

Structural inspection and analysis of former British Consulate in Shanghai

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ABSTRACT: The building of former British Consulate in Shanghai is a protective historical building. The 2-story building is a composite structure of masonry and timber. The aged building has been used for more than one hundred years. Several retrofits have been performed and the structure has been partially changed. To ensure the safety of the current building and protect the building efficiently, structural inspection and analysis were performed based on the inspection techniques and the theoretical method developed by the authors. It was indicated by the inspection and the analysis results that most of the load bearing members are safe, however, some indispensable structural measures demanded by the current code to ensure the seismic capacities are missed, and proper retrofit is needed to realize these measures on the structure without affecting the original profile of the building.

1 INTRODUCTION

The building of former British consulate in Shanghai is located at the head of the Bund where the mother rivers, Suzhou river and Huangpu river are crossed (Figure 1). It was designed by R. Williams Crossman and R. H. Boyce in 1872 and constructed in 1873. The 2-story building which has an “H” shaped architectural plane is a composite structure of masonry and timber (Figures 2–4). Because of its unique location where is the

initial beginning place for the development of modern Shanghai city, and its special architectural style which is different from Chinese traditional buildings, it is protected by the municipal government of Shanghai.

Being an aged building with special structural style, it raises many problems in the maintenance and protection. Effective sections of the horizontally load-bearing timbers or vertically load-bearing masonry walls have decreased under continuous corrosion, and the structural materials may also have degenerated

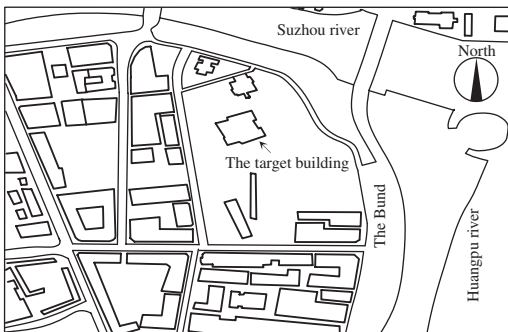


Figure 1. The head of the Bund along Huangpu river in Shanghai.

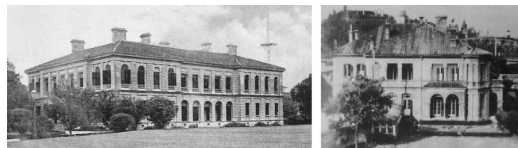


Figure 2. Building facade in 20s last century.



Figure 3. Building facade now.



Figure 4. Overlook of the building.



Figure 5. Inspection of the foundation.

after more than a hundred years of use. Besides, the composite structure of timber and masonry has weak joints between horizontal and vertical load-bearing members, and is vulnerable to external effects (Weng et al. 2000). The several partial changes of the structure may impair the entirety of the structure. Meanwhile, the density, the stiffness and strength of the steel and concrete used during the previous retrofits are far different from the original timber. The difference may result in further uneven settlements and the redistribution of inner forces in the structure. The problems may be more serious because many underground infrastructures and new tall buildings are now being constructed near the old building and properties of the ground soil in the Bund area are complicated and generally soft.

To ensure the safety and serviceability of the historical building, thoroughly inspection and assessment were performed, and the scientific retrofit proposal was made based on the inspection and analysis results.

2 INSPECTION

2.1 Survey of building drawings

All of the original design materials for the building have been lost. So, the architectural and structural drawings for the building were surveyed firstly. Most of the drawings were measured in-situ directly

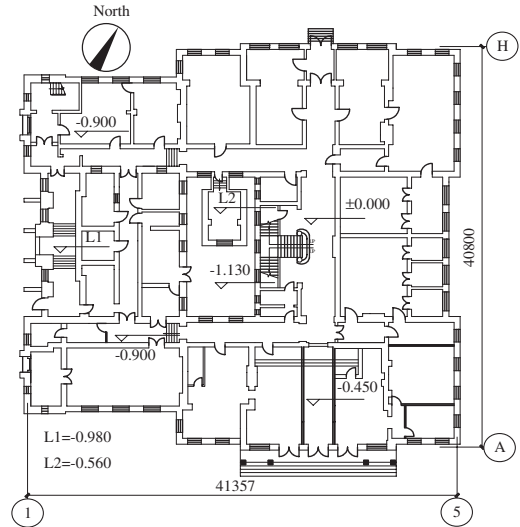


Figure 6. Architectural plane of the 1st floor.

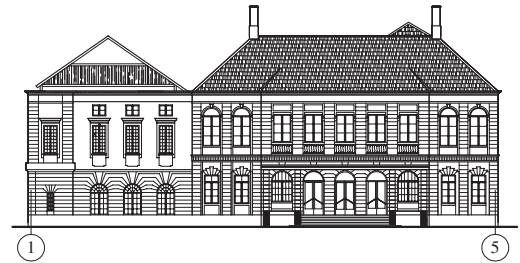


Figure 7. The south elevation.

according to the status of the building. The foundation of the building was inspected by digging (Figure 5).

Typical architectural drawings, the details of the foundation and the structural plane of the second floor are shown in Figures 6–9 respectively. In the original structure, the foundation of the building was built by stone standing on the top of wood piles with the diameter of 150 mm and the space of 500 mm in the longitudinal direction (Figure 8), the second floor was constructed using 10-millimeter-thick wood plank supported by orthogonal timber grille (Figure 10). Section sizes of the bars used in the grille are 84×200 mm, 62×300 mm, 76×300 mm and 76×200 mm. Spacing between the bars are 360 mm and 395 mm. Wood sheathings covered by waterproof layer and fired clay shingles were used to construct the roof, which is supported by timber purlin on timber trusses (Figure 11). Size of the purlin section is 75×140 mm and the spacing is 625 mm. Section sizes of the bars used in the supporting trusses are 157×304 mm and 170×300 mm for

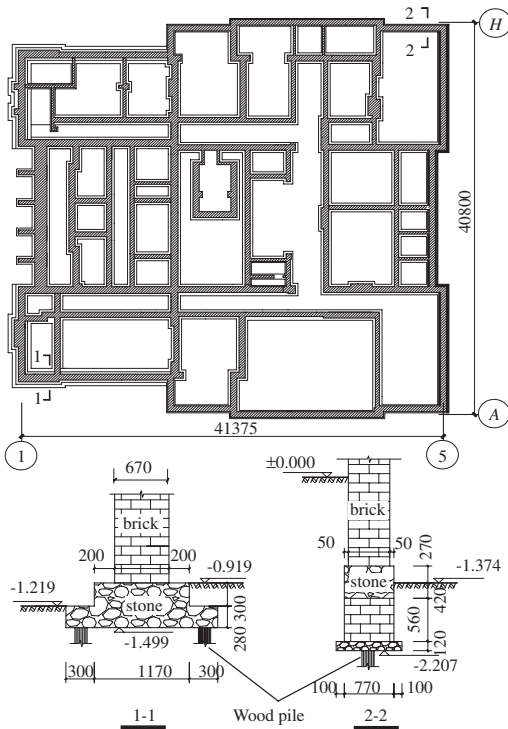


Figure 8. Details of the foundation.

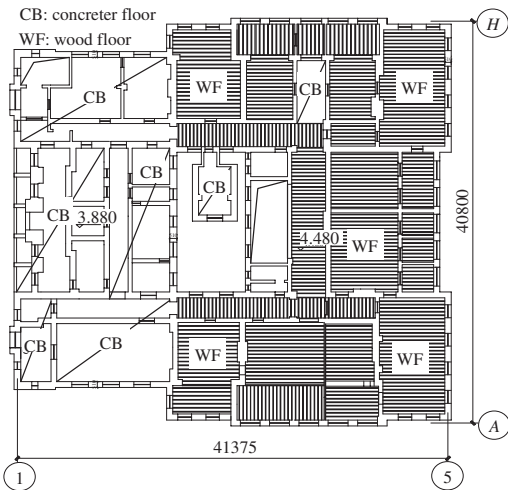


Figure 9. Structural plane of the 2nd floor.

the upper chords, 145×345 mm and 180×440 mm for the lower chords, 150×200 mm, 154×154 mm, 170×200 mm and 170×150 mm for the web members. Typical thickness of the load-bearing masonry walls is 510 mm. There are also walls with other thicknesses.

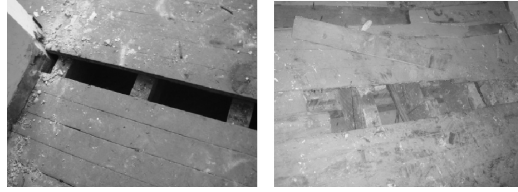


Figure 10. Timber grille on the 2nd floor.



Figure 11. Connection of the roof structure.

The building has been undergoing several retrofits after its establishment. Although main structure of the building has been reserved, local changes have been made. The original timber floor on the 2nd floor in the west part of the building has been replaced by concrete floor, and the original roof supported by timber truss there has been substituted by asbestos shingle roof supported by steel truss.

2.2 Testing of the strength of timber materials

Bending strength and compression strength parallel to the grain of the timber were determined by random sampling test. The samples were chosen from all load-bearing timber members mentioned above. 5 bending samples of $300 \times 20 \times 20$ mm and 3 compression samples of $30 \times 20 \times 20$ mm were prepared for the test. After the percentage of water content had been determined, the bending tests were performed by simply supporting the sample and loading on the mid-span, and the compression tests were performed by putting the samples directly in the test machine (Figure 12). The test results for the strength of timber material are listed in Table 1, which have been converted to the values of the strength for timber materials under the percentage of water of 12% for the purpose of computation.

2.3 Testing of the strength of masonry materials

Strength of the masonry can be determined according to the mortar strength and the brick strength.

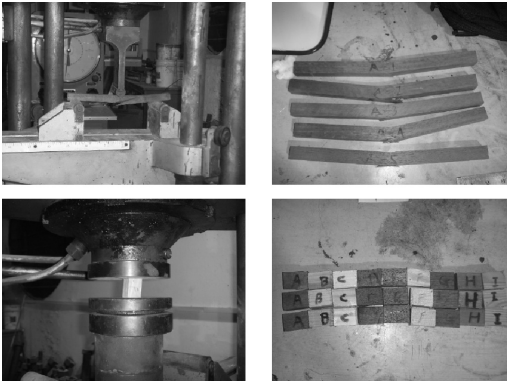


Figure 12. Bending and compression test for timber materials.

Table 1. Strength of timber materials.

Location	Type of wood	Bending strength (N/mm ²)	Compression strength (N/mm ²)
2nd Floor	Lauan	96.2	35.0
2nd Floor	Lauan	66.0	36.1
Roof	Red deal	55.6	23.2
Roof	Red deal	46.0	42.6



Figure 13. Testing of the strength of the mortar.

Mortar strength was determined by penetration resistance method. Eight and seven pieces of wall panel on the 1st and the 2nd story were chosen respectively for the test. On each panel, 8 mortar beds with thickness greater than 7 mm were tested. The rendering coat was demolished and the surface of the wall panel was smoothed before the test, and then the probe pin was penetrated into the mortar bed. The penetration depth was measured after clearing the mill dust in the penetration hole (Figure 13). According to the penetration depth, the compressive strength of the mortar was calculated using Equation 1, which was proposed and calibrated by Jiang & Chen (2005).

$$f_2 = 611.47d^{-3.0589} \quad (1)$$

Table 2. Strength of the mortar and bricks.

Sample	Location	Strength of mortar (N/mm ²)	Strength of bricks (N/mm ²)
SGA-1	1st Floor	0.5	10.3
SGA-2	1st Floor	1.6	12.8
SGA-3	1st Floor	2.7	12.6
SGA-4	1st Floor	0.1	8.1
SGA-5	1st Floor	0.8	8.6
SGA-6	1st Floor	0.4	7.9
SGA-7	1st Floor	0.6	10.8
SGA-8	1st Floor	0.7	6.0
SGA-9	2nd Floor	0.7	8.3
SGA-10	2nd Floor	1.1	11.1
SGA-11	2nd Floor	0.5	7.7
SGA-12	2nd Floor	1.6	10.8
SGA-13	2nd Floor	1.0	8.3
SGA-14	2nd Floor	0.2	8.0
SGA-15	2nd Floor	0.3	4.8

Table 3. Strength of the concrete.

Sample	Sampling location	Sample diameter (mm)	Sample height (mm)	Compression strength (N/mm ²)
BX-1	2nd floor	75	94	37.5

where, f_2 = compressive strength of the mortar (MPa); and d = the penetration depth (mm).

In Chinese standard, the method of evaluating the fired common brick strength grading by rebound hammer (JC/T96-1999), a convenient method using rebound hammer was recommended to test the strength of bricks in the lab. This method was also employed to evaluate the strength of bricks in the building. Considering the status of bricks in the building is different from that of bricks in the lab, the rebound value was modified by using Equation 2 (Guan et al. 2004).

$$n'_m = 0.84n_m + 2.13 \quad (2)$$

where, n'_m = the modified rebound value; n_m = the rebound value measured in-situ.

The test results both for mortar and bricks are shown in Table 2.

2.4 Testing of the strength of concrete materials

Strength of the concrete used in the floor were determined through drilling hole sampling. To avoid disturbing the structure and considering the durability of the concrete materials, compression test was performed on only 1 cylinder sample drilled out from proper location on the floor (Table 3).

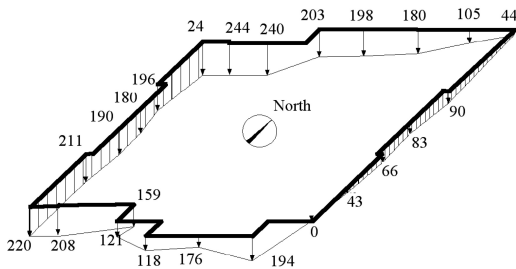


Figure 14. Relative settlements along the outer walls.

Table 4. Leaning of the building.

Observe point	Leaning direction	Horizontal difference (mm)	Vertical distance (mm)	Leaning angle (‰)
North west corner	To west	—	—	—
	To south	9	8112	1.11
North east corner	To west	11	8178	2.43
	To north	22	7754	2.84
South west corner	To west	42	7536	5.57
	To south	36	7536	4.78

2.5 Measurement of uneven settlements and the leaning of the structure

Considering the difference of density of materials used in the structure, the weak connections between load-bearing members and the soft characteristic of the ground soil, relative settlements and the leaning of the building structure were measured and the results are listed in Figure 14 and Table 4 respectively. The results indicate that the uneven settlements result in obvious leaning of the building.

2.6 Inspection of structural damages and faults

Obvious damages have been made in the structure during the past one hundred years. The main damages include leaking of the floors and walls, corrosion of steel bars in concrete members, leaking and corrosion of the roof, shrinkage-induced cracking of wood bars in the roof trusses, and disjunction of the trusses.

There are some faults in the load-bearing systems of the building. There are no roof braces. Connection between the purlins and the trusses are missed. Some linking bolts on the lower end of roof truss braces are also missed. Besides, many bars are connected in the inner joints of the trusses and fastening measurements on the joints are missed. Large deformation of the joint under normal loading might affect safety of the trusses (Doherty et al. 2002). Further more, there are no ring beams and structural concrete columns inside the bearing masonry walls, and spacing between

Table 5. Strength of structural materials used in the calculation (N/mm²).

	Mortar	Clay brick	Timber	Concrete
1st floor	0.4	6.0	46.0	37.5
2nd floor	0.5	4.8		

some inner lateral walls is great. The structure is more vulnerable to earthquake (Casolo & Pena 2007).

3 STRUCTURAL ANALYSIS AND ASSESSMENT FOR THE BUILDING

3.1 Calculation model

The load-bearing masonry walls were replaced by wall elements and the roof trusses were replaced by bar element in the calculation model. The elemental stiffness matrix were formed by the input geometry and material properties determined by the structural inspection (Table 5). The floors supported by timber grilles were analyzed separately using the model of simply supported beam.

Structural responses of the building to static loads and earthquake action were calculated. The static loads and earthquake action were determined by the actual condition of the structure and the Chinese building codes. In the static analysis, floor dead load was taken as 1.5 kN/m² for the timber floor and 3.5 kN/m² for the concrete floor, and roof dead load was 2.0 kN/m² for the timber trusses supported area and 2.5 kN/m² for the steel trusses supported area. In the seismic analysis, the earthquake intensity was taken as grade 7 according to the Chinese Code for Seismic Design of Buildings (GB50011-2001).

3.2 Assessment method for the safety of existing building structures

The safety assessment for existing building structures is different from the design for new building structures because the status of an existing structure can be inspected, the performance of structural materials in the building can be determined by tests, and the dimension of structural members can be measured in-situ.

For the convinence of the use, Equation 3 was proposed by the authors to assess the safety of existing building structures (Gu et al. 2004).

$$\gamma_0(\gamma_G S_{Gk} + \gamma_{Q1} S_{Q1k} + \sum_{i=2}^n \gamma_{Qi} \psi_{ci} S_{Qik}) \leq \frac{R(f, a, \dots)}{\gamma_R} \quad (3)$$

where, γ_0 = coefficient of importance, and it was taken as 1.1 for the historical buildings; γ_G = partial

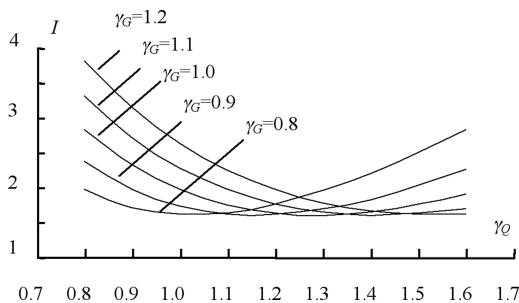


Figure 15. Determination of partial factors for dead and live load.

factor for dead load; γ_{Q1} , γ_{Qi} = partial factors for the first live load and the i th live load; S_{Gk} = dead load effect; S_{Q1} = the first live load effect which is the largest one among all of the live load effects; S_{Qi} = the i th live load effect. ψ_{ci} = combination coefficient for live load effects which can be determined according to Chinese load code for the design of buildings; $R(\cdot)$ = function of structural resistance which can be calculated according to Chinese design codes for buildings; γ_R = resistance partial factor; f = strength of the material tested in-situ; a = dimension of the structural member measured in-situ.

According to the probability models of the load and the resistance for existing building structures, optimal analysis was done to typical structural members taking into account of different ratios of live load effect to dead load effect and 3 types of simple load combinations for dead load and live load for the determination of the partial load factors. The typical results are shown in Figure 15. In Figure 15, vertical axis “ I ” refers to the error between the assessment result by using probability analysis directly and the assessment result calculated by Equation 3. From the results shown in Figure 15, it can be concluded that the optimal value of partial factor for dead load γ_G is 1.0, and the optimal value of partial factor for live load γ_Q is 1.3. Based on the suggested load partial factors, resistance partial factors, γ_R , for different kinds of structural members, was determined by further optimal analysis. The calculation results are shown in Table 6.

3.3 Calculation results

It is indicated by the static calculation results for the timber grille that the safety margin of the grille is acceptable and no measure is needed to strengthen the grille under the current condition (Table 7).

Also, the bearing capacities of the bars in the roof truss are greater than the according inner forces. The horizontal load bearing members are safe without any strengthening.

The static and seismic analysis of the masonry wall indicates that compression capacities or shearing

Table 6. Value of the resistance partial factor γ_R .

Type of member	State of loading	Resistance partial factor γ_R
Concrete member	Axial tension	1.13
	Axial compression	1.23
	Compression with small eccentricity	1.23
	Compression with large eccentricity	1.14
	Bending	1.13
	Shearing	1.57
	Twisting	1.47
Brick masonry member	Axial compression	1.50
	Compression with eccentricity	1.82
	Bending	1.41
	Shearing	1.44
Timber member	Bending	1.14
	Axial compression	1.14
	Axial tension	1.14
Steel member	Axial compression	1.15
	Axial tension	1.15
	Compression with eccentricity	1.11
	Tension with eccentricity	1.11
	Bending	1.11
Thin-walled structural steel member	Axial compression	1.16
	Axial tension	1.16
	Compression with eccentricity	1.12
	Tension with eccentricity	1.12
	Bending	1.12

capacities of several wall panels in the 1st floor are small than the according inner forces, and the minimum ratio of capacity to inner force is 0.79. So, proper strengthening is needed for these members to ensure safety.

Meanwhile, some indispensable structural measures demanded by the current code to ensure the seismic capacities are missed. Proper retrofit is needed to realize these measures on the structure without affecting the original profile of the building.

4 CONCLUSIONS

The building of former British consulate in Shanghai was constructed using composite structure of timber and masonry. After more than one hundred years of using and several retrofits, the original structure has been changed partially and minor damages have been made. From the angle of today's design theory, there are some unreasonable structural details in the

Table 7. Calculation results of the timber grille.

Structural member	Section size (mm ²)	Computational moment at the mid-span $\times 1.1$ (kN-m)	Bending capacity of the member/1.14 (kN-m)
ML201	76 \times 200	8.7	20.5
ML202	62 \times 300	9.7	46.2
ML203	76 \times 200	3.4	20.5
ML204	62 \times 300	13.2	37.7
ML205	76 \times 300	6.4	46.2
ML206	76 \times 300	5.6	46.2
ML207	76 \times 300	9.9	46.2
ML208	76 \times 200	1.7	20.5
ML209	62 \times 300	3.0	37.7
ML210	62 \times 300	11.0	37.7
ML211	62 \times 300	3.2	37.7
ML212	62 \times 300	10.8	37.7
ML213	62 \times 300	2.9	37.7
ML214	62 \times 300	9.6	37.7
ML215	62 \times 300	1.7	37.7
ML216	62 \times 300	5.2	37.7
ML217	76 \times 200	1.9	20.5
ML218	62 \times 300	5.3	37.7
ML219	84 \times 200	11.0	22.7

building. It is the basic work to make a thoroughly inspection and a scientific assessment for the structure to guarantee the safety of this historic building in the future. Considering the weak connection between load bearing members of the structure, horizontal and vertical load bearing members can be analyzed independently under different load case based on the inspection results. The analysis results show that most of the members have acceptable safe margin. However, proper structural measures are needed to enhance the safety and serviceability of the building. According to

the inspection results, the detailed strengthening and retrofiting plan is being studied for the purpose of the protection.

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