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# Analysis of Strengthening Methods for Retained Exterior Walls During a Structural Retrofit

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**Abstract** A three-story old building made up of masonry and wood will be retrofitted to be a new 14-story building, retaining two exterior walls and removing all internal members. To prevent the retained walls form deforming severely or collapse during the retrofit is necessary. The finite element analysis software, ANSYS, is used to calculate the responses of the retaining walls under possible loading conditions. The original retrofit proposal for the old building is refined based on the calculation results.

**Keywords**: Composite structure， strengthening， finite element method， ANSYS

## Introduction

The old building to be retrofitted is a composite structure of masonry and wood. It has 3 stories and an attic immediately under the roof. There are load-bearing longitudinal and lateral masonry walls in the building. The thickness of the east and south exterior walls is 510mm. The old building will be retrofitted to be a 14-story office building. All members except the east and south exterior walls, will be demolished according to the retrofit plan. The unbraced height of the retained walls will be about 15 m, partially 20 m beside the roof window, during the retrofit construction. The strength of the locally damaged masonry walls is quite low. No favorable structural measures for integrity of the building have been adopted. It is difficult to guarantee the stability of the retained walls under the circumstance. Excavation of ground soil beside the walls will be conducted to construct foundation of the new building, from which uneven settlement and oblique of the walls can be caused. Therefore, reasonable strengthening measures should been conduct for the retained wall during the retrofit. Comprehensive consideration for various factors, original consolidation program has been drawn up. In this paper, simulation of the responses of the retained walls under different loading conditions during the proposed retrofit procedure is conducted using a finite element software package ANSYS (Jiang 1984, Liu and Meng 2006). The retrofit proposal is then refined.

## Strengthening Proposal for the Retained Exterior Walls

Strengthening measures for the retained walls during retrofitting of the permanent and temporary bracing. Concrete columns are laid between the openings on the inner surface of the walls, from bottom to top. The walls are indented along each column to facilitate reliable connections. New concrete ring beams are placed under each floor slab. The inner wall surface is then covered by a layer of steel grids and reinforced mortar. These permanent reinforcements are favorable for constraining the wall and improving its integrity (GB50367-2006).

Lateral supports to the retained walls are lost after demolishment of the inner walls and floors. The retained walls will be unstable under the situation. To avoid severe oblique or collapse, steel trusses will be installed at both side of the wall as temporary lateral supports during the retrofit. There is a road outside the south retained wall. The shape of the steel truss placed outside the south wall is properly designed to avoid interrupting the traffic. Steel trusses on both sides are connected through bars crossing the wall openings and become a redundant and stable structure. The south retained wall intersects the east ones by a right angle. Additional steel brace is used to connect steel trusses inside the corner.

**Finite Element Analysis of the Strengthening Proposal**

**Modeling** SOLID65 element is used to model the walls, concrete structural columns, concrete ring beams, and the reinforced mortar layer. LINK8 element is used to model the members of the temporary steel trusses and brace. SOLID65 element is 8-node isoparametric element with 3 transitional degrees of freedom at each node. LINK8 element is 2-node linear element with 3 transitional degrees of freedom at each node. The model is shown in Figure 1.

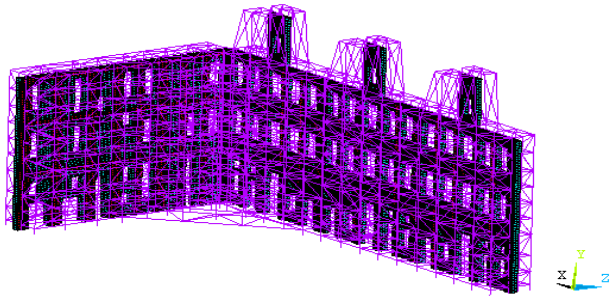

*Figure1: The model of partial exterior walls*

Material and geometry properties of the model are listed as following,

1) For the retained exterior walls, self-weight is 18kN/m$^3$. The compressive strength is 0.75 N/mm$^2$. The uniaxial tensile strength is 0.04 N/mm$^2$. The elastic modulus is 525 N/mm$^2$. The shear modulus is 210 N/mm$^2$.

2) For the concrete structural columns and ring beams, parameters are those of C20 concrete listed in the Chinese building code. 400mm * 400mm rectangular section is used for the beams. Thickness of columns is 200 mm.

3) For the steel members. self-weight is 78 kN/m$^3$, yield strength is 310 N/mm$^2$, elastic modulus is 210000 N/mm$^2$.

4) Thickness of the reinforced mortar layer is 50mm. Value of possible exterior affections are as the following,

1) Basic wind pressure is 0.55 kN/m$^2$.

2) Uneven settlement and oblique of the retained wall adopted are experience-base. A settlement of 20mm at the corner and a oblique of 0.7% are adopted.

**Birth and Death of Elements and Distribution Construction** ANSYS provides function of birth and death of elements, which can be used to simulate the retrofit procedure step by step. Elements representing the concrete columns and ring beams, the reinforced masonry layer, and the steel members are initially killed, or being death. They will be gradually activated, or being birth, in different calculation steps representing the retrofitting phases.

**Analysis of Calculated Results** The finite element analysis considers the role of the following factors, time of the wind load applies, uneven settlement and oblique result from groud soil excavation for the foundation of the new building, and so on. Four possible strengthening procedures are analyzed. Accoding to the first one, the loading procedure is: (1) self-weight is applied → (2) wind load is applied→ (3) the column elemnts are activated → (4) lateral supports at level of the 2nd and 3rd floors are removed → (5) the ring beam elemnts are activated → the reinforced mortar layer elemnts are activated → (6) the exterior steel truss elemnts are activated → (7) lateral supports at level of the top floors are removed → (8) lateral supports provided by all inner walls are removed → (9) inner steel truss elemnts are activated → (10) a: uneven settlement is input, b: oblique is input, c: uneven settlement and oblique are input.

The wind load is time-dependent and it value is not constant. Difference of the first and the second strengthening procedure is that, in the second ones, wind load will be appled on the wall after inner steel truss elemnts are activated. As the steel trusses are based on a rigid ground on the soil, they mitht oblique along with the retained walls. Therefore, the third and fourth procedures are different from the first and second procedures in that the steel trusses are oblique with the wall in step10. Displacements

of the first procedure in X direction are summarized in Figure 2, and displacement values of the wall of procedure 1 to 4 are listed in table 1.

Figure 2 and Table 1 show that, for procedure 1, removal of the second and third floors, removal of the top floor, removal of inner walls and excavation of ground soil are most unfavorabel steps, which will result in large displacements of the retained walls. When the inner walls are removed, displacement in X direction changes dramatically. A peak value is observed on the corner of the top floor, indicates this position should be properly treated during retrofit. It also shows that the displacements of the roof windows are large. Favorable connection between walls and trusses at this position is necessary.

Uneven settlement and oblique have a significant influence on wall displacements. It can be found that, Oblique of walls is more unfavorable then the Uneven settlement. Displacement of walls in X direction reach 63.78 mm when the oblique of 0.7% input. Propor control of the oblique and monitoring during the retrofit are necessary. And a threshold on actual oblique should be set under 0.6%. In procedure 2, wind load is imposed on the wall after completion of trusese. Displacements of walls are less than them in the same step of procedure 1.

The steel trusses are constructed on a rigid ground and the retained walls are built on reinforced foundation under the rigid ground. Calculation results of procedure 3 and procedure 4 show that, if walls and steel trusses deform together under uneven settlement and obliuqe, the stress will reduce and out-of-plane displacements will increase. Therefore, connections between reinforced foundation of walls and rigid ground should be ensured.

Analysis results of the four procedures show that, uneven settlement and oblique caused by excavation of ground soil have greater unfavorable effects on displacements and stress distributions of the walls. Partial damage of the walls is induced. Since uneven settlement and oblique can not be exactly predict, it is suggested to conduct excavation after wall reinforcement. During the excavation the settlement and oblique should be precisely monitored. The monitoring data can be used as boundary conditions for re-analysis by ANSYS if necessary. If deformation or stress value were over the threshold, additional reinforced measures should be taken before the excavation can be continued.

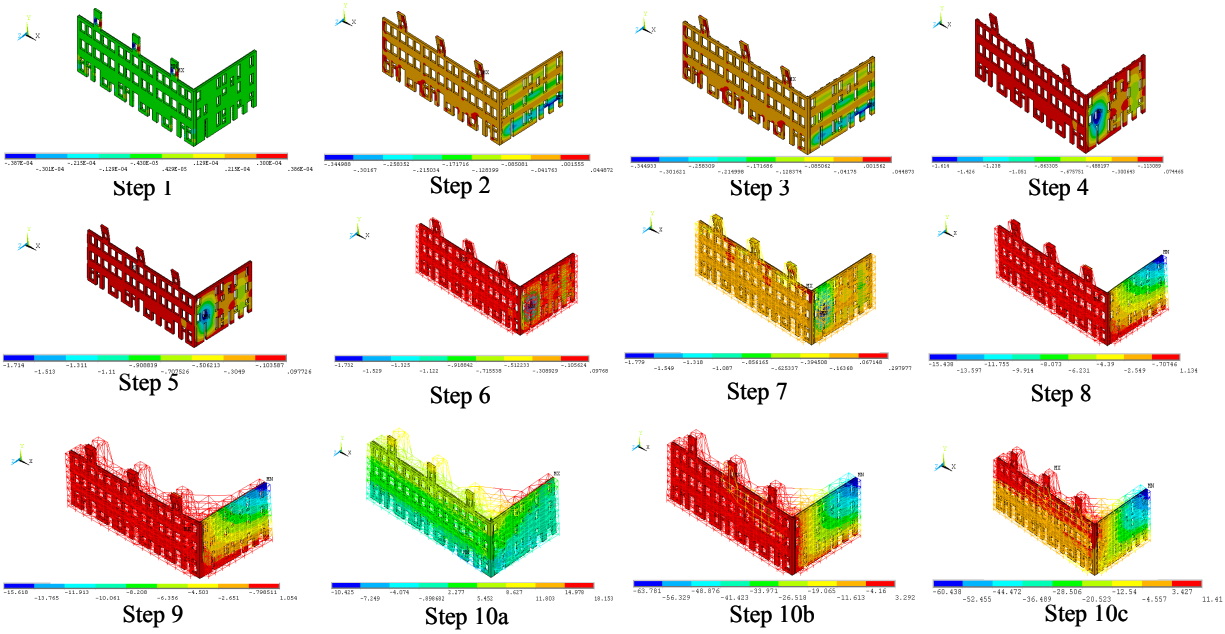


*Figure2: Displacements in x direction of strengthening procedure 1*

*Table 1: Displacements in X and Z direction of procedure 1-4*

| *Processes* | *Scheme 1(3)* | | | | *Processes* | *Scheme 2(4)* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Displacements in X direction* / mm | | *Displacements in Z direction* / mm | | | *Displacements in X direction* / mm | | *Displacements in Z direction* / mm | |
| | *minimal* | *maximum* | *minimal* | *maximum* | | *minimal* | *maximum* | *minimal* | *maximum* |
| 1 | -0.387e-4 | 0.386e-4 | -0.794e-5 | 0.926e-5 | 1 | -0.387e-4 | 0.386e-4 | -0.794e-5 | 0.926e-5 |
| 2 | -0.345 | 0.045 | -0.017 | 14.398 | 2 | ---- | ---- | ---- | ---- |
| 3 | -0.345 | 0.045 | -0.017 | 14.398 | 3 | -0.015 | 0.015 | -0.003 | 0.004 |
| 4 | -1.614 | 0.074 | -0.137 | 14.398 | 4 | -0.033 | 0.015 | -0.015 | 0.028 |
| 5 | -1.714 | 0.098 | -0.148 | 14.398 | 5 | -0.033 | 0.015 | -0.015 | 0.028 |
| 6 | -1.732 | 0.098 | -0.149 | 15.072 | 6 | -0.059 | 0.097 | -0.048 | 0.685 |
| 7 | -1.779 | 0.298 | -0.189 | 19.186 | 7 | -0.060 | 0.092 | -0.052 | 1.024 |
| 8 | -15.438 | 1.134 | -0.823 | 35.499 | 8 | -0.092 | 1.816 | -0.025 | 2.241 |
| 9 | -15.618 | 1.054 | -0.878 | 34.705 | 9 | -8.374 | 0.299 | -0.190 | 16.225 |
| 10a | -10.425 (-1.843) | 18.153 (18.138) | -16.083 (-16.595) | 16.785 (17.449) | 10a | -10.438 (-1.767) | 9.846 (9.961) | -10.309 (-1.055) | 19.429 (17.638) |
| 10b | -63.781 (-65.646) | 3.292 (3.471) | -135.540 (-137.952) | 1.595 (1.594) | 10b | -66.627 (-69.885) | 2.943 (3.118) | -115.313 (-117.781) | 2.403 (2.316) |
| 10c | -60.438 (-62.344) | 11.41 (11.713) | -132.991 (-135.917) | 15.215 (15.214) | 10c | -63.320 (-66.612) | 10.864 (11.198) | -112.766 (-115.749) | 15.312 (15.311) |

Note: Values in brackets are wall displacements taking into account co-deformation of the wall and steel trusses correspond to the procedure 1 and 2.

## Conclusions

Finite Element Analysis is used to predict the responses at each phase of the retrofit procedure, Considering changes of load distribution, stiffness distribution, and constraints. The unfavorable conditions can be found based on the results of the displacement, stress and strain values.

Through the analysis, the following conclusions can be made:

1) Change of displacement and stress is different at the phases of the retrofit procedure. Sudden increases are occurred during the removal of floors and inner walls. Therefore, real-time monitoring of displacement is necessary during the retrofit.

2)Excavation of ground soil has a significant effect on displacement of walls. It is necessary to monitor the settlement and oblique precisely and use these data as boundary conditions for re-analysis by ANSYS. If calculated deformation or stress were higher than the threshold, strengthening measures should be conducted before the excavation continues

3) During the retrofit, connections of walls and temporary steel trusses should be ensured. Stress concentration is predicted on the joints of steel trusses and walls, corner of walls and openings . Proper measures should be adopt on these parts.

4) Connections of rigid ground and reinforced wall foundations has a significant effect on deformation and stress distribution of the strengthened wall system. To reliably ensure the connections, the rigid ground and walls foundation should be casted together. To properly control the values of internal stresses, the oblique and deformation, monitoring should be conducted during the retrofit.

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