Simulation of the Dynamic Behavior of Masonry Structures using the Applied Element Method

University of Tokyo, Institute of Industrial Science, Student Member, Paola MAYORCA
University of Tokyo, Institute of Industrial Science, Regular Member, Kimiro MEGURO

1. Introduction

Masonry has being worldwide used since early stages of human life. Despite its long traditional use, past and recent experiences have shown that it is still one of the most hazardous types of building material. Especially, unreinforced masonry buildings have poorly performed during earthquakes leading to the complete collapse of the structures and a great number of casualties. One of the main reasons for this is that in most of the cases, the unreinforced masonry is used in rural areas of developing countries where they are erected on a traditional knowledge basis rather than on engineering criteria.

The damage to unreinforced masonry structures induced by earthquakes can be classified into four categories: (1) collapse of parapets, (2) corner damage, (3) out-of-plane collapse, and (4) in-plane cracking. The first category corresponds to the overturning of parapets and the consequent threat to the life-safety. The second one is produced by the biaxial stresses caused by the fact that the seismic forces do not coincide with the principal axes of the buildings. The third and forth category are caused by out-of-plane and in-plane loading of masonry walls, respectively.

Despite the damages observed during earthquakes, extensive research has concluded that masonry can efficiently sustain seismic loads if properly designed and constructed. Due to the large number of existing masonry structures that do not fulfill seismic resistance standards, research on strengthening and retrofitting techniques has been undertaken. In most of the cases, those studies have focused on the improvement of historical buildings [1,2]. Among the methods to upgrade masonry structures are: (a) filling of cracks and voids by grouting; (b) stitching of large cracks and other weak areas with metallic or brick elements or concrete zones; (c) application of reinforced grouted perforations to improve the cohesion and tensile strength of masonry; (d) external or internal post-tensioning with steel ties, to tie structural elements together into an integrated three dimensional system; (e) single or double sided jacketing by shotcrete or by cast-in-situ concrete, e.g. ferrocement; and (f) fiber-reinforced polymers. The applicability of these techniques in areas of scarcity of materials and economic limitations is a matter of discussion. In these cases, the use of locally available materials and technologies could most likely lead to economic and efficient strengthening methods with a great impact on the earthquake disaster reduction.

Compared to other construction materials, masonry has a great variability around the world. Not only due to the different characteristics of its components, block and mortar, but also due to the different construction practices. In addition to these issues, the element arrangement has a great influence on the behavior of the overall structure. The great variability of the material together with the limited economic resources make it difficult to carry out experimental studies for all types of existing masonry. If, in addition, the use of locally available materials for strengthening is considered, the possibility of testing each retrofitting proposal is even less likely. For this reason, the numerical simulation appears as a powerful tool to discuss the vulnerability of a wide range of structures as well as to design appropriate countermeasures.

The overall objective of the present research is to propose efficient and economic techniques of strengthening of masonry structures with emphasis on the use of locally available materials by using numerical simulation to verify the suitability of the proposed methodologies. This paper reports the currently attained progress.

2. Methodology of the study

In order to achieve the overall objective, the research is divided in four stages: (1) development of a numerical technique for the analysis of masonry structures, (2) modification of the numerical technique to include the retrofitting effects, (3) optimization of the solution based on the parametric study using the numerical tool, (4) preparation of the environment to make the simulation tool readily available through the INTERNET. In order to validate any numerical technique, it is indispensable to compare numerical and experimental results. For this purpose, a series of tests of strengthened and non-strengthened masonry will be executed on the shaking table recently acquired by the Institute of Industrial Science. The results of these experiments will be complemented with the data from previous experimental

Key Words: Masonry, strengthening, AEM, retrofit, earthquake, numerical simulation
Contact Address: 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Tel. 03-5452-6385, Fax. 03-5452-6476

researches. At the present time, the research is on its first stage, namely, development of the numerical simulation for masonry structures.

3. Numerical simulation

The development of an efficient and accurate technique of structural analysis of masonry structures is a complex task due to the heterogeneity of the material as well as the non-linearity of its components, moreover, if it is used for a performance-based design in which the understanding of the non-linear behavior of the structure is important. There are basically two approaches for the analysis of masonry structures: micro modeling and macro modeling. In the first case, bricks and mortar are represented by continuous elements while the behavior of the mortar-brick interface is represented by either discontinuous elements or discontinuities. In the second case, the bricks, mortar and interfaces are globally represented by the same element.

Lopez et al (1999) [3] proposed a homogeneous constitutive model (macro model) for masonry, which is based on a study of the compatibility and equilibrium of a "basic cell" of masonry under different loading conditions. The constitutive model is based on the formulation of equilibrium and compatibility equations for each of the deformation modes of the basic cell and the constitutive equations of each material component. In this way, expressions for the stress-strain behavior of the composite, as well as the homogenized mechanical parameters are obtained. The advantage of the method is that it permits a simplified treatment of masonry and leads to a simple mesh generation, which considerably reduces the computation time. However, this model is not capable of identifying the fracture mechanisms. In general, the disadvantage of the macro modeling is that the non-linear response (ultimate load and mode of failure) cannot be accurately followed. For the purpose of the present study, the non-linear response is a key issue for the discussion of the efficiency of the strengthened structures. Therefore, it was decided to adopt the micro modeling.

The micro modeling of masonry can be readily implemented in the Applied Element Method (AEM) [4]. The AEM is a new technique of structural analysis that can simulate the structural behavior from load application until total collapse of the structure. For the analysis, the system is virtually divided into a series of elements, carrying only mass and damping of the system, connected with normal and shear springs representing the material properties. The stress and strain fields are calculated from the spring deformations. The AEM is particularly suitable for the analysis of masonry structures. The brick and mortar constitutive models are assigned to two different types of connecting springs, which are distributed according to the brick pattern. In such a way, the anisotropy of the masonry is considered.

The adopted failure criterion is the linearised "cap-model" (see Fig 1). A comprehensive discussion on masonry failure criteria can be found in [5]. Laboratory tests show that mainly three types of failure modes are activated in masonry panels: shear failure of bed joints (g_{L1}), compression strength of masonry (g_{L2}), and tensile strength of masonry (g_{L3}). Failure criteria g_{L1} and g_{L3} are applied to the mortar springs whereas criterion g_{L2} is used for the brick springs.

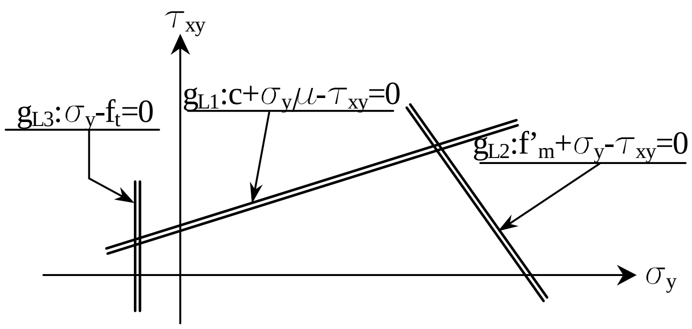

Figure 1. Linearised "cap model" for unreinforced masonry wall (f_t: mortar adhesion, c: mortar shear strength, f'_m: block compression strength)

The necessary modifications to the AEM source code are currently being carried out to account for the above-mentioned features of masonry. The results of the analysis will be reported at the annual conference of the JSCE.

References

[1] Triantafillou, T. C., Fardis, M. N., 1997, Strengthening of historic masonry structures with composite materials, *Materials and Structures*, **30(202)**, 486-496.

[2] Ballio, G., Structural preservation of the Fraccaro tower in Pavia, 1993, *Structural Engineering International, Journal of IABSE*, **3(1)**, 23-29.

[3] Lopez, J., Oller, S., Oñate, E., and Lubliner, J., 1999, A homogeneous constitutive model for masonry, *International Journal for Numerical Methods in Engineering*, **46**, 1651-1671.

[4] Tagel-Din, H. and Meguro, K., 2000, Applied Element Method for simulation of nonlinear materials: theory and application for RC structures, *Structural Eng./Earthquake Eng., JSCE*, ******, ***-***.

[5] Andreaus, U., 1996, Failure criteria for masonry panels under in-plane loading, *ASCE Journal of Structural Engineering*, **122(1)**, 37-46.