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PROBABILISTIC FAILURE MODES ANALYSIS AND FRAGILITY ASSESSMENT OF STEEL FRAME WITH ROCKING TRUSS

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The ideal failure mode of building structures is the full beam-hinge mode. However, in the actual earthquakes, the beam-hinge failure mode is unpredictable due to the existence of various uncertainties. The story failure mode, local beam and column failure modes can be transformed to the global deformation and full beam-hinge failure mode with the function of rocking truss. The random incremental dynamic analysis (IDA) was used to identify the probabilistic earthquake failure modes of steel frame, steel frame with rocking truss. Then the probabilistic seismic collapse capacities of structures were compared through the collapse fragility. Thus the optimization and control of failure modes of steel frames will be achieved with rocking truss, and the structural seismic performance and collapse capacity of steel frames can be significantly improved with adoption of the proposed rocking truss.

Keywords: Steel frame, rocking truss, failure mode, collapse capacity, collapse fragility.

1 Introduction

Conventional seismic force-resisting systems rely on inelastic deformations of primary structural members to dissipate seismic energy and protect buildings against collapse, which always causes the unacceptable residual deformation and unexpected failure modes[1][2]. However, the unacceptable damages cannot be avoided according to the design methods in current building code; in addition, performance-based earthquake engineering (PBEE) also emphasizes avoiding the structural damages which can result in business interruption and death of occupants. So it is worth taking measures to improve the structural performance when suffering from earthquake or other catastrophes. In general, higher performance can be achieved by minimizing inelastic residual drifts and damage of primary structural components. Thus, series of new approaches have been considered to mitigate the bad consequences caused by earthquakes, and rocking frame is a typical structure system, which can effectively change structural failure modes, concentrate the damage in replaceable structure members and eliminate residual drifts.

Particularly, the rocking structures has been investigated for a long time, Clough and Huckleridge[3] performed the earliest shaking table tests of rocking steel frames, which demonstrated the potential benefits of rocking elements. Then a number of experimental and numerical researches were conducted. Midorikawa et al.[4] added baffle plate to the column base to allow the column of rocking frame uplifted under earthquakes, and the results showed that the buckling of the plate could significantly dissipate energy. Gunay et al.[5] evaluated the using of rocking concrete walls to create a rigid core to attract seismic forces and limit demands on non-ductile frame, potentially preventing soft-story failures. Qu et al.[6] proposed and perfected the design theory of rocking concrete walls through a practical engineering. However, once the rocking concrete wall has been damaged, it is difficult to repair immediately and the cost may be relatively high. On the other hand, Deierlein et al.[7] explored using dampers at the rocking column bases to reduce seismic response. In the rocking system, there were some different typical elements[8][9] (such as rocking wall, rocking frame and self-centering energy dissipative devices) which are useful for mitigating structural damage and providing sufficiently self-centering capacity.

With considering a widely used rocking system, and combing the advantages of the rocking truss and the self-centering energy dissipative devices, a new composite structural system was proposed in this research. The finite element model was also established in OpenSEES. The failure modes and structural capacity fragility of the steel frame (SF) and steel frame with rocking truss (SFWRT) were analyzed, and a novel probabilistic failure mode evaluation was also implemented in the example structures with taking the variability in structural response into account.

2 Design of the Example Structures

Two eight-story example structures were introduced to implement the structural analysis. The structures are located on firm rock (site Class II in GB50011-2010[10]), and the location site has the fortification earthquake intensity of VIII degree with the design fundamental acceleration of 0.2g (g is the gravity acceleration), which has a corresponding design characteristic period of 0.4s. Elevation views of the frames are shown in Figure 1. It deserves to be mentioned that 4 typical loads are considered in the structure. The floor dead load, live load are considered as 3.0kN/m^2, 2.0kN/m^2, respectively. The environmental actions are represented by the basic wind load and the snow load, in which the basic wind load is chosen as 0.45kN/m^2, and the basic snow load is 0.25kN/m^2. More detail information about columns, beams and other geometrical configurations of the steel frame structure are listed in the Table 1.

Table 1 The detail information of the steel frame

Story	Story height (mm)		Column section[11]		Beam section[11]	Thickness of the floor
8	1F	3900	1F-2F	HW350×350×12×19	HW250×250×9×14	100mm
	2F-8F	3300	3F-5F	HW344×348×10×16		
			6F-8F	HW300×300×10×15		

Finite element (FE) models of the SF and SFWRT were developed in the Open System for Earthquake Engineering Simulation (OpenSEES). The nonlinear-Beam-Column element was used to simulate the beam–column members, with considering the gravity second-order effect (gravity P-Δ effect), and the corresponding constitutive hysteretic models of the materials were chosen. The rocking truss and Self-Centering Energy Dissipative [9] (SCED) were simulated by the Truss element, Two Node Link element, respectively. The SCED consists of structural members, pre-tension tendons, abutting element and energy dissipation devices. Component design was performed in advance to determine the geometrical and physical properties of the SCED. In this paper, the outer tube size was designed as 80mm×80mm×2.0mm; and the inner flat plate core size was 50mm×50mm×2.0mm, 4 Technora-T200 fiber cables with diameter 7.5mm were adopted, and the friction force and pre-tension were set as 35.862kN, 30 kN, respectively.

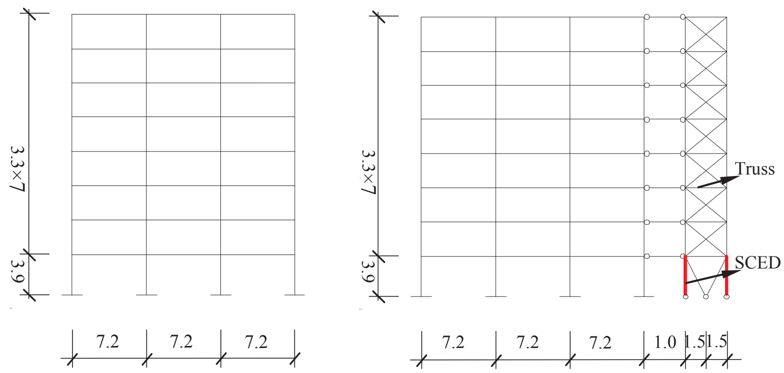
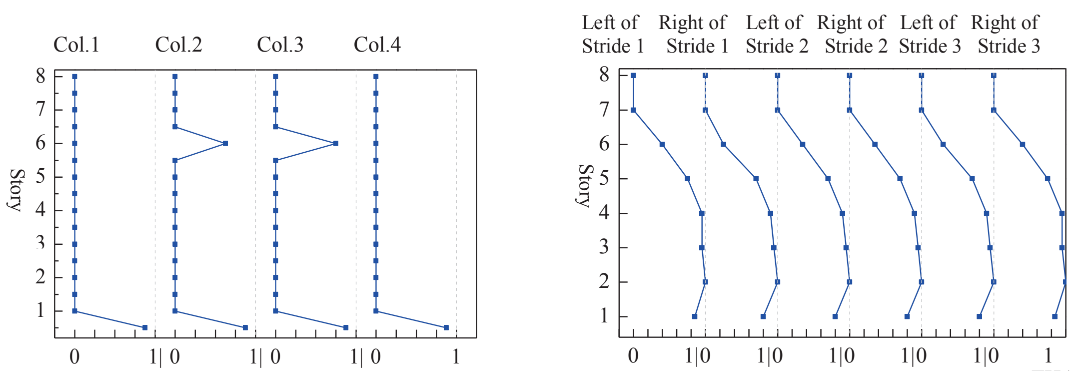


Figure 1. The elevation configuration of the example structures.

3 Structural Probabilistic Failure Mode Analysis

The study used the FEMA P695[12] suit of 22 strong far-field ground motions (with relative higher peak ground velocity) that were selected specifically for the failure mode analysis and collapse assessment of structures. Under the specified 22 earthquake records, the occurrence probabilities of the plastic hinges which concentrate at the component ends of the two different structural systems were calculated. Then the statistic information was collected as shown in the Figure 3 and 4. When suffered from a rare earthquake, for the SF, most of the column bases can reach the plastic stage, and the inner columns of the top 3 stories form plastic hinges with high likelihood, while the side columns are difficult to develop plastic zones. Besides, the probability of yielding is close to 100% for the beams in the 2-4 stories, and the probability decreases with the height increasing until the probabilities drop to a negligible level for the top 2 stories. The structural failure mode demonstrated that the SF is likely to develop a cross-story failure mode when a rare earthquake happens.

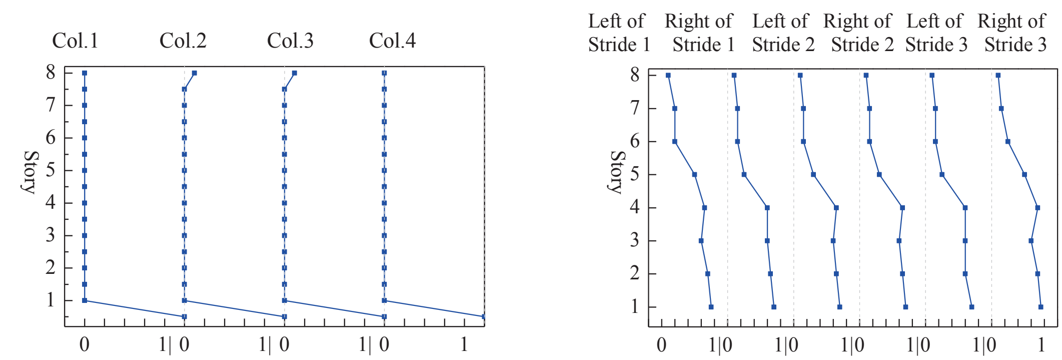


a) The statistical probability of the plastic hinges on the column ends

b) The statistical probability of the plastic hinges on the beam ends

Figure 3. The statistical probability of the plastic hinges of SF under the rare earthquake.

The SFWRT has a similar mechanical property when subjected to a rare earthquake with equal intensity, and the column bases almost reach the plastic stage. The side columns show an elastic property during the loading stages except for the inner columns which develops into plastic deformation with a very small probability. In addition, the beam members of the main steel frame begin to yield at the bottom story and then develop to the upper stories, and the plastic deformation is not observed to concentrate at one story. Thus, it is reasonable to conclude that the implementation of rocking truss makes the plastic hinges appear more uniform, which avoids the story plastic concentrated failure mode.



a) The statistical probability of the plastic hinges on the column ends

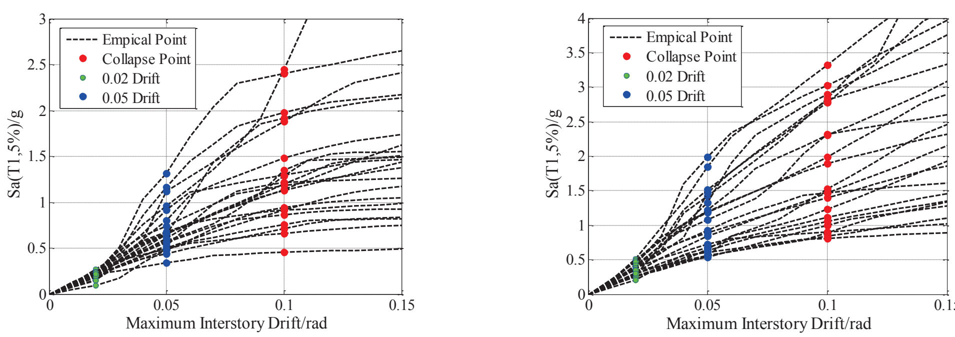
b) The statistical probability of the plastic hinges on the beam ends

Figure 4. The statistical probability of the plastic hinges of SFWRT under the rare earthquake.

4 Assessment of Structural Collapse Fragility

4.1 Analysis of Structural Collapse Resistance Capacity

The chosen 22 earthquake records were scaled based on the fundamental period. The Incremental Dynamic Analysis (IDA) was used to evaluate the lateral collapse resistance capacity of SF and SFWRT, and the results are depicted in the Figure 5.



a) SF

b) SFWRT

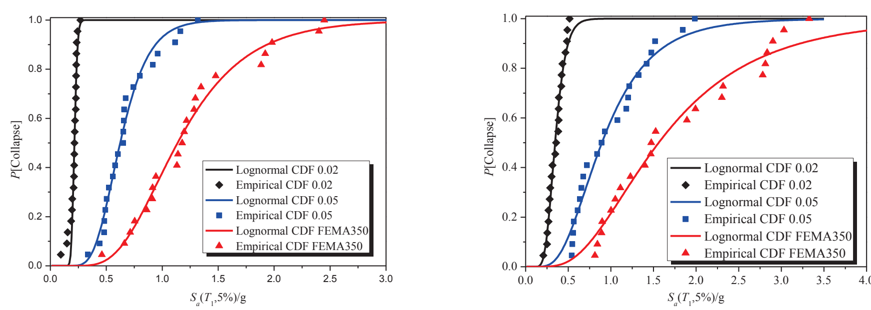
Figure 5. The IDA curves of the SF and SFWRT.

A one-to-one match relationship can be found between the IDA curve and a specified ground motion. If an IDA curve is given, then the structural response is uniquely determined, and the randomness of ground motions will cause a discrepancy of the structural responses among different ground motions. Figure 5 shows that the randomness of different ground motions has less effect on the structural responses in the initial elastic stage. While the structures reach the non-linear stage, there is a coupling amplification effect between the ground motion randomness and structural nonlinear behavior, which causes the gradually increasing dispersion of structural responses.

4.2 Assessment of Structural Collapse Fragility

Three limit states were adopted in this section to assess the structural seismic performance. Limit State 1: The Chinese Code for Seismic Design of Buildings [10] recommended that the performance level for the steel frame structures is defined as maximum inter-story drift angle limited to 2.0% under the rare earthquake, which was chosen as the limit state 1. Limit State 2: As recommended by FEMA273 [13], the inter-story drift angle collapse limit should be less than 5%, which was adopted for the limit state 2 for the example structures. Limit State 3: The FEMA350[14] document indicated that the frame collapse intensity is defined as the intensity at which the slope of IDA curve is very small (i.e., the flat-line), or the intensity that cause the inter-story drift of the structure to exceed 10% (beyond which the gravity framing is assumed to lose its ability to support the gravity loads).

The collapse points were aggregated and the lognormal fitting was performed to form the collapse fragility curves of the SF and SFWRT with considering 3 limit states, as shown schematically in Figure 6. The results show that the collapse probabilities of the SF and SFWRT corresponding to limit state 3 are the lowest, and the collapse probabilities of structures corresponding to limit state 1 are the largest. The increment of collapse probabilities is due to the decrease of collaspe story drift angle limit. As shown in Figure 7, the collapse fragility curves of SFWRT all locate below those of SF, which indicated that the rocking truss is effective to reduce the structural collapse probability under earthquakes.



a) SF b) SFWRT

Figure 6. The schematic of collapse fragilities of the SF and SFWRT.

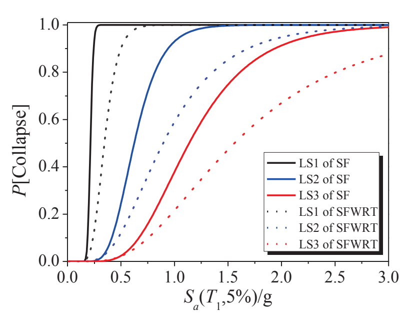


Figure 7. Comparison of the collapse fragility curves of the SF and SFWRT.

5 Conclusions

This study focused on the structural collapse fragility of 8-story SF without and with rocking truss, the probabilistic failure modes were also discussed. The results of the investigations are summarized as follows:

(1) The use of rocking truss in SF makes the appearance probabilities of plastic hinges formed in the structure members more uniform compared with the SF.

(2) The collapse failure probability of SFWRT are obviously lower than those of SF, which suggests that the rocking truss can significantly improve the seismic performance of the SF.

(3) The probabilistic failure modes and collapse fragility analysis are proposed to validate the improvement efficiency with assembling rocking truss. It concludes that the local damage concentration is always observed for SF, which leads to a weak spot even a collapse failure caused by the intensified local damage. On the contrary, SFWRT shows a more uniform damage and has a better overall performance, the collapse capacity is also better than SF under an earthquake.

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