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Seismic Analysis of the Structure with Viscous Damper Bracings of the Theme Hall of The World Expo 2010 Shanghai China

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Abstract

The Theme Hall of The World Expo 2010 Shanghai China consists of four exhibition halls, and is designed as a large spatial steel moment frame. For resisting the earthquake force, at first steel bracings with great horizontal stiffness are inserted into the structure. Then the temperature stress of the structure would be very large. At last a viscous damper bracing is introduced in the Theme Hall, which can dissipate the earthquake energy and reduce the temperature-induced stress.

The viscous damper bracing consists of inverted V-shaped steel brace, two viscous dampers and two rubber isolators for each one. In the bracing, the viscous damper and rubber isolator are supported on inverted V-shaped steel brace in one end and connected with frame joint. The dampers can dissipate earthquake energy and the rubber isolators can keep the damper bracings vibrating in their direction, which also can dissipate a part of earthquake energy.

Through time history analysis it can be found that the seismic performances of the structure are greatly enhanced with the help of the damper bracing. And these advantages are verified by comparison of dynamic responses of three kinds of bracing systems: a) steel moment frame with steel bracings(ST1), b) partially damper bracings(ST2) in which some steel bracings are replaced by damper bracings, and c) totally damper bracings(ST3) in which all steel bracings are replaced by damper bracings. From the comparison, it is found that the inter-storey shear forces, the inter-storey drifts and the torsion effects of ST3 and ST2 are much less than those of ST1. And also the axial forces in columns (induced by temperature differences) near the bracing system and the axial brace forces in ST2 and ST3 are much less than those in ST1. The ST2 system has been chosen in the last and the construction was completed in the end of 2008.

Keywords: Theme Hall, viscous damper, steel moment frame, seismic performance, temperature stress

1. Introduction

The Theme Hall of The World Expo 2010 Shanghai China consists of four exhibition halls, and is designed as a spatial steel moment frame. The structure is large and asymmetrical, in which the length along X-direction is 288m, and the width along Y-direction is 188m and the height is 23.3m, the largest span is 180m in X-dir and 126m in Y-dir(see Fig.1). The structure between the axis 1/1 and 9 is 1-story. Those are 2-story structures from axis 10 to axis 14, axis 15 to axis 25. And the rest are 4-story structures. Fig.1 shows the plan view of the stucture.

The period ratios T_3/T_1 and T_3/T_2 (T_i is the i th period of the structure, i =1,2,3. T_3 is the torsional period) would be greater than 0.85 for the pure moment frame and can not meet the code requirement. It is necessary to add some bracing systems in it. However, the expansion joint is not suggested in this large spatial structure due to the seepage. Then, if the steel braces with great horizontal stiffness are installed, the temperature stress in the some elements would be very large. So a viscous damper bracing[1] is introduced which has small resistance to the temperature change but has the effective energy dissipation ability under earthquake.

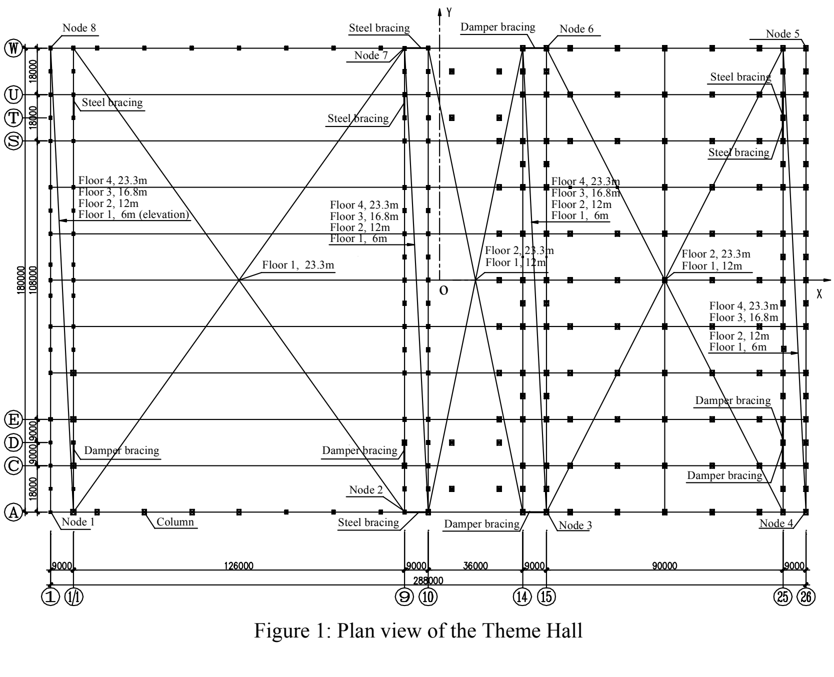

Figure 1: Plan view of the Theme Hall

2. Layout of the bracing system

2.1. Layout along Y direction of structure

Take the ST2 for example, Fig.1~ Fig.4 show the layout of damper bracings in axis 1/1, 9 and 25. In these figures, BR represents the steel bracing, DBR represents the viscous damper bracing. For the ST1, the layout of bracing system are similar to that of ST2, only the viscous damper bracings in ST2 are replaced with steel bracings. For the ST3, the layout of bracing system are similar to that of ST2, only the steel bracings in ST2 are replaced with viscous damper bracings. The maximal damping force of every damper is 1000 kN, except DBR installed in the ground floor of axis 25 (see Fig.4), the damping force of which is 1500kN.

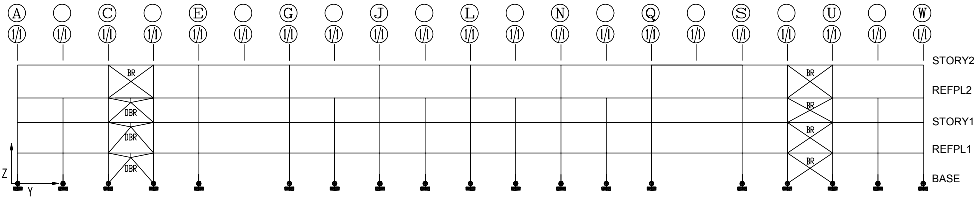

Figure 2: Layout of bracing system in axis 1/1 (Y dir., ST2)

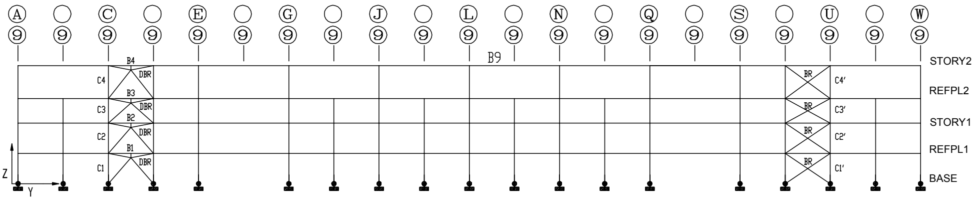

Figure 3: Layout of bracing system in axis 9 (Y dir., ST2)

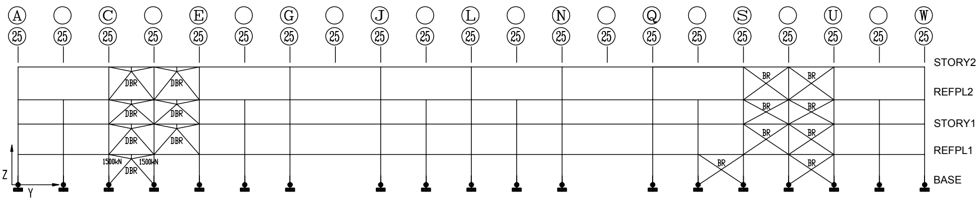

Figure 4: Layout of bracing system in axis 25 (Y dir., ST2)

2.2. Layout along X direction of structure

The BR and DBR in Fig.5 and Fig.6 have the same meaning of those in layout Y direction frame. The maximal damping force of every damper is also1000 kN.

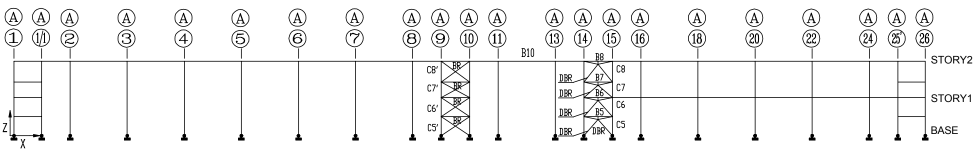

Figure 5: Layout of bracing system in axis A (X dir., ST2)

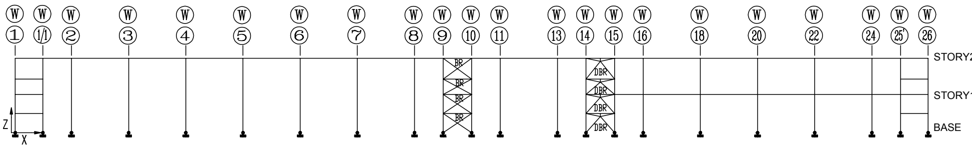

Figure 6: Layout of bracing system in axis W (X dir., ST2)

2.3. Description of the viscous damper bracing system

The viscous damper bracing system consists of inverted V-shaped steel brace, two viscous dampers and two lead rubber bearings (see Fig.7 , Fig.8). In the system, the viscous damper and rubber isolator are supported on inverted V-shaped steel brace in one end and connected with frame joint. The dampers can dissipate earthquake energy and the lead rubber bearings can keep the damper bracings vibrating in their elevations, which also can absorb a part of earthquake energy.

The static stiffness of viscous damper is small. The yield force and the yield displacement of the lead rubber bearing are also small. So the viscous damper bracing system would not add the static stiffness to the structure almost, and produce small reaction to temperature change.

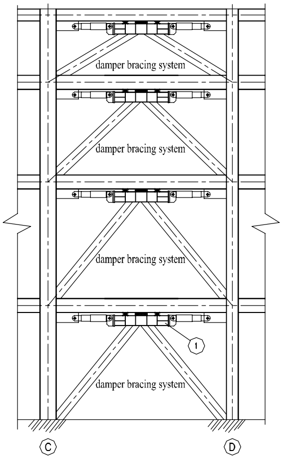

Figure 7: View of damper bracing system

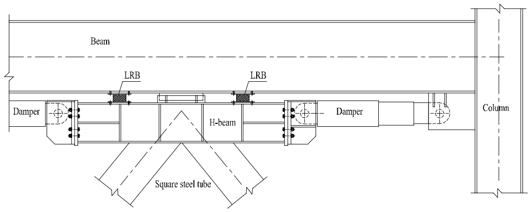

Figure 8: View of the node 1 in Fig.7

2.4. Parameters of viscous damper bracing

2.4.1. Parameters of damper

The viscous damper force is presented as:

$$F_d = C_d \,\mathrm{sgn}(V_d)\left|V_d\right|^{\alpha} \tag{1}$$

Where, C_d is the damper coefficient, V_d is the relative velocity of the damper, k_d is the initial stiffness of the damper, α is the damping exponent.

$C_d = 400kN/(mm/s)^{\alpha}$, $k_d = 280kN/mm$, $\alpha = 0.2$ (1000kN damper)

$C_d = 600\,kN/(mm/s)^{\alpha}$, $k_d = 420kN/mm$, $\alpha = 0.2$ (1500kN damper).

2.4.2. Stiffness of the inverted V-shaped steel braces

K_b is the horizontal stiffness of the inverted V-shaped steel brace in the damper bracing system. $K_b = 600kN/mm$ (floor height is 6.5m), $K_b = 700kN/mm$ (floor height is 6m), $K_b = 1000kN/mm$ (floor height is 4.8m).

2.4.3. Lead rubber bearing (LRB)

Two LRBs are installed in the damper bracing system(see Fig.8), which has the initial stiffness $K_u = 177\,kN/mm$, the post-yield stiffness $K_{ud} = 0.6kN/mm$, the yield shear force $Q_y = 80kN$, and the yield displacement $u_y = 0.45mm$.

3. Dynamic response analysis

3. 1 Natural period of structures

Table 1 shows the natural periods and the natural period ratios. The initial stiffness is taken as equivalent stiffness of the viscous damper bracings in the calculation of the natural periods, k_d for the viscous damper, K_b for V-shaped steel brace and K_u for Lead rubber bearing.

Table 1 Natural periods of structures

Period	T 1	T 2	T 3	T3/T1	T3/T2
ST1	1.29	1.07	0.90	0.70	0.84
ST2	1.30	1.09	0.92	0.71	0.84
ST3	1.31	1.10	0.95	0.73	0.86

3.2 Inter-story drifts and inter-story shear forces

Three artificial ground motions(SHW1, SHW2 and SHW4) are chosen as the input[3]. The design ideology of three levels is adopted in Chinese seismic design code. Frequently occurred earthquake, basic earthquake, and seldomly occurred earthquake represent the three levels of input motions. And the corrseponding PGA (peak ground acceleration) is 35cm/s^2, 100cm/s^2 and 200cm/s^2 , respectively. Table 2 and Fig.9 show the average inter-story drift angles of structures under these input motions. The average means the average value of the inter-story drift angles under ground motion of SHW1, SHW2 and SHW4. Under seldomly occurred earthquake, it is assumed that only one diagonal element in steel brace playing a part in resistanting earthquake.

According to Reference [2], the elastoplastic responses under seldomly occurred earthquake can be estimated through the results of linear responses by multipling an amplification coefficient. From Table 1, it could be found that if the inter-drift angles by multiplying the coefficient 1.15, the maxium drift is smaller than 1/80, which is the code requirement.

From Table 2 and Fig. 9, it could be found that the inter-stroy drift angles of structures (ST2,ST3) with viscous damper bracing are smaller than those of structure (ST1) without damper bracings. So the viscous damper bracing system is a more effective system in the control of inter-story drifts, comparing to the steel bracing system.

Table 2 Average Interstory drift under time history analysis

Case	NO. of story	Y Direction					X Direction				
		ST1 θ_1	ST2 θ_2	ST3 θ_3	$\frac{\theta_2-\theta_1}{\theta_1}$	$\frac{\theta_3-\theta_1}{\theta_1}$	ST1 θ_1	ST2 θ_2	ST3 θ_3	$\frac{\theta_2-\theta_1}{\theta_1}$	$\frac{\theta_3-\theta_1}{\theta_1}$
Fre.	1	1/643	1/703	1/840	-8.5%	-23.5%	1/412	1/467	1/629	-11.8%	-34.5%
	2	1/398	1/450	1/765	-11.6%	-48.0%	1/558	1/637	1/884	-12.4%	-36.9%
Bas.	1	1/225	1/260	1/288	-13.5%	-21.9%	1/144	1/162	1/218	-11.1%	-33.9%
	2	1/139	1/159	1/208	-12.6%	-33.2	1/195	1/203	1/239	-3.9%	-18.4%
Sel.	1	1/134	1/142	1/152	-5.6%	-11.8%	1/98	1/105	1/123	-6.7%	-20.3%
	2	1/94	1/101	1/132	-6.9%	-28.8%	1/116	1/125	1/136	-7.2%	-14.7%

Notation: Fre. represents frequently occurred earthquake, Bas. represents basic earthquake and Sel. represents seldomly occurred earthquake.

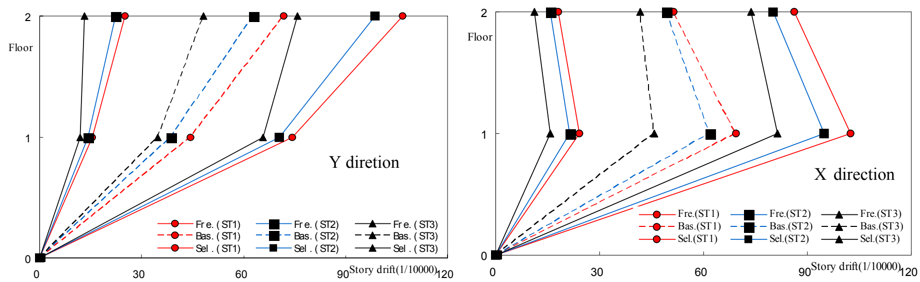

Figure 9: Comparison of average inter-story drift angles

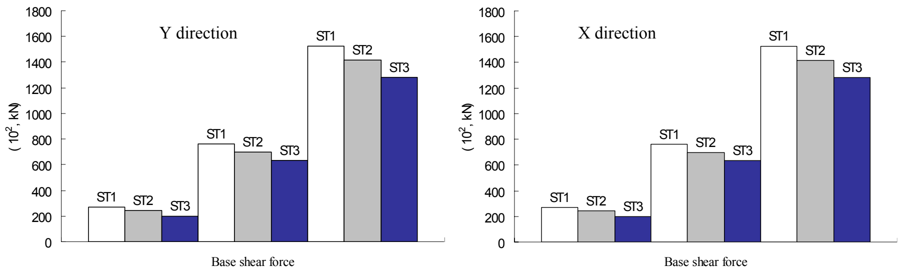

Figure 10: Average base shear forces

Table 3 and Fig.10 show the base shear forces under different input motions. The shear forces is the sum of the shear forces of the ground floor columns and the average is the average value of the base shear forces under ground motion of SHW1, SHW2 and SHW4. From Table 3 and Fig.10, it could be found that the inter-stroy shear forces of structures (ST2,ST3) with viscous damper bracings are smaller than those of structure (ST1) without damper bracing. That is to say, the damper bracing system is a more effective system in the control of inter-story shear forces, comparing to the steel bracing system.

Table 3 Average base shear forces (kN)

Case	Y Direction					X Direction				
	ST1 Q_1	ST2 Q_2	ST3 Q_3	$\frac{Q_2-Q_1}{Q_1}$	$\frac{Q_3-Q_1}{Q_1}$	ST1 Q_1	ST2 Q_2	ST3 Q_3	$\frac{Q_2-Q_1}{Q_1}$	$\frac{Q_3-Q_1}{Q_1}$
Fre.	26700	24620	19810	-7.8	-25.8	28030	23090	22000	-17.6	-21.5
Bas.	76270	69650	63130	-8.7	-17.2	80080	79210	69860	-1.1	-12.8
Sel.	152450	141480	127900	-7.2	-16.1	174510	163350	145280	-6.4	-16.7

3.3 The additional damping ratio

For the velocity-dependent damper, if the phase differences between the maximum inter-story displacements and the maximum damper forces are neglected, the additional damping ratio can be calculated as follow:

$$\zeta_d = \frac{[(W_d)_{\max} + (W_{LRB})_{\max}]}{4\pi (W_s)_{\max}} \tag{2}$$

Where, $(W_d)_{\max}$ is the energy dissipated by the dampers in a single cycle of motion at the maximum displacement. It is given by:

$$(W_d)_{\max} = 4\sum_i (W_d^i)_{\max} \tag{3}$$

In which, $(W_d^i)_{\max}$ is the energy dissipated by the i th damper during its 1/4 period. $(W_{LRB})_{\max}$ is the energy dissipated by LRB. It is calculated as:

$$(W_{LRB})_{\max} = 4\sum_i (W_{LRB}^i)_{\max} \tag{4}$$

Where, $(W_{LRB}^i)_{\max}$ is the energy dissipated by the i th LRB during its 1/4 period. $(W_s)_{\max}$ is the maximum strain energy of the structure. It can be represented by:

$$(W_s)_{\max} = \frac{1}{2}\sum_j [(Q_j)_{\max} \times (\Delta_j)_{\max}] \tag{5}$$

In which, $(Q_j)_{\max}$ is the maximum shear force of the j th floor, $(\Delta_j)_{\max}$ is the maximum interstory drift of the j th floor.

According to Eqn.(2)~Eqn.(5), the additional damping ratios can be calculated. Table 4 shows the calculated additional damping ratios and the average is the average value of the calculated additional damping ratios under inputs SHW1, SHW2 and SHW4.

Table 4 Average additional damping ratios(%)

Case	Y Direction		X Direction	
	ST2	ST3	ST2	ST3
Fre.	5.5	16.7	3.2	9.6
Bas.	3.6	9.2	1.9	5.2
Sel.	3.5	8.4	1.5	3.9

4. Comparisons of temperature effects

When the thermal deformations are contrained, the temperature stress would be very large. The temperature differences include the temperature difference in seasonal temperatures (TD1), the temperature difference between indoor and outdoor of the structure (TD2) , the temperature difference between days and nights temperature (TD3) and so on. For the structures, the main temperature difference should be considered is TD1[4] . In this paper, two temperature differences (TD1 and TD2) have been considered and the value of temperature difference is ±30℃.

The axial forces (induced by temperature differences) of some columns near the bracing system are chosen during the analysis of temperature effects. In the axis 9 (Y direction), columns C1~C4 and C1'~C4', beams B1~B4 and B9 are chosen (See Fig.3). In the axis A (X direction), columns C5~C8 and C5'~C8', beams B5~B8 and B10 are chosen (See Fig.5). In the analysis, the temperature differences of TD1 and TD2 is assumed +30℃, i.e. the outdoor temperature value of the structure is 30℃ higher than that of the indoor temperature. The positive values in the tables means the tensile force, and the negative values in the tables means the pressure force.

Table 5 Comparison of axial forces induced by temperature differences or load combined with dead loads and live loads (ST1, in axis 9, kN)

Loads	Axial forces of columns							
	C1	C2	C3	C4	C1'	C2'	C3'	C4'
1.2dead+1.4live(1)	-6276	-6059	-5875	-4577	-6138	-6002	-5813	-4545
TD1 (2)	-3077	-1413	-499	-120	-3033	-1389	-486	-115
TD2 (3)	-2788	-2132	-1740	-1080	-2759	-2120	-1734	-1076
(2)/ (1) (%)	49	23	9	3	49	23	8	3
(3)/(1) (%)	45	35	30	24	45	35	30	24

Table 6 Comparison of axial forces induced by temperature differences or load combined with dead loads and live loads (ST1, in axis A, kN)

Loads	Axial forces of columns							
	C5	C6	C7	C8	C5'	C6'	C7'	C8'
1.2dead+1.4live(1)	-3799	-2591	-1241	-544	-896	-1055	-781	-202
TD1 (2)	-297	-502	-399	-91	-1246	-411	+140	+172
TD2 (3)	-217	-607	-568	-150	-835	-655	-267	+61
(2)/ (1) (%)	8	19	32	17	139	39	20	85
(3)/(1) (%)	6	23	46	28	93	62	34	30

For the ST1, Table 5 and Table 6 show the comparisons of axial forces induced by temperature differences or by the loads combined with dead load and live load. From the comparisons, it could be found that the axial forces induced by temperature differences are very large and they can not be neglected. For the columns C1 and C1', the ratio of the axial forces induced by temperature difference over that by combination loads is about 49%. The reason is that the horizontal stiffnesses of steel bracings are too large and the thermal deformation of the beams between the frames with steel bracing would be constrained. The force to contrain the thermal deformation is very large, therefore, the counterforce transferring to the columns is also very large. So the viscous damper bracing system with small static stiffness is introduced in the structure, then the reaction to temperature change would be small.

Table 7 Comparison of axial forces induced by TD1 (ST1, in axis 9, kN)

	Axial forces of columns								Axial forces of beams				
	C1	C2	C3	C4	C1'	C2'	C3'	C4'	B1	B2	B3	B4	B9
ST1	-3077	-1413	-499	-120	-3033	-1389	-486	-115	-724	-418	-337	-39	-154
ST2	-386	-153	-63	36	-2188	-900	-256	-46	-946	-405	-363	-73	-84
ST3	-313	-120	-47	35	-301	-112	-42	35	-948	-460	-387	-63	-59
(ST2-ST1)/ST1(%)	-87	-89	-87	-70	-28	-35	-47	-60	+31	-3	+8	+87	-45
(ST3-ST1)/ST1(%)	-90	-91	-91	-71	-90	-92	-91	-70	+31	+10	+15	+62	-62

Table 8 Comparison of axial forces induced by TD1 (ST1, in axis A, kN)

	Axial forces of columns								Axial forces of beams				
	C5	C6	C7	C8	C5'	C6'	C7'	C8'	B5	B6	B7	B8	B10
ST1	-297	-502	-399	-91	-1246	-411	+140	+172	236	-363	-4	-368	-610
ST2	-244	-187	-137	-15	-1226	-419	+123	+163	-111	-508	-103	-492	-529
ST3	-193	-158	-117	-13	-282	-22	+48	+24	-113	-444	-93	-401	-434
(ST2-ST1)/ST1(%)	-18	-63	-66	-84	-2	-2	-12	-5	-53	+40	+25	+34	-13
(ST3-ST1)/ST1(%)	-35	-69	-71	-86	-77	-95	-66	-86	-52	+22	+22	+9	-29

Table 9 Comparison of axial forces induced by TD2 (ST1, in axis 9, kN)

	Axial forces of columns								Axial forces of beams				
	C1	C2	C3	C4	C1'	C2'	C3'	C4'	B1	B2	B3	B4	B9
ST1	-2788	-2132	-1740	-1080	-2759	-2120	-1734	-1076	290	313	291	-820	-483
ST2	-456	-366	-291	-2	-2040	-1543	-1312	-912	404	624	819	-267	-327
ST3	-368	-293	-232	4	-359	-287	-227	+6	399	591	790	-226	-222
(ST2-ST1)/ST1(%)	-84	-83	-83	-100	-26	-27	-24	-15	+39	+99	+200	-67	-32
(ST3-ST1)/ST1(%)	-87	-86	-87	-100	-87	-86	-87	-99	+38	+89	+200	-72	-54

Table 10 Comparison of axial forces induced by TD2 (ST1, in axis A, kN)

	Axial forces of columns								Axial forces of beams				
	C5	C6	C7	C8	C5'	C6'	C7'	C8'	B5	B6	B7	B8	B10
ST1	-217	-607	-568	-150	-835	-655	-267	+61	278	-794	59	-610	-959
ST2	-271	-285	-215	-31	-861	-609	-210	+73	-138	-886	-100	-736	-774
ST3	-228	-250	-188	-27	-281	-167	-74	+24	-139	-865	-91	-627	-660
(ST2-ST1)/ST1(%)	+25	-53	-62	-79	+3	-7	-21	+20	-50	+12	+69	+21	-19
(ST3-ST1)/ST1(%)	+5	-59	-67	-82	-66	-75	-72	-61	-50	+9	+54	+2.8	-31

Table 7, Table 8 and Fig.11 show the axial forces of elements near the bracing system under temperature load TD1. Table 9, Table 10 and Fig.12 show the axial forces of elements near the bracing system under TD2. From the comparison of temperature effects of structure (ST1~ST3), it could be found that damper bracings are more wonderful in the control of temperature effects comparing to the steel bracings. Besides, the axial forces (induced by temperature differences) of bracings in the damper bracings system are much smaller than those of steel bracings.

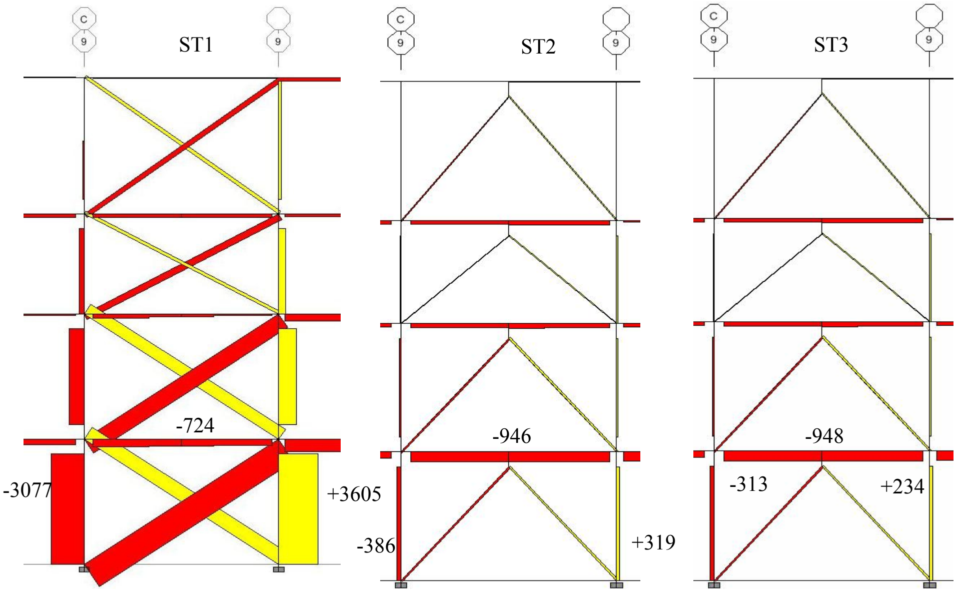

Fig.11 Comparison of axial forces induced by TD1 (in axis 9)

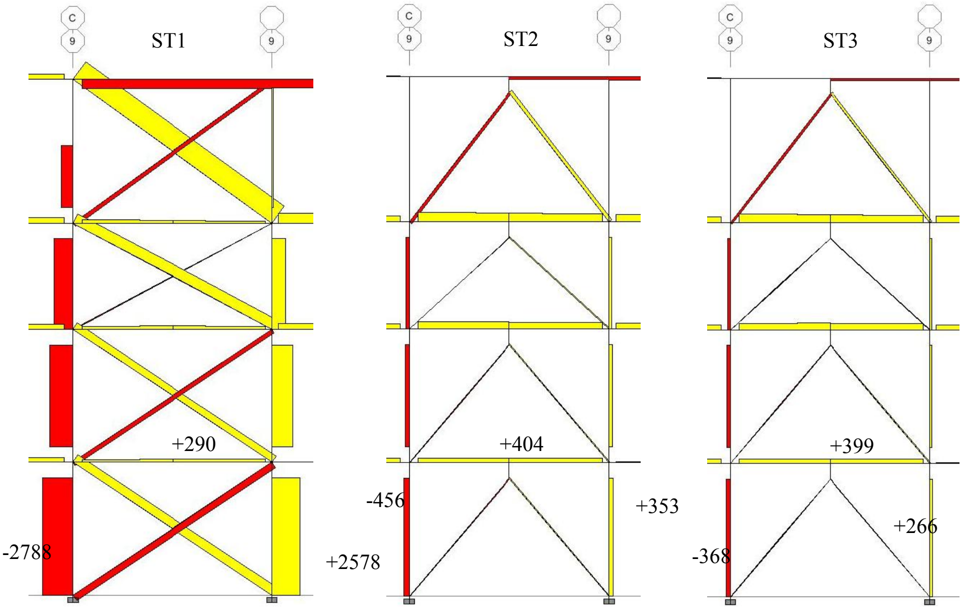

Fig.12 Comparison of axial forces induced by TD2 (in axis 9)

5. Conclusion

(1) From the analysis of temperature effects induced by temperature change, it could be found that the temperature stresses of the structure with damper bracings (ST2,ST3) are much smaller than those of the structure with steel bracings (ST1).

(2) From the analysis of dynamic responses, it could be found that the seismic performance of the structures with viscous damper bracings (ST2,ST3) are more excellent than that of the structure with steel bracings(ST1).

Acknowledgement

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