Seismic Performance Assessment of High-rise Structure with Unbonded Brace as Outriggers-belt Members

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SUMMARY:
Super high-rise structure often used steel braces (SB) as outriggers-belt members. However steel braces were often in danger of loss of stability under rare earthquake. In order to improve the seismic performance of such structures, the Unbonded Brace (UB) can be used as a substitute for ordinary steel braces. It had better stable tension-compression performance and its stiffness and strength can be controlled more easily. Nonlinear time-historey analysis by ABAQUS was carried out to evaluate the seismic performance of a typical super high-rise building with UB and SB respectively. The deformation, member force and shearwall damage were compared comprehensively. The results showed that the UB had better seismic performance. Its hysteretic behavior was more stable under large deformation and it can yield prior to the main structure to absorb the seismic energy under rare earthquake.

Keywords: seismic performance, high-rise structure, Unbonded Brace (UB), nonlinear time-historey analysis

1. INTRODUCTION

Super high-rise structures often set several stories with outriggers-belt members to improve the lateral stiffness of the whole structure, reduce the horizontal displacement under wind loads and absorb the overturning moment caused by horizontal load. For example, Shanghai Jinmao Tower which total height 421m used three steel braces as outriggers-belt members, Taipei 101 Financial Center which total height 508m used ten steel braces as outriggers-belt members and etc. Structures with ordinary steel braces as outriggers-belt members had many advantages, such as the materials can be used effectively, the freedom can be changed easily and the design of building elevation had more development. However the lateral stiffness and member force of the stories with outriggers-belt members increased dramatic and caused weak stories which was detrimental to the seismic performance of structure. As key members the outriggers-belt members transfered axial force to outer frame column. When used ordinary steel braces (SB) as outriggers-belt members larger cross-section and stiffness were needed to ensure the in-plane stability and out-plane stability. By using the Unbonded Brace (UB) as outriggers-belt members the compressive and tensile instability problem did not exist who had better stable tension-compression performance and its stiffness and strength can be controlled more easily. And limited stiffness stories were formed to reduce sudden change of the stiffness and force. Main structure showed ductile yield mechanisms under rare earthquake which was favorable.

Unbonded Brace (UB) had the dual function of steel brace and metal damper. UB was in linear-elastic deformation under frequency earthquake which was similar to steel brace. While UB can absorb seismic energy first under rare earthquake with stable tension-compression performance and improve the structure seismic performance. Therefore, UB was widely used in practical engineering in recent years. Many buildings adopted UB after 1995 Kobe earthquake in Japan. Currently Japan was the country who developed the most types of UB. Also many buildings adopted UB after 1994 Northridge Earthquake in USA. As of year 2005 more than 25 buildings had been used it in USA. Else more than 100 buildings used UB in Taiwan. UB was first used in Beijing General International Business Center in China. Because of the superior seismic performance the application of UB increased in various types new buildings after 2008 Wenchuan earthquake and 2010 Yushu earthquake. For example, Shanghai World Expo Center and other high-rise structures adopted UB as outriggers-belt members. Previous the studies of UB focused on its performance, while the role UB played in improving the structure seismic performance in practical engineering should be noted.

In this paper, by general finite element package ABAQUS, two 3-D finite element models representing 50 stories building (230.2 m height) using UB and SB as outriggers-belt members were built to perform the nonlinear time-historey analysis. Structure overall seismic performance were compared such as the storey displacement, storey drift and core wall damage etc. when using UB and SB as outriggers-belt members respectively. It provided important information for additional design guidance on structure seismic performance.

2. STRUCTURE OVERVIEW

2.1. Structure Design Scheme

This project was a super high-rise Class A height office space. The structure type was mixed structure system which contained by frame-corewall structure and storey with outriggers-belt members. The structure had 50 stories and the height of main structure was 222.7m, which belonged to Class B limit height. Its plane size was 36.0m × 55.2m, the core wall size was 13.1m × 33.1m, typical floor plan was shown in Figure 2.1. The ratio of structure height and width was H / B = 222.7/36 = 6.2 <7, meeting code requirements. Floor adopted cast-in-situ concrete beam and slab system. The embedded solid parts of the upper structure was set as the first floor. The thickness and concrete strength grades of perimeter shear wall were shown in Table2.1. The corner and side column section size and concrete strength grade were shown in Table 2.2 and Table 2.3. Three stories number with outriggers-belt members were 16, 28 and 40. The storey with outriggers-belt members height was 4.8m, the standard storey height was 4.3m. Due to structure weak stiffness in X direction, the outriggers members between the core wall and frame column along the X direction were set and the belt members in the three stories were set too, as shown in Figure 2. The design seismic intensity was 7 (0.1g), the classification of seismic protection of building constructions was Type C (bottom 5 stories was in Type B), the design seismic group was group 1, site soil classification was Class II, the design seismic characteristic period of ground motion was 0.35s.

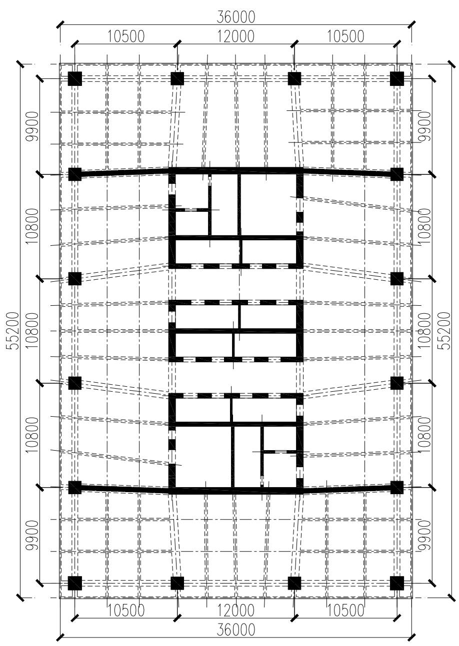
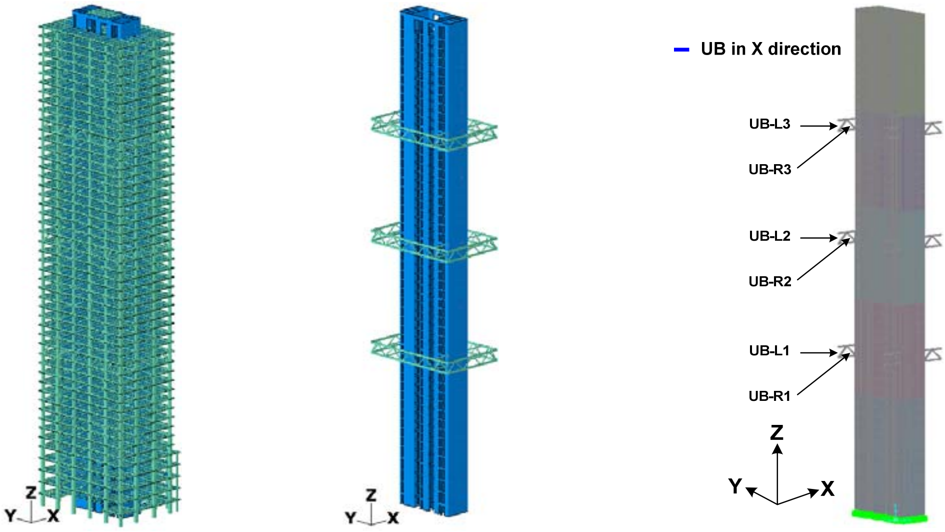


Figure 2.1. Typical plan layout of structure (bold dash line represents outriggers members)

2.2. Unbonded Brace Performance and Layout

The typical structure of Unbonded brace was shown in Figure 3below, which was composed of two parts mainly. The first part was the core plate (--shaped or cross-shaped, etc.) bearing the axial force, the second part was the outsourcing constraints tube (round shape or rectangle) providing lateral restraint to prevent the overall instability and local buckling. Between the core plate and constraints tube was the filler. Between the core plate and filler coated with a layer of unbonding material, whose role was to ensure that the axial force was not transmitted to the filler and constraints tube. The filler and constraint tube worked together to prevent the buckling of support.



(a) The overall structure (b) The core wall and storey with outriggers-belt members (c) UB number

Figure 2.2. The 3-D finite element model and layout of Unbonded brace

Table 2.1. The thickness and concrete strength grade of perimeter shear wall

Storey number	Perimeter shear wall thickness (mm)	Concrete strength grade
1~6	800	C60
7~11	700	C60
12~21	600	C55
22~28	500	C50
29~31	400	C50
32~41	400	C45
42~52	400	C40

Table 2.2. The corner column section size and concrete strength grade

	Concrete section			Steel section			
Storey number	H(mm)	B(mm)	Concrete strength grade	H(mm)	B(mm)	t_f(mm)	t_w(mm)
1~5	1500	1500	C80	1100	270	48	48
6~7	1500	1500	C70	1100	270	48	48
8~14	1400	1400	C70	1000	270	48	48
15~17	1300	1300	C70	950	270	40	40
18~23	1300	1300	C60	950	270	40	40
24~30	1200	1200	C60	800	270	40	40
31	1200	1200	C50	800	270	40	40
32~38	1100	1100	C50	700	270	36	36
39~41	1000	1000	C50	600	270	32	32
42	900	900	C50	500	250	26	26
43~50	900	900	C40	500	250	26	26

Note: "+" Cross steel section and Q345 was used in steel reinforced concrete column.

Table 2.3. The side column section size and concrete strength grade

	Concrete section			Steel section			
Storey number	H(mm)	B(mm)	Concrete strength grade	H(mm)	B(mm)	t_f(mm)	t_w(mm)
1~5	1400	1400	C80	1000	270	48	48
6~7	1400	1400	C70	1000	270	48	48
8~14	1300	1300	C70	950	270	40	40
15~17	1200	1200	C70	800	270	40	40
18~23	1200	1200	C60	800	270	40	40
24~31	1100	1100	C50	700	270	36	36
32~41	1000	1000	C50	600	270	32	32
42	900	900	C50	500	250	26	26
43~50	900	900	C40	500	250	26	26

Note: "+" Cross steel section and Q345 was used in steel reinforced concrete column.

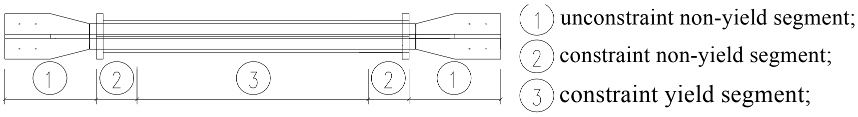


Figure 2.3. Unbonded brace construct schematic

In longitudinal construct, Unbonded brace(UB) was composed of the constraint yield segment, the constraint non-yield segment, unconstraint non-yield segment, unbonded expandable material and buckling constraints institutions, as shown in Figure 2.3. Constraint yield segment yield under cyclic loading, was the main energy-consuming part. Constraint non-yield segments wrapped in tube and mortar was an extension of the constrained yield segment, as the transition part of the unconstrained non-yield segment. Unconstrained non-yield segment was the connecting part with frame, usually adopt bolts or welded connections. Unbonded expansion materials (rubber, polyethylene, etc.) can effectively reduce or eliminate the shear of core material between the constrained segment and mortar. Buckling constraints institutions mostly compose of mortar and hollow steel tube.

This project used the Unbonded brace (UB) produced by the China Academy of Building Research, who had done a lot of tests, and the Unbonded brace had stable performance, as shown in Figure 2.4.

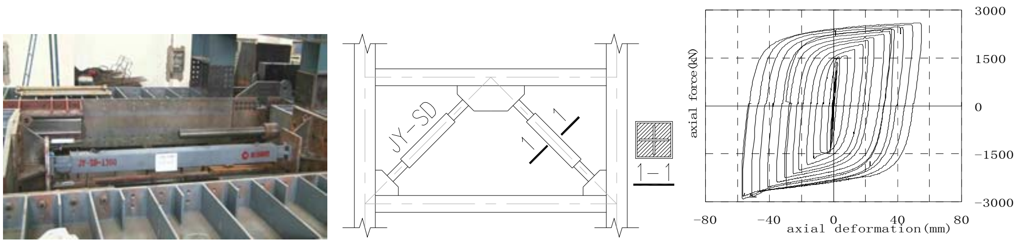


Figure 2.4. Unbonded brace member test, gable elevation layout and test hysteresis curve

According to the structural design performance goals, the performance-based seismic design objectives of UB used in this project was non-yield under the design earthquake intensity. The UB main design parameters was follows: the equivalent cross-sectional area of the inner core was $0.0425m^2$, the yield force was 10500kN, the effective stiffness was 1.3e6kN/m.

The Unbonded brace used gable elevation layout. Three positions were set by UB along the structural height, each eight UBs (four pairs), for a total of 24 UBs. The location and number of UB for later analysis was shown in Figure 2.

3. NONLINEAR TIME-HISTOREY ANALYSIS

In accordance with the relevant national code requirements, the structure exist a high degree of overrun characteristics and vertical irregular seismic characteristics. The overall seismic performance of the structure was difficult to grasp only through the elastic analysis, so the nonlinear time-history analysis under rare earthquake should be used to obtain the deformation, member forces and its plastic damage, etc. to find the weak parts of the structure.

Shell element and beam element were used to simulate the whole structure incorporating non-linear material characteristics, non-linear geometric behavior and non-linear construction process. The technology of cell life and death was used for construction simulation with 5 construction stages (Unbonded brace installed later).

3.1. Materials Model of Concrete and Steel

The material properties of all the structural steel components were modeled using an elastic-plastic material model from ABAQUS. The stress-strains relationship in compression and tension were assumed to be the same in ABAQUS. Steel bilinear kinematic hardening model was used and taking into the Bauschinger effect in the stress-strain cycle without considering the stiffness degradation. As shown in Figure 3.1. The material would behave as a linear elastic material up to the yield stress of the material. After this stage, it went into the strain hardening stage until reaching the ultimate stress. Steel strength and yield ratio was 1.2 and the ultimate strain was 0.025.

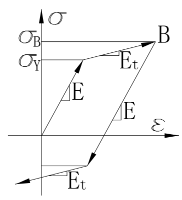


Figure 3.1. Steel bilinear kinematic hardening model

The concrete was modeled by using a concrete damage plasticity model considering the tension and compression strength differences, stiffness and strength degradation and the stiffness recovery nature in tension and compression cycle cracks closed and etc. Else self-developed concrete material user subroutine was used to simulate the beams and columns concrete materials. The concrete axial compressive and tensile strength value was obtained from the Code for design of concrete structures (GB50010-2010) Table 4.1.3. And the constraint enhanced effect of stirrups was not considered. Constitutive relation for concrete was shown in Figure 3.2.

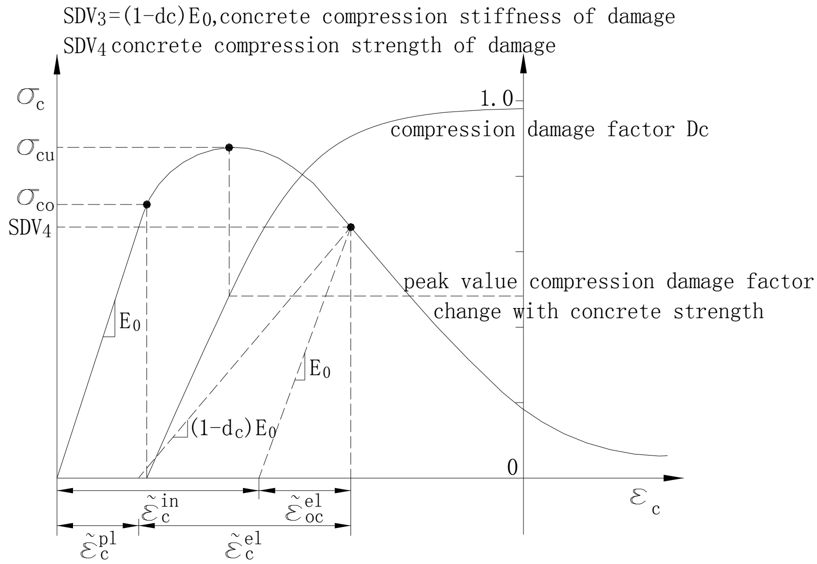


Figure 3.2. Response of concrete to uniaxial loading in compression and damage schematic

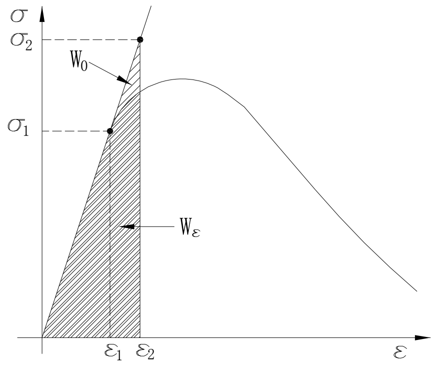


Figure 3.3. Strain energy density diagram

The tension damage factor d_t and compression damage factor d_c was used to express the stiffness reduction in concrete damage plasticity model. Najar's damage theory was used and the brittle solid material damage was defined by the Eqn. 3.1. (as shown in Figure 3.3.).

$$D = \frac{W_0 - W_\varepsilon}{W_0} \tag{3.1}$$

Where, $W_0 = \frac{1}{2}\varepsilon : E_0 : \varepsilon$ and $W_\varepsilon = \frac{1}{2}\varepsilon : E : \varepsilon$ represented the strain energy density of undamage and damage material respectively. E_0 and E represented the fourth-order elastic coefficient tensor of undamage and damage material respectively. ε represented the corresponding second-order strain tensor.

3.2. Finite Element Model

All the beams, columns, belt members and Unbonded brace non-yield segment were simulated by using *BEAM elements in the ABAQUS element library. And the linear integral fiber beam element was based on the Timoshenko beam theory which taking into account shear deformation and rotation effects of inertia.

The slab and core wall were simulated by using three or four nodes *SHELL elements whose bending and membrane stiffness terms were available from the ABAQUS library. The layered shell element can consider the multi-storey reinforcement.

The Unbonded brace yield segment was simulated by using *CONNECTOR element in the ABAQUS element library.The model was supported at the bottom.

4. ANALYSIS RESULTS DISCUSSION

4.1. Earthquake Input Records

Based on current design guidance three group earthquake records with two directions were selected and the response spectrum curves were shown in Figure 4.1. The design seismic intensity was 7 degree (0.1g) and the rare earthquake peak acceleration of ground motion was 220gal. The super design seismic intensity was 8 (0.2g) and the rare earthquake peak acceleration of ground motion was 400gal. The earthquake peak acceleration ratio of the main direction to second direction was 1:0.85. Structural damping ratio was 5%. Taking into account the structural damping ratio would be greater than 5% under rare earthquake. In this paper conservative results were obtained by using 5% damping ratio and the difference by using UB and SB as outriggers-belt members respectively would become more apparent.

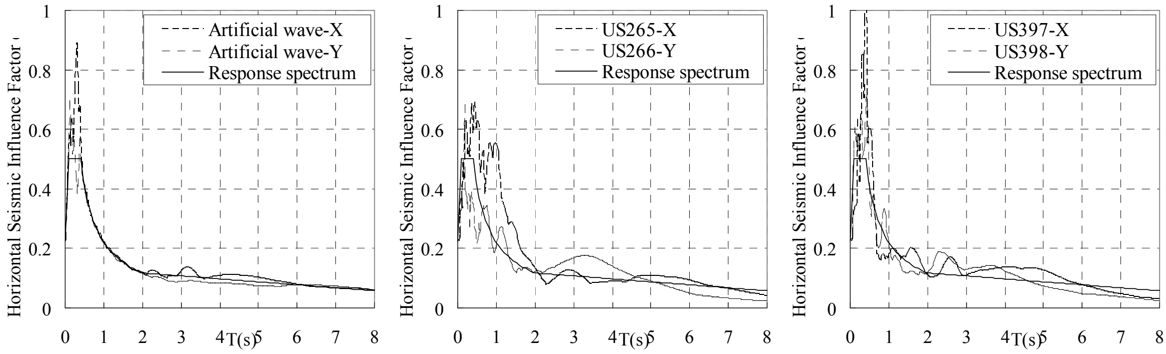


Figure 4.1. Response spectrum curves of earthquake records

4.2. Structure Characteristics

The model was firstly built up in SAP2000 and then converted into ABAQUS after meshing. The static and modal analysis was done by SAP2000. Construction simulation and modal analysis was done by ABAQUS. The results were shown in Table 4.1. Table 4.1. showed that the model for nonlinear time-history analysis was reasonable.

Table 4.1. Model total mass and periods

	Vibration modes	Sap2000	ABAQUS
Total mass（ton）		176063	177909
T_1(s)	X first-oder	5.77	5.73
T_2(s)	Y first-oder	4.59	4.54
T_3(s)	torsion first-order	3.50	3.45

T_l/T_t = 3.45/5.73 = 0.6<0.85 which met the technical specification for concrete structures of tall building (JGJ3-2010) 3.4.5.

4.3. Results of Unbonded Brace Structure and Steel Brace Structure

The UBs were in yield energy-consuming stage differently under rare earthquake 7 degree (0.1g) with bidirectional seismic input. As shown in Figure 9 the axial force-deformation curve of UB positive represented in tension and negative represented in compression.

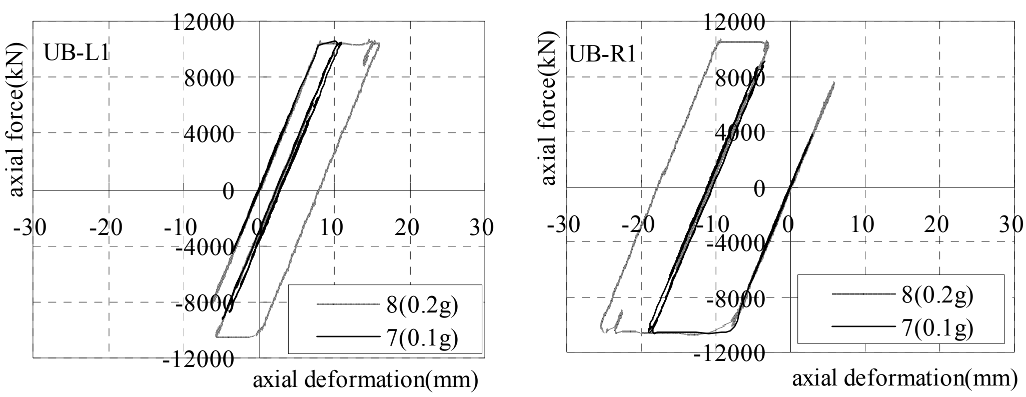


Figure 4.2. The axial force-deformation curve of UB under rare earthquake US265 X input

UB-L1 was in tension at initial stage and the axial force-deformation curve increased linearly under rare earthquake US265 X input, 7 degree (0.1g). UB-L1 was at tension yield platform with force increasing further. At the same time the axial deformation increased to 11mm, the axial force reached yield force 10500kN. UB-L1 changed from tension to compression with the force decreased. UB-R1 was in compression when UB-L1 was in tension at initial stage. When the compression deformation reached to 8mm, UB-R1 came into compression yield platform. UB-R1 reached to yield force 10500kN with compression deformation increasing further. UB-R1 maximum axial compression deformation reached to 19mm. UB-R1 changed from compression to tension with the force decreased. Figure 10 showed that UB-L1 and UB-R1 work together very well and showed good performance of tension and compression which benefit to structure seismic performance.

The area surrounded by axial force-deformation curve of UB represented its capacity of seismic energy consumption under earthquake inputs. As shown in Figure 9 the stronger capacity of seismic energy consumption was described by larger area and more cycles of hysteresis loop. The results showed that the right series UB-R1, UB-R2 and UB-R3 had more full and more cycles hysteresis loop and more energy consumption than the left series UB-L1, UB-L2 and UB-L3.

Therefore, the performance parameters of UB should be optimized in actual project. It will be more economical to use different types UB.

When SB was used as a substitute for UB as the outrigger web member, ordinary steel brace SB-L1, SB-L2 and SB-L3 were in linear-elastic stage, did not yield under rare earthquake US265 X input, 7 degree (0.1g). It showed that UB yield first to absorb seismic energy under the same intensity earthquake. The right series of steel braces SB-R1, SB-R2 and SB-R3 were in the compression buckling failure mode under three groups wave as shown in Figure 4.3.

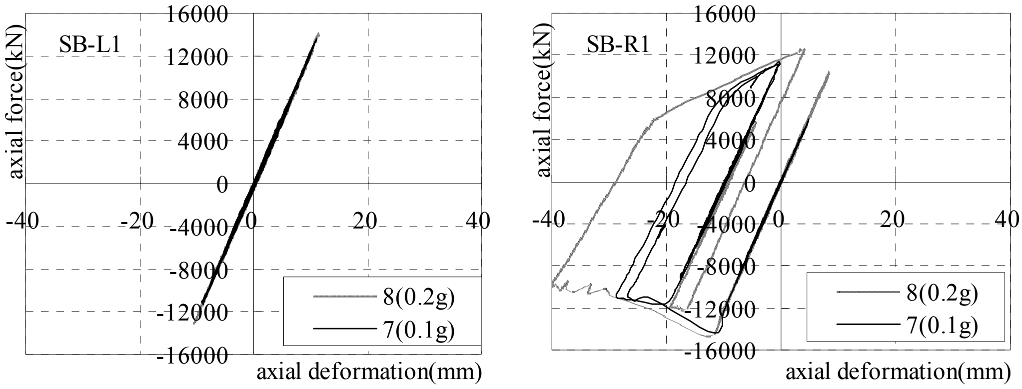


Figure 4.3. The axial force-deformation curve of SB under rare earthquake US265 X input

SB-R1 was in compression at initial stage and the axial force-deformation curve increased linearly under rare earthquake US265 X input, 7 degree (0.1g). The pressure of SB-R1 began to decline after reaching a peak value 14384kN (whose yield was As × fy = 42500mm^2 × 345N/mm^2 = 14662.5 kN, SB-R1 did not yield). Meanwhile the axial compression deformation of SB-R1 increased from 12mm to 29mm and showed a significant nonlinear relationship between the axial force and deformation. SB-R1 was in compression buckling and failed. Ordinary steel brace was in compression buckling and failed under actual earthquake, can not transfer axial force from core to outer frame column which was very negative to structures.

UB can absorb more energy under rare earthquake 8 degree (0.2g) as shown in Fig. 4.2. and Fig. 4.3.

The axial force time curve of UB-R1 and SB-R1 under rare earthquake US265 X input, 7 degree (0.1g) were shown in Figure 4.4, UB-R1 first reached yield capacity at 13s which also happened at 16.4s, 19.4s and 21.9s. SB-R1 reached yield capacity fist time at 12.9s and then axial force decreased to

11257kN which was only the 11257kN/14662.5kN = 76.8% of yield capacity at 16.6s. It indicated that the can not bear the internal force after reaching the compression buckling which increased the burden of other adjacent lateral resisting members.

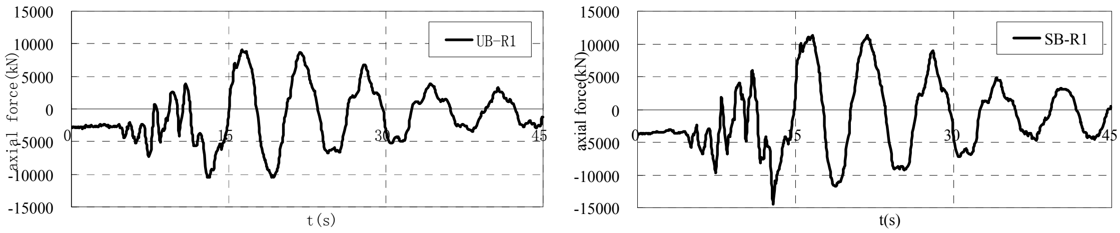


Figure 4.4. The axial force time curve of UB and SB under rare earthquake US265 X input

4.4. Structure Deformation Results Under Rare Earthquake

The deformation of structures with UB and SB respectively were basically the same under rare earthquake 7 degree (0.1g) US265 X input as shown in Figure 4.5. The deformation of structure with UB increased slightly above the third outriggers-belt members for the higher mode effect but it was still in specification limits.

The storey drift below the first outriggers-belt members of structure with UB was less significantly than structure with SB under rare earthquake 8 degree (0.2g) US265 X input as shown in Figure 4.5.

Not only structure deformation but also base shear can be controlled effectively by setting UB. The base shear of UB and SB programs were V_x=153.3MN and V_x=155.9MN respectively under rare earthquake 7 degree (0.1g) US265 X input. The base shear of UB and SB programs were V_x=182.8MN and V_x=183.3MN respectively under rare earthquake 8 degree (0.2g) US265 X input.

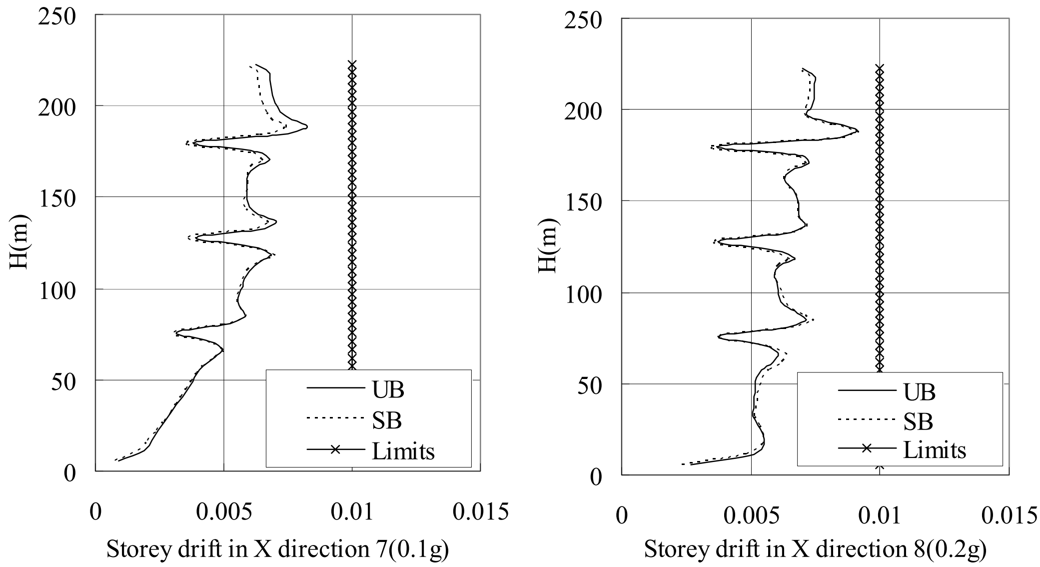
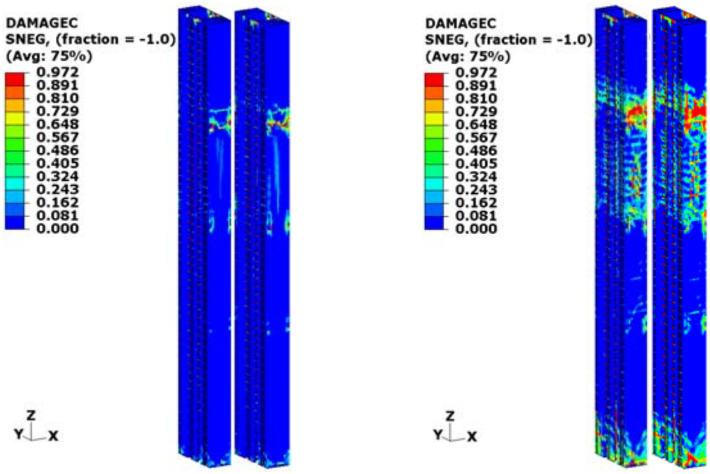


Figure 4.5. Structure storey drift under rare earthquake US265 X input

4.5. Structure Damage under Rare Earthquake

The compression damage factor of core wall under rare earthquake 7 degree (0.1g) US265 X input was shown in Figure 4.6. The region over 0.3 of compression damage factor was reduced effectively by using UB as outriggers-belt members.



(a) UB/SB 7 degree (0.1g) (b) UB/SB 8 degree (0.2g)

Figure 4.6. Core wall compression damage factor diagram under rare earthquake US265 X input

5. CONCLUSIONS

In this paper, two 3-D finite element models using UB and SB as outriggers-belt members respectively were built with ABAQUS to simulate structure nonlinear behavior under rare earthquake 7 degree (0.1g) and 8 degree (0.2g). The high-rise structure was 230.2m and incorporated non-linear material characteristics, non-linear geometric behavior and non-linear construction process. Below are the main findings:

(1) When using ordinary steel brace as outriggers-belt member web, the web showed compression buckling failure mode which was very negative to structure. When using Unbonded Brace (UB) as outriggers-belt member web, it can increase the structure overall lateral stiffness, yield prior to the main structure to absorb seismic energy under rare earthquake, reduce core wall compression damage factor and etc.

(2) The results of nonlinear time-history analysis shew that in this project using UB as structure outriggers-belt member web was very favorable. UB at different locations played a various role under rare earthquake. So according to the actual need optimized the layout and parameters of UB can improve the structure force transmission system.

The methods and conclusions of this study can provide a reference for similar high-rise structure seismic performance design. The research toward the seismic performance of high-rise structure with UB is still in its infancy. Further work still needed.

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