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Rigid block and spring homogenized model (HRBSM) for masonry subjected to impact and blast loading

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ABSTRACT

In the present study, a simple and reliable Homogenization approach coupled with a Rigid Body and Spring Model (HRBSM) accounting for high strain rate effects is utilized to analyse masonry panels subjected to impact and blast loads.

The homogenization approach adopted relies into a coarse FE discretization where bricks are meshed with a few elastic constant stress triangular elements and joints are reduced to interfaces with elasto-plastic softening behaviour including friction, a tension cut-off and a cap in compression. Flexural behaviour is deduced from membrane homogenized stress-strain relationships by on-thickness integration (Kirchhoff–Love plate). Strain rate effects are accounted for assuming the most meaningful mechanical properties in the unit cell variable through the so-called Dynamic Increase Factors (DIFs), with values from literature data. The procedure is robust and allows obtaining homogenized bending moment/torque curvature relationships (also in presence of membrane pre-compression) to be used at a structural level within the HRBS model, which has been implemented in a commercial software. At structural level, the approach resorts to a discretization into rigid quadrilateral elements with homogenized bending/torque non-linear springs on adjoining edges.

The model is tested on a masonry parapet subjected to a standardized impact and on a rectangular masonry slab subjected to a blast load. In both cases, a number of previous results obtained by literature models are available for comparison, as well as experimental data. Satisfactory agreement is found between the present results and the existing literature in the field, both experimental and numerical.

1. Introduction

Masonry is an ancient and still widespread construction material [1]. Unreinforced masonry (URM) buildings are very common in the urban historical centres which allow them to usually foster an intrinsic historic and cultural value [3]. Besides the cultural importance, or at least the historic one, URM buildings can have also an important economic and societal value, being still used as commercial, services or housing buildings. However, these are typically vulnerable to out-of-plane failures even for low forces applied [2]. This highlights the importance of their maintenance and conservation, but also the need of mitigating excessive risk by making them more prone to resist dynamic actions such as earthquakes, impacts, explosions or other possible extreme loading cases.

In recent decades, a great deal of effort has been made to develop solutions to reduce destructive damage and casualties due to blast loads and impacts (also in light of a major protection of the built heritage against terrorist attacks). Needless to say, masonry structures are in the majority of the cases rather vulnerable to explosions and impacts. In this regard, the scientific community is eager to share advanced numerical studies conceived for a better understanding of the blast/impact structural response of masonry walls [8,11–13]. This is achieved in conjunction with a quantitative insight into the behaviour of the masonry material at high strain rates [4–9], also in regard of an optimal strengthening with innovative materials allowing for a safety increase [10].

Bearing in mind specifically high-strain rate loads, research was conducted to increase the insight of the behaviour of structures when subjected to these extreme cases. The city bombing event in Oklahoma (1995) addressed the importance to carry on such studies, being the target the decrease of potential casualties and buildings damage. Experimentation is still nowadays at a higher level than numerical modelling in this field. Even if more attention was

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devoted to concrete [14–16,29] and steel [17,18] structures, some different experimental campaigns are also available for masonry. For instance, some works regarding masonry panels subjected to blast loads [6,19–21], and impacts [22,23] are worth mentioning.

It is known that URM walls subjected to dynamic loads can resist accelerations higher than their static strength, the so-called dynamic stability [24,25]. Additionally to the fact that the use of static or quasi-statics approaches preclude the consideration of important dynamic phenomena (see [25]), existing research proved that assuming static material properties could lead to an underestimation of the bearing capacity of structures [26,27]. Therefore, according to the applied load strain rate, material properties may exhibit a dynamic enhancement [28] which is of the most importance for blast and impact loads.

Thorough experimental campaigns are difficult to carry out due to the involved costs. This brings the need of developing numerical models that may predict with accuracy the dynamic response of structures. Simple models based on a single degree of freedom (SDOF) systems could be found in the literature to study the dynamic behaviour of structures subjected to blast loading [20–21,30]. These are easy to use and practical-oriented, allowing a fast evaluation of the approximate collapse load value. They constitute helpful tools for large structures in case studies, albeit conclusions upon structures damage, deformed shape and debris velocity are not possible.

More advanced strategies, for instance the typical 1-scale Finite element (FE[1]) based models allow more accurate solutions, overcoming in part the latter drawbacks. The classical approaches are still macro- and micro- models [31,32]. They differ in the mechanical scale level of analysis consideration. In the former method, masonry is considered as a fictitious homogeneous material without an explicit distinction between units and joints. It is useful to study large structures but it lacks in accuracy at a local scale and demands a considerable number of parameters calibration [33]. In the latter method, the description of the micro-structure of masonry is modelled, meshing bricks and mortar separately. Hence, both constitutive materials are represented with complex models describing the behaviour in the elastic and inelastic range [34].

Micro-modelling allows obtaining results with great accuracy, but the complexity at the modelling stage and the considerable computational time required at the processing stage makes it more suitable for the analysis of masonry walls with small dimensions [35]. Still, simplified micro-modelling FE approaches are found in literature. As example, Eamon et al. [6] applied such strategy to study concrete masonry walls under one-way bending induced by blast loads. Several simplifications aiming at a reduction of the computational cost regarding mesh size, element type and material properties were undertaken. Despite that, the authors obtained noteworthy results. Likewise, Burnett et al. [26] introduced a simplified micro-modelling approach and implemented into a finite element software. The strategy was based on a simple masonry contact interface model, but proved to reproduce with fair accuracy the response of a masonry wall subjected to an impact load.

Homogenization methods are in-between with these two modelling FE schemes [36–39] and constitute a promising alternative. Homogenization is basically aimed at studying the structural problem at different scales [40]. Research on the topic showed the clear advantages of this process, both at a quasi-static and dynamic range, see for instance [37,41,42] and [7,43,44], respectively. Concisely, a mechanical characterization of masonry at a cell-level is firstly achieved and the resultant information is then transferred as averaged quantities to be used at a structural-level. Hence, according to the intrinsic complexities assumed, masonry texture (orthotropy) may be envisaged, together with the nonlinear behaviour and softening of its constituents, both at tension and compression, without the need of a thorough discrete representation of bricks and mortar joints at a structure level. The homogenization strategy, the so-called multilevel, multi-scale finite element method or as FE[2] approaches, appears to be an interesting procedure once non-linear analyses can be conducted with an acceptable trade-off between results accuracy and computational time-cost [41].

In this context, the present paper addresses a simple two-step procedure within the scope of homogenization approach. The strategy was validated already for quasi-static purposes in [45]. Aiming to achieve a better insight regarding the behaviour of masonry walls under high-rate loading, the model is herein extended for the out-of-plane dynamic analysis range.

The novelty introduced is focused on the implementation at a meso-scale of a simple procedure, embedded on the homogenization scheme, which accounts for the strain-rate dependency of material properties via a dynamic increase factor approach. The simple bespoke Homogenized rate-dependent model is coupled to a commercial software package (ABAQUS [46]) through a novel Rigid Body and Spring Mass model (denoted hereafter, HRBSM). The procedure directly allows the use of the obtained rate-dependent homogenized curves with material softening by exploiting the commercial software built-in capabilities.

Insomuch, the strategy is intended to be a fast and an accurate solution predictor tool. Thus, the following assumptions are made: (i) the adoption of a simplified micro-modelling FE displacement-based approach for the meso-scale step that limits the computational effort required to find homogenized quantities; (ii) the implementation of a novel HRBSM model at a macro-scale in a commercial software like ABAQUS [46], in which powerful built-in procedures are already at disposal and; (iii) the use of a discrete FE (HRBSM) model whereas the elements that carry the upward-scale transfer of information are linear ones, simplify the procedure and avoid numerical convergence problems.

Also, the strategy offers the possibility to spread the work to a wide range of potential stakeholders, from researchers to engineering practitioners. Its validation will be achieved through comparison with experimental results on masonry structures subjected to blast and impact loads ([22] and [47], respectively).

2. Meso-scale

2.1. Out-of-plane homogenized model

A multi-scale homogenized–based approach is assumed for the study of masonry panels subjected to different load types. Such strategy lies on the periodicity feature of a given media and it is therefore a suitable strategy for masonry [48]. First, a meso-scale mechanical characterization on a representative volume element (hereafter, RVE) is achieved by solving a boundary value problem (BVP). Then, the macroscopic constitutive response is accomplished through the assemblage of these RVE units. The strategy allows defining the mechanical properties of each material at the unit cell only, obtaining the inelastic stress and strain response by introducing considerations at the component level. Such framework is schematically described in Fig. 1 and poses noticeable advantages. Masonry texture is indirectly represented at a macro-scale by an approach that resorts to a RVE micro-scale description with first-order kinematics keeping a relatively low computational effort.

The present out-of-plane homogenization model is based on the initial in-plane identification of an elementary cell. The main features will be explained in what follows and, for further information of the quasi-static approach, the reader is referred to [49] and [45]. Please note that the description will be made for the arrangement of the units (texture) presented in Fig. 2, namely a running bond texture.

In brief, homogenization consists in deriving the upper-scale properties by introducing averaged quantities for macroscopic strain and stress tensors (E and Σ, respectively) obtained at a micro-scale