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STUDY ON SEISMIC REINFORCEMENT MEASURES AND SCHEMES OF IRREGULAR FRAME STRUCTURES

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Abstract:

The SAP2000 finite element analysis software was applied to model the original frame and carry out the elasto-plastic time-history analysis method, with an existing irregular plane framework in Tianjin as the object of the study. Buckling-Restrained Brace (BRB) damping and anti-torsional reinforcement scheme was proposed based on the analysis results and the characteristics of the project. The results indicate that compared with the original frame, the period ratio of BRB frame was reduced by 26%; torsional displacement ratio was decreased by 15%; decreasing of inter-story displacement angle could reach 31%, and the maximum displacement angle of the top layer can be controlled within the scope of the code. BRB not only increases the anti-lateral stiffness of the structure, but also improves the seismic performance of the structure, which is an effective approach to control torsional effect of irregular structures.

Keywords: irregular plane, time-history analysis, BRB, seismic reinforcement

ISTRAŽIVANJE O SEIZMIČKIM MJERAMA I ŠEMAMA ARMIRANJA NEREGULARNIH OKVIRNIH KONSTRUKCIJA

Apstrakt:

Predmet istraživanja je postojeći neregularni ravanski okvir u Tjencinu. Modeliranje originalnog okvira i analiza elasto-plastičnog ponašanja u vremena izvršeni su programom na bazi konačnih elemenata SAP2000. Na osnovu rezultata analize i karakteristika konstrukcije predložena je šema prigušenja pomoću okvira sa dijagonalnim podupiračima otpornim na izvijanje (BRB – Buckling-Restrained Braces) i armiranja za torziju. Rezultati pokazuju da je, u poređenju sa originalnim okvirom, odnos perioda okvira sa dijagonalnim podupiračima (BRB frame) smanjen za 26%; odnos torzionog izvijanja je smanjen za 15%; smanjenje međuspratnog ugla torzije bi mogao dosegnuti 31%, a maksimalni ugao torzije posljednjeg sloja se može kontrolisati u okviru koda. Dijagonalni podupirači (BRB) ne samo da povećavaju bočnu krutost konstrukcije, već i poboljšavaju seizmička svojstva, što predstavlja efikasan pristup kontroli uticaja torzije na nepravilne konstrukcije.

Ključne riječi: nepravilna ravan, analiza u vremenu, , seizmičko armiranjeKljučne riječi: nepravilna ravan, analiza u vremenu, BRB, seizmičko armiranje

1. INTRODUCTION

Due to mis-alignment of rigidity center and center of mass, irregular plane structures[1] would generate obvious shear-torsion coupling effect encountering horizontal earthquake, making even worse earthquake damage of buildings, as well as structural damage even collapse. Therefore, the key to enhance seismic performance of torsional irregular structures is how to strengthen torsional stiffness of structures in aseismic design. In addition, braces were generally added in frame structures to dissipate earthquake energy in the case of improving fortification intensity, however, traditional brace-frame structures are easy to buckle when compressed under severe earthquake, thus the energy-dissipating capacity of which could not be fully exerted. Compared with brace-frame structures, Buckling Restrained Brace[2-3] (referred to as "BRB") could effectively solve the problem of misalignment of stiffness center and center of mass in irregular structures' floors, and also has good ductility, as well as stable and plump hysteretic feature, so as to ensure safety and normal usage of structures under severe earthquake. Studies of Prof. Guo Yanlin, Liu Jianbin from Tsinghua University[2], Prof. Zhou Yun from Guangzhou University[3], Dr. Jia Mingming from Harbin Institute of Technology[4] also indicated that BRB could greatly consume earthquake energy, and reduce displacement of the structure during earthquake.

Original earthquake fortification intensity in Tianjin was 7 degrees (0.15g), which was adjusted to 8 degrees in 2016 (0.2g)[5]. Thus, it's necessary to review seismic performance of certain specific existing buildings.SAP2000 finite element analysis software was used to model an existing irregular building located in Tianjin, and carried out elasto-plastic time-history analysis, BRB seismic reinforcement scheme was proposed,seismic performance of structures were compared and analyzed before and after reinforcement.

2. ANALYSIS OF PROJECT CASE

2.1. PROJECT PROFILE

The building is located in Tianjin, which is a ten-storied frame structure, and mainly used for offices, stores and hotel. Story height of the building could be divided into three sections, the 1st floor's height is 3.9m, story height from 2nd to 5th floor is 3.6m, story height of the 6th floor and above is 3m, total height is 33.3m,length of the structure from east to west is 42.8m, width from north to south is 23.4m, plane layout is in the form of letter L, belonging to the irregular building, the overall plan is as shown in Figure.1, main sectional dimensions of structural components and the corresponding strength grades of concrete are shown in Table 1. Original earthquake fortification intensity was 7 degrees, designed fundamental acceleration was 0.15g. As earthquake fortification intensity was enhanced to 8 degrees, designed fundamental acceleration was changed to 0.20g; site classification is Ⅱ class, design earthquake group is the 2nd group. Figure.1 Overall Plan

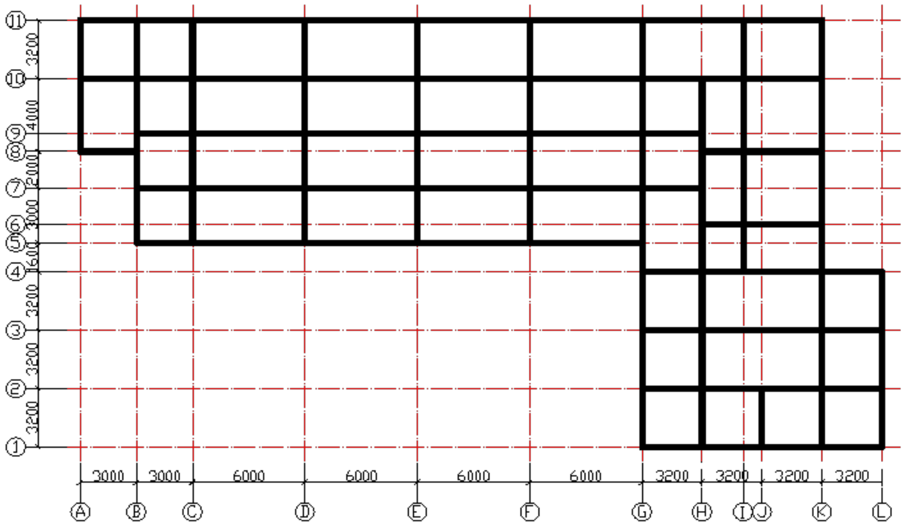


Figure 1. Overall Plan

Table 1. Sectional Dimensions of Components and Strength Grades of Concrete

Component	Floor	Sectional Dimensions	Concrete Strength Grades	Steel Strength Grades
Side Column in Frame	1～5F	700×700	C35	HRB400
	5～10F		C30	
Center Column in Frame	1～5F	600×600	C35	HRB400
	5～10F		C30	
Main Beam in Frame	1～5F	300×500	C35	HRB400
	5～10F		C30	
Secondary Beam in Frame	1～5F	200×400	C35	HRB400
	5～10F		C30	

2.2. MODELING AND SEISMIC PERFORMANCE ANALYSIS

SAP2000[6] was used to model and analyze the original frame. linear bar element was adopted to simulate both beams and columns in the frame, shell element was adopted to simulate floorboard. To rationally reflect overall stiffness of the frame, floorboard of each floor was uniformly set to be rigid clapboard. Overall model of the original frame is as shown in Figure.2, constitutive relations of steel and concrete used are as shown in Figure. 3 and Figure. 4.

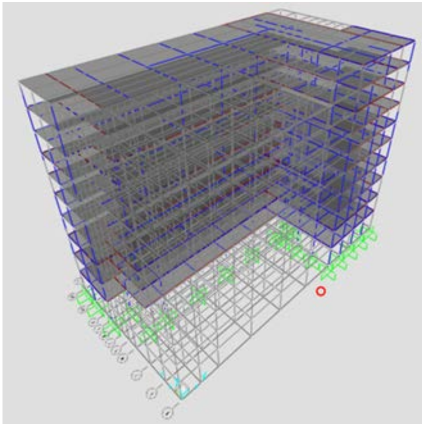


Figure 2. Overall Model of the Original Frame

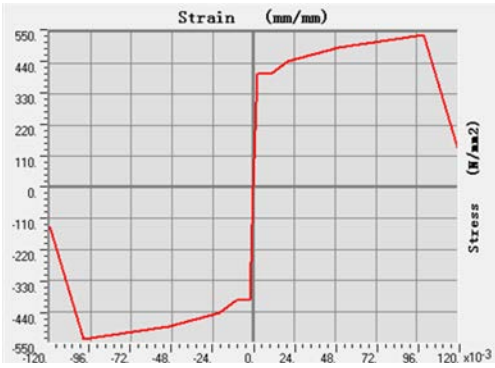


Figure 3. Constitutive Relation of Steel

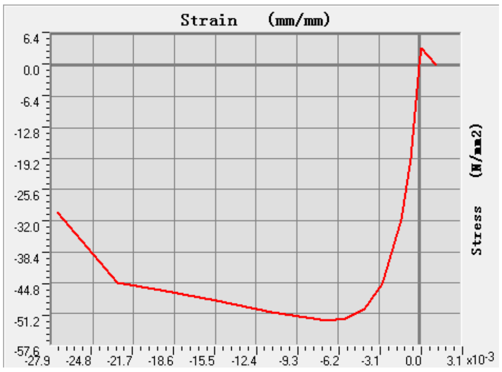
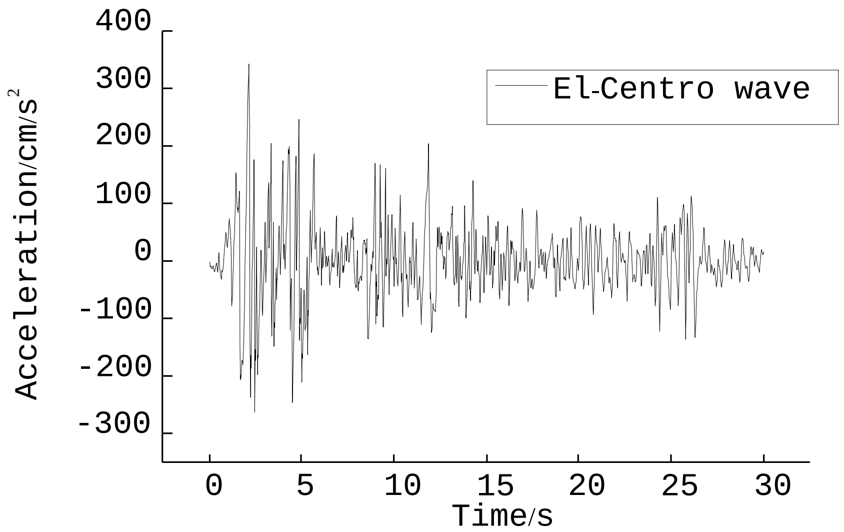


Figure 4. Constitutive Relation of Concrete

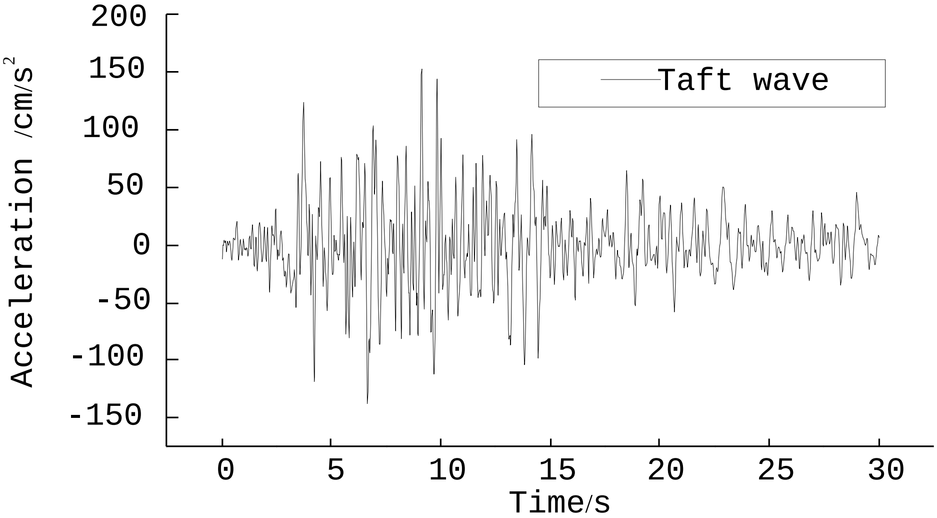
According to requirements of "Code for seismic design of building” (GB 50011-2016)[5], El-Centro wave and Taft wave, as well as an artificial simulated seismic wave were selected for time-history analysis under 7 degrees frequent earthquake, 8 degrees frequent earthquake and 8 degrees rarely occurred earthquake[7]. Three kinds of seismic wave acceleration time-history curve are shown in Figure.5. According to the Code, acceleration peak values of the three seismic waves were adjusted to a certain extent, and the adjustment coefficients are shown in Table 2.

Table 2. Adjustment Coefficients of Acceleration Peak Values of the Three Seismic Waves

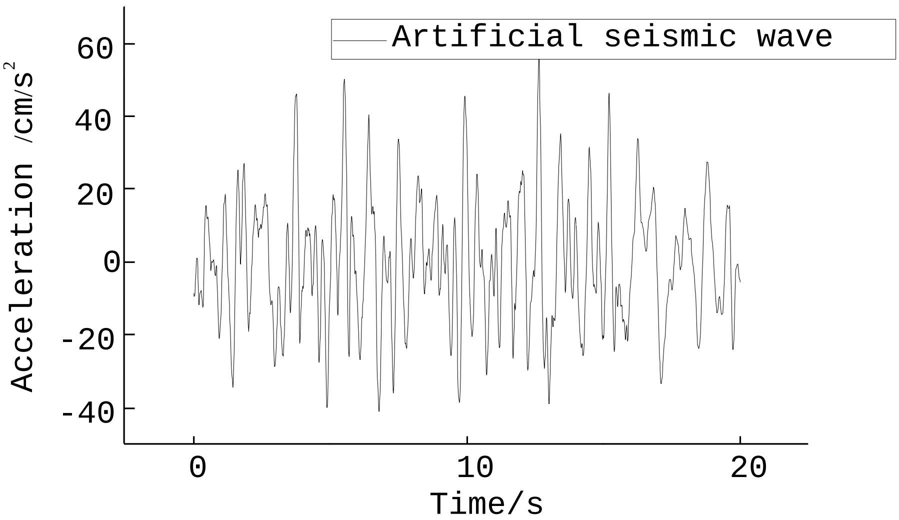
	El-Centro Wave	Taft Wave	Artificial Seismic Wave
Frequent earthquake (7 degrees)	1.02	2.23	6.31
Frequent earthquake (8 degrees)	2.05	4.47	12.62
Rarely occurred earthquake (8 degrees)	11.71	26.20	72.09



(a) Acceleration time-history curve of El-Centro wave



(b) Acceleration time-history curve of Taft wave



(c) Acceleration time-history curve of artificial seismic wave

Figure 5. Three kinds of seismic wave acceleration time-history curves

2.3. RESULTS OF THE ORIGINAL FRAME

The former six order modes of the original frame were chosen for modal analysis, the original frame Tl =1.498s, taking translation in Direction Y as principal; while T2=1.378s, taking translation in Direction X as principal; T3=1.265s, taking torsion as principal; period taking the first torsion as principal Tt=1.265s, then: Tt/Tl =1.265/1.498=0.84<0.90, meeting the requirements of seismic code.

Interlayer displacement angles of part of the original frame floors under El-Centro wave and Taft wave, as well as artificial seismic wave during 8 degrees frequent earthquake were showed in Table 3. The interlayer displacement angles from 1st to 6th floor of the original frame under the action of 8 degrees frequent earthquake obviously exceeded the required 1/550; although torsional displacement ratio of the original frame under the action of 8 degrees frequent earthquake was smaller than the limiting value 1.5 of "Technical specification for concrete structures of tall building"(JGJ3-2010)[8], it's nearly greater than the suggestive value 1.2 of "Technical specification for concrete structures of tall building".

Table 3. Inter-layer displacement angles of part of the original frame floors under 8 degrees frequent earthquake

Floor	El-Centro wave		Taft wave		Artificial Seismic Wave	
	X	X	Y	X	X	Y
1	1/620	1/652	1/616	1/652	1/652	1/616
2	1/466	1/519	1/509	1/519	1/519	1/509
3	1/475	1/537	1/511	1/537	1/537	1/511
4	1/503	1/549	1/516	1/549	1/549	1/516
5	1/559	1/594	1/548	1/594	1/594	1/548
6	1/730	1/777	1/705	1/777	1/777	1/705

3. REINFORCEMENT SCHEMES SELECTION AND DESIGN

It is necessary to reinforce the original frame as the interlayer displacement angles from 1st to 6th floor of the original frame did not meet the requirements of the specification, while torsional displacement ratio exceeded suggestive value of the specification,. As the project is a comprehensive office building, as long as the building process equipment layout was determined, there would be hardly any room for changing the body type and structural arrangement, it's not suitable to arrange shear walls either in the north or in the east; as for enhancing weakness part of the frame through increasing sectional size of the beams and columns, although seismic performance of the original frame could meet the specification requirements, the caused "large beams and large columns" would not only bring inconvenience to building use, but also lead to brittle failure of the frame on account of oversized stiffness; although the addition of conventional braces could achieve the purpose of seismic strengthening under the action of frequent earthquake, the braces would be extremely easy to be compressed and buckled under the action of rarely occurred earthquake, and be unable to give full play to tensile behavior of the steel. To sum up, BRB is the best choice for this project, which could not only improve lateral stiffness of the frame, but also adjust torsional deformation of the frame, as well as reduce brace section and shear force of the node area.

In order to give full play to BRB, the brace should be arranged as far away from rigidity center as possible, to increase torque and improve torsional rigidity. The arrangement form is as shown in Figure. 6: arrange totally 33 BRBs at 8-11 of Axle A and 10-11 of Axle K from 1st to 6th floor, G-H and J-K of Axle 1 and J-K of Axle 11 from 1st to 5th floor.

Wen element was adopted to simulate BRB. Q235 cross section steel was applied, the elasticity modulus of which was E=200GPa, the length was 5000mm, the cross sectional area of each floor was equal, which is 3.96×10-2m2, and the yield bearing capacity was estimated to be 3500kN. The damping coefficient was 2000kN•s/m, the damping exponent was 0.5, Poisson's ratio was 0.3, with the connection type of Multilinear-plastic. The connecting format was hinge joint, diagonal bracing was used for arrangement.

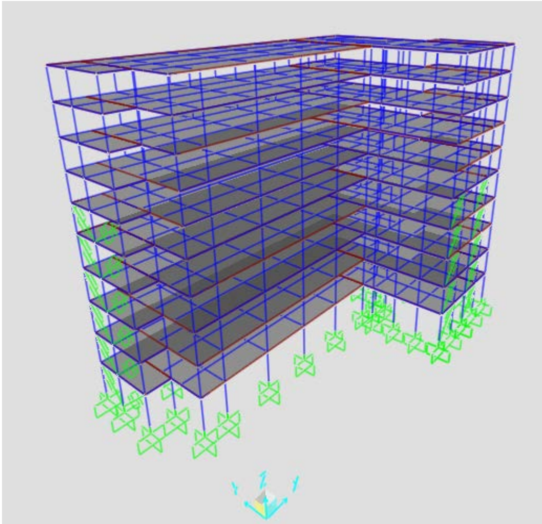


Figure 6. Arrangement Form of BRB

4. STRUCTURAL SEISMIC PERFORMANCE ANALYSIS UNDER THE 8 DEGREES FREQUENT EARTHQUAKE

4.1. RESULTS OF THE ORIGINAL FRAME

The former six order modes of BRB frame were chosen for modal analysis, the results are shown in Table 4.

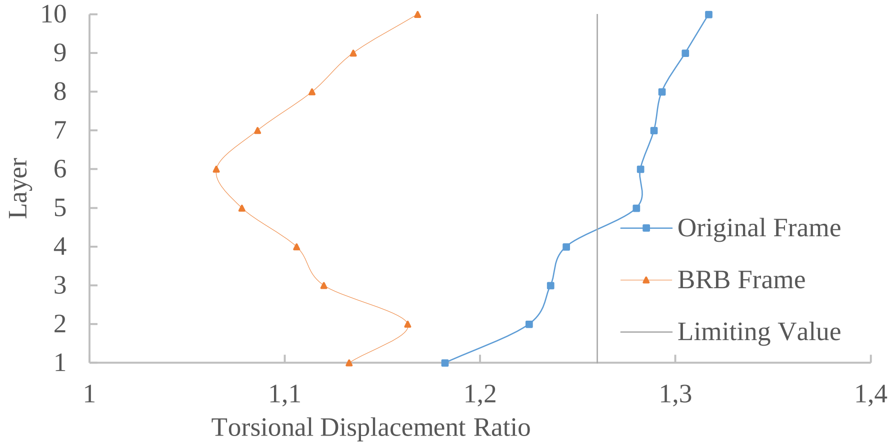
Table 4. Structural Periods of BRB Frame

Mode No.	BRB Frame	Type
1	1.1829	X
2	0.8680	Y
3	0.8330	T
4	0.4515	X
5	0.3268	Y
6	0.2813	T
Torsional Period Ratio	0.7	

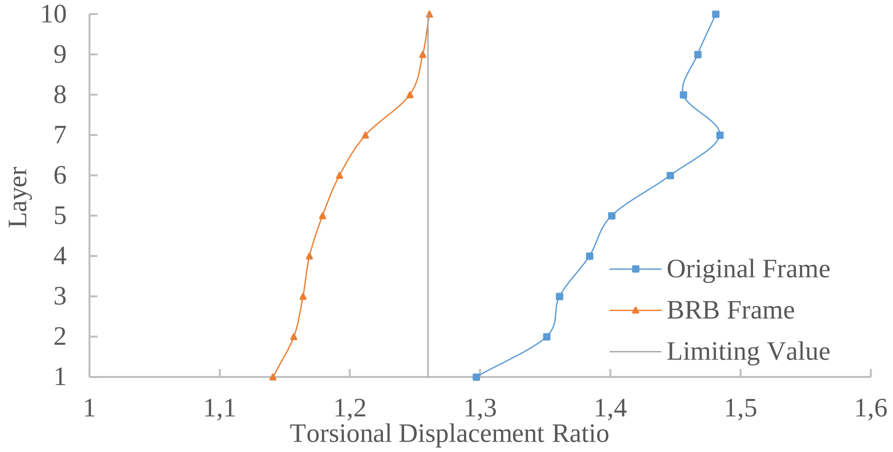
As shown in Table 4, the BRB frame T1=1.1829s, Tt=0.8330s, and the period ratio is only 0.70, which is decreased by 26.3% compared with the original frame. In addition, period of each order of vibration mode of BRB frame decreases, indicating that the lateral stiffness of the frame is improved, and the torsion phenomenon is controlled.

4.2. TORSIONAL DISPLACEMENT RATIO

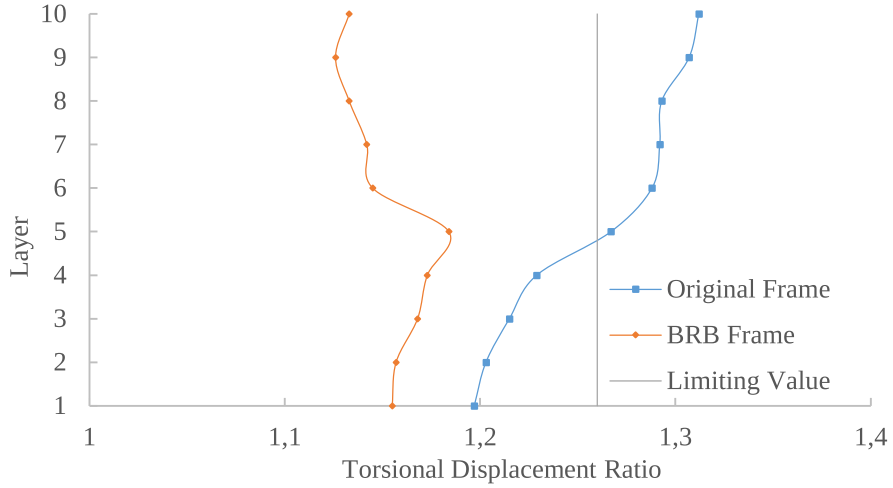
Torsional displacement ratio should also be controlled for the torsional irregular structure, as torsional displacement ratio could directly reflect the torsional linearity of the frame, in addition to the control of period ratio[9]. Figure. 7 shows torsional displacement ratios of both the original frame and BRB frame under three kinds of seismic wave.



(a) under the action of El-Centro wave



(b) under the action of Taft wave



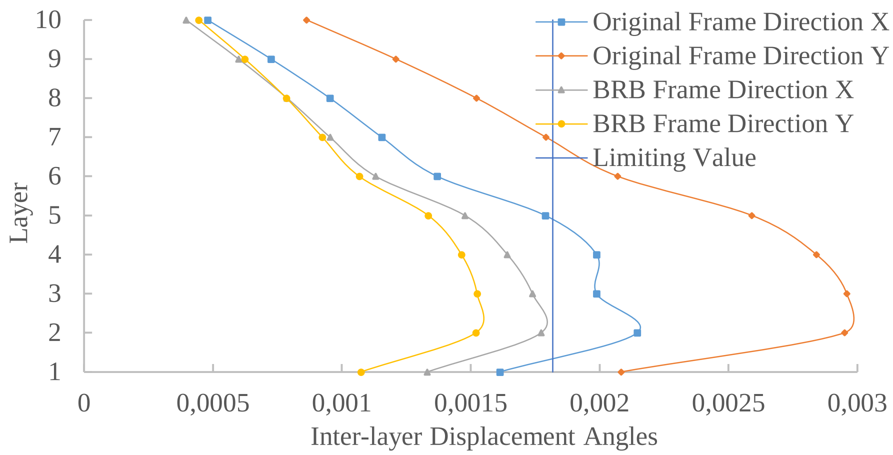
(c) under the action of artificial seismic wave

Figure 7. Torsional displacement ratios under the 8 degrees frequent earthquake

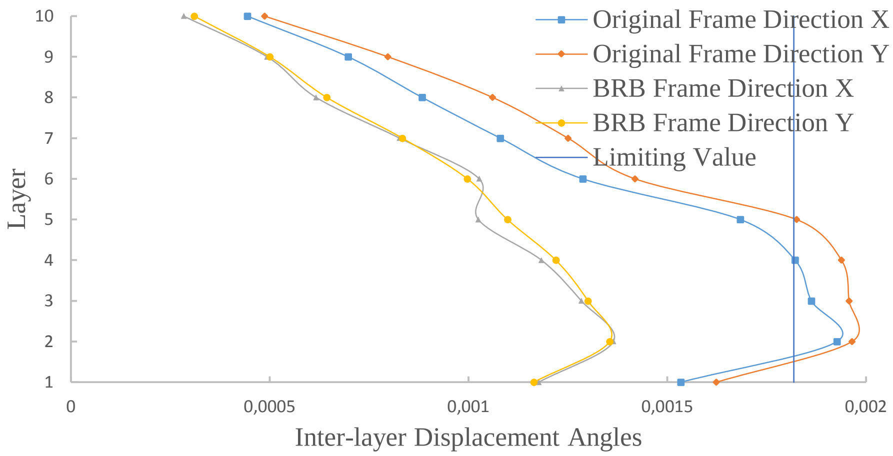
As shown in Figure. 7, torsional displacement ratio of BRB frame is 11% lower than that of the original frame under the action of El-Centro wave, while 15% under the action of Taft wave, and 15% under the action of artificial seismic wave, indicating that displacement ratio could be decreased through reasonable layout of BRB, while the uneven rigidity distribution of the original frame could be improved.

4.3. COMPARISON OF INTER-LAYER DISPLACEMENT ANGLES

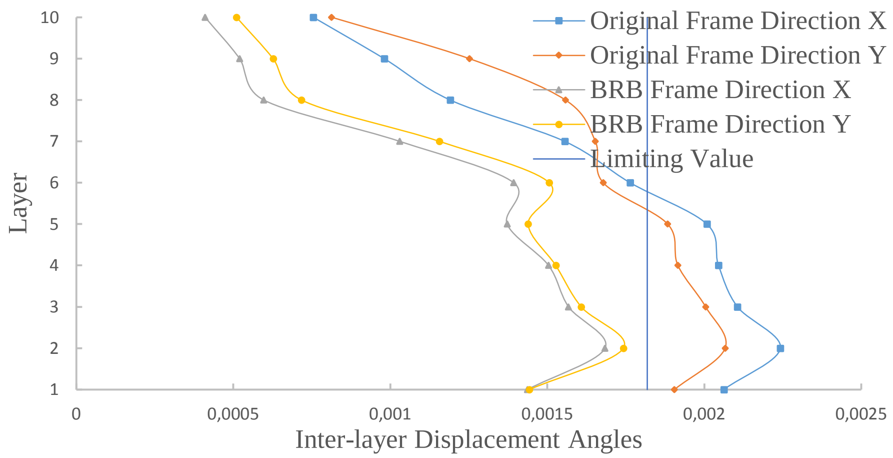
The differences of interlayer displacement angle was shown in Figure8 between the original frame and BRB frame under the action of 8 degrees frequent earthquake through time-history analysis.



(a) under the action of El-Centro wave



(b) under the action of Taft wave



(c) under the action of artificial seismic wave

Figure 8. Inter-layer displacement angles under the action of 8 degrees frequent earthquake

Interlayer displacement angles is obviously non-conforming to the required 1/550 in “Technical specification for concrete structures of tall building” from 1st to 6th floor of the original frame under the action of 8 degrees frequent earthquakeAs for the BRB frame, horizontal displacement of the floors is greatly decreased compared to that of the original frame, and the rigidity changing among floors is more even. Thereinto, interlayer displacement angle decreases by 16% in Direction X under the action of El-Centro wave, interlayer displacement angle decreases by 28% in Direction Y, interlayer displacement angle decreases by 29% in Direction X under the action of Taft wave, interlayer displacement angle decreases by 31% in Direction Y, interlayer displacement angle decreases by 25% in Direction X under the action of artificial seismic wave, interlayer displacement angle decreases by 16% in Direction Y, which all meet the requirements of the specification.

5. STRUCTURAL SEISMIC PERFORMANCE ANALYSIS UNDER THE 8 DEGREES RARELY OCCURRED EARTHQUAKE

According to the requirements of “Code for seismic design of building”and “Techinical specification for concrete structures of tall building”, plasticity development of the frame should be analyzed through elasto-plastic time-history analysis under the action of 8 degrees rarely met earthquake. El-Centro wave,Taft wave, and artificial seismic wave should be input the same as in the case of 8 degrees frequent earthquake to simulate seismic action during the elasto-plastic time-history analysis under the action of 8 degrees rarely met earthquake,

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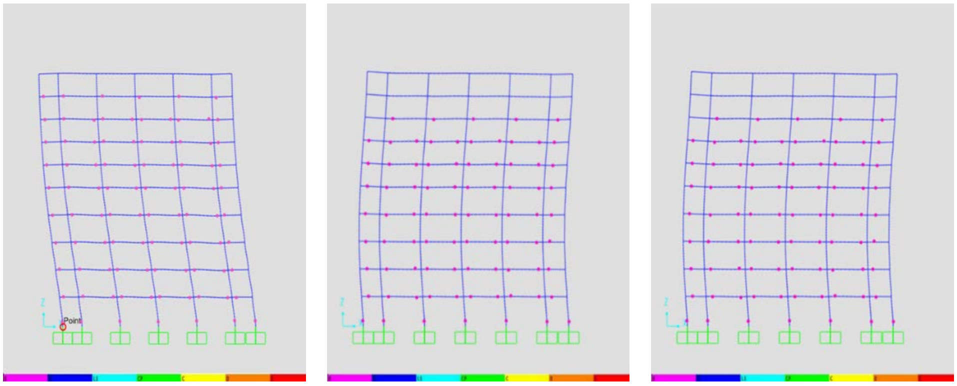
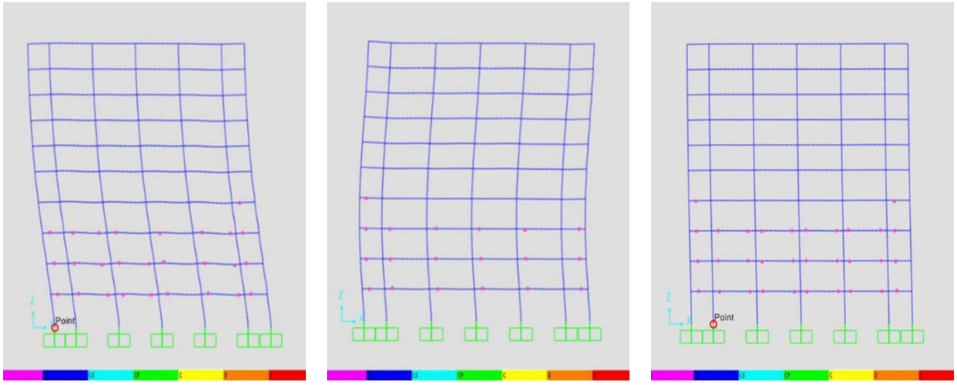
5.1. PLASTIC HINGES DISTRIBUTION

Plastic hinge development of the original frame and BRB frame is shown in Fig.9 and Fig.10 under the action of 8 degrees rarely met earthquake respectively.



(a) under the action of El-Centro wave *(b) under the action of Taft wave* *(c) under the action of artificial seismic wave*

Figure 9. Plastic hinges forming diagram of the original frame under the action of 8 degrees rarely occurred earthquake



(a) under the action of El-Centro wave *(b) under the action of Taft wave* *(c) under the action of artificial seismic wave*

Figure 10. Plastic hinges forming diagram of the BRB frame under the action of 8 degrees rarely occurred earthquake

Compared plastic hinge forming diagram of the original frame with that of the BRB frame, it could be found that: under the effect of three kinds of seismic wave, plastic hinge of BRB frame basically appeared on the beams, hardly on the columns, which verified that BRB frame conforms to seismic requirements of "strong column and weak beam". Moreover, the number of hinge of BRB frame was obviously smaller than that of the original frame, which indicated that BRB frame fully exerted the characteristics of good dissipation capacity under the action of 8 degrees rarely met earthquake.

5.2. TOP DISPLACEMENT COMPARISON

The top displacement could more visually describe the damping and anti-torsional effect of the original frame after adding BRB.The top displacement values of the original frame and BRB frame is shown in Table 5 under three kinds of seismic wave.

From Table 5,the top maximum displacement value of the BRB frame is significantly smaller than that of the original frame under the action of 8 degrees rarely occurred earthquake, and the overall changing trend is obvious. Interlayer displacement angle of the original frame under the action of El-Centro wave, Taft wave, and artificial seismic wave exceeded the required 1/50, while interlayer displacement angle of BRB frame under the action of three kind of seismic wave could not only be controlled within 1/50, but also be controlled within the suggested 1/80 in literature [10], indicating that compared to the original frame, seismic performance of BRB frame could be greatly improved during the phase of rarely met earthquake.

Table 5. Top maximum displacement under the action of 8 degrees rarely occurred earthquake

Seismic Wave	Top Maximum Displacement in Direction X		Inter-layer Displacement Angles of Original Frame	Inter-layer Displacement Angles of BRB Frame	Top Maximum Displacement in Direction Y		Inter-layer Displacement Angles of Original Frame	Inter-layer Displacement Angles of BRB Frame
	Original Frame	BRB Frame			Original Frame	BRB Frame		
El-Centro Wave	66.51	11.02	1/45	1/272	46.21	13.11	1/65	1/229
Taft Wave	69.76	17.65	1/43	1/170	52.34	20.87	1/57	1/143
Artificial Seismic Wave	26.92	9.68	1/111	1/310	17.56	8.67	1/171	1/346

6. CONCLUSIONS

(1) As for irregular plane frame, BRB could be the dissipative members to reduce structural seismic response, and enhance structural rigidity, while further reduce structural torsional effect through rational plane layout, to protect the main structure well.

(2) As for irregular plane frame in high intensity area, BRB could be used for reinforcement of the original frame, on the basis of meeting requirements of aseismic design, which could provide a simple and effective approach for seismic reinforcement of similar structures without changing the original building outline.

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