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A Macro-element Model for Nonlinear Analysis of Masonry Structures

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ABSTRACT: In this study, the macro modeling of masonry structures is used based on homogenous models, and an equivalent planar-frame model-based analytical method is proposed for masonry structure assessment. The equivalent frame model is a simple applicable approach that is almost accurate and time-saving. Also, it holds proper convergence compared to the exact analytical and experimental methods. In the formulation of beam-column elements, the distribution of nonlinearity is chosen. The nonlinear constitutive model is simulated in the cross-sections and also along the length by the usage of fiber elements. For the consideration of shear behavior, bed joint sliding mode of failure, and diagonal tension mode, a smeared crack approach-based interface element is developed in the MATLAB framework. To consider the seismic assessment of masonry walls, constitutive models are considered according to Instruction for seismic rehabilitation of existing buildings (No. 360) through a subroutine in the main program. The accuracy of the suggested approach is verified through a comparison of experimental results and existing analytical methods.

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1- Introduction

Due to the limited experimental and analytical information on the nonlinear behavior of masonry structures and the complexity of their behavior due to the probability of occurrence of different failure modes, more research with more detailed and comprehensive studies is needed. Various methods have been proposed or developed for modeling masonry members, among which, macro element modeling such as the fiber-element method has been considered by many researchers [1-5]. The fiber-element method uses the formulation of beam-column elements and enables axial and flexural interaction effects. Although fiber-element methods have sufficient simplicity in modeling the nonlinearity, due to not considering the effects of shear deformation, in cases where shear deformation modes govern the behavior of the structure, are not accurate enough in estimating stiffness, strength, and failure modes.

This study aims to provide a comprehensive but practical method for nonlinear simulation of unreinforced masonry structures as well as masonry members strengthened with a reinforced concrete layer. For this purpose, a fiber element-based model is proposed for equivalent frame modeling of the masonry structure. To consider shear behaviors including shear slip failure mode and diagonal tensile failure in masonry elements, as well as nonlinear shear behavior of reinforced concrete layer, an interface element based on smeared-cracking approach has been introduced and developed. The proposed method can describe different failure mechanisms with relatively appropriate accuracy and acceptable computational cost.

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2- Methodology

In this research, the weak formulation of the updated Lagrangian (UL) method is used to derive the finite element equations of a two-node Timoshenko plane beam element. The suggested approach evolves from cubic Hermitian polynomials, which has been well established by Bazoune *et al.* [6]. The main advantage of the developed expressions of shape functions over the classical shape functions is the shear deformation factors that can account for shear effects.

Also, two types of interface elements have been implemented in the main program. The first element is based on the shear analysis of membrane elements using the fixed smeared crack approach. The second element is implemented based on the behavioral model of Instruction for Seismic Rehabilitation of Existing Buildings (Code No. 360) [7].

3- Constitutive models

The elastoplastic fracture model of Maekawa and Okamura [8] has been used for concrete and masonry elements under compression. After cracking, the stiffness and strength of the element in the direction of compressive stress decrease. This is applied by applying a modification factor to the uniaxial behavior.

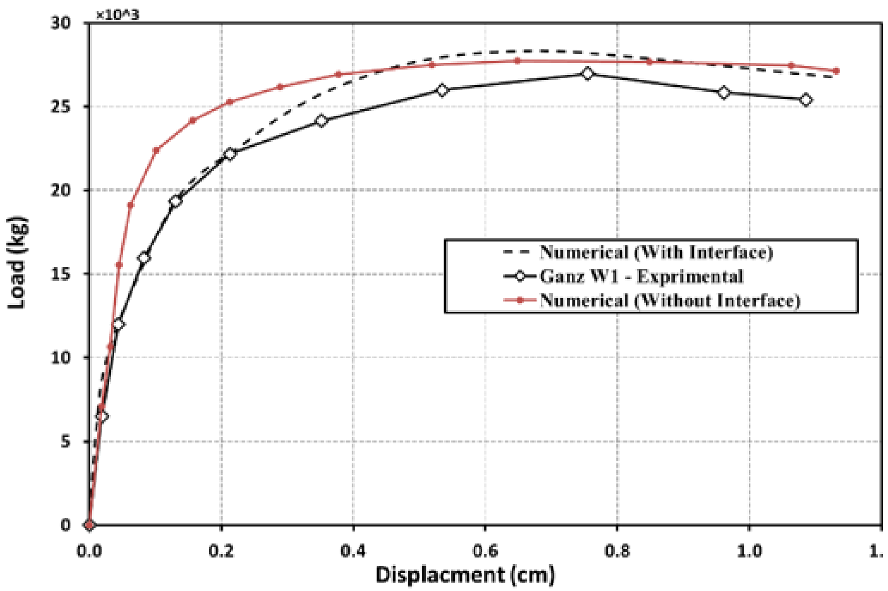

Fig. 1. Comparison of load-displacement diagram of the wall W1 tested by Ganz and Thürlimann

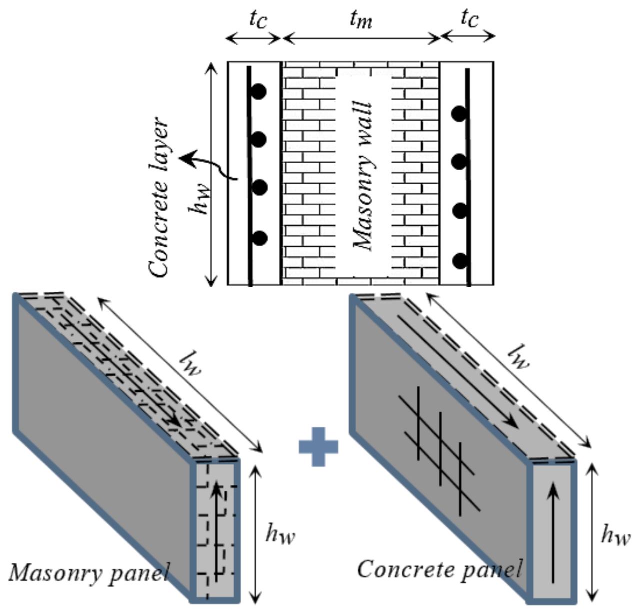

Fig. 2. Proposed procedure for masonry wall strengthening with reinforced concrete layer placed

The tensile behavior model has been considered in such a way that according to the governing failure mode with less strength, the sliding-tensile mode or the diagonal-tensile mode controls the tensile behavior of the element. If cracks occur in the joint between the mortar and the brick, a sliding ductile mode will form and if it passes between the brick and mortar, a diagonal tensile mode with low ductility will occur.

The shear behavior of the element is based on the contact density model of Li *et al.* [9]. This model, which was originally developed for the cracked concrete surface, can simulate the behavior of the stress transfer mechanism through aggregates interlock. The model is modified for masonry to simulate shear sliding along the mortar-brick interface.

4- Numerical Results and Solution

To validate and test the proposed method, several different experimental works have been selected for simulation, including unreinforced masonry walls tested by Ganz and Thürlimann [10] (Fig. 1) and Shah and Abrams [11] and also masonry wall with RC layers tested by Yaghoubifar [12] (Fig. 3). The iterative-incremental method (Arc-Length method) with a variable stiffness scheme was applied to analyze structures.

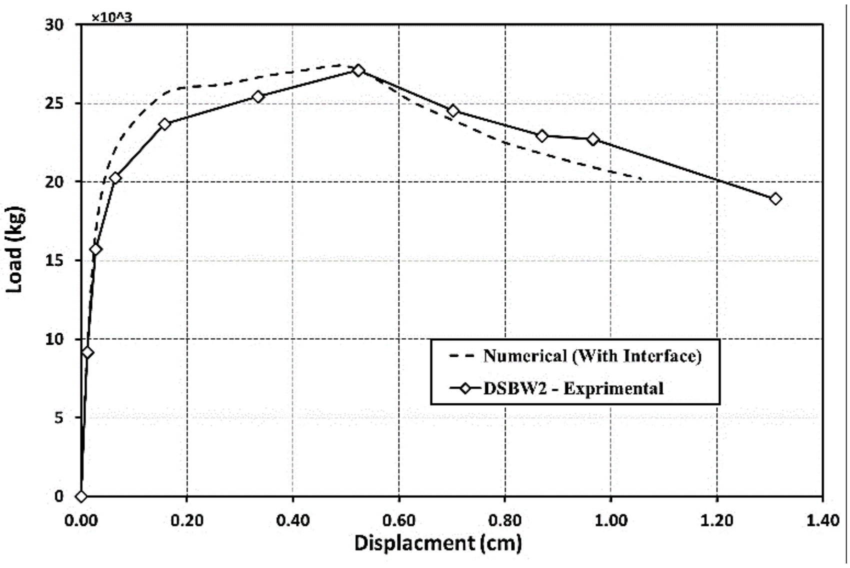

Fig. 3. Comparison of load-displacement diagram of the wall DSBW2 tested by Yaghoubifar

Based on the aforementioned aspects, the contribution of a masonry panel beside a concrete panel is obtained by definition of variable ζm for a masonry panel, and ζc for a concrete panel as Eqs. (1) and (2), and Fig. 2.‌ These parameters can control the participation of each panel in the shear capacity evaluation.

$$\zeta_m = \frac{t_m}{t_m + t_c} \quad \therefore \quad \zeta_c = 1 - \zeta_m$$
$$\{\sigma_{Gm}\} = {T_m}^T \zeta_m \{\sigma_{lm}\} \quad \therefore \quad \{\sigma_{Gc}\} = {T_c}^T \zeta_c \{\sigma_{lc}\} \qquad (1)$$
$$\{\sigma_G\} = \{\sigma_{Gm}\} + \{\sigma_{Gc}\}$$

$$[\boldsymbol{E_{eq}}]_G = \boldsymbol{T_m}^T \begin{bmatrix} E_{1m}\zeta_m & 0 & 0 \\ 0 & E_{2m}\zeta_m & 0 \\ 0 & 0 & E_{12m}\zeta_m \end{bmatrix} \boldsymbol{T_m} + \boldsymbol{T_c}^T \begin{bmatrix} E_{1c}\zeta_c & 0 & 0 \\ 0 & E_{2c}\zeta_c & 0 \\ 0 & 0 & E_{12c}\zeta_c \end{bmatrix} \boldsymbol{T_c} \qquad (2)$$

t_m and t_c are the thickness of masonry, and concrete panel, respetively. The components T_m and T_c are transformation matrix of the global and localoordinates for masonry panel and concrete panel. E_{1m}, E_{2m}, and E_{12m} are respectively local secant stiffness of masonry panel based on related constitutive models. Also, σ_{Gm} and σ_{Gc} are stress vectors in global coordination for a masonry panel and a concrete panel, respectively.

5- Conclusion

In this study, a macro model based on the equivalent frame method was introduced to simulate the nonlinear behavior of masonry structures. The proposed method in this research is based on the formulation of a fiber model with the effects of axial, flexural, and shear interactions in the domain of each element. Also, the method mentioned in the Code No. 360 was implemented in the interface elements. According to the results of the analysis, the proposed equivalent frame method, in addition to being applicable in concrete, masonry, or a combination of both, in linear and nonlinear ranges, has appropriate accuracy and acceptable convergence.

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