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A model for the out-of-plane dynamic analysis of unreinforced masonry walls in buildings with flexible diaphragms

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ABSTRACT

This paper proposes a model for simulating the dynamic behaviour of slender external walls of unreinforced masonry buildings with flexible diaphragms subjected to out-of-plane bending. The proposed model is characterized by two degrees of freedom (2DOF) and allows to perform time-history analyses in order to study the influence of diaphragm flexibility on the displacement capacity and demand of walls in out-of-plane bending. The wall has been modelled as an assemblage of two rigid bodies connected by an intermediate hinge and restrained at the top by a spring: the damping has been modelled through the introduction of the coefficient of restitution. The equations of motion of the 2DOF system have been derived and integrated in the time domain. Dynamic analyses of a set of walls subjected to Gaussian impulses and recorded ground motions have been performed in order to compare the response of the simply supported wall with that of the wall with an elastic spring at the top.

1. Introduction

The observation of damage produced by earthquakes on historical unreinforced masonry buildings pointed out that out-of-plane collapses of the external walls are frequent and very dangerous even in terms of loss of human lives. Historical buildings are in fact characterized by weak connections between the different structural elements and tend therefore to exhibit local collapses before global ones. During earthquakes single parts separate from the rest of the building, often behaving as quite independent structural elements. The study of the behaviour of such mechanisms is then essential and has been undertaken by many authors. Different approaches have been proposed, like static, kinematic or dynamic analyses, elasto-plastic, no-tension or rigid models. The experimental tests have been concentrated mainly on the simplest failure modes because of their simpler reproducibility and interpretation (parapet wall or simply supported wall). Among the experimental tests performed in the past on one-way bending, ABK [1] is to date the largest laboratory campaign and still remains a primary source for seismic codes and guidelines [2]. With reference to other experimental works, Meisl et al. [3] considered a poor bond between units and mortar in order to simulate an historic masonry. Based on this study Sharif et al. [4] suggested a revision of the ASCE 41 [5] height-to-thickness ratio limits. Wilhelm et al. [6] and Dazio [7] accounted for very weak mortar and different boundary conditions. Derakhshan et al. [8,9] compared experimental results with previous models and performed in situ testing.

Housner's work [10] represented the basis of the dynamic studies on the wall as a single rigid block. Other studies followed the one of Housner and delved into this topic [11–15]. Some analytical and experimental studies [16–21] highlighted the necessity of dynamic analysis in order to understand the real behaviour of walls in out-of-plane bending and to assess, without an over conservative approach, the vulnerability against earthquake action. They pointed out the fact that out-of-plane failures of walls are caused essentially by an excessive displacement demand rather than force or acceleration demand and that static methods, focused on the comparison between forces and resistance, cannot then account for some specific aspects related to the dynamic behaviour. In order to improve static strength-based procedures, some authors [22,23] proposed also corrected approaches to account for strain.

Almost all previous works considered simplified hypotheses about the interaction of the wall with the rest of the building, assuming diaphragms as rigid and reducing therefore the complexity of the dynamic problem and the number of the degrees of freedom [24,25]. The path of the seismic action from the ground to the out-of-plane walls implies both a filtering effect of the shear walls and a diaphragm response [26]: when the diaphragms cannot be considered as rigid, like in most historical buildings, it is

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necessary to consider multi-degree-of-freedom (MDOF) instead of the usual single-degree-of-freedom (SDOF) models.

There are few studies [27–33] that take directly into account the influence of flexibility of diaphragms on the displacement capacity and demand. In this research some formulations proposed by other authors [16,20,27] are extended in order to develop a 2DOF model for the analysis of the dynamic out-of-plane behaviour of a single wall with the hypothesis of flexible diaphragm. The proposed approach differs from that by Simsir et al. [27] and Derakhshan [32] because it accounts directly for the finite thickness in the modelling of the upper and lower portions of the wall. It considers also that the intermediate hinge could be at any position along the height, instead at 2/3 of the height. Considering a finite thickness allows to describe different possible configurations of the two portions of the wall, following the change of the position of the base and intermediate hinges on the internal or external side of the wall. These different configurations correspond then to different sets of equations of motion.

In the research presented here the equations of motion of the wall have been derived on the basis of the mentioned different configurations, and an algorithm for their numerical integration has been developed. This paper describes in particular the characteristics of the algorithm, the validation with available experimental data and the results of some preliminary applications. In these analyses the filtering effect of the shear walls has been neglected. Anyway this effect can be included in the model, so it will be one of the goals of future developments of the research. Since the objective of the paper is the presentation of the model, the preliminary analyses have been performed in order to calibrate the model and to highlight the differences with more simplified and widely used models.

2. Description of the model

A 2DOF model has been developed with the purpose to analyse the dynamic out-of-plane behaviour of a single wall, with an intermediate hinge and an elastic translational spring at the top. The wall, as shown in Fig. 1, is modelled as an assemblage of two rigid bodies, a lower and an upper part, each one free to rotate around the intermediate hinge.

In Fig. 1 W_1 and W_2 are the weights of the lower and upper part of the wall, W_d is the overburden load from the diaphragm, K_d is the translational stiffness of the spring at the top that simulates the in-plane stiffness of the upper diaphragm and is considered perfectly elastic, q_1 and q_2 are the rotations, respectively of the lower and the upper portion of the wall related to the axis orthogonal to the plane of movement, which have been assumed as independent variables.

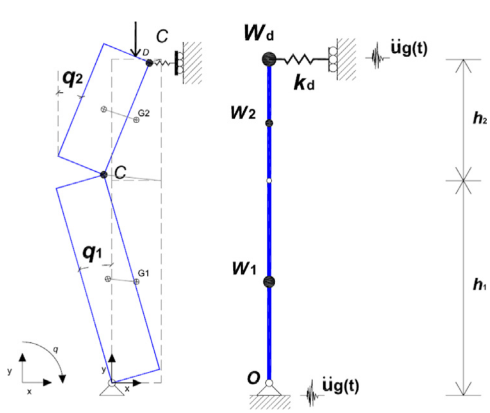

Fig. 1. 2DOF model of the wall in out-of-plane bending.

The total height of the wall is h while the thickness is b. The model is assumed already cracked with the formation of the intermediate hinge at a generic height h_1 from the base. The lower and upper parts of the wall are then characterized by the heights h_1 and h_2, with $h = h_1 + h_2$. The overburden load is applied with a generic eccentricity e with respect to the middle of the thickness. The clockwise rotations of the two parts of the wall are assumed as positive.

3. Equations of motion

The equations of motion of the 2DOF system have been derived by applying the Lagrange equations, considering the kinetic energy due to the translational velocities of the masses and to the rotational velocities of the two parts of the wall around the respective centroids and the potential energy due to the translational spring at the top and to the contribution of the gravitational loads. The above mentioned quantities have been calculated with the assumption of small displacements.

3.1. Possible geometric configurations

The equations of motion are highly nonlinear because of the sudden change of the point of rotation at the base and at the intermediate hinge. There are four different conditions described by four corresponding sets of equations (see Fig. 2). The passage from one condition to another is determined by an impact at the bottom or at the intermediate hinge associated with the change of the centre of rotation (see Fig. 3).

Every time q_1 passes through the zero, there is an impact at the bottom and a change of the centre of rotation (O to O' or O' to O): similarly, every time $q_1 = q_2$ there is an impact at the intermediate hinge and a change of the centre of rotation (C to C' or C' to C).

3.2. Energy dissipation

Following the Housner's model [10], the dissipation of energy is concentrated at every impact at the base of the wall and is modelled through the introduction of the coefficient of restitution, $e_r < 1$, that relates the velocities after each impact to those immediately before, reproducing the loss of kinetic energy at each impact.

3.3. Derivation of the equations of motion

The following relationship illustrates the fundamental equations of Lagrangian dynamics, in the hypothesis that the potential energy does not depend on velocity and in absence of damping, which in the Housner's model (adopted in this study) is concentrated in the impacts, thus affecting only the initial conditions at every cycle:

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_i}\right) - \frac{\partial E_c}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \tag{1}$$

where E_c represents the total kinetic energy, V is the total potential energy and Q_i are the generalized forces corresponding to the generalized coordinates q_i (that are q_1 and q_2). The equations of motion are therefore a system of two equations in the two variables q_1 and q_2:

$$\begin{cases} \frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_1}\right) - \frac{\partial E_c}{\partial q_1} + \frac{\partial V}{\partial q_1} = Q_1 \\ \frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_2}\right) - \frac{\partial E_c}{\partial q_2} + \frac{\partial V}{\partial q_2} = Q_2 \end{cases} \tag{2}$$