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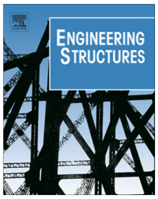

Blast resistance of tuff stone masonry walls

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ABSTRACT

Gas explosions frequently occur in residential buildings inducing the out-of-plane collapse of single structural components which may trigger the progressive collapse of the structure. In this study, the out-of-plane collapse capacity of load-bearing tuff stone masonry (TSM) walls subjected to blast loading is investigated. A finite element macro-modelling strategy was adopted and dynamic analysis was carried out through LS-DYNA software to derive pressure–impulse diagrams for blast resistant design and assessment. Different modelling assumptions were considered. A sensitivity analysis allowed the evaluation of the influence of vertical pre-compression level and aspect ratio of TSM walls on blast collapse capacity. Numerical predictions of blast capacity were then compared to those provided by simplified analytical models, design code pressures and peak pressures estimated after real incidents.

1. Introduction

A large fraction of the world's population live in buildings constructed with load-bearing masonry. There is a wide range of variety for the application of masonry such as load-bearing walls, partition walls, infill walls of framed structural systems, and many other applications. Load-bearing masonry walls are especially used for low-rise buildings in several countries, but they may be particularly vulnerable to dynamic loads such as earthquake, explosion, and impact actions. In the case of blast and impact loads, load-bearing walls may suffer out-of-plane failure mechanisms and trigger the progressive collapse of the structure, namely a partial or total collapse mechanism that is disproportionate to an initial local damage [1]. This is also reflected by the catastrophic consequences of explosive events that often take place in residential buildings as a result of accidental gas leaks from the building utility service system, inducing loss of life and heavy damage to property. Even from a historical point of view, the structural engineering issue of progressive collapse initiated in 1968 with a natural gas explosion that occurred at the 18th floor of a 22-storey residential apartment tower with precast load-bearing wall panel construction, namely the Ronan Point Tower in Canning Town, London. The initial failure of an exterior load-bearing wall panel led to loss of support of upper floors, which fell down and impacted over the lower floors causing progressive collapse of the building corner [2]. Leyendecker and Burnett [3] carried out one of the first studies on the frequency of gas explosions in residential buildings located in USA, reporting that natural gas explosions are the most significant abnormal loads in terms of incidence. Indeed, those researchers estimated: (1) an annual average number of gas explosions equal to 1217; (2) a mean annual rate of explosion conditional upon gas leakage equal to $3.85 \cdot 10^{-3}$; (3) a mean annual rate of occurrence $\nu = 18 \cdot 10^{-6}$/dwelling unit/year for gas explosions in house buildings, regardless of their effects in terms of losses; (4) $\nu = 2.5 \cdot 10^{-6}$/dwelling unit/year for gas explosions causing moderate damage, i.e. an economic loss greater than USD1000; and (5) $\nu = 1.6 \cdot 10^{-6}$/dwelling unit/year and $\nu = 1 \cdot 10^{-3}$/apartment building/year (corresponding to 2 gas explosions causing severe damage per week) for gas explosions causing major damage, i.e. an economic loss greater than USD10,000. In Italy, a recent (unpublished) document by the Italian Gas Committee reported 464 gas accidents causing explosions and fire in residential buildings (out of 1381 total gas accidents) over the period 2006–2013. In 2013, the fatality rate of gas accidents in Italy was $7.5 \cdot 10^{-2}$ whereas the injury rate was 2.3. In the Netherlands, ν turns out to be $5 \cdot 10^{-6}$/dwelling/year [4]. All such data emphasise the high socio-economic impact of investigating the resistance of structural components of residential buildings against gas explosions, as a basis for disaster risk assessment and mitigation. In the framework of a multi-risk approach to the safety of structures against progressive collapse [5], these data highlight that gas explosion represents a hazard typology that deserves further investigation in structural engineering, to be explicitly considered into structural design and assessment methodologies.

In the last decade, several studies have been carried out to assess the dynamic response of masonry walls to explosive loads. Special emphasis has been given to the out-of-plane behaviour of

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unreinforced masonry (URM) walls made of concrete masonry units (CMUs), considering both as-built and retrofitted configurations [6–16]. In many cases, infill masonry walls subjected to detonations have been investigated by means of analytical/numerical approaches and experimental tests. From a theoretical standpoint, blast damage to URM walls may be predicted through nonlinear dynamic analysis of single-degree-of-freedom (SDOF) systems or numerical models. For instance, Olmati et al. [17] assessed the probability of exceeding different limit states through Monte Carlo simulation and equivalent SDOF models of non-structural precast concrete wall panels subjected to bomb detonations. Conversely, other researchers such as Eamon et al. [6] performed nonlinear time-history analysis of CMU walls by using finite element (FE) micro-mechanical models where masonry units and mortar joints were distinctly modelled. In detail, the presence and behaviour of mortar joints were taken into account by means of unit-mortar interface elements, namely weak contact elements with zero thickness. Eamon et al. also found a good theoretical–experimental comparison for the specific case of CMU walls.

In the case of other masonry assemblages, only a few experimental and theoretical research studies have been carried out. Wei and Stewart [18] performed numerical simulations on clay brick URM walls through LS-DYNA software [19], where a dynamic plastic damage model including strain rate effects was used for bricks and mortar. Those researchers found that boundary conditions and wall thickness significantly affected the blast response of the case-study walls. The boundary condition with pinned top section and fixed base section was found to be the most conservative assumption in terms of collapse capacity. Given a magnitude of the blast load, pinned-fixed masonry walls were subjected to one-way bending and reached the maximum level of deflection and damage with respect to fixed–fixed walls. Conversely, the maximum level of blast resistance was found in the case of masonry walls which were pinned or fixed along their perimeter, thus allowing two-way bending resisting mechanisms and damage levels significantly lower than those expected for walls subjected to one-way bending. Riedel et al. [20] investigated the nonlinear response of brick masonry walls with openings under two types of explosive loads, separately, that is bomb detonations and gas explosions. Finally, Pereira et al. [21] tested URM infill walls using confined underwater blast wave generators and developed a nonlinear FE model to derive pressure–impulse diagrams for blast-resistant design.

In this paper, the out-of-plane behaviour of load-bearing tuff stone masonry (TSM) walls subjected to blast loading as a result of gas explosion is explored. Since ancient times, TSM has been widely used for instance in Mediterranean countries for load-bearing walls and vaults in buildings, and more rarely for infill walls of reinforced concrete (RC) framed buildings. In many cases, cultural heritage constructions and public office buildings are made of load-bearing TSM walls, highlighting the need for structural assessment against both accidental and deliberate explosive loads. In this study, a numerical investigation on TSM wall response to gas explosion loads is presented and compared to simplified analytical models, design code pressures and peak pressures estimated after real incidents.

2. Methodology

The main goal of this work was to develop a numerical model for dynamic response analysis and collapse safety assessment of TSM walls subjected to gas explosion loads. The lack of experimental data on this type of walls and loads motivated a numerical investigation by means of LS-DYNA software [19], which is an advanced computer program for structures subjected to impulsive and dynamic loads. A macro-mechanical FE model was developed for tuff stone masonry. The macro-modelling approach is based on the assumption of an equivalent homogeneous material for the whole masonry assemblage without distinguishing between masonry units and mortar joints [22]. Although this strategy does not provide suitable predictions of local response within masonry, including failure mechanisms that involve the interface between bricks and mortar, it strongly reduces the computational work and provides acceptable results when macroscopic response predictions are needed and a large number of analyses must be run. The suitability of homogeneous FE material models for masonry walls was assessed, for instance, by Wong and Karamanoglu [23] that found a very good agreement between numerical results and specific experimental data on masonry walls subjected to gas explosions.

Unreinforced TSM walls that collapse as a result of out-of-plane one-way bending failure were investigated so both geometry and boundary conditions of the FE model were set up accordingly. Several hundreds of explicit dynamic simulations were carried out on TSM wall sub-assemblages subjected to triangular pressure time-histories with the peak overpressure occurring at half the duration of the impulse, in order to simulate gas explosion loads [24,25]. Different values of peak overpressure and impulse duration were considered. In that context, it is emphasised that close-in blast pressures for structural assessment are provided by some building codes such as Eurocode 1 (EC1) – Part 1–7 [25] and Italian Building Code (IBC) [26], where uniform lateral loading is assumed over all walls of a closed building volume, acting as an equivalent static loading condition. Nevertheless, no specific rules for dynamic response analysis or pressure–impulse (*P–I*) diagrams are provided by those codes to allow structural assessment for the ultimate limit state of life safety or near collapse. Therefore, the main output of this research is the direct derivation and comparison of *P–I* diagrams at near collapse. As shown in Fig. 1, each *P–I* diagram is an iso-damage hyperbolic curve that provides the combinations of peak overpressure and impulse corresponding to the same level of damage, such as low damage (LD), medium damage (MD) and near collapse (NC). The pressure and impulse levels of a *P–I* combination associated with a prescribed damage level are herein termed critical pressure (P_{cr}) and critical impulse (I_{cr}). In detail, the *P–I* diagram defines the failure conditions in three regions of structural behaviour associated with impulsive, dynamic and

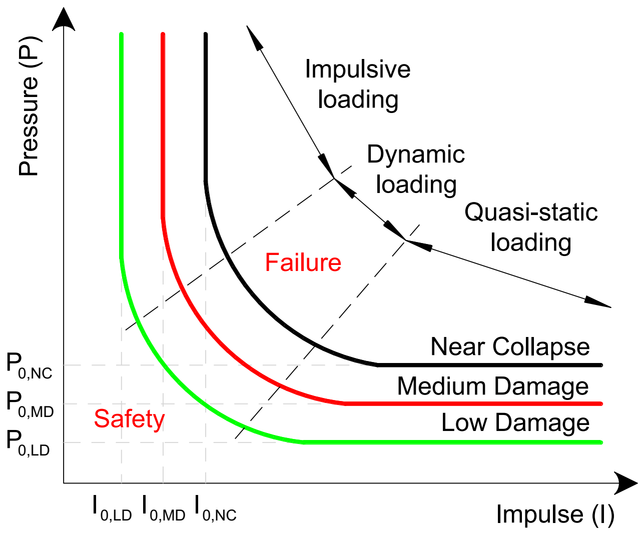

Fig. 1. Typical pressure–impulse diagrams associated with increasing levels of damage.