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Introduction of rhombus frame to improve building performance in earthquake.

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ABSTRACT: The primary focus of this study is to present a frame shape which will improve building performance in earthquake excitations. The investigation started with 3-story frame. The proposed Rhombus Shape is introduced to compare with the Rectangular Shape frame, keeping the height-to-width ratio and the loading same. The performance of the proposed Rhombus Shape Frame is compared with the popular Rectangular Moment Resisting Frame for different earthquake records. The seismic performance of the frame is evaluated based on the inter-story drift. This study report, that even with significant amount of member reduction, the proposed frame shape exhibits higher lateral stiffness than the equivalent rectangular moment resisting frame.

1 INTRODUCTION

Steel moment resisting frame, eccentrically braced frame, concentrically braced frame are some of the steel framing systems generally used to resist the lateral forces. Prior to Northridge earthquake in 1994, it was presumed that the ductility of a framing system is an added advantage, and thus the steel moment resisting frames were considered to be a popular choice. Large force reduction factors are used for this frame which demands lighter member sections (Bruneau, M. et al. 1998). This design philosophy was based on assuring that the lateral force resisting frame will not collapse as a whole structurally. But this allows flexibility which in turn allows excessive nonstructural damage (Sindel, Z. et al. 1996). Again, the higher drift demand from this framing system should be withstand by the beam to column connections, and it was questioned in 1994 after Northridge earthquake. After that earthquake, many connections in steel frames were reported being damaged by brittle failure (FEMA-355F).

The significant amount of monetary losses due to structural and non structural damages during the Northridge and Loma Prieta earthquakes convinced the engineering community that damage control, in addition to life safety, should be incorporated in structural design. This realization triggered the popularity of the performance based seismic design. Vision 2000 report by the SEAOC (1995) highlighted the fact of economic losses even in the moderate earthquakes. It was identified the need of a design and construction procedure which could control the damage to acceptable limits. These limits were same as those described in the FEMA-273 developed by the Applied Technology Council (ATC). The four performance levels labeled as Operational, Immediate Occupancy, Life Safety and Collapse Prevention were the state of the defined and observable damage in the structure. Federal Emergency Management Agency published the FEMA-355F prepared by the SAC joint venture in September 2000, where it narrated performance prediction and evaluation technique for moment resisting frames along with the seismic hazard levels and analysis procedures. An important feature of this procedure was to state capacity and demand in terms of story drift. FEMA-356 tabulated some typical drift values to describe the overall structural response. Also, the connection requirements according to the Seismic Provisions of AISC 2005 requires that beam to column connections be able to carry minimum 0.04 radians of inter story drift angle.

Connection detailing is out of the scope of this study. The purpose of this study is to focus on the control of damage by increasing the stiffness and thereby reducing the drift demand under earthquake excitations. For this reason, the present study proposes a new steel framing system which will control the drift values to the acceptable limits. To keep the inter story drifts within the specified limits, a rhombus shape is proposed as a seismic load resisting system instead of the popular rectilinear assemblage of beams and columns. The idea behind this shape is to utilize the advantage of both the rectangular moment resisting frames and concentrically braced frames.

2 BASE SAC BUILDINGS

The Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the California Universities for Research in Earthquake Engineering (CUREe) formed the SAC joint venture. They proposed 3-story, 9-story and 20-story model buildings and commissioned three consulting firms to model these three model buildings following the local code requirements of the following three cities: Los Angeles (ICBO 1994), Seattle (ICBO1994) and Boston (BOCA 1993) (Gupta, A. & Krawinkler, H. 1999). This study initially considered the geometric dimensions of the 3-story SAC building to model the base rectangular shape moment resisting frame. Structural design is out of the scope of this study. Figure 1 illustrates the lateral force resisting frame for the 3-story SAC building.

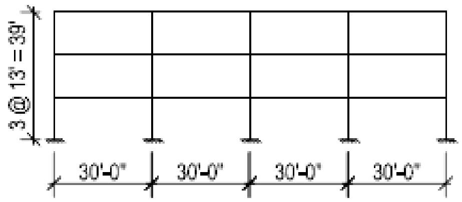

Figure 1. Elevation for 3-story SAC building

3 INTRODUCTION OF PROPOSED FRAME SHAPE

The proposed rhombus shape is created from the rectangular moment frame by placing a rhombus inside, with the same height and width as the rectangular frame. Then the pure rhombus shape is generated by removing all the members outside of it, which makes 40~45% reduction in member than the common rectangular moment resisting frame. Figure 2 illustrates the proposed frame generated from the frame in Figure 1. The idea behind the proposed frame is to incorporate the advantages of both the rectangular moment resisting frames and concentrically braced frames. The first type of framing system uses the flexural stiffness of the members to gain lateral stiffness; while in the later type, internal axial stiffness of the diagonals are the main sources for lateral stiffness. The dissipative capacity of the beam ends allow ductility and the stiffness provided by the diagonals limit inter story drift. This proposed frame is expected to behave structurally like a vertical truss, where the diagonal components form a vertical cantilever truss to withstand horizontal loading. Due to the moment resisting connections, flexural rigidity of the members will provide lateral stiffness to the system. But it was expected that the axial stiffness of the diagonal members will form the main units to resist lateral loading.

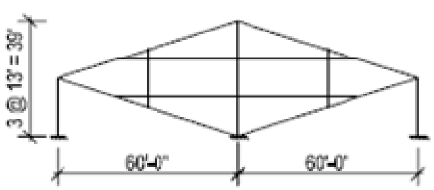

Figure 2. Proposed Frame Shape

4 NUMERICAL MODELING

The performance of the proposed frame shape as a lateral load resisting system is compared with the equivalent rectangular shape frame. Lateral load resisting systems, located at the perimeter of the 3-story SAC building along with its equivalent rhombus shape frame are modeled for numerical analysis. All the two dimensional frames are modeled in Opensees software. All the support conditions are assumed to be fixed. The beam-to-column connections are considered to be rigid. All the beam and column member sizes are selected as W14X283. The frames are given half of the total seismic mass of the buildings at each floor level. Mass on each floor level is concentrated in the beam-to-column joints as nodal mass. The mass properties on different floor levels are as shown in Table 1.

Table 1. Mass values at different floor levels for SAC buildings. (Gupta, A. & Krawinkler, H. 1999)

3-Story Structures Floor Level	Total Mass at Floor Level (kips-sec^2/ft)
Roof	70.90
Floor 3 and Floor 2	65.53

5 GROUND MOTIONS

Seismic demands are evaluated based on the time history analysis. As part of the SAC steel research project, sets of ground motions which are representative of different hazard levels have been assembled for three different geographic locations. Each set consist of ground motions with a probability of exceedence of 2% (referred to as the 2/50 sets, with a returning period of 2475 years) and 10% (referred to as the 10/50 sets, with a returning period of 475 years) in 50 years (Somerville, P. et al. 1997). Each set consist of 20 time histories for 10 ground motions.

For this study, frames are analyzed under 8 earthquake records, 4 of these records are from the 2/50 sets and rest of the 4 are from the 10/50 sets. These records are generated for the Los Angeles site. All the records are taken from SAC earthquake database. The information for the selected earthquakes is tabulated in Table 2.

Table 2. Details of Los Angeles ground motions selected for this study. (FEMA-355C)

SAC Name	Record	Earthquake Magnitude	Probability of Exceedence	Scale Factor	DT (sec)	Duration (sec)	PGA (cm/sec^2)
LA01	El Centro, 1940	6.9	10%	2.01	0.02	39.38	452.03
LA02	El Centro, 1940	6.9	10%	2.01	0.02	39.38	662.88
LA11	Loma Prieta, 1989	7	10%	1.79	0.02	39.38	652.49
LA12	Loma Prieta, 1989	7	10%	1.79	0.02	39.38	950.93
LA21	Kobe, 1995	6.9	2%	1.15	0.02	59.98	1258.00
LA22	Kobe, 1995	6.9	2%	1.15	0.02	59.98	902.75
LA27	Northridge, 1994	6.7	2%	1.61	0.02	59.98	908.70
LA28	Northridge, 1994	6.7	2%	1.61	0.02	59.98	1304.10

6 RESULTS FROM THE NUMERICAL ANALYSIS

To see the seismic performance of the proposed frame shape, it is subjected to dynamic analysis and compared with the popular rectangular shape moment resisting frame. It is found that the natural time period of vibration for the proposed frame is less than the rectangular frame. The natural time period and frequency for the first five mode shapes of the moment frame of SAC building and proposed frame is tabulated in Table 3.

Table 3. Modal Time Period and Frequencies for 3-Story Frame.

Mode	Moment Frame of SAC Building		Proposed Rhombus Shape	
	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)
1	0.944399	1.058874	0.262705	3.806553
2	0.278652	3.588704	0.171622	5.826759
3	0.151846	6.585615	0.110013	9.08982
4	0.085003	11.76427	0.074777	13.37312
5	0.079595	12.56367	0.070176	14.2498

The shorter time period of the proposed frame is significant. Same frame section and mass values are used for both the frame shapes in dynamic analysis. Though the proposed frame shape required almost 40~45% less members than the rectangular shape, even then it has shorter time period than the equivalent rectangular shape.

This implies that the proposed rhombus frame is stiffer than the rectangular frame. This is due to the inherent property of the proposed frame shape, which exhibits more lateral stiffness than the rectangular shape using even less members

Inter story drift values are plotted in Figure 3 and Figure 4. This parameter is very significant in performance based engineering and should be within acceptable limit as per the requirement of different performance levels. This study does not deal with the structural design problem to satisfy the serviceability limits. Here the main consideration is given to the fact, that if rhombus shape frame will experience less or more drift than the equivalent rectangular frame using same member sections. It is observed that the rhombus shape has less inter story drift ratios compared with the rectangular shape in all of the cases.

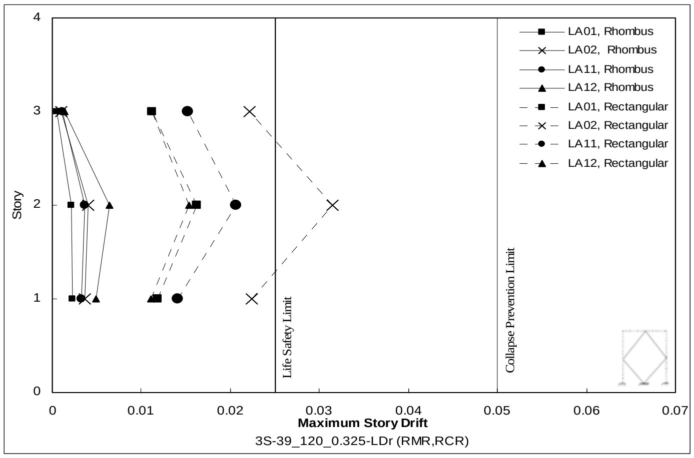

Figure 3. Inter story drift for earthquakes with 10% probability of exceedence in 50 years

For the selected earthquakes with 10% probability of exceedence in 50 years, all stories in the 3-story rectangular frame experience significantly higher inter story drift than the proposed frame. This is because; even the smallest frequency for the 3-story rhombus frame is greater than the first few dominant frequencies of the earthquakes

For the selected earthquakes with 2% probability of exceedence in 50 years, all stories in the 3-story rectangular frame experience significantly higher inter story drift than the proposed rhombus shape frame.

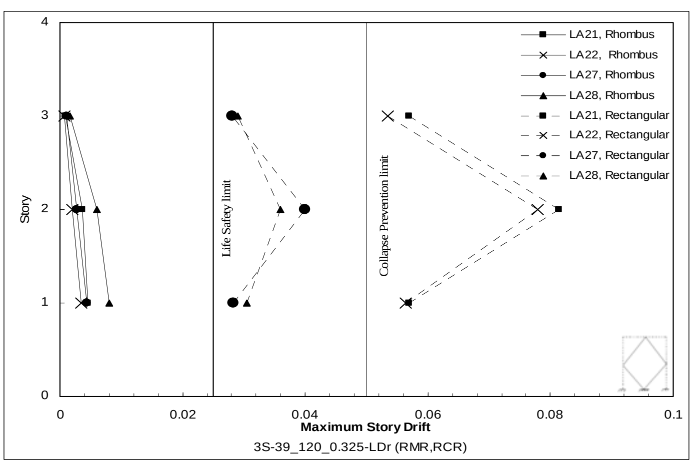

Figure 4. Inter story drift for earthquakes with 2% probability of exceedence in 50 years.

7 CONCLUSION

The main objective of this study was to present an efficient geometric shape for lateral force resisting frame system. A rhombus shape is created from the popular rectangular moment resisting frame for this purpose. The proposed shape is analyzed with ground motions of different hazard levels and then the results are compared with the rectangular frame with the same geometric aspect ratio. The following conclusions can be drawn from this study:

- The proposed rhombus shape frame achieves a 40~45% reduction in members than the rectangular frame. Even With this significant reduction in member, the rhombus shape frame exhibits higher lateral stiffness than the rectangular frame. Rhombus shape provides significantly higher natural frequency than the rectangular shape.
- Rhombus shape frame demands less inter story drift than the rectangular shape frame. For selected earthquakes from 2/50 and 10/50 sets, each and every floor level of rhombus shape demand less inter story drift than the rectangular shape moment resisting frame.
- The shorter time period in the rhombus shape frame indicates that excess stiffness and strength are included in that shape, which is due to expected truss action of the frame shape.

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