COLLAPSE MITIGATION STRATEGIES FOR STEEL MOMENT RESISTING FRAMES THROUGH E-DEFENSE FULL SCALE SHAKING TABLE COLLAPSE TESTS

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Full scale shaking table collapse tests of a 4-story steel structure, were recently conducted at the National Research Institute for Earth Science and Disaster Prevention in Japan (known as E-Defense). These tests indicated that it is possible for steel structures to collapse with a sidesway first story collapse mechanism when subjected to severe earthquake shaking even when the strong column-weak-beam criterion is employed. State-of-the-art numerical models that simulate strength and stiffness deterioration of steel components reproduced successfully the experimental data from the collapse test. Based on these models collapse mitigation strategies were investigated that enhance strength or ductility of steel columns. A strength enhancement of steel columns is the key for increasing the collapse capacity of steel structures subjected to extreme earthquakes.

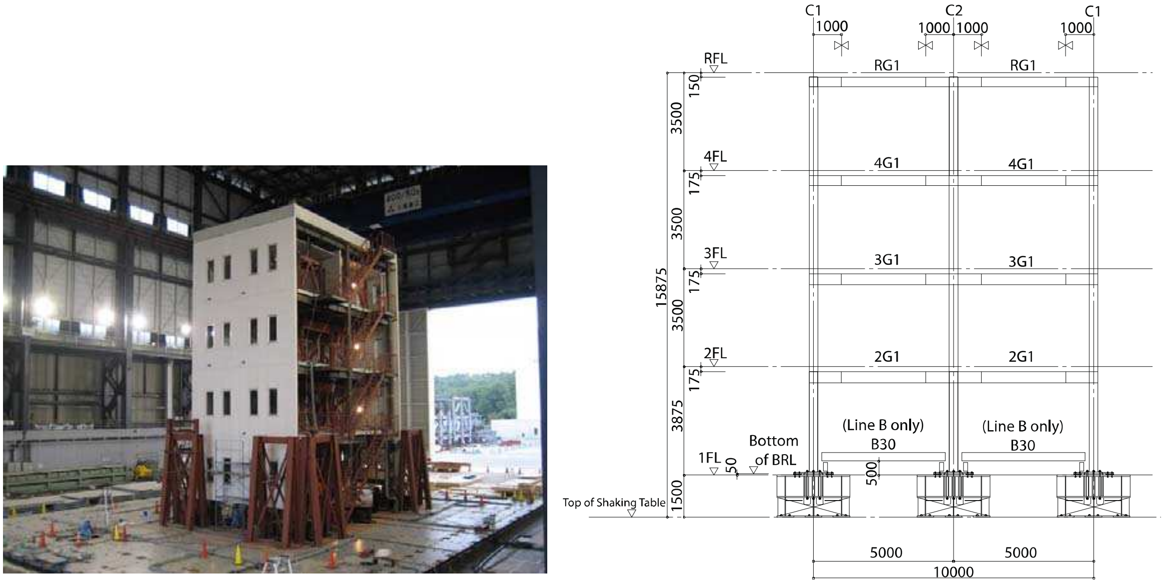
1. INTRODUCTION

Reliable collapse assessment of steel structures under earthquakes requires experimental data to validate the seismic performance of these structures and their components through collapse. Lignos et al. [1] conducted a series of shaking table collapse tests of a 1:8 scale model of a 4-story steel moment resisting frame designed based on current US design provisions. These tests were conducted at the Network for Earthquake Engineering Simulation (NEES) facility at University at Buffalo and demonstrated the importance of P-Delta and component deterioration in accurate numerical simulations of steel moment frames to collapse. However, due to the small scale and simplified assumptions of the test specimens used in these studies, the actual redundancy of real beam-to-column connections including composite action, the contributions of nonstructural components, and the effect of 3-dimensional dynamic loading on the collapse behavior of a steel structure was not possible to be assessed. Thus a full scale collapse test of a 4-story steel structure was conducted at the world's largest shake table at the E-Defense facility [2,3]. These tests indicated that it is possible for steel structures to collapse with a first story collapse mechanism when subjected to severe earthquake shaking since columns are not typically designed for increased forces due to strain hardening even when the strong-column-weak-beam criterion is employed.

This paper demonstrates that numerical models that simulate component deterioration and P-Delta are able to predict the sidesway collapse of the E-Defense test. Based on the validated numerical model of the 4-story structure, two scenarios are investigated in which the collapse capacity of the same steel structure is increased.

2. FULL SCALE 4-STORY COLLAPSE TEST

A full-scale four-story steel structure, designed based on current Japanese seismic provisions, was tested to collapse at the E-Defense facility. Progressively increased ground motion intensities (20%, 40%, 60%, 100%) of the JR Takatori motion recorded during the 1995 Hyogoken-Nanbu earthquake were used as the testing protocol. The main objectives of the test series were (1) to evaluate the seismic performance of the 4-story structure under design level earthquakes and (2) to quantify the margin against collapse under severe earthquakes. The test specimen, shown in *Fig. 1a*, was 10x6 meters in plan view. The lateral resisting system of the structure consisted of moment resisting frames in both X, Y loading directions. The elevation view of the 2-bay frame in the Y direction is shown in *Fig. 1b*. Each floor of the structure consisted of a 175mm thick concrete slab, i.e. full composite action was expected. Around the perimeter of the 4-story structure Autoclaved Lightweight Concrete (ALC) panels were installed. A detailed description of the test specimen including the outline of the test can be found in [2,3]. The test specimen had a predominant period of 0.80 sec in the X direction and 0.76 sec in Y direction, respectively, based on white noise tests prior to the main testing phase. The damping ratios for the first mode of vibration in the same directions were 2.1% (X) and 2.3% (Y) as discussed in [2,3]. During Level-1 design earthquake (20% of the un-scaled JR Takatori record) the building behaved elastically with peak story drift ratios (SDRs) not exceeding 0.5% rad along the height of the structure. At Level-2 design earthquake (40% of the un-scaled JR Takatori record) yielding occurred at the base of the interior first story column and the interior panel zones of the 2nd and 3rd floor beam-to-column connections. Maximum SDRs reached about 1% rad in the first and second story of the structure (see *Fig. 2*). During 60% of the JR Takatori record, which was 1.5 times larger than a Level-2 earthquake (equivalent to a Maximum Considered Event based on US seismic provisions), peak SDRs in the Y-direction of the building were about 2% rad in the first story and progressively decreased in the upper stories (*see Fig. 2*). Plastification occurred at the interior and right exterior 2nd and 3rd floor panel zones and at the top and bottom locations of the interior base columns of the test specimen resulting to a sidesway mechanism. The ALC and partition walls of the structure were severally damaged.



(a) setup after the completion on the shaking table (b) elevation view (Y-direction)

Fig. 1 Full scale 4-story structure tested at E-Defense

During 100% JR Takatori record, the building collapsed with a first story sidesway mechanism after 6.57sec elapsed. At that time, the peak SDR in the first story was about 8% and 19% in the X and Y directions, respectively (see *Fig. 2*). From the same figure it is concluded that there was a transition from the overall sidesway yielding mechanism of the building to a first story collapse mechanism. The reason was the severe strength deterioration of the first story columns due to local buckling. Note that the weak-beam strong-column-criterion was employed during the design of the building. However, the columns by design provisions, were not designed for the increased forces caused by strain hardening [2,3].

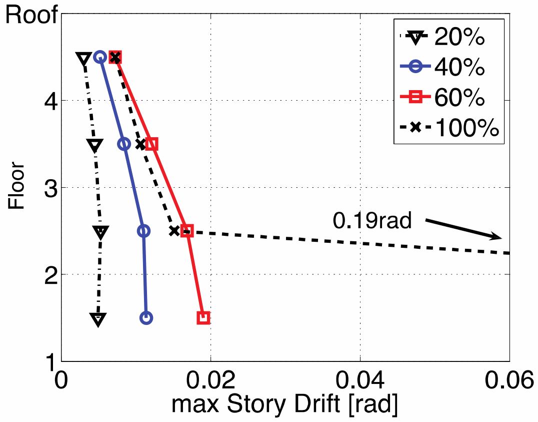
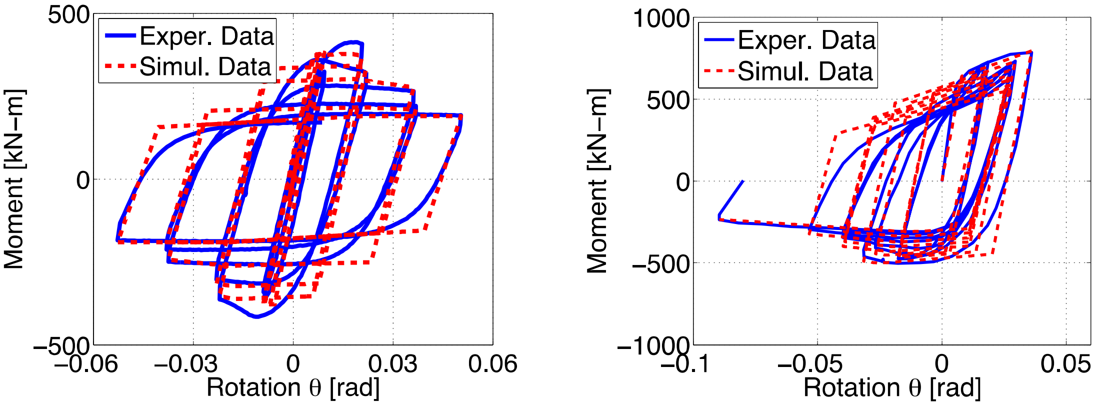


Fig. 2 Maximum story drift ratios along the height of the test frame in the Y direction

3. NUMERICAL MODELING FOR COLLAPSE PREDICTION

A two dimensional (2-D) numerical model was built in order to assess the effect of component deterioration and P-Delta on the collapse capacity of the test specimen. The Open System for Earthquake Engineering Simulation platform was used [4] to model the test frame in the Y direction of loading. The geometric and section properties of this moment resisting frame are summarized in [3,5]. Steel components are modeled as elastic beam column elements with concentrated plasticity springs at their ends. These springs are able to deteriorate in strength and stiffness according to the modified Ibarra–Krawinkler deterioration model [6, 7]. The shear force-shear distortion of the panel zones is modeled with the Krawinkler model as discussed in [3]. P-Delta effects are modeled using a large deformation transformation. Slabs are not modeled explicitly in the numerical model but their effect on lateral stiffness is considered by using a composite steel beam. Deterioration parameters for the steel tubular columns and steel beams are determined from calibration of the hysteretic response of the modified Ibarra-Krawinkler deterioration model based on component tests that were conducted prior to the shaking table test (see *Fig. 3*).



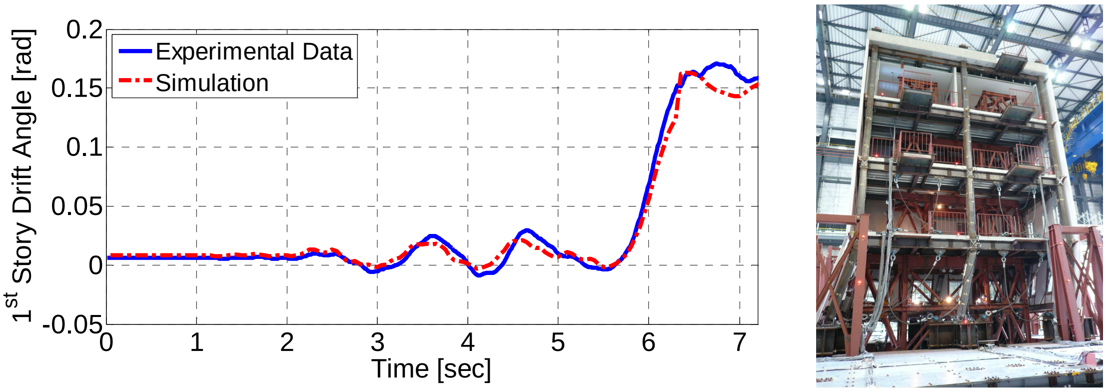
(a) HSS300x9 column tested in 45^o (b) H-400x200x8x13 composite beam

Fig. 3 Hysteretic response of steel components from pre-test cyclic component tests

In order to assess the seismic response of the 4-story steel moment resisting frame in the Y direction near collapse the 20%, 40%, 60% and 100% JR Takatori record is applied sequentially to the numerical model. Cumulative damage effects are considered in the analysis from phase to phase. Figure 4a illustrates the simulated response of the first story drift for the 100% JR Takatori motion. This figure indicates a relatively good match between simulated and experimental data. From the same figure it can be seen that collapse is predicted slightly later (t=6.7sec) compared to the experimental data. This is attributed to the fact that biaxial effects are not considered in the 2-D analysis. Figure 4b shows the first story collapse mechanism after the completion of the shaking table test series.

4. COLLAPSE MITIGATION STRATEGIES

The focus of this section is on alternative ways that can shift the first story collapse mechanism of the test specimen to a full mechanism, i.e., collapse can be delayed. Two scenarios are investigated based on the validated numerical model, which was presented in the previous section. In the first case scenario (noted as Case 1) an HSS 350x12 section is used for the steel columns. This corresponds to a depth D to thickness t, D/t ratio equal to 29.2 (original test had D/t = 33). The plastic bending strength of the columns is 1.54 times larger than the plastic bending strength of the column used in the test specimen (noted as M_p). Assuming that the plastic rotation capacity of the column used in the test specimen is θ_p, the plastic rotation capacity of the HSS350x12 section given the level of axial load is 1.02 θ_p.



(a) (b)

Fig. 4 Collapse level earthquake; (a) Simulated versus experimental response of first story drift ratio during 100% JR Takatori; (b) 1-story collapse mechanism

The original rigid plate connections at the column base increased the likelihood for local buckling and according strength deterioration to occur at the same location. It has been shown experimentally that controlled yielding of anchor bolts in exposed column bases substantially increases the plastic deformation capacity of these columns [9]. To examine if such an increase in plastic deformation capacity is beneficial against collapse, a second case (Case 2) was analyzed. A self-centering material available in [4] is utilized in the numerical model to simulate the hysteretic response of the exposed column bases. Figure 5 summarizes the peak story drift ratios along the height of the 4-story steel moment frame for the two cases discussed in this section after running the scaled intensities of the JR Takatori motion up to 100% sequentially. In the same figure the experimental data from the collapse test are superimposed. It can be seen that in both cases collapse is prevented for the 100% Takatori record.

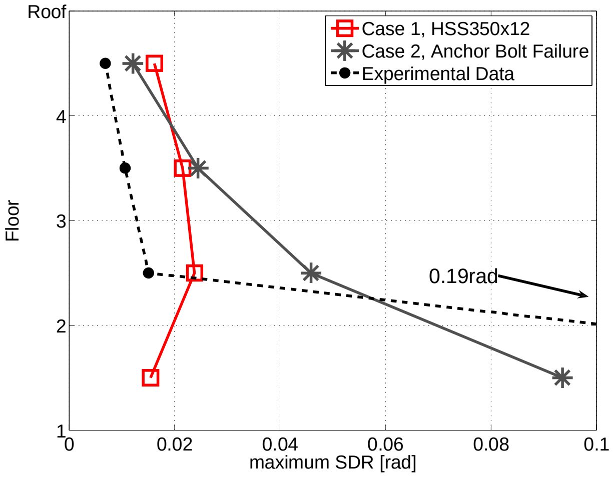


Fig. 5 Seismic response of the 4-story structure at 100% JR Takatori for Cases 1 and 2

For Case 1, the distribution of drift ratios along the height of the steel moment frame is almost uniform indicating that the yield mechanism is a complete 4-story mechansim. For Case 2, absolute maximum SDR_1 of about 9.0% develops, indicating that despite the larger deformation capacity of this story the maximum absolute SDR is still concentrated in the first story. The implication is that the larger the bending strength enhancement of the column is, the more uniform the distribution of maximum SDRs along the height (see *Fig. 5*).

To assess how beneficial each alternative mitigation strategy would be in terms of the enhancement of capacity against collapse, incremental dynamic analysis was carried out with JR Takatori. In Case 1 (Use of HSS350x12 columns), the frame collapsed at 200% JR Takatori with a complete 4-story collapse mechanism. This can be seen in Fig. 6 that shows the story drift histories of this structure during the 200% JR Takatori ground motion. Note that the WBSC ratio in this case is 2.1 for the interior first story joint. This indicates that many present seismic provisions around the world underestimate the effect of dynamic loading on moment redistribution in columns particularly for the first story of steel moment frames. To avoid plastic hinges in columns during severe ground motions, a WBSC ratio of at least 2.0 appears to be more effective. This confirms earlier analytical studies on a number of steel moment resisting frames [10, 11]. In Case 2 (exposed column bases with controlled yielding of anchor bolts), the frame collapsed at 135% JR Takatori with a first story collapse mechanism. Despite that local buckling of columns is delayed in this case compared to the original steel moment frame, its collapse mechanism is still a local first story.

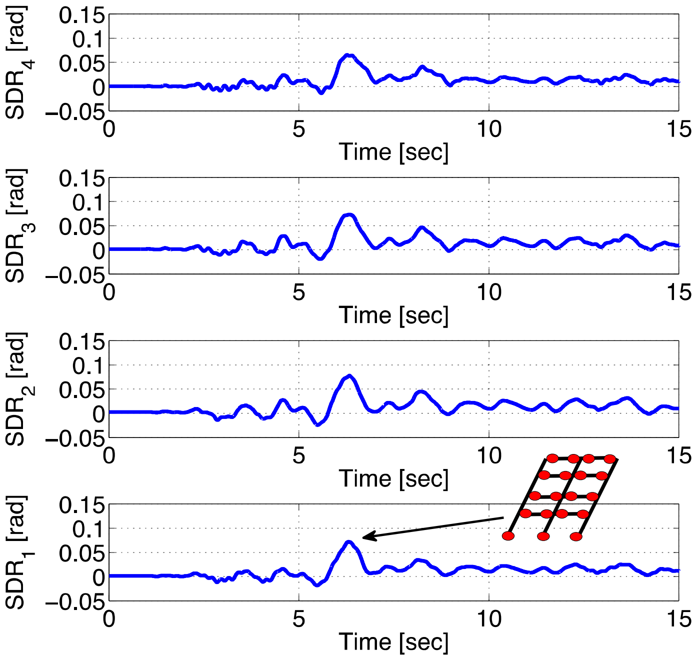


Fig. 6 Seismic response of the 4-story structure at 200% JR Takatori for Case 1

5. CONCLUSIONS

This paper summarizes the collapse assessment of a 4-story steel structure based on recently conducted full scale collapse tests on the E-Defense earthquake simulator in Japan. Experimental data from this test showed that it is possible for a steel structure designed based on current seismic provisions to collapse under severe ground shaking. Using an analytical model based on concentrated plasticity concept it was shown that the collapse mechanism of the test specimen can be predicted given that deterioration of steel components is accurately represented in the simulations. Using the validated analytical model two scenarios are investigated that could delay or shift the first story collapse mechanism of the test frame to a complete frame collapse mechanism. A Weak-Beam-Strong-Column ratio of about 2.0 seems to be adequate in order to avoid column plastic hinges and consequently the development of individual story mechanisms in a steel structure. In that respect, presently available seismic provisions around the world are not necessarily adequate to prevent plastification of columns caused by dynamic redistribution of moments that typically occur under severe ground shaking.

6. ACKNOWLEDGMENT

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ΔΙΕΡΕΥΝΗΣΗ ΜΗΧΑΝΙΣΜΩΝ ΑΠΟΦΥΓΗΣ ΚΑΤΑΡΡΕΥΣΗΣ ΜΕΤΑΛΛΙΚΩΝ ΠΛΑΙΣΙΩΝ ΜΕΣΩ ΠΕΙΡΑΜΑΤΩΝ ΠΡΑΓΜΑΤΙΚΗΣ ΚΛΙΜΑΚΑΣ ΣΕ ΣΕΙΣΜΙΚΗ ΤΡΑΠΕΖΑ

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Το διεθνές κέντρο αντισεισμικών ερευνών E-Defense στην Ιαπωνία διεξήγαγε μία σειρά πειραμάτων κατάρρευσης ενός 4-όροφου μεταλλικού κτιρίου πραγματικής κλίμακας. Τα πειράματα αυτά απέδειξαν ότι είναι πιθανό να σχηματιστεί μηχανισμός κατάρρευσης πρώτου ορόφου σε μεταλλικές κατασκευές όταν αυτές υποβάλλονται σε υψηλή σεισμική διέγερση. Σύγχρονα αριθμητικά προσομοιώματα, τα οποία λαμβάνουν υπόψη τους την πτώση αντοχής και δυσκαμψίας μεταλλικών δοκών και υποστυλωμάτων υπό ανακυκλιζόμενη φόρτιση, μπόρεσαν να αναπαράγουν με επιτυχία τα δεδομένα του πειράματος κατάρρευσης της 4-όροφης μεταλλικής κατασκευής. Με βάση αυτά τα προσομοιώματα διερευνήθηκαν τεχνικές αποφυγής κατάρρευσης, οι οποίες ενισχύουν την καμπτική αντοχή και πλαστιμότητα των μεταλλικών υποστυλωμάτων. Η ενίσχυση της καμπτικής αντοχής των υποστυλωμάτων είναι η πιο ενδεδειγμένη λύση για την αποφυγή κατάρρευσης μεταλλικών κατασκευών που υποβάλλονται σε υψηλές σεισμικές δονήσεις.