Structural Analysis of Historical Constructions – Jerzy Jasieńko (ed)
© 2012 DWE, Wrocław, Poland, ISSN 0860-2395, ISBN 978-83-7125-216-7

NUMERICAL SIMULATION FOR RETROFIT OF THE ANDREWS & GEORGE BUILDING IN SHANGHAI

Peng, B.[1], *Gu, X. L.*[2], *Ouyang, Y.*[3], *Sun, K.*[4], *Liu, N. K.*[5]

ABSTRACT

Fast development of Shanghai now raises the issue of historical buildings conservation in the city. To effectively preserve the facade walls of the Andrew & George Building, which is over 100 years old and being retrofitted, detailed numerical simulations for the retrofit procedure were conducted in this paper. The walls were made up of masonry, and were temporarily strengthened by reinforced concrete layers and a steel frame during the retrofit. The walls and the strengthening members were modelled using 3-dimensional finite element method. Material properties of the simulation model were determined by structural inspection and mechanical test. Based on the simulation results of the walls to be preserved, unfavourable loading cases were analysed, and then the retrofit design proposal was verified.

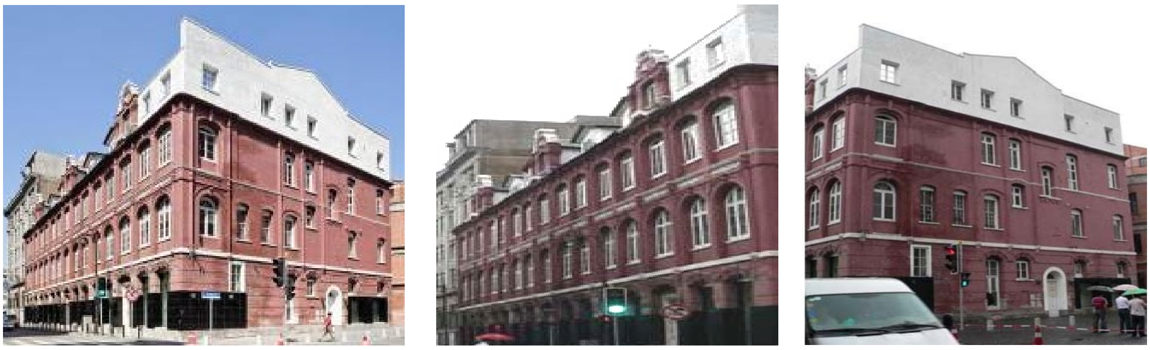
Keywords: *Numerical simulation, Historical building, Retrofit, Masonry*

1. INTRODUCTION

The city of shanghai has been an engine of the booming Chinese economy. Years of double-digit increases make infrastructure upgrading a key issue faced in the city. When the conservation of the city's hundreds of famous historic buildings gets involved, the issue is even more challengeable. For example, deformations of the famous buildings along the Bund have to be strictly monitored on a high frequency basis, during the construction of an underground tunnel nearby. However, monitoring by itself is not sufficient for conservation of the old buildings [1, 2]. For the buildings to be retrofitted, or disturbed by surrounding constructions, counter measures for possible impacts must be made in advance [3]. This is impossible without insights of performances of load-bearing members. Since mechanical tests are not suitable for historic structures, numerical simulation can be an efficient tool to quantitatively investigate the mechanical behavior of structural members [4].
The Andrews & George building has stood for over 100 years at the Bund in Shanghai. The south and east facades of the building are shown in Figure 1. A retrofit of the building is now required by the new developer of the district. In the preliminary scenario, all inner walls, floors, and roof trusses of the building are to be removed. The south and east facade walls will be preserved for their unique architectural styles, and then fasten to a new high-rise structure, which will be constructed right within the lot of the original building.
For the purpose of conservation, intensive numerical simulations on the retrofit proposal of the building were conducted in the following sections. Current state of the structure was firstly inspected. Structural

[1] Associate Professor, School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanhgai 200093, China. Email address: BinPeng@usst.edu.cn
[2] Professor, College of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China. Email address: gxl@tongji.edu.cn
[3] Associate Professor, Department of Civil Engineering, Shanghai University, 149 Yanchang Road, Shanghai 200072, China. Email address: oyy_wly@sina.com
[4] Engineer, Shanghai Tongrui Software Co. Ltd, 1398 Siping Road, Room 801 of Tower B, Shanghai 200092, China. Email address: sunkai@reases.com.cn
[5] Engineer, Shanghai Tongrui Civil Engineering Co. Ltd, 1398 Siping Road, Room 802 of Tower B, Shanghai 200092, China. Email address: vicliunengke@163.com

configuration and essential material properties were determined. The retrofit procedure, which would be simulated, was then introduced. After that, 3-dimentioanl finite element model of the Andrews & George buildings was built. Taking into account the possible disturbances, the retrofit process was simulated. Quantitative findings, along with the comments on the simulation, were presented in the conclusions.



(a) The general view (b) The south facade (c) The east facade

Fig. 1 The Andrews & George building

2. STRUCTURAL CHARACTERISTICS OF THE ANDREWS & GEORGE BUILDING

2.1. Configuration

The building is a 3-story hybrid structure with masonry walls, timber floors and roof trusses. As can be seen in Figure 2, the structural plan is in a rectangular shape, spanning 39.4 m from east to west, and 21.0 m from south to north. Heights are 5.50 m, 4.92 m, and 4.39 m for the 1st, 2nd, and 3rd story respectively. Insides of the building at each story are irregularly partitioned for residency. Many locally retrofits were made and some openings in the walls have been filled.

The thick of the south facade walls, which are to be preserved, is 510 mm. Most of the east facade walls to be preserved are 510 mm in thick, except some parts in story 3, which is 380 mm in thick.

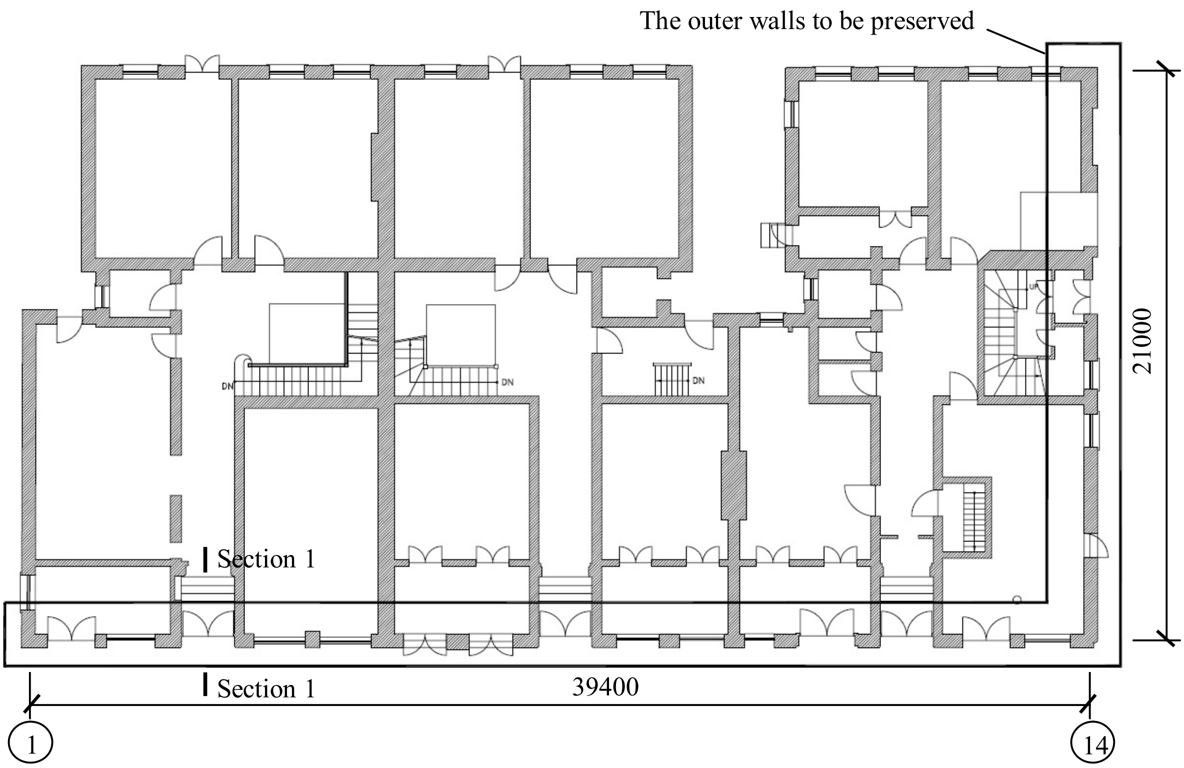


Fig. 2 Plan of the Andrews & George building

Ribbed timber floors are used in each story. Section of the rib beams is rectangular. For those run from south to north, the section height is varied from 130 mm to 180 mm, the section width is varied from

60 mm to 80 mm, and the interval is varied from 340 mm to 400 mm. For those run from east to west, the section height is 250 mm, the section width is 250 mm, and the interval is 370 mm.
Height of the triangular timber trusses is 3.58 m. In the upper chord, size of the rectangular sections of the members is 175 mm × 300 mm; in the lower chord, it is 200 mm × 400 mm. The members are connected with each other by mortise and tenon.

2.2. Material properties

Strength of clay and lime composite mortar was evaluated through 6 in-situ penetration tests. The tests were conducted in the 1st and 2nd story, and the test zones were evenly distributed. In accordance with the *Chinese Standard of Structural Inspection and Assessment for Existing Buildings* (DG/TJ08-804-2005), the characteristic value of compressive strength for composite mortar was determined as 0.53 N/mm^2.
Compressive strength of bricks was evaluated by in-situ rebound tests and lab tests. For the rebound test, there were 2 testing zones in the facade walls. In accordance with the *Chinese Standard of Structural Inspection and Assessment for Existing Buildings* (DG/TJ08-804-2005), each of the testing zones consisted of 10 bricks, and for each brick, the rebound was conducted 12 times. The resulting characteristic value of the strength for bricks was 9.1 N/mm^2.
Compressive strength of masonry in the inner and outer walls was assessed through in-situ test and lab tests. The setup of the in-situ test is shown in Figure 3. Size of the rectangular sections of the specimens was 250 mm × 242 mm. In accordance with the *Chinese Standard of Structural Inspection and Assessment for Existing Buildings* (DG/TJ08-804-2005), the resulting characteristic value of the strength for masonry was 1.081 N/mm^2.

a) The test setup b) The crushed masonry

Fig. 3 The in-situ compressive test

2.3. Existing deficiencies

The structure was built before development of the modern design theory. No structural columns and ring beams were used, and the connection between the timber floors and their supporting walls were weak. The structural integrity was inadequate, and its safety has been significantly deteriorated by long-term residency, improper retrofits, and environmental effects. Many cracks and seeping debris can be seen on the facade walls to be preserved. Some ends of floor ribs supported by the walls have severely corroded. Deformations of some openings are obvious.

3. RETROFIT PROCEDURE

The building is distinguished within the landmark historical buildings along the bund of Shanghai, but its structure is vulnerable with the extremely low material strength and the existing deficiencies. To guarantee the structural safety, temporary strengthening and bracing measures were involved in the retrofit proposal.
Steps of the retrofit are illustrated in Fig. 4, in which the position of section 1-1 is marked in Fig. 2. First, all openings of the facade walls to be preserved will be strengthened. After that, bottom parts of the walls

will be strengthened by a clamping truss, as shown in fig. 5, which will resist most of the bending moments during the following foundation replacement. The brick foundation will then be replaced by a reinforced strip foundation. The next step is to remove the clamping truss, and then strengthen the walls using reinforced concrete layer, structural columns and ring beams. There will be no openings in the layer. The measures will be applied on the inner surfaces of the walls. The subsequence is to construct a steel brace frame inside the walls. After the strengthening, all lateral walls, timber floors, and roof trusses will be removed. As a result, the strengthened walls and the steel brace frame will form a temporary structure, whose plan is in an L shape. Deep excavation will be conducted along and inside the temporary structure, and the structure must keep stable during the excavation.

4. NUMERICAL SIMULATION FOR THE RETROFIT PROCEDURE

The impacts of the retrofit on the preserved walls have to be strictly controlled. However, no in-situ structural test is allowed on the facade walls, and the unfavorable disturbances in each retrofit step are random. To evaluate the feasibility of the retrofit proposal, finite element simulation is one of the best choices [5].

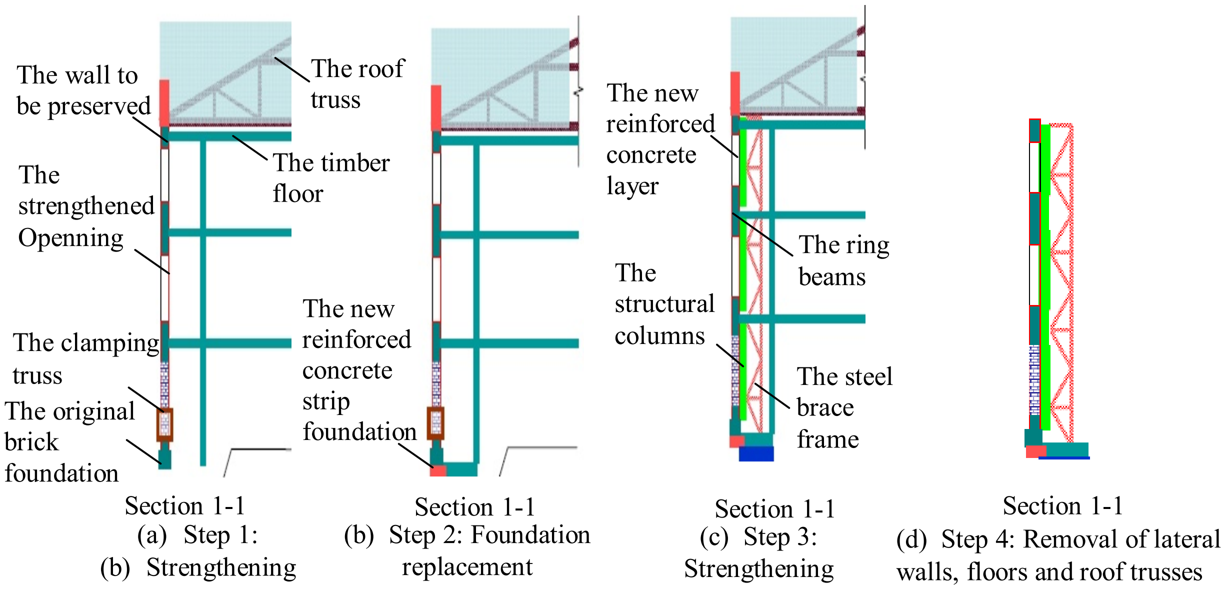


Fig. 4 The retrofit procedure

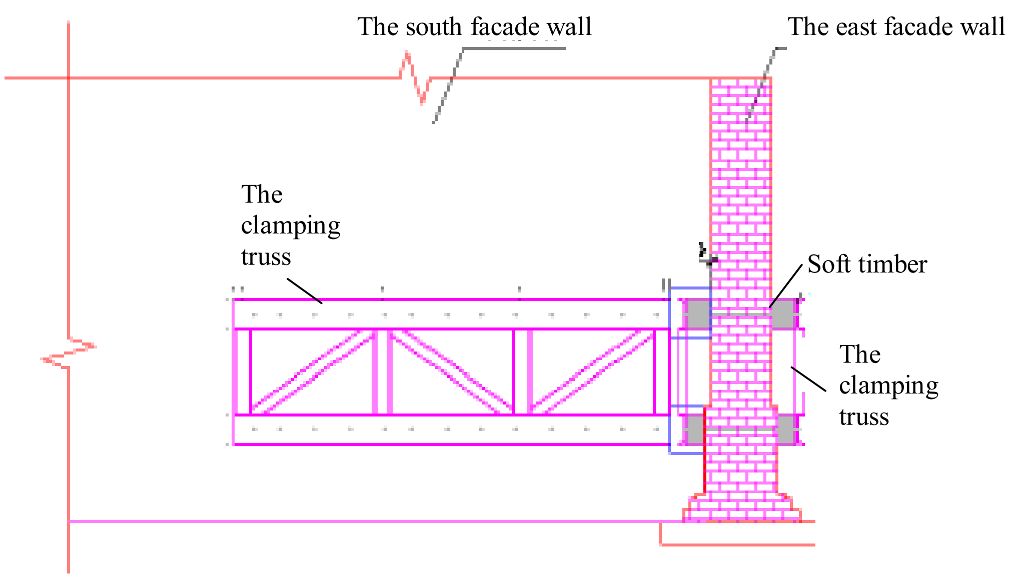
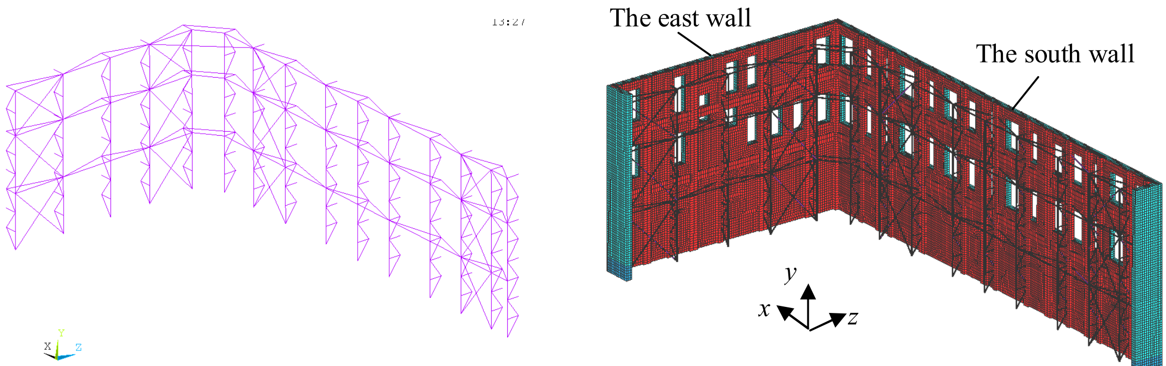


Fig. 5 The clamping truss at the corner

4.1. Element type

Eight-node solid elements were used to model the masonry walls to be reserved. The element was isoparametric, and had 3 translational degree-of-freedoms (DOFs) at each node. Principle stresses within the element, which were used to define constitutive relation and damage criteria for the masonry, were calculated through transforming between element coordinate system and the global one.
Four-node thin shell elements were used to simulate the reinforced concrete layer. The element was based on the Mindlin-Reissner theory for thin shell, and had 3 translational DOFs and 3 rotational DOFs at each node. Normal stress was linearly distributed alone the thickness of the element.
Two-node Bernoulli beam elements were used to model the steel brace frame. The element had 3 translational DOFs and 3 rotational DOFs at each node.
The finite element model is shown in Figure 6.



(a) The steel brace frame (b) The braced walls

Fig. 6 Finite element model of the walls to be preserved

4.2. Mechanical models

The William-Warnke damage criteria were used for the masonry and concrete [6], which keep elastic within the damage surface. If the material crushes, the stiffness will be multiplied by a small value; if the material cracks, the tensile stiffness perpendicular to the crack will gradually decrease, as shown in figure 7, in which f_t is the uniaxial tensile strength, and R^t is the modulus for cracked materials. The model was effective in preventing possible convergence difficulties.

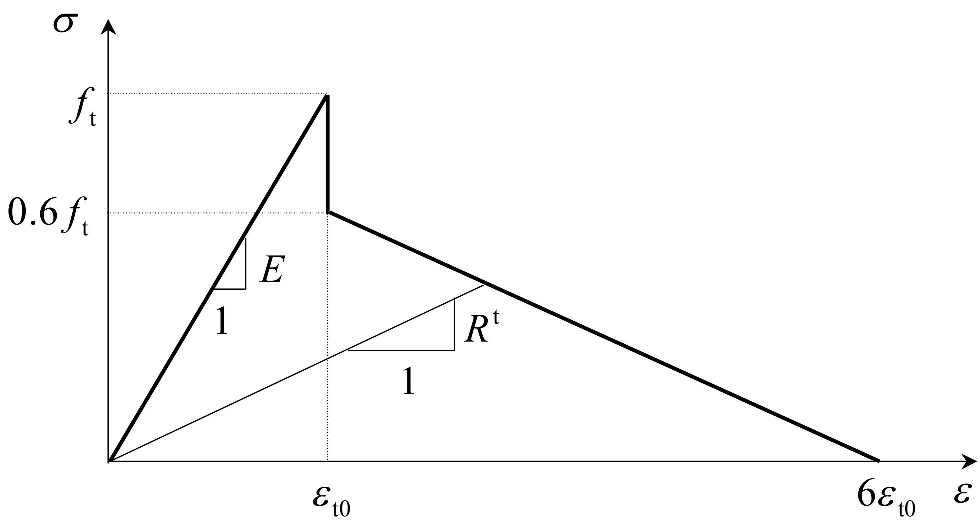


Fig. 7 Stress relaxation after cracking

The Von Mises yielding criteria were used for the steel. The uniaxial constitutive relations were bilinear. To help converging, a small stiffness was imposed after the steel yields.
Main mechanical parameters of the materials are list in Table 1. The masonry parameters were determined by mechanical tests [7], the concrete parameters were in accordance with that of the C30 concrete, which is listed in the *Chinese Code for Design of Concrete Structures* (GB50010-2010), and the steel parameters were given by the *Chinese Code for Design of Steel Structures* (GB50017-2003).

4.3. Loading and boundary conditions

Material self-weight and evenly distributed wind pressures of 0.8×10^{-3} N/mm^2 were the governing loads in the calculations. The self-weight was applied first, and the wind pressure was imposed based on the results under the self-weight.

Bottoms of the walls were fixed. Uneven settlements and tilting of the walls and the steel brace frame were applied to study the structural responses under unfavourable impacts by the excavation.

Table 1 Mechanical properties of the materials

Material	Self-weight N/mm^3	Elastic modulus N/mm^2	Poisson's ratio	Tensile strength N/mm^2	Uniaxial compressive strength N/mm^2
Masonry	1.7×10^{-5}	778	0.20	0.033	1.081
Concrete	2.5×10^{-5}	3.00×10^5	0.17	2.010	20.100
Steel	7.8×10^{-5}	2.06×10^5	0.30	235 (yield strength)	

4.4. Simulations results

Displacement developments on the top of walls during the retrofit are presented in figure 8. It is apparent that the displacement will dramatically increase when the lateral walls, the timber floors and the roof truss are going to be removed (step 4 in figure 4). The big displacement will affect the stability of the walls, so the step 4 is critical for the control of retrofit process. To mitigate the unfavorable impacts, the removal of members should be conducted gradually, and other field works should be stop during the removal. Local crush, development of existing cracks, and deformation of the openings should be promptly monitored.

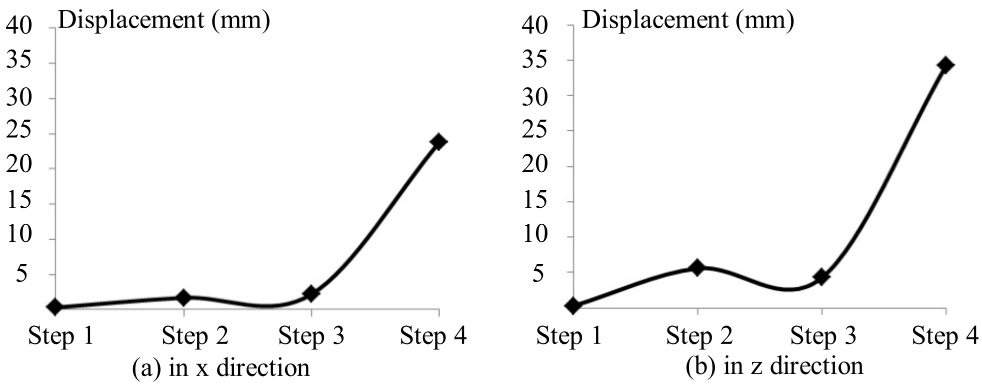
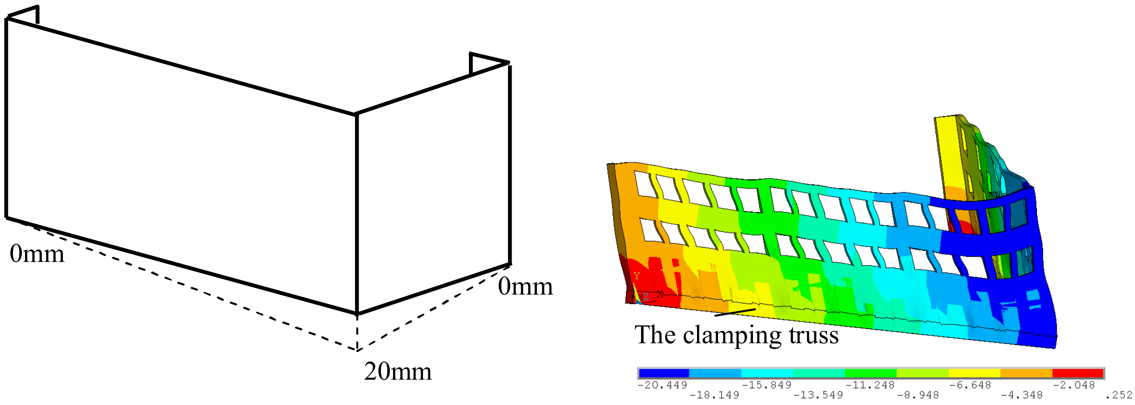


Fig. 8 Maximum displacement on the top of walls

No significant change of top displacement was shown before the removal of members. However, the replacement of foundation and may disturb the ground soil and cause the uneven settlements. Possible uneven settlements may result in tensile stress in the vulnerable masonry walls. This situation must be evaluated.

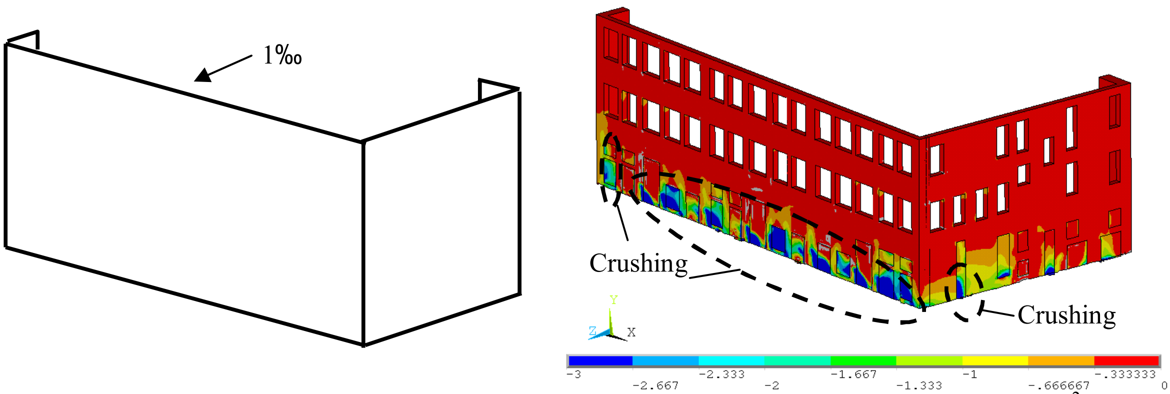
Figure 9 gives the displacements of the braced walls under a linearly distributed settlement. The effects of the clamping truss can be clearly seen in the figure. The clamping truss worked with the masonry and significantly enhanced the stiffness of the wall. Local crush or cracking at the bottom of the wall were avoided, and an integral deformation occurred. The integral deformation was also shared by the new added reinforced concrete layers, structural columns, and ring beams. The measures were effective in improving the stiffness and integrity of the walls.

Disturbance of ground soils may also tilt the walls. The above mentioned measures are of less help in this case. Figure 10 shows the 3rd principle stress if the braced south wall tilted by 1‰ southward. Significant bending moment could be resulted near the bottom of the wall. It was shown that the compressive stresses in the most part of the bottom were higher than the compressive strength of the masonry material, indicating the severe crushing. Collapse of the walls may occur in this case which is extremely dangerous. To prevent the collapse, stresses in the bottom parts of the walls need to be continuously and carefully monitored. Mounted strain transducers are the effective way for the monitoring.



(a) Settlements (b) Vertical displacement (mm)

Fig. 9 Vertical displacements under uneven settlements



(a) 1‰ southward tilting (b) The 3rd Principle stress (N/mm^2)

Fig. 10 The 3rd principle stress under tilting

The simulation results show that the strengthened walls are stable during the retrofit under normal conditions, but may be dangerous under some special cases. Since the unfavourable cases are highly possible, and it is difficult to simulate all the unfavourable conditions, reliable in-situ monitoring is necessary in retrofit process. The monitored data can be used to verify the simulation results, or provide sound inputs for simulations. The verified simulation model can then be used to expand the monitoring results, and to predict the wall performances under successive retrofit steps. Specific counter measures for each unfavourable case can be made in advance based on the simulations.

5. CONCLUSIONS

The retrofit of the ANDREWS & GEORGE building is a challenge for engineers and researchers. Over 100 years' exposure to environmental impacts results in the extremely low strength of its mortar, and then intensively impairs the resistance of all masonry walls. Structural integrity of the building is weak without ring beams and structural columns. Existing deficiencies influence the structural safety. Removal of lateral walls and floors and ground soil disturbances are involved in the retrofit proposal. Those measures could be fatal to the structural stability.

However, the proposed numerical simulations, that took into account the structural characteristics and possible disturbs, furnished plenty of prediction data. Performance evolution of the walls to be preserved was reliably trailed. Based on the simulations, the following conclusions can be used with monitoring measures to guarantee the structural safety during construction:

1) Significant out-of-plan deflections on the top of walls will be developed after the removal of lateral walls and floors.
2) Uneven settlements may substantially change the deforming modes of the walls, and give rise to unfavorable strain distribution.
3) After the removal of lateral walls and floors, a tilting of 0.1% of the walls may result in high compressive stress in the masonry, and then cause crushing in some vulnerable parts.
4) Stability of the walls may be impaired by ground soil disturbances.

The impacts on the braced walls of the following deep excavation could also be evaluated using the same modal and inputting the monitoring data.

The research efforts show the advantages of using numerical simulation method in retrofit of historic structures. Although mechanical tests for load-bearing members are unavailable, the simulation gives quantitative insights of member performances, and appropriate retrofit proposals can then be made.

REFERENCES

[1] Keypour H, Fahjan YM., Bayrakta A. (2007). Analysis and strengthening methods for historical masonry structures. In: *Proc. of the 5th International Conference on Seismology and Earthquake Engineering*, Tehran, Iran.

[2] Vicente R, Rodrigues H, Varum H, da Silva, JARM. (2011). Evaluation of Strengthening Techniques of Traditional Masonry Buildings: Case Study of a Four-Building Aggregate. *Journal of Performance of Constructed Facilities*, 25(3): 202-216.

[3] Maes, MA., Schueremans L, Van Balen K. (1999). Reliability Based Assessment of Existing Masonry Structures. *Proceedings of the 8th International Conference on Applications of Statistics and Probability*, Sydney, Australia, 689-695.

[4] Mourad, SA, EI-Hakirnz, FA. (1996). Evaluation of Structural Integrity of Damaged Masonry Building. *Journal of Performance of Constructed Facilities*, 10(2): 73-78.

[5] Peng B, Gu XL, Chen GL. (2008). Computer Simulation of Load-deformation Curves for Masonry Walls in Pseudo-static Tests. In: *Proc. of the 14th International Brick/Block Masonry Conference*, Sydney, Australia, paper 66.

[6] Willam KJ, Warnke ED. (1975). Constitutive Model for the Triaxial Behavior of Concrete. In: *Proc. of International Association for Bridge and Structural Engineering*. Vol. 19, ISMES, Bergamo, Italy, p. 174

[7] Li X, Gu XL, Gao ZN , Ouyang Y, Liu NK. (2012). Determinant of Mechanical Properties of Historical Brick Masonry Materials. *A manuscript contribute to the 8th International Conference on Structural Analysis of Historical Constructions, Wroclaw, Poland*