Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)

Strengthening design of Ganxi's Former Residence

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ABSTRACT: Some key questions in strengthening of a modern architecture called Ganxi's Former Residence are roundly discussed, including foundation reinforcement, brick wall reinforcement, seismic reinforcement, wood floor and wood roof truss reinforcement. The original foundation was strengthened by adding new reinforced concrete strip foundation, which expanded the bottom area and increased bearing capacity and rigidity of the foundation. The wall were strengthened by one-side or two-sides composite mortar laminate reinforced by mesh reinforcement, which increased compressive bearing capacity and seismic bearing capacity of the wall. By setting up the steel plate constructional columns and steel plate ring beams, which improved the seismic behavior but not occupied the useable area. These methods can be referenced for strengthening design of modern half-timbered architectures.

1 INTRODUCTION

The main strengthening and renovation project of Ganxi's Former Residence is one half-timbered building. Built in the 1920s and 1930s, it is now on the priority protection lists of cultural heritage defined by Nanjing City Government. This building has two stories, with east-west length 17.75 m, south-north length 10.15 m, construction area 320 m^2, 10.57 m in height. The floor and roof are wooden. The structure is mainly bear by longitudinal-cross masonry walls, with outer wall thickness 380 mm and inner wall thickness 260 mm. The wall is made of solid soil bricks, and constructed by soil mortar. The roof structure is space wood truss. The foundation is made of large footing bricks. Despite years of exposure to sunshine and rain, the construct is not seriously damaged, yet it severely weathered. For later safe use, it needs to be strengthened and renovated. (Fig. 1, Fig. 2)

After survey, the earthquake intensity is set as 7, the basic design acceleration of ground motion is set as 0.10 g, and the anti-seismic grade is set as third-grade, with the building site set as Grade II. The characteristic value of ground bearing capacity is 70 kPa. The result of sampling test of the original structure shows that bricks' strength is of MU2 grade, with the mortar strength belong to M1 grade.

2 STRENGTHENING DESIGN

PMCAD™ is used to check the seismic bearing capacity of the building (Fig. 3). Partial brick walls of the ground floor and second floor cannot meet the bearing

Figure 1. Elevation of the building.

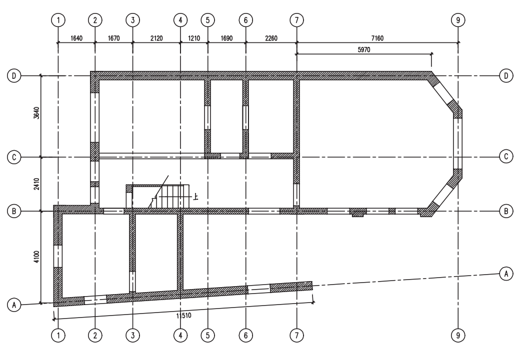

Figure 2. First floor plan of the building.

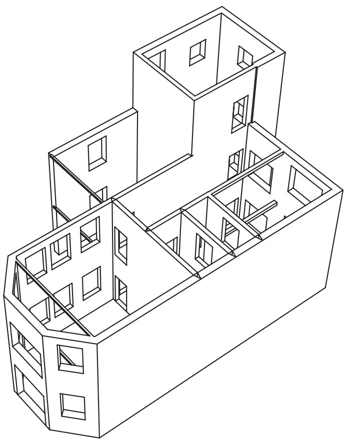

Figure 3. Computer model of the building.

capacity requirements. The bearing insufficiency of the ground floor is mainly located in the western wall, and the outer and inner of the southern wall, 50% less at the most; The bearing insufficiency of the second floor mainly lies in the outer of the southern wall and the inner wall of axis (C), 38% less at most. Seismic bearing insufficiency exists in each floor: the outer of the eastern and western walls and the inner wall of axis (B) and axis (C) on the ground floor, 33% less at most; and the outer of eastern and western walls on the second floor, 35% less at most. None of the brick walls on the three floors satisfy bearing capacity.

The original construct was built without ring beams and constructional columns, unable to meet the applicable seismic standards.

2.1 *Brick wall reinforcement*

Bar-mat reinforced cement mortar are used to strengthen the walls, the bearing capability of which is presented in the following equation:

$$N = \varphi_{com}\left(fA + f_c A_c + \eta_s f_y' A_s'\right) \tag{1}$$

Where φ_{com} is the stability coefficient of combination brick member; A is the cross section area of brick masonry; f_c is the design value of cement mortar compressive strength; A_c is the cross section area of mortar layer; η_s is the strength correction coefficient of compressive bars, take 0.9 for mortar layer; f_y' is the design value of reinforcement compressive strength;

The enhance coefficient of its anti-seismic capacity can be calculated with the following equation:

$$\eta_{pij} = \frac{240}{t_{w0}}\left[\eta_0 + 0.075\left(\frac{t_{w0}}{240} - 1\right) / f_{VE}\right] \tag{2}$$

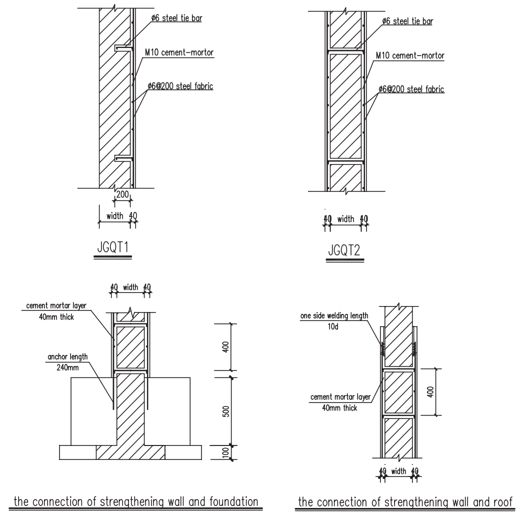

Figure 4. Diagram of strengthening wall.

Where η_{Pij} is the enhance coefficient for jth wall of ith floor; η_0 is the benchmark enhance coefficient; t_{w0} is the depth of the original walls; f_{VE} is the design value of original wall's shear strength.

The brick wall is strengthened by mesh reinforcement (Fig. 4), using Φ6@ × 200 steel bars. The mesh reinforcement are connected by "S" shape Φ6 bar connectors. The bar connectors drill through walls when connecting double sides mesh reinforcement, and anchor in walls with 800 mm spacing while connecting single side mesh reinforcement. 40 mm thick cement mortar layer of M10 grade is used to cover the mesh reinforcement. Φ8 oblique reinforcement are placed in the corner of door and window openings to prevent from cracking. Reinforced by two-side mesh reinforcement, 380 mm thick wall's compressive capacity can be increased by 175%, and its seismic bearing capacity can be increased by 252%. While reinforced by one-side mesh reinforcement, the wall's compressive capacity can be increased by 85%, and its seismic bearing capacity can be increased by 192%. Compressive capacity of 260 mm thick wall reinforced by two-side mesh reinforcement can be increased by 256%, and its seismic bearing capacity can be increased by 300%. The calculation results indicate that the bearing capacity and rigidity of the reinforced brick walls of each floor meet the applicable standards.

2.2 *Anti-seismic constructional strengthening*

Some constructional columns and ring beams are added so that the integrity of the building is strengthened, hence satisfying the criteria based on modern seismic architectures. The addition of constructional columns and ring beams is performed through adding

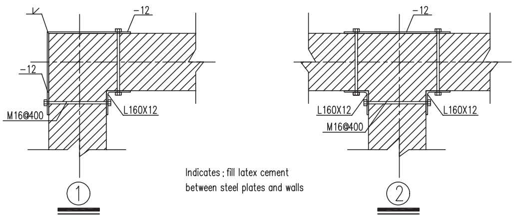

Figure 5. Practice of the addition of constructional columns.

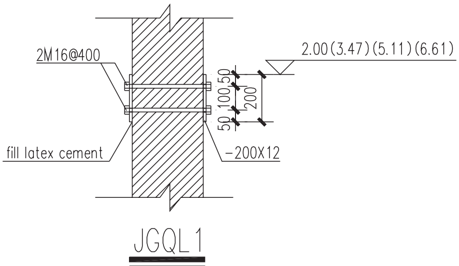

Figure 6. Practice of the addition of ring beams.

Figure 7. Construction of the addition of constructional columns and ring beams.

steel plates (Fig. 5, Fig. 6, Fig. 7), which will not occupy the construction area nor ruin the beauty of the building. It is the new attempt in China. Steel plates have some solder joints to strengthen the connection and to avoid cracks in the steel-meshed cement mortar layer.

2.3 *Foundation strengthening*

The survey reports reveal that soil beneath the foundation of the building is miscellaneous fill with low strength. The calculation result indicates that foundation pressure is 124 kPa, which is bigger than the characteristic value of foundation bearing capacity, namely 70 kPa. Therefore, the foundation is strengthened with double beams, which ensures the foundation bearing capacity and rigidity.

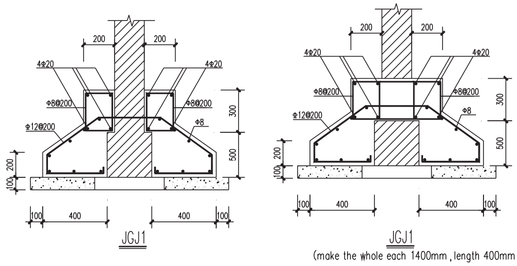

Figure 8. Diagram of strengthening foundation.

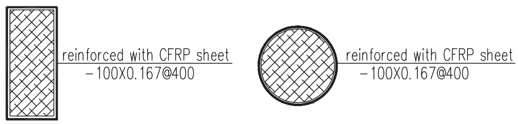

Figure 9. Diagram of strengthening timber beams and joists.

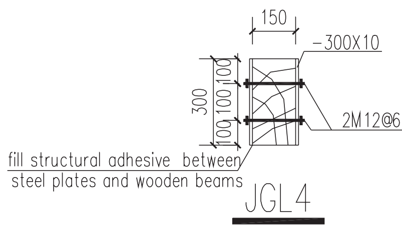

Figure 10. Diagram of strengthening timber beams of the second floor.

2.4 *Wood floor strengthening*

In order to deal with the cracks in timber beams and joists, externally bonded reinforcement by CFRP is used (Fig. 9) to increase their circumferential confining and bearing capacity; Some timber beams and joists are replaced when there is severe corruption or warp or distortion.

Since the second floor will be converted to a sightseeing spot after renovation, the change in its function increases the floor live load. The original floor cannot satisfy the bearing capability. After a comprehensive analysis, joists in the second floor are reinforced by doubling its amount. After that, distances between joists are original half. Beams are strengthened by steel-timber composite.

2.5 *Wood roof truss strengthening*

The wood roof of this building is a truss system. SAP2000™software is used to calculate its bearing capacity (Fig. 11). The results show that the original components' sections can meet the bearing requirements, but the joints need some treatments. Since the

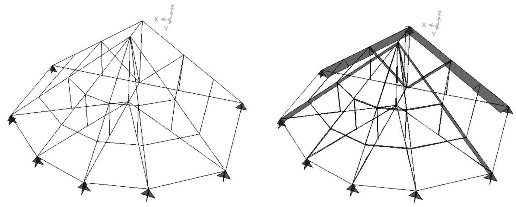

Figure 11. Result of the wood roof truss (axial force).

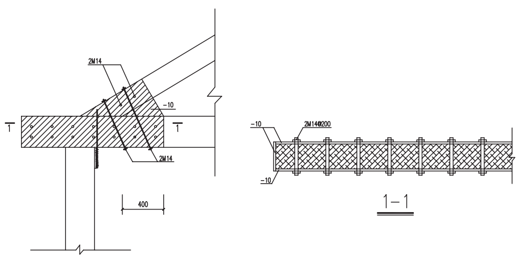

Figure 12. Diagram of strengthening ending joints of the wood roof truss.

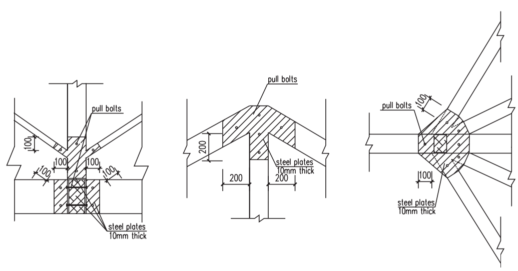

Figure 13. Diagram of strengthening middle joints of the wood roof truss.

Figure 14. Construction of strengthening joints of the wood roof truss.

ending joint is connected in tooth profile, its ultimate state is determined by shear parallel to wood grain, so it is the weak link. In addition, the axial force of top chord at the end is the biggest, thus the shear force translated to the ending joint is much more bigger. Therefore, the ending joint must be strengthened (Fig. 12). Strengthening for the middle joint is presented in Figure 13. Figure 14 is the field construction photos.

3 CONCLUSION

The strengthening work has basically been finished. The building is in rather good shape, which shows that the strengthening design is reasonable and feasible, and can be referred to for strengthening of half-timbered architectures of the same kind.

(1) Before strengthening, the modern half-timbered architecture should undergo thorough test, calculation and appraisement, followed by corresponding strengthening program.
(2) In order to ensure the effects of strengthening, the newly added concrete should be the microdilatancy concrete; proper treatment should be done to the interface between the new and original concrete, so that the two parts are solidly connected.
(3) On the premise of not influencing the architectural appearance, using bar-mat reinforced cement mortar to reinforce brick wall can increase compressive bearing capacity and seismic bearing capacity to a higher level.
(4) Using steel plates in Anti-seismic Constructional Strengthening can save area and does no harm to architectural appearance.
(5) The use of CFRP in strengthening timber beams and joists can effectively improve bearing capacity.
(6) The ending joint of wooden roof truss bears great shear force due to its tooth profile connection, so it need special strengthening treatments.

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