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STRENGTHENING METHOD OF UNREINFORCED MASONRY WALLS BY BRACE ELEMENTS

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The ductility and strength properties of lightweight steel brace element for structural strengthening of unreinforced masonry (URM) wall is reported in this study. The performance of URM wall without brace and with brace is evaluated by an elastoplastic nonlinear analysis including the yield criterion, flow rule and hardening rule. Masonry constituent is implemented into two-dimensional finite element model developed in Fortran code. The brittle failure of URM wall is analyzed using by an interface element to model bricks and joints. Two types of steel brace elements which can resist only tension and both tension and compression have been considered to increase the ductility of URM wall. The comparison between experimental and numerical results adopted in simplified-micro masonry modeling is illustrated with the relationship between force and displacement. The ductility and strength of masonry wall with the tension and the tension-compression brace element were different results of URM wall by in-plane pushover analysis. As for the simplification for a calculation of masonry wall, equivalent masonry model is discussed and besides diagonal brace elements, the additional vertical brace element is assumed for the high masonry wall by the numerical analysis.

Keywords: Masonry modeling, Joint element, Finite element, Elastoplastic analysis.

1 INTRODUCTION

Most of the low-rise buildings in Ulaanbaatar city, Mongolia covers the clay brick masonry buildings. After the Govi-Altai earthquake occurred in a remote area of Mongolia in 1957 (Mw 8.1), seismic building code for masonry structure of Soviet Union was being adopted in Mongolia until 1990. The unreinforced masonry buildings constructed before the Govi-Altai are still existing without strengthening throughout Mongolia. There is a need to enhance performance of their buildings under seismic load. Scientists noted that various influences of masonry structures depend on two different material properties and quality of workmanship (Lourenço and Rots 1997). As such, masonry modeling is complex. Also, the weak connection between brick and mortar is assumed to be the ability to not endure the tension force. To increase the ultimate strength and ductility of masonry wall, diverse strengthening methods are employed all over the world.

The purpose of this study is to develop a low cost and effective strengthening method. A suitable strengthening method is considered by the steel brace element. In our study, two types of brace elements are analyzed to increase the ductility capacity of masonry wall in the numerical analysis. The first type of the brace element only resists the tension force and the second type is the tension-compression brace element. Also, if the bending moment occurs in the wall, additional steel braces are installed in the vertical direction of the wall. Finally, the force-displacement relation of the numerical and experimental analysis was compared with braces and without braces for the brick wall.

2 FINITE ELEMENT ANALYSIS

In this study, the elastoplastic nonlinear analysis of a two-dimensional load-bearing masonry wall is highlighted in the finite element program. Simplified micro modeling is utilized in the finite element analysis to consider the failure mechanism (see Figure 1). The connection between brick and mortar is assumed together in the model because of presuming zero thickness of mortar (Lourenço 1996).

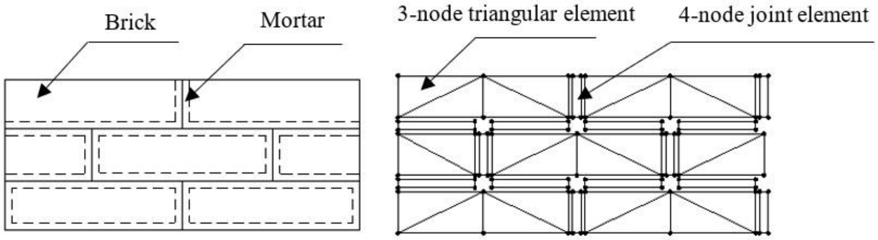

Figure 1. Finite element modeling of masonry structure.

Brick is discretized into 3-node triangular elements and joint elements in the vertical and horizontal direction are developed by 4-node interface elements in the finite element analysis to calculate a masonry wall. The interaction between brick and mortar displays the stress and displacement relation. It shows in Eq. (1) used in an elastic case.

$$\sigma = D^{e} \times \varepsilon \tag{1}$$

For a 2D formulation, $D^e = \mathrm{diag}[K_s, K_c]$, $\varepsilon=(\Delta u, \Delta v)^T$. k_s and k_c denote shear and compression stiffness of joint element, Δu and Δv are relative displacements. When defining the relation between stress and displacement, yield function for slip and potential function related to non-associated flow rule are adopted in the elastoplastic case. This means that the adhesion of brick and mortar is assumed in the present study. The non-associated flow rule presents in shear and compressive stress. Eq. (2) shows stress-displacement relation based on elastoplastic theory.

$$D^{ep} = \left[D^{e}\right] - \frac{\left[D^{e}\right]\cdot\left\{\frac{\partial Q}{\partial \sigma}\right\}\cdot\left\lfloor \frac{\partial F}{\partial \sigma}\right\rfloor\cdot\left[D^{e}\right]}{\left\lfloor \frac{\partial F}{\partial \sigma}\right\rfloor\cdot\left[D^{e}\right]\cdot\left\{\frac{\partial Q}{\partial \sigma}\right\}} \tag{2}$$

F is yield function for slip, *Q* is a potential function. Stiffness matrices of 3-node triangular brick elements and 4-node interface joint elements state the superposition principle in Fortran program developed on finite element analysis whereas global stiffness matrices for a system consider integrating the stiffness matrices of each element. It shows in Eq. (3).

$$[K]^{global} = \sum[K]^{brick} + \sum[K]^{mortar} \tag{3}$$

$[K]^{\mathrm{global}}$ – global stiffness matrices, $[K]^{\mathrm{brick}}$ – stiffness matrices of triangular elements and $[K]^{\mathrm{mortar}}$ – stiffness matrices of interface joint element.

3 STRENGTHENING METHOD

The purpose of this study is to choose a low cost and effective strengthening method. As for the unreinforced brick masonry wall, the shear capacity is low due to lateral loads. In order to increase the ductility of the brick wall, we chose the steel brace element to strengthen the unreinforced brick masonry wall. The tension brace and the tension–compression brace were computed for the unreinforced brick wall in the numerical analysis. Brace is installed by diagonal direction on the wall. As for the numerical analysis we considered a masonry sample developed by Raimakers and Vermelfoort. This wall size is 953 mm x 950 mm x 100 mm, a brick size is 204 mm 98 mm x 50 mm and mortar thickness is 10 mm in Figure 2. An analytical model of the masonry wall sample is exhibited with brace in Figure 3.

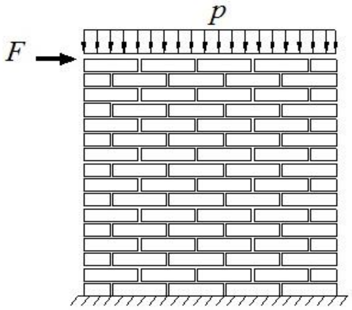

Figure 2. A masonry wall sample.

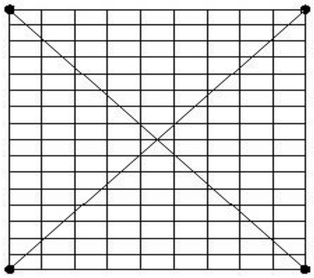

Figure 3. An analytical model of the masonry wall with braces.

The unreinforced masonry wall with 10cm^2 cross-section area of brace element was computed and compared with the brick wall without brace elements. The result of the numerical analysis with diagonal brace elements shows the load-displacement diagram by 300 kN/m^2 initial stress in Figure 4. Figure 4 emphasizes a relationship between the load-displacement of the wall compared with both braces and without braces. Masonry is brittle material. Therefore, the brick wall without braces are suddenly broken as shown in Figure 4.

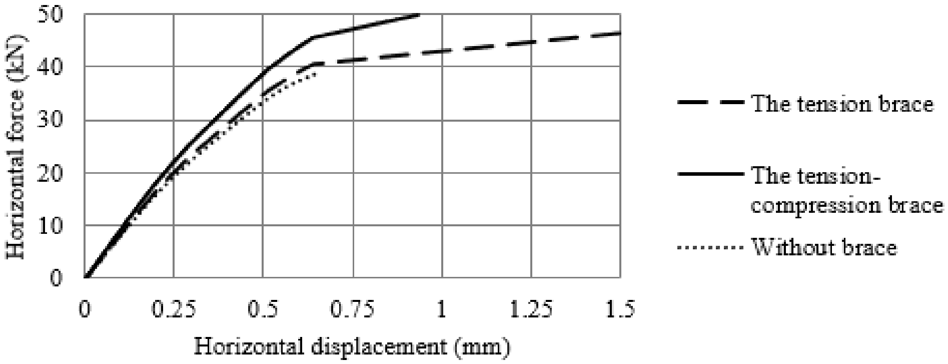

Figure 4. The load-displacement diagram of the brick wall with braces and without braces of the numerical analysis.

The brick wall with the tension braces can be more capable of bearing. The principal goal of brace elements is to enhance the ductility of the masonry wall. But the tension-compression brace element is not enough to increase the ductility capacity of the wall than the tension brace elements. If size of masonry wall increases in the vertical direction, the bending moment besides shear forces will happen in the wall under the lateral force.

Also, the data preparing is the time consuming for the simplified-micro modeling in the numerical analysis and a memory area of the personal computer needs a more large capacity. To avoid the circumstance, we considered the equivalent model of the brick masonry wall. The equivalent model is shown in Figure 5. In this model, three different types of wall (case A, case B and case C) were used to compare the effectiveness of an additional vertical bar element. Case A is the brick wall without brace elements. Case B is the brick wall with only diagonal brace elements. Case C is the brick wall with both diagonal and vertical brace elements.

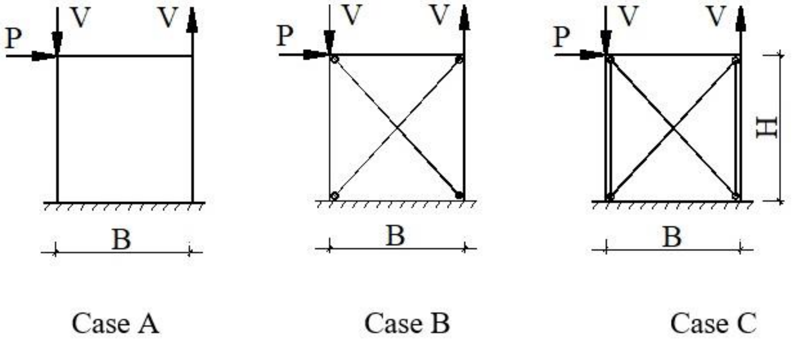

Figure 5. The equivalent model of the high masonry wall without braces and with braces.

If the solid brick wall (953 mm x 950 mm x 100 mm) is assumed one story, we increased it until five stories. Figure 6 shows the load-displacement relation of the top point of the five stories masonry wall (n=5) compared with cases A, B and C. As shown in Figure 6, the ultimate horizontal force of case C is four times more than case A and two times more than case B. Therefore, the vertical bar elements are effective to perform the lateral loads.

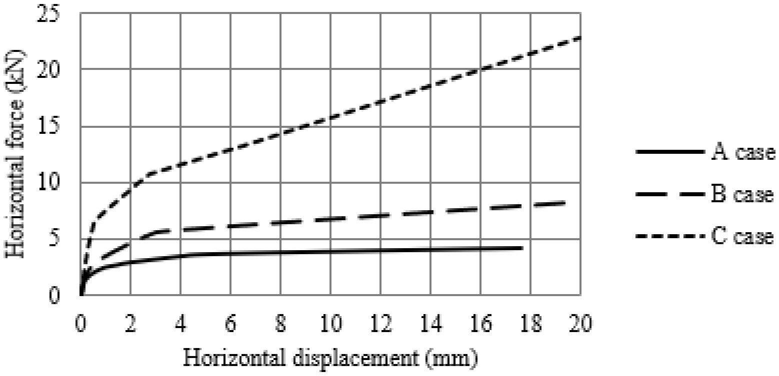

Figure 6. The load-displacement diagram of cases A, B and C (the story number n=5).

4 EXPERIMENT

4.1 Material Test

Experiments were conducted to define the elastic and inelastic properties of masonry material employed in this study. Cement sand ratio of mortar is 1:10 in this study. The test specimens were constructed by a brick size 210 mm x 100 mm x 60 mm. Elastic properties of the material (Young's module and Poisson's ratio of brick, and shear and compression stiffness of the joint element) were acquired in accordance with brick and mortar tests. Inelastic properties (frictional coefficient and cohesion of the joint element) were obtained from the brick–mortar interface test. Material test results are presented in Table 1.

Table 1. Elastic and inelastic properties of brick and joint element.

Element	**Elastic**				**Inelastic**	
	Young's module (MPa)	Poisson's ratio	Shear stiffness (kN/m^3)	Compressive stiffness (kN/m^3)	Frictional coefficient	Cohesion (kPa)
Brick	$1.567 \cdot 10^4$	0.13	-	-	-	-
Joint	-	-	$1.50 \cdot 10^6$	$3.45 \cdot 10^6$	0.54	40.5

4.2 Wall Test

To simulate empirical condition, the solid clay brick walls were tested under compression and an incremental lateral loads. The brick wall size is 650 mm x 480 mm x 100 mm and mortar thickness is 10 mm. Two types of wall (with brace and without brace) are tested to characterize the load-displacement relation. The steel brace used for this experiment is 9 mm diameter bar on both side of the wall face in Figure 7. An actual diameter of a bar element to perform due to lateral force is 7 mm. A load-displacement relationship in Figure 8 from finite element analysis have been compared with experimental values. The load-displacement diagram from the finite element analysis is an approximate with the experimental values of the URM wall. A result of the numerical analysis is slightly stiffer than the experimental result. This is related to model like homogeneous material for the finite elements as compared with the non-homogeneous real wall. The ultimate force presumed by the numerical analysis is 3.7 kN which is more than the force of 3 kN from the experiments.

Figure 7. The brick wall specimen without braces.

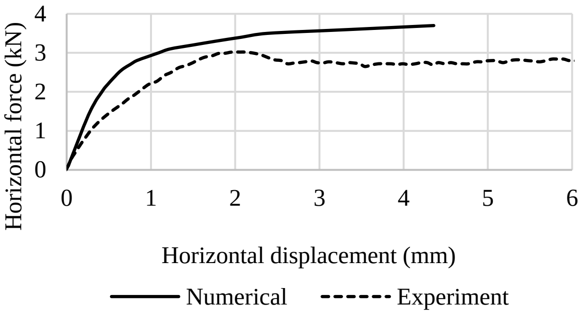

Figure 8. Load-displacement diagram of the brick wall.

The failure mechanism of the brick wall without brace element occupied the sliding of the bottom part of the wall (see Figure 9). This sliding shear failure usually reveals in case of the weak mortar, stiff brick and low vertical load (Tomaževič 1999). As for the wall with brace elements, there are not any damages to both joint element and brace element.

Figure 9. The brick wall specimen with braces.

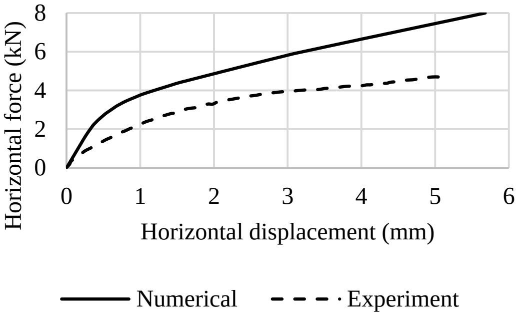

Figure 10. Load-displacement diagram of the brick wall with braces.

Figure 10 shows that load-displacement diagram of URM wall strengthened by braces. The numerical analysis is little higher than the experimental result. The ultimate force of the finite element analysis is 8 kN which is higher than 4.3 kN from the experimental data. It is also related to assume as homogenous modeling for the finite element analysis. Strengthening technique used by steel brace elements is significant to increase in-plane strength and ductility of the unreinforced brick wall.

5 CONCLUSION

This research emphasized the numerical analysis and experimental study of the unreinforced brick masonry wall without braces and with braces under the static vertical and horizontal forces. An elastoplastic non-linear finite element analysis was dealt with to presume the calculation of URM wall and URM wall with brace elements. The numerical results were received employing finite element software Fortran. Selecting the simplified micro modeling of masonry structure is appropriate to assess the failure mechanism and also, the simple finite elements is a reasonable model for assessing in the calculation. URM wall with the tension brace element is effective to increase the ductility capacity of the brick wall. But the tension-compression brace element increases the ultimate strength of the brick wall. The vertical bar elements reduce the bending moment influence than only using diagonal braces on the brick wall.

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