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Analytical model for the dynamic response of blast-loaded arching masonry walls

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ABSTRACT

The dynamic response of arching masonry walls subjected to blast loads is rather complex and is accompanied by different physical aspects such as: opening/closing of cracks, unloading-reloading effects, and variable arching force magnitude and line of action with time. The longitudinal and lateral inertial forces result in a coupled in-plane/out-of-plane dynamic response. These aspects, which are not considered in present single-degree-of-freedom (SDOF) models for masonry walls simulation, enhances the wall behaviour modelling and make the dynamic analysis complex and challenging. This article presents the development procedure of a new simplified yet realistic SDOF model for the one-way dynamic response of such walls. The model is based on a new recently developed analytical model for calculating the static force-displacement relationship, which is implemented within the equation of motion. Geometric and material nonlinearities, together with loading/unloading paths in the mortar material are considered, and their effect on the dynamic response is investigated. Results of this model were compared with available test results of one-way arching URM walls exposed to blast loads. The model well predicts the maximum peak displacement as well as the overall displacement-time history within the inbound phase. New insights regarding the test specimens and the dynamic characteristics affecting the arching wall behavior are gained.

1. Introduction

1.1. General

The use of unreinforced masonry (URM) walls is common in the construction of building envelopes and interior partition walls. Generally, and especially in modern construction, these walls are not intentionally designed to function as structural elements that contribute to the global stiffness and strength of the structure. Nevertheless, their stiffness and strength do provide an ability to resist loads to a certain extent, and undoubtedly to interact with the structural building system and affect its overall response. When exposed to exterior lateral blast, their relative large surface area and their limited ability to resist out-of-plane loads create a potential large-scale problem. Therefore, it is of great interest to understand the behavior of URM walls under such conditions, to reduce the hazard of damage, and to increase the safety of occupants.

The construction method of the URM wall has a significant effect on its structural behavior. The boundary conditions of a URM wall that is built before casting the surrounding structural elements are different from those of a URM wall built inside an already existing frame. The difference is attributed to the possible lack of contact at the upper and side edges of the wall in the latter case. However, when the URM wall is in contact with the frame element at its top, a membrane thrust force, commonly known as the ‘arching action’, can develop during a vertical wall one-way bending action under lateral loading (when the wall is supported at its bottom and top edges and isolated from the side columns), yielding a much higher resistance to the out-of-plane loads [1]. A more complex two-way bending may develop when restraints are provided between the wall and its side columns due to contact between the wall and the side columns. The two-way action is beyond the scope of this paper.

Different retrofitting techniques of masonry walls are reported [2–4] in the context of in-plane response of such walls to lateral loads. Recent studies on the out-of-plane response of URM walls to lateral loads have presented two approaches for enhancing their out-of-plane resistance. The first approach deals with strengthening techniques using composite materials such as FRP (Fiber Reinforced Polymers) for providing the wall with tensile resisting reinforcement [5,6]; this approach mainly aims at enhancing the wall bending performance. The second approach is enforcing the arching action by restraining the upper edge of the wall and preventing its in-plane movement. The latter approach

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may significantly improve the URM wall performance even under the action of blast loads [7]. Findings of several works have shown that arching URM walls could resist out-of-plane loads practically as well as strengthened walls did [8,9]. However, the dynamic behavior of arching URM walls under blast loads is more complex and has gained less attention than non-arching or strengthened URM walls.

Studies dealing with the out-of-plane dynamic behavior of arching URM walls [10,11] have indicated that under such loads, the response is accompanied by different physical aspects such as: opening and closing of cracks, unloading-reloading effects, and variation with time of the arching force magnitude and the location of its line of action. Another phenomenon that characterizes the out-of-plane dynamic response of these URM walls is the rocking effect, in which the point of contact between adjacent masonry units shifts from one side of the mortar joint to the other. The longitudinal arching and rocking effects also yield significant longitudinal inertial forces that result in a coupled in-plane/out-of-plane dynamic response. These aspects contribute to the complexity of the dynamic behavior of these masonry walls and make the dynamic analysis of these walls challenging.

1.2. Experimental studies

The behavior of masonry walls subjected to free-field explosions has been studied through experimental investigations in a number of studies [6,12–14]. Most of these studies aimed to investigate the out-of-plane capacity of non-arching URM walls, or to evaluate the strength increase when fiber-reinforced polymers were used as a retrofit technique [13,15]. Other studies [16,17], evaluated the effect of frame flexibility on the arching mechanism and the consequent infill wall capacity.

The effect of the arching mechanism on URM wall resistance to blast loads was demonstrated in several experimental works. Gabrielsen et al. [18] performed extensive blast tests on arching URM walls. The tests showed that arching walls are considerably stronger, by as much as four to five times, than non-arching walls. Gabrielsen et al. [16,19] also conducted shock-tunnel tests including arching walls with an initial gap at the upper support that was closed during the wall response. The investigation revealed that such walls were significantly weaker than the arching walls without an initial gap, as expected.

Many of the conclusions in the above-mentioned studies were based on visual observations of the physical damage inflicted on the URM wall. Yet, very few experimental works [7,20,21] aimed at investigation of the pre-failure dynamic response of arching URM walls subjected to blast loads. Gagnet et al. [21] published experimental results of the response of non-arching and arching URM walls exposed to blast loads. The displacement-time histories demonstrated the significant effect of the arching phenomenon on the dynamic response, as the arching walls developed considerably smaller peak displacement than the non-arching walls. Their study showed that if arching action is enabled but ignored in the analysis, a significant amount of energy absorption would be omitted, resulting in significant under-prediction of the blast load capacity of the URM wall.

Abou-Zeid et al. [7] conducted field experiments with ANFO charges that were detonated at various scaled-distances away from one-way URM walls. It was concluded that enabling URM walls arching between rigid supports significantly enhances their out-of-plane blast resistance compared to similar non-arching (flexural) URM walls. According to displacement measurements at the back face of the walls, the study [7] revealed that the deflected shape at the inbound stage of all tested arching walls resembled a symmetric three-hinged-arch pattern. However, for the rebound stage of the response, this typical deflected shape was no longer valid as two additional hinges were detected at $h/4$ and $3\,h/4$ along the wall height (h).

Dynamic response that is characterized by the three-hinged-arch mechanism was also obtained in the experimental work conducted by Li et al. [22,23]. In their study, the behavior of unreinforced clay brick masonry walls under gas explosion was examined and discussed by full-scale field test and numerical simulations. They concluded that because of the relatively long pressure duration, the response mode of masonry walls under gas explosion loads is similar to that under quasi-static loadings. Moreover, they revealed that the thickness and boundary conditions of masonry walls also significantly influence the response.

Eamon et al. [24] qualitatively demonstrate that the typical three-hinged-arch mechanism, as obtained in Abou-Zeid tests [7], depends on the blast pressures intensity (although the actual blast loads were not reported). In addition, the resulting modes of behavior and failure may change at various combinations of peak pressure and impulse. In this study [24], different modes of failure were qualitatively demonstrated, corresponding to several ranges of blast pressures. It was shown that the typical three-hinged-arch mechanism developed at low intensity blast pressures, whereas different other mode types developed at higher blast intensities. The different modes were expressed by the development of additional hinges along the wall height.

1.3. Analytical studies

Although arching URM walls possess infinite degrees of freedom, the dynamic analysis of such walls to blast loads has been commonly based on the assumption that one mode predominates the response [14,25–28]. The experimental instrumented results reported above show that a three-hinged-system may represent the wall geometry during its response until reaching its maximum deflection whereas more complex deflection modes may develop then after. The early response of the wall is of major importance as it indicates the maximum deflection in the inbound phase, enables to follow the internal stresses and damage evolution and to determine whether the wall will follow a rebound phase or be breached. Thus, the three-hinged-arch mode is considered to pre-define the behavior of the arching URM wall and has the advantage that the problem may be simplified by a single-degree-of-freedom (SDOF) system whose properties are those of the assumed fundamental mode of the wall. Basically, this approach assumes that the wall behavior may be characterized by the typical three-hinged-arch mode, in which the two segments of the wall rotate with respect to the cracked cross sections.

Different studies included the development of SDOF models for the dynamic analysis of strengthened masonry walls [26,28], reinforced masonry walls [27,29], and arching URM walls [21,25]. In many works (e.g. [25,26,29,30]), the equation of motion includes an inertia term and a resistance term. The latter commonly adopts the static load-displacement curve, which is often calculated using over-simplified assumptions. More comprehensive description and details about existing models for obtaining static force-displacement curves can be found in a previous work by Edri and Yankelevsky [31]. The experimental work of Abou-Zeid et al. [7], which included deflection measurements along the blast-loaded wall height, shows that the use of the simplified three-hinged-arch mode response of arching URM walls can be justified, at least for the inbound stage, and for the blast load range examined in their tests. An attempt made by Abou-Zeid et al. [25] to model the wall response using an SDOF representation was based on a rigid-body analysis. The equation of motion was formulated by the requirement of mechanical equilibrium including the acting blast load and the resultant inertial forces. Further efforts [25] were made to use a 2DOF model to represent the different behavior mode that was experimentally observed at the rebound stage [7]. This analysis was in reasonable agreement with the experiment in the early stage of the response, whereas relatively large deviations exist at a later stage of the deflection time-history. Only slight differences are observed in the calculated response of the SDOF and 2DOF analyses. It should be mentioned that different attempts were made in these papers to calibrate the static stiffness components to enforce better matching with the test results, for both SDOF and 2DOF systems. These calibrations were done by arbitrarily tuning the initial stiffness of the static force-displacement curve,