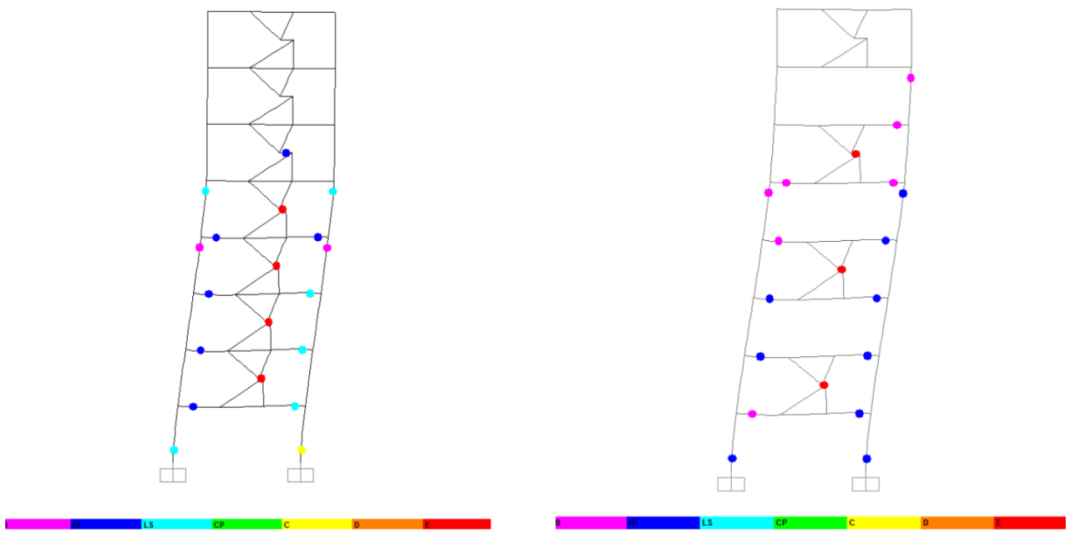


Figure (12): Capacity-demand spectrum curves for the RBF and conventional frame systems

Discussion of the Layout Configuration of the R-BRACE System

As previously stated, since the installation of R-BRACE units in the RBF system did not affect the vertical load's transfer path and the axial forces generated in the R-BRACE elements did not transmit between floors, for the horizontal axial force, there was a no-load superposition in the vertical direction. Therefore, the R-BRACE units could be set up in a vertically discontinuous mode. To test this assumption, two models were created and investigated using the pushover analysis, one with R-BRACE units placed continuously above the second floor and the other with R-BRACE units placed discontinuously in ordered intervals along the stories, as shown in Figure 13. The plastic hinge distribution results indicated that the discontinuous layout's yielding mechanism was comparable to that of the continuous case. The slope and the maximum peak of the capacity curve corresponding to the discontinuous layout, shown in Figure 14, were slightly lower than those for the continuous layout, but the curves for the two RBF models were evidently higher than those for the conventional frame system, ensuring acceptable structural stiffness and seismic ductility.



R-BRACE units placed above the ground floor

R-BRACE units placed in ordered intervals along the stories

Figure (13): Plastic hinge distribution for a vertically discontinuous layout of R-BRACE

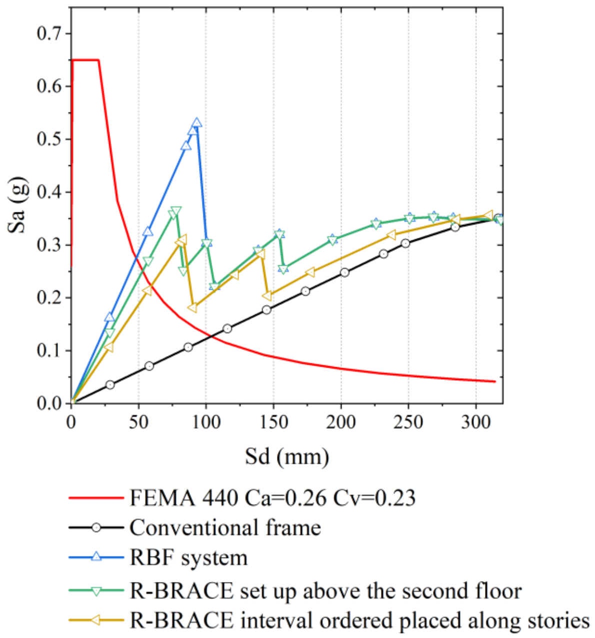


Figure (14): Capacity-demand spectrum curves for a discontinuous layout of R-BRACE

Figure 15 shows an increase in the inter-story drift ratio for specific floors without R-BRACE units in the discontinuous layout, but the absolute value of the increase was still relatively insignificant when compared with the drift ratio of the conventional frame. As a result, the arrangement of R-BRACE units in the RBF system can be adapted for a flexible and variable plan. They can even be arranged only on certain local floors subject to considerable lateral displacements to avoid the risk of forming a soft-story mechanism.

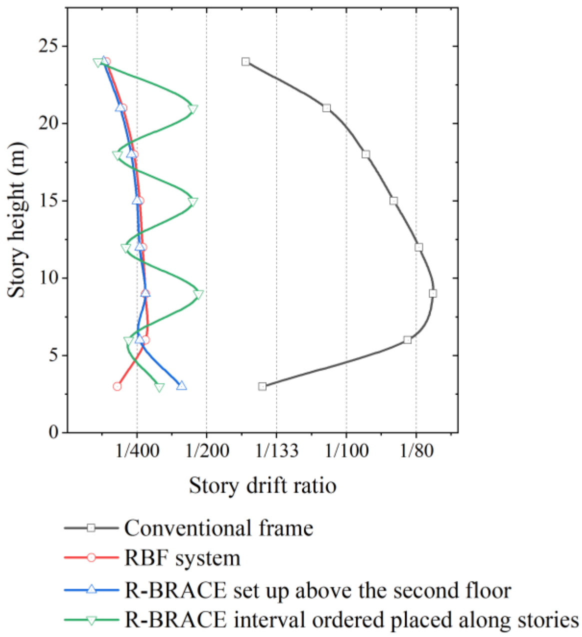


Figure (15): Inter-story drift ratio envelopes for a discontinuous layout of R-BRACE units under major seismic activity

A pushover analysis was conducted on an eight-story structure with three bays in both the transversal and longitudinal directions, with a bay length of 7.0 m in both directions and an inter-story height equal to 3.0 m.

The structure was retrofitted with R-BRACE units, as shown in Figure 16. Compared with traditional frames, Figure 18 shows that the addition of R-BRACE units significantly improved the lateral stiffness of the frame structure in the early stages. The plastic hinge distribution results for the same target displacement indicated, as shown in Figure 17(a), that in the early stage of pushing, the R-BRACE units mainly resisted lateral forces and yielded in sequence during a simulated major earthquake and the plastic hinges of the frame beams and columns scarcely appeared. With the increase of the pushing displacement, the buckling steel links provided good energy dissipation capacity, protecting the main structure from severe damage, as shown in Figure 17(b). Even in the event of the complete yielding of all connecting steel links, the entire structure could degrade into a ductile moment-resisting frame, ensuring that the retrofitted structure maintained an adequately high seismic ductility.

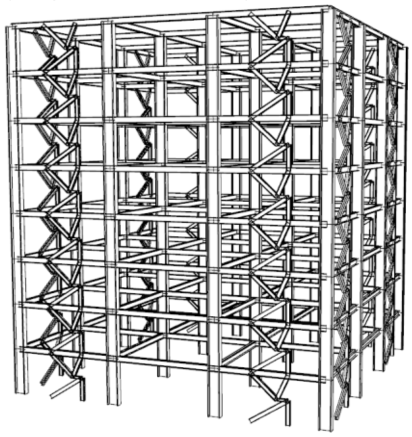
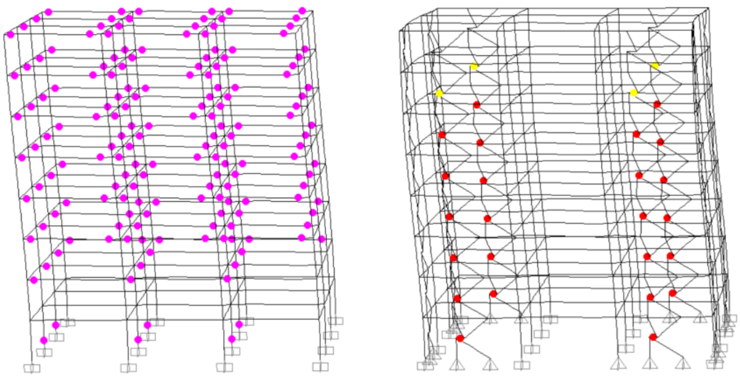
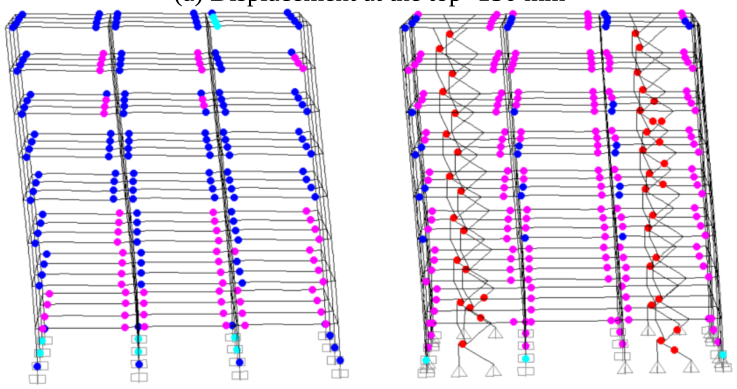


Figure (16): A 3D frame with R-BRACE units modeled in SAP2000



3D frame 3D frame+RBF system

(a) Displacement at the top=150 mm



3D frame 3D frame+RBF system

(b) Displacement at the top=350 mm

Figure (17): Plastic hinge distribution for the pushover analysis

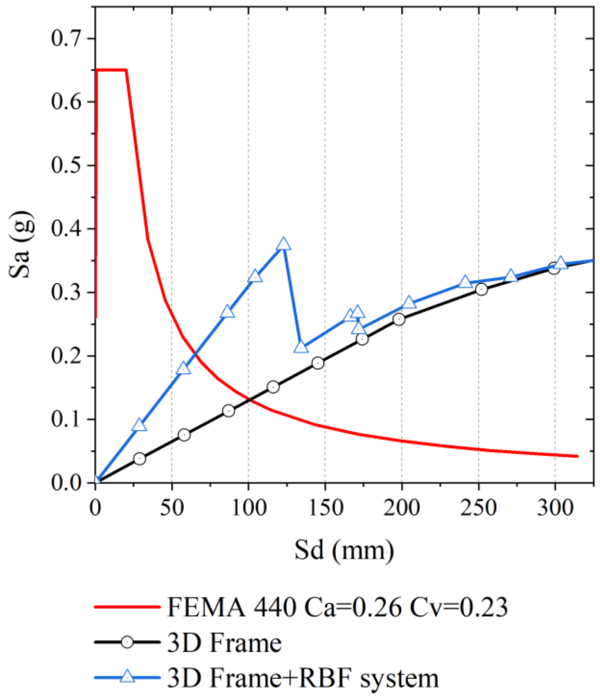


Figure (18): Plastic hinge distribution for the pushover analysis

Based on the results discussed above, several design guidelines were proposed for the arrangement of R-BRACE units:

(1) The RBF system is applicable for a "vertical discontinuous layout." By conceiving a reasonable structural design plan, an appropriate number of R-BRACE units placed only on certain local floors with critical inter-story displacements could produce a considerable enhancement of the structure's seismic performance.

(2) The RBF system allows "no superposition of axial forces in the vertical direction." The installation of these lateral force-resistant R-BRACE units on local floors requires no additional reinforcement of the foundation, making it a desirable option when retrofitting existing buildings.

(3) In order to meet ductility requirements, the R-BRACE units cannot be arranged throughout the full span of a beam, so the passage spaces can be set on both sides of a unit that has a relatively limited influence on the function of the building. The addition of the R-BRACE units does not change the vertical load's transmission path and the axial forces of the R-BRACE elements generated by horizontal loads are not superimposed vertically between floors. These are the main functional advantages of RBF systems over other reinforcement methods, such as diagonal bracing.

CONCLUSIONS

The innovative lateral force resisting system introduced in this paper can provide a significant increase in stiffness and high seismic ductility for tall buildings. The R-BRACE sub-units can be arranged in a variety of configurations, including, but not limited to, continuous, placed at alternating floors and staggered distribution layouts, depending on the selected building plan. This diversity of forms ensures that the RBF system has both structural safety and adaptability to widely available architectural solutions as a flexible design method. The following design principles should be considered when conceiving a structure to attain the desired functional performance:

(1) To ensure that the R-BRACE units do not lose their efficacy in the early stages, the elements of the upper and lower trusses must be prevented from yielding or buckling before the horizontal steel links yield. Moreover, the connecting steel links with high energy-dissipation capacities can provide effective additional damping for the structure, significantly improving the seismic performance.

(2) Proper design of the frame beams directly connected to R-BRACE units is crucial to ensure the effective functioning of the yielding mechanism. As revealed in this research, the addition of R-BRACE units alters the bending moment distribution of the components and increases the number of points of contraflexure of the beam. Therefore, the connection position of the R-BRACE units with the structural beam requires local reinforcement, especially for concrete beams with asymmetrical sections. This is to prevent weak points from appearing in the above position and to ensure that the frame beam only has plastic hinges at the end.

(3) Since the addition of R-BRACE units does not change the vertical load's transmission path and the axial forces of the R-BRACE elements generated by horizontal loads are not superimposed vertically between floors, this system could be especially valuable for enhanced seismic design or post-earthquake strengthening of existing buildings.

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