SEISMIC PROTECTION SYSTEM AND ITS ECONOMIC ANALYSIS ON THE BEIJING HIGH-RISE BUILDING PANGU PLAZA

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ABSTRACT :

Pangu Plaza, located at Beijing close to 2008 Olympic main stadium, 191 meter, 39-story steel high-rise building，was analyzed under earthquake and wind loads by us, with both Fluid Viscous Dampers (FVD) and Buckling restrained braces (BRB or UBB), as the seismic protection system. A repeated iteration procedure of design and analysis was finished for the optimization. The complete seismic response on the horizontal and vertical directions was shown the Fluid Viscous Dampers are highly effective to reduce the structural response, as well as the secondary system response.
A comparative analysis of structural seismic performance and economic effect was considered, by the traditionally increasing steel columns and beams size; increasing seismic braces versus using FVD to absorb the seismic energy. Both structural response and economic analysis results show that using FVD to absorb the seismic energy not only can make the structure satisfied the Chinese seismic design code for the “rare” earthquake，but it greatly improves the resistant capacity of seismic performance and also is the most economic way for both one-time direct investment and a long term maintenance for reducing seismic vibration..

KEYWORDS: Fluid Visco-Elastic dampers(FVED), Cross Brace configuration, Damping Ratio, Secondary System, One-time investment, Maintenance Factor

1. INTRODUCTION

More than ten high-rise buildings were installed Taylor Devices FVD for seismic protection. The Silvertie Hotel is one of the dominant high-rise structures located in the Central Business District of Beijing. The 62-story steel building (249.9 meters) is the first in China to adopt the energy dissipation technology.

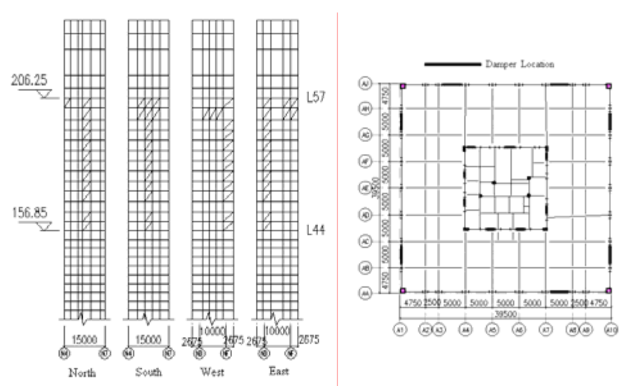


Fig.1 Damper Location in the Silvertie hotel

Using 73 nonlinear FVD in this building, not only the acceleration caused by wind successfully reduced to satisfy the Chinese code, but also the seismic performance greatly improved. After comparatively many analyses (Ductility design, Base Isolation, TMD), we recognized that directly use FVD to protect structure is the best way to perform seismic design for High-rise building. Finally, the result from the optimization analysis, we installed 108 Taylor’s dampers on this High-rise building, Beijing Pangu Plaza recently. A totally seismic analysis show the whole structure seismic response with this dampers, including the inter-story displacement, the top displacement and acceleration, the base shear force and moment, the torsion of the structure, the response of the secondary system, subjected the minor, moderate and rare earthquake by Chinese seismic code criteria, respectively, were obviously reduced,

We also did response and economic analysis. Four models:

1) Original design structure, based on Chinese code model analysis, finished by John Martin
2) Make the larger column sizes and add more Braces to satisfy the criteria of rare earthquake of Chinese design code
3) Make more steel braces to satisfy the criteria of rare earthquake of Chinese design code
4) Utilize 100FVD and 8FVED as a primary means of seismic energy dissipation

The structural response results of seismic time history analysis shown, all of the 2) 3) 4) cases can satisfy the seismic design code. However, the case 4) gave a better response and most economic solution, even in one-time investment.

The design follow up both US and China design codes.

2. Structure and Dynamic Specification of Pangu Plaza

Table 2.1 Structural Principal Period of Pangu Plaza

Mode	Period	UX	UY	RZ
1	5.993	74.281	0.003	0.010
2	5.191	0.005	70.123	3.889
3	4.323	0.005	3.681	73.719
4	1.847	13.283	0.001	0.006
5	1.659	0.003	12.639	0.966
6	1.466	0.002	1.373	9.559

Beijing Pangu Plaza is one of the huge Beijing Olympic area projects. The 5A steel office building is 191.5*m* high，39-story above ground, 5-story underground, total area $112800m^2$. The structure designed the diagonal braced core with outrigger truss at 16^{th} and 30^{th} floors connected inner core and out side moment frames.

The dynamic analysis by ETABS computer program result the first 6 model dynamic properties listed at table2.1.

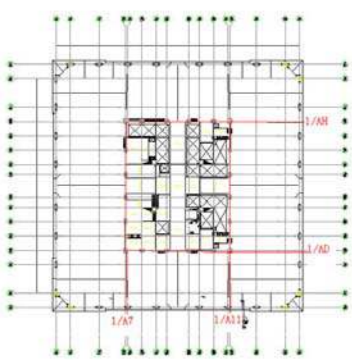


Fig.2 Structure Plans

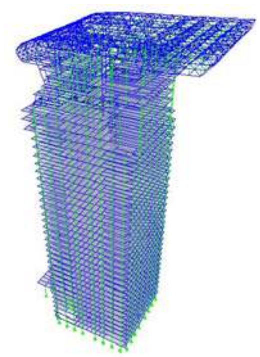


Fig.3 Structure Model

3. The Seismic Protection System Application

108 dampers and 36 buckling restrained braces (BRB) were used to protect structure from earthquake, 8 Chinese Intensity, III type soil. 104 chevron braces and diagonal braces were installed in 24^{th}～29^{th} and 31^{st}～39^{th} each story. We have to use some cross brace configuration(Fig.8) since the limited space and 8 of them are Fluid Visco-Elastic Dampers (Fig.4) were used the location, where even no space for the brace but structure need stiffness.

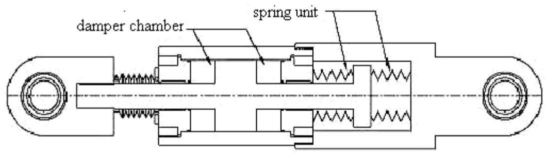
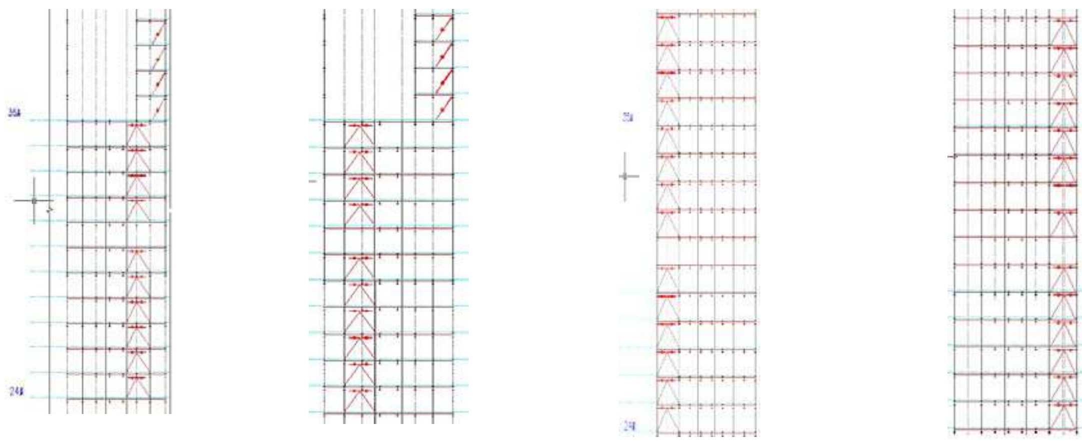


Fig.4 Viscous Elastic Dampers Sketch

$$F = K_{eff} \cdot u + C\dot{u}^{\alpha} \quad (3.1)$$

Where K_{eff}= equivalent stiffness of the Liquid flexible unit; C=damping coefficient; u= the displacement of the piston rod; $\dot{u}$ =the motion velocity of the piston rod; α= velocity exponent.

At the top cantilever truss, 4 units of 1500kN dampers were installed to reduce the vertical vibration caused by wind and seismic (Fig.6, 7).



Axis 1/AD Axis 1/AH Axis 1/A7 Axis 1/A11

Fig.5 Damper Location in the Pangu Plaza (elevation)

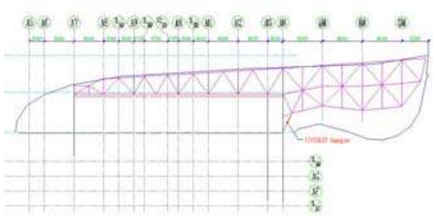


Fig.6 Four 1500kN Dampers Location

Fig.7 Installed 1500kN Damper

Fig.8 Cross Brace Damper

Table 3.1 General Information of Damper Parameter

	Type	Stiff. (*kN/m*)	Vel. Exp. α	C (*kN*(s/m)*$^{\alpha}$)	*F* (*kN*)	*D* (*mm*)	*Qua.*
1	FVED	700	0.3	3000	1000	±100	8
2	FVD	No	0.3	3000	1000	±100	96
3	FVD	No	0.5	4000	1500	±150	4

4. Time History Analysis and Seismic Response

Three natural and an artificial time history records are used to ETABS model to do the three dimensional analysis. All were according to the Beijing site requirement of seismic analysis. The peak acceleration of records 70cm/s^2, 200cm/s^2 and 400cm/s^2, for the minor, moderate and rare earthquake respectively. The duration of records use 30sec. Each record time factor 1.00，0.85, and 0.65 gives the X, Y, and Z directions combination by Chinese code criteria. All records are provided by the Earthquake Engineering Institute of China Academy of Building Research.

Table 4.1 Earthquake Record Information

Name	Direction	Type
AY1-D,Z,S-X,Y,Z	Horizontal and Vertical	Natural
AY2- D,Z,S-X,Y,Z	Horizontal and Vertical	Natural
AY3- D,Z,S-X,Y,Z	Horizontal and Vertical	Natural
SYS4- D,Z,S-X,Y,Z	Horizontal and Vertical	Artificial

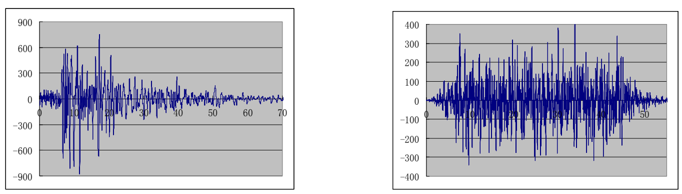


Fig.9 Natural Record AYL1-D-X and Artificial Record SYS4-D-X

From the energy calculation we obtained the additional damping ratio by the dampers listed in the Table 4.2.

Table 4.2 Structure Additional Damping ratio(by dampers)

	Direction X	Direction Y
Additional Damping ratio ξ_1(%)	2.21	2.36

The statistic results of all response shown the dampers are effective for reducing the structural response listed in the following table4.3.

5. Three models for the Economic Analysis And Seismic Responses

In order to obtain a comparative results for both seismic response and economic effective of the traditional ways, to enlarge the size of structural column/beam sizes and braces and to use seismic dampers

5.1. Enlarge the sizes of columns and brace (Plan 1)

Table 5.1 Part of Enlarge columns

Original Size of column	Enlarged Size of column	Length (m)	Number	Original weight of column（t）	Plan 1 weight of column（t）	add
900×60	900×65	4.6	244	1776.3	1912.8	7.7%
800×60	800×65	4.6	208	1333.9	1435.3	7.6%
500×30	500×35	4.6	61	124.2	143.4	15.4%
Other	neglect	neglect	neglect	neglect	neglect	neglect
Sum				9835.4	10768.2	

Table 5.2 Add more Braces

Size	Number	Original weight of brace（t）	Plan1 weight of brace（t）	add
W14×233	30	72.5	85.3	17.6%
W14×211	80	164.1	196.9	20.0%
W14×193	96	180.2	215.6	19.7%
W14×176	96	164.4	218.6	32.9%
W14×159	90	123.5	172.3	39.5%
UC305-305-198	80	103.4	151.8	46.8%
UC305-305-137	192	157.1	256.3	63.2%
Sum		965.2	1297.0	34.4%

5.2. Enlarge Original Brace size and number （Plan2）

Additional X type braces put at 1～40story. (Fig.11)

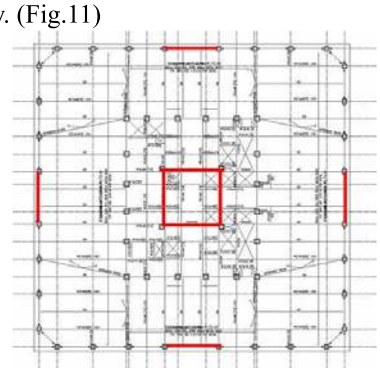


Fig.11 Layout of increased braces

Table 5.3 Add more Braces and enlarge some braces

Size	Number	Brace Original weight(t)	Plan 2 Brace weight (t)	Add some brace's weight (t)
W14×233	2	72.5	12.8	34.3
W14×211	5	164.1	32.8	79.1
W14×193	6	180.2	35.4	86.6
W14×176	6	164.4	54.2	87.8
W14×159	5	123.5	48.8	69.2
UC305-305-198	5	103.4	48.4	61.0
UC305-305-137	11	157.1	99.3	103.0
Sum	40	965.2	331.8	521.1

These two plans will compare to the original design (without damper, without enlarge) and the structure with dampers as above introduced. The new structures dynamic properties listed in the Table5.4.

Table 5.4 Original and New structures dynamic properties

Plan	**Original**	**Plan 1**	**Plan 2**	**Dampers plan**
The first mode	5.99	5.82	5.05	5.99
The second mode	5.19	4.99	4.39	5.19
The third mode	4.32	4.19	3.37	4.32
The forth mode	1.84	1.77	1.50	1.84
The fifth mode	1.65	1.57	1.36	1.65

6. The Economic Comparative Result

6.1. The effect of reducing seismic response

Both Plan1 and Plan 2 can make the original design structure satisfy the Code criteria of inter-story displacement. However, the structure with Fluid Viscous Dampers is better, shown in the following Fig.12.

6.2. One time investment Compare

We compare the three options which make structure satisfy the Chinese design code. The cost with 108 Taylor devices dampers included the all of shipping, costumes duty, Chinese Tax, braces and installation fee.

We calculate the steel columns and brace material, processing and installation cost by RMB 10,000 each ton roughly.

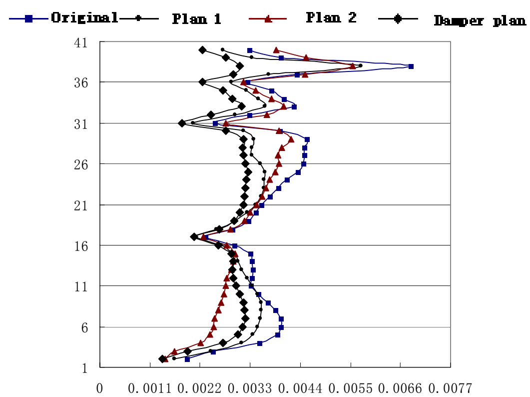


Fig.12 The Story Drift X When Moderate Earthquake

Obviously, using dampers is the most economic way even in one time investment which can save about RMB 2 million to 7 millions.

Table6.1 Economic Comparison with different plans

Item		Plan	Direct costs (￥ten thousand)
Traditional plan	Plan1	Enlarge the sizes of columns and brace	Column(932.8) Brace(331.8) Sum to 1264.6
	Plan2	Enlarge Original Brace size and number	Sum to 852.9
Damper plan		Through install viscous dampers in the structure to add the attached damping ratio for the structure, improve the capacity of resist seismic.	Sum to 580

6.3. Long period Economic Estimate

Concern a long period, the building may subjected to heavy wind and a rare earthquake. The building may not suffer serious damage but possibly some damage in the secondary system. The inter-story displacement may cause the damage of nonstructural members, glass and windows, curtain wall and so on; The large acceleration may cause the electronic devices and furniture damage.

We used the method introduced by dereference to calculate building's Maintenance Factor and lost rate when meet a rare earthquake to give us a quantitative answer.

Table6.2 Maintenance Factors and Loss ratios due to inter-story displacement

Item	Maintenance Factor				Loss ratio			
	Original	**Plan 1**	**Plan 2**	**Damper plan**	**Original**	**Plan 1**	**Plan 2**	**Damper plan**
Rigid Frame	0.09	0.08	0.06	0.05	0.04	0.04	0.03	0.02
Shear Wall	0.60	0.60	0.60	0.60	0.30	0.30	0.30	0.30
Main Wall	0.88	0.82	0.64	0.46	0.44	0.41	0.32	0.23
Secondary Beam	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01
Windows	1.44	1.41	1.32	1.23	0.96	0.94	0.88	0.82
Non-seismic Frame	1.08	0.99	0.73	0.46	0.86	0.79	0.58	0.37
Floor	0.16	0.14	0.11	0.07	0.10	0.10	0.07	0.05
Foundations	0.13	0.12	0.10	0.07	0.09	0.08	0.06	0.05
Building Equipment and Plumbing	0.17	0.16	0.13	0.10	0.13	0.13	0.10	0.08
Furniture	0.13	0.13	0.10	0.08	0.13	0.13	0.10	0.08
Sum	4.70	4.48	3.80	3.13	3.08	2.93	2.47	2.00
Mean	0.47	0.45	0.38	0.31	0.31	0.29	0.25	0.20

Table6.3 Maintenance Factors and Loss ratios due to acceleration

Item	Repair multiplier				Loss ratio			
	Original	**Plan 1**	**Plan 2**	**Damper plan**	**Origina l**	**Plan 1**	**Plan 2**	**Damper plan**
Floor	0.28	0.15	0.13	0.08	0.18	0.10	0.09	0.05
Ceilings and Lights	0.84	0.75	0.66	0.36	0.67	0.60	0.53	0.29
Building Equipment and Plumbing	0.60	0.56	0.50	0.29	0.48	0.45	0.40	0.23
Elevator	0.81	0.75	0.66	0.38	0.54	0.50	0.44	0.25
Foundations	0.28	0.15	0.13	0.08	0.18	0.10	0.09	0.05
Furniture	0.70	0.63	0.57	0.37	0.66	0.60	0.54	0.35
Sum	3.50	2.99	2.64	1.54	2.73	2.35	2.08	1.22
Mean	0.58	0.50	0.44	0.26	0.45	0.39	0.35	0.20

From the sum of both table we can found that by using Fluid Viscous Dampers can reduce the maintenance factor and lost rate by 40%.
From similar analysis we can found that with only moderate earthquake levels, the damper's plan also can reduce the building maintenance factor and lost rate by 25%.

7.Conclusion

From the analysis

1) Add Fluid Viscous Dampers to the bracing system can have an important effect to reduce the overall seismic responses, including the inter-story displacement, the top displacement and acceleration, the base shear force and moment, the torsion of the structure, and the response of the secondary system.
2) The located dampers can play important role in reducing the located response, i.e. four dampers can reduce the top acceleration on the top cantilever truss obviously.
3) The damper's system of Pangu Plaza not only have significant effect for reducing seismic response, but also can save one-time investment and longtime maintenance cost.

Table 4.3 Summary of damper's shock absorption effect

Item	Analysis case	Without damper	With damper	Effect	Remark
Story Drift Corner	Minor Earthquake Direction X	1/650~1/1100	1/850~1/1600	15%~40%	Max. allowable drift ratio 1/500 by code
	Minor Earthquake Direction Y	1/400~1/1100	1/650~1/1600	15%~40%	
	Moderate Earthquake Direction X	1/220~1/400	1/300~1/500	12%~30%	Generally less than 1/300 for Super-high steel structure
	Moderate Earthquake Direction Y	1/200~1/450	1/300~1/550	12%~30%	
	Rare Earthquake Direction X	1/80~1/200	1/120~1/240	8%~15%	Max. allowable drift ratio 1/70 by code
	Rare Earthquake Direction Y	1/60~1/180	1/80~1/230	9%~16%	
Vertex Displacement (*m*)	Minor Earthquake Direction X	0.146	0.122	16.4%	The important parameter to structural response
	Minor Earthquake Direction Y	0.117	0.099	15.5%	
	Moderate Earthquake Direction X	0.496	0.444	10.6%	
	Moderate Earthquake Direction Y	0.268	0.235	12.1%	
	Rare Earthquake Direction X	0.670	0.593	11.5%	
	Rare Earthquake Direction Y	0.705	0.636	9.8%	
Torsion Displacement Ratio	Moderate Earthquake	STORY40 STORY1~ 15 all larger than 1.2	All story Less than 1.2	20%	China Seismic Code Criteria: the ratio (the most flexible floor displacement/ the average of the two ends displacement) less than 1.2
Floor Acc. Spectrum Max (m/s^2)	35th story	6	3	50%	The important parameter to secondary system response
	40th story	10	6	40%	
Peak Vertical Acc./ Ground vertical Acc.	Rare Earthquake	4	2	50%	The important parameter to vertical response
Base Shear (*kN*)	Rare Earthquake Direction X	91527	76203.38	16.7%	The important parameters to evaluate the Resisting Seismic Capacity of the structure.
	Rare Earthquake Direction Y	151107	108130.5	28.4%	
Base Bending Moment (*kN*m*)	Rare Earthquake Direction X	3950811	3686721	6.7%	
	Rare Earthquake Direction Y	3885778	3611556	7.1%	
Base Torsion Moment (*kN*m*)	Rare Earthquake Direction X	3523130	2681187	23.9%	
	Rare Earthquake Direction Y	4898810	3650227	25.5%	

Note: Minor Earthquake means the peak acceleration is 70 cm/s^2
Moderate Earthquake means the peak acceleration is 200 cm/s^2
Rare Earthquake means the peak acceleration is 400 cm/s^2

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