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System Based Seismic Strengthening Design Analysis for A Historic Building

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Abstract In system based seismic strengthening design, the redistribution of inner forces brought by the change of structural members can be considered, which is very important to guarantee the safety of a strengthened structure. Using SAP2000, the seismic behavior of a historic building was analyzed. After that, a system based seismic strengthening plan and a member based seismic strengthening plan were proposed. And the seismic behaviors of the building before and after strengthening were compared. The results show that the seismic behavior of the building can be improved with the system based seismic strengthening and the style and the feature of the building can be protected well.

Keywords: Historic building, structural system, seismic strengthening

Introduction

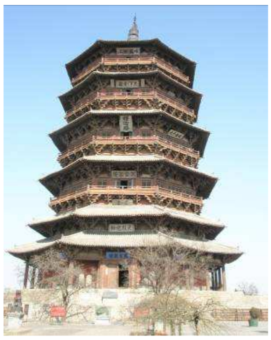
Because of the architectural styles, the structural systems, and the different functions, historic buildings are the important testimony of the history in a country (Fig.1). In China, lots of historic buildings, which are widely distributed all over the country, are protected by the government. But some of historic buildings are located in seismic zone, and they are weak to resist earthquake action. So, it is significant to strengthen these buildings properly for the purpose of protection.

(a) Guangzhou Sun Yat-sen Menorial Hall

(b) Shanghai Post Office Building

(c) Sichuan West China Dam Building

(d) Qingdao Christianity Church

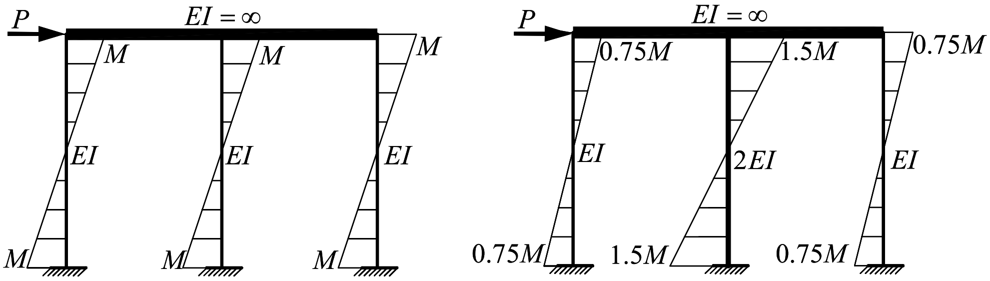


(e) Shanxi Ying County Wooden Pagoda

(f) Xizang the Potala Palace

Figure 1: Different historic buildings in China

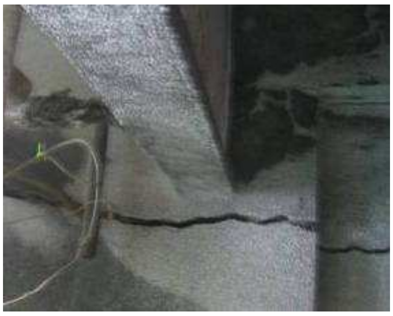
The strengthening way, in which the weak structural members are strengthened separately according to the primary global structural analysis results and the redistribution of internal forces caused by the change of the stiffness of the strengthened structural member is usually not considered, is called the member based strengthening. Fig. 2 shows the redistribution of inner forces caused by the stiffness change of the middle column after strengthening in a single-storey two-span frame structure under horizontal load. The middle column in this frame might still not be safe because of the increase of the inner force caused by the strengthening of the column. Accordingly, the strengthening way, in which the redistribution of inner forces caused by the strengthening is thoroughly considered and the bearing capacities of un-strengthened structural members are checked according to the analysis results of the redistribution of inner forces, is called the system based strengthening. Besides, the change of structural system is also called the system based strengthening.



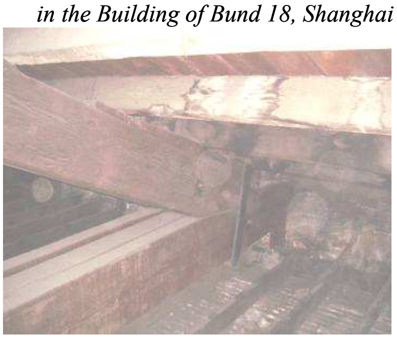
Befroe strengthening *After strengthening*

Figure 2: Redistribution of inner forces inside a single-story frame structure caused by the strengthening of the middle column

Earthquake brings catastrophic consequences to different kinds of buildings. The research results of historic buildings in different regions show that the earthquake fortification and details of seismic design were not considered when historic buildings were designed and built. In their long service life, longer than the design reference period of structures, the mechanical behaviors of the structures might deteriorate (Fig. 3). Once earthquake happens, both the economic and the cultural loss caused by the damage of the historic buildings will be larger than that caused by the damage of ordinary existing buildings.


(a) Corrosion of steel in the Building of Bund 18, Shanghai *(b) Cracking of structural member in a building in Guangzhou Shamian* *(c) Out of joint in Sichuan Linyun Temple*



(d) Desiccation fissure of wood member in Shanghai official mansion *(e)Decayed of wood member in Sichuan Zhaojue Temple* *(f) Efflorescence of brick walls in Guangzhou Shoin*

Figure 3: Different diseases of historic buildings in China

In this study, the seismic behavior of a historic building was analyzed. After that, a system based seismic strengthening plan and a member based seismic strengthening plan were proposed, and the effectiveness of the system based seismic strengthening for historic building structures was verified through the comparison analysis.

Overview of the Building

Bund 18 (Fig. 4), built in 1923, designed for bank office building initially, is one of the excellent historic buildings at the Bund of Shanghai. The building, with area of 10,450m^2 and high of 28.52m, contains one floor of basement and five floors up the ground. Currently the building was proposed to transform into a commercial building. Belonging to the second-class protective category classified by the Shanghai municipal government, the protect details and demands of modification works include the followings (Meng et al. 2007): first, the original appearance, structural system, plane layout (Fig. 5) and special interior decoration can not be changed. Second, decoration and characteristic of the ceiling of the enter hall, grand hall and the lobby need to be protected. Finally, spatial pattern of stair well and special decorations should be protected. Obviously, protection is the first principle in the strengthening of this historic building. It means that new building function should be satisfied without too much direct strengthening.

Figure 4: Picture of the Bund 18 building

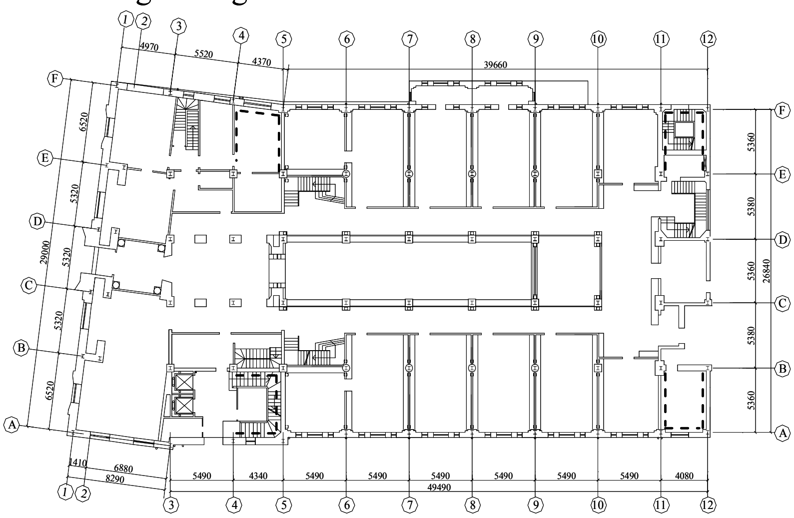


Figure 5: Plan layout of standard floor

Computation Model

The building was constructed with100mm thickness cast-in-situ RC slabs, steel beams and columns. I-steel beams and columns were encased with concrete and bricks respectively. The contribution of the surrounded concrete is not taken into account during the calculation. The stiffness contribution but not the bearing capacity contribution of the surrounded bricks for steel columns is considered. It is assumed that steel columns would not buckle and the corrosion effect would be neglected due to the good protection of surrounded bricks. Steel beams are connected with steel columns only by steel angles, so the beam-column joints can be taken as hinged ones and the structure can be considered as a hinged frame for the analysis (Zhang et al. 2006). From the test report (Tongji 2003), the ultimate strength of the steel is 287MPa, the yield strength is approximately 201MPa.

Hinged spatial frame model for the building (Fig. 6) was established by using SAP2000, with which the seismic behavior of the structure can be analyzed.

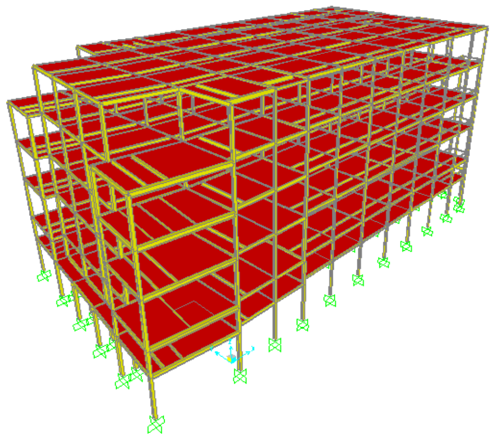


Figure 6: Hinged spatial frame model for the building of Bund 18

Seismic Behavior of the Structure before Strengthening

Under the guideline of the Chinese code, the seismic behavior of the building was calculated. The inner forces of the steel columns at the base floor are shown in Table 1. From the table, it can be seen that the stresses inside the columns are smaller than the strength of the steel (215MPa), the requirements of the bearing capacity can be guaranteed.

Table 1: Inner forces and normal stresses of the steel columns at base floor under earthquake

Floor	*Axis A(F)*			*Axis B(E)*			*Axis C(D)*		
	M(kN.m)	*N*(kN)	σ(MPa)	*M*(kN.m)	*N*(kN)	σ(MPa)	*M*(kN.m)	*N*(kN)	σ(MPa)
1	154	1145	128	168	2092	147	168	2045	145

The drifts of the building were also calculated as shown in Table 2. The value in the parenthesis is the calculated result not considering the contribution of the bricks. According to Chinese code for seismic design of buildings (GB50011-2001), the limit value of elastic angular drift between adjacent floors is 1/550. From the table, it can be concluded that whether the contribution of surrounded bricks was considered or not, the drifts are all bigger than the limit value. By comparison of the calculated results, it is feasible to reduce the drifts under earthquake by making full use of the surrounded bricks for the columns. If the infill masonry walls can work well under earthquake, the lateral rigidity of the structure can be further improved.

Table 2: Drifts of the building under earthquake before strengthening

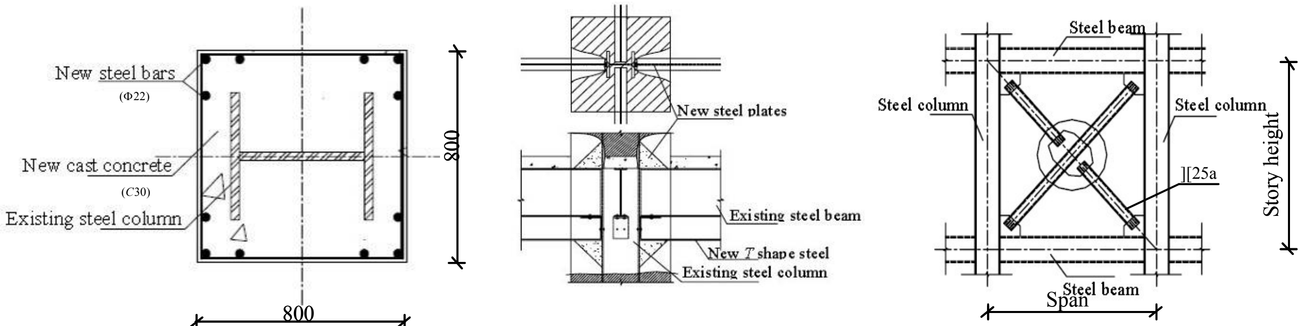
Floor	*Elastic drift of the floor(mm)*	*Elastic drift between floors(mm)*	*Elastic angular drift between floors*
5	215.04(248.84)	40.47(44.17)	1/128(1/117)
4	174.57(204.67)	44.81(52.10)	1/110(1/94)
3	129.76(152.58)	46.49(53.65)	1/105(91)
2	83.27(98.92)	48.01(57.10)	1/114(1/96)
1	35.26(41.82)	35.26(41.82)	1/228(1/192)

Seismic Behavior of the Structure after Strengthening

Based on the results above, member based seismic strengthening design and system based seismic strengthening design were designed respectively. Details are shown in Table 3. The typical strengthening design for the joints, struts, columns are shown in Fig. 7a, b, c.

Table 3: Details of seismic strengthening design

Contents	*Member based seismic strengthening design*	*System based seismic strengthening design*
Aims	Elastic angular drift between floors	Elastic angular drift between floors
Objects	Members（Columns）	Structural system
Details	Encasing structural members with RC (Fig. 7a)	Renovating hinged joints into rigid joints(Fig. 7b) Adding channel steel brace struts(Fig. 7c)



(a) Strengthening of the column *(b) Strengthening of the joint* *(c) Steel brace struts*

Figure 7: Details of strengthening design

The drifts of the building strengthened by the member based seismic strengthening method and the system based seismic strengthening method are shown in Table 4 respectively. To improve the bearing capacity of columns, method of encasing structural members with RC, which is regarded as a typical member based seismic strengthening way, was chosen. Types of the existing steel columns in building are different, but the column size after strengthening with RC is 800×800mm. System based seismic strengthening method includes strengthening joint, adding brace, strengthening joint plus adding brace. The bearing capacity of each column in every strengthening design is satisfied. From the table, it can be seen that the drifts are still bigger than the limit value after the strengthening using RC encasing method. The drift value of the building can be reduced significantly by using the system based strengthening method renovating hinged joints into rigid joints or adding steel braces every floor in the dotted lines of Fig. 4. The drift values are all smaller than the limit value if the building were strengthened both with strengthening joints and adding steel braces. Because the structural type should be protected and hinged joints are good to resist progressive collapse, strengthening method of adding braces should be chosen first.

Table 4: Drifts of the building under earthquake after strengthening

Floor	*Member based seismic strengthening*		*System based seismic strengthening*					
	Encasing structural members with R.C		*Strengthening joints*		*Adding steel brace*		*Strengthening joints + Adding steel brace*	
	Elastic drift between floors(mm)	*Elastic angular drift between floors*	*Elastic drift between floors(mm)*	*Elastic angular drift between floors*	*Elastic drift between floors(mm)*	*Elastic angular drift between floors*	*Elastic drift between floors(mm)*	*Elastic angular drift between floors*
5	36.518	1/142	9.080	1/571	8.996	1/576	6.356	1/816
4	36.313	1/135	12.307	1/399	9.142	1/538	6.979	1/704
3	33.147	1/147	14.237	1/342	9.054	1/538	7.155	1/682
2	29.621	1/185	18.900	1/290	9.552	1/574	8.104	1/677
1	18.645	1/431	20.027	1/401	9.146	1/879	8.486	1/947

Table 5 shows the natural frequencies of the building. From the comparison, it can be seen that the natural frequencies of the building increase after strengthening, which can be inferred that the rigidity of the structure are improved dramatically. It is also shown that the system based seismic strengthening is an effective way to increase the stiffness of the structure.

Based on the results above, comparison between the two kinds of strengthening methods is shown in Table 6. From the table, the effectiveness of system based seismic strengthening can be verified.

Table 5: Comparison of natural frequencies before and after strengthening

Results	Member based seismic strengthening			System based seismic strengthening								
	Encasing structural members with R.C			Strengthening joints			Adding steel brace			Strengthening joints s+ Adding steel brace		
	f_1	f_2	f_3	f_1	f_2	f_3	f_1	f_2	f_3	f_1	f_2	f_3
Before	0.1916	0.1963	0.2081	0.1916	0.1963	0.2081	0.1916	0.1963	0.2081	0.1916	0.1963	0.2081
After	0.2619	0.2903	0.3033	0.3518	0.3975	0.4584	0.4925	0.5659	0.8608	0.6028	0.6486	0.9528

Table 6: Comparison between member based seismic strengthening and system based seismic strengthening

Contents	*Object*	*Effect*	*Strengthening amount*	*Destructiveness*
Member based seismic strengthening	Member	Normal	Big	Serious
System based seismic strengthening	Structural system	Good	Small	Lighter

Conclusions

The system based seismic strengthening method is quite better than the member based seismic strengthening. Balance between protecting and strengthening should be taken into account by using comparison analysis method in the strengthening design for historic buildings.

Acknowledgements

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