Variability in masonry behaviour and modelling under blast and seismic actions

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**Abstract**

This paper presents a state-of-the-art review of the existing analytical and numerical modelling approaches available for masonry structures that are subjected to blast and seismic events; from basic single-degree-of-freedom (SDOF) models to three-dimensional multi-degree-of-freedom models. The primary aim of this paper is to demonstrate the need to adopt a probabilistic/uncertainty approach when analysing masonry structures, thus considering the inherent variability in design and construction. This review forms part of a larger research project, initiated to characterise uncertainties in masonry response to blast actions.

**Keywords** **chosen from ICE Publishing list**

Brickwork & masonry; Risk & probability analysis; Dynamics

**Introduction**

Masonry structures have been used over the world for centuries. During their design life, masonry structures might be subjected to seismic and blast events. Being able to fully quantify how such structures perform when subjected to these events is paramount to the provision of efficient and safe design solutions. Research on the structural behaviour and design of masonry spans back to last century, however, general ‘rules of thumb’ have been established over several centuries.

Masonry is a heterogeneous material, formed by masonry units joined together with or without mortar. These are generally referred to as masonry components. Masonry is known to exhibit strength enhancement and nonlinear anisotropic behaviour when subjected to rapidly applied loading conditions. Analytical or numerical models of masonry should accurately capture these characteristics, along with representative degradation and failure mechanisms (Linse and Gebekken 2010). While several models have been developed to study the structural behaviour of masonry, model selection is often based on factors such as engineering judgment, the required accuracy and output, loading conditions, computational time and/or technical capability of the analyst.

Replicating the behaviour of masonry under blast and seismic actions is challenging and difficulties in model validation are commonplace, especially after cracking and degradation are observed. Difficulties stem from the challenge of incorporating high levels of mechanical, physical and construction variability into the models. The modelling and validation process sometimes involves model updating over numerous iterations to account, for example, for the lack of perfect bonding at the brick-to-mortar interface (Vermeltfoort and van der Pluijm 1991). Frequently, should test conditions change, the model’s accuracy cannot be assumed. The scarcity of physical data in the open literature regarding masonry component properties and the need to have well-defined key parameters for model inputs are acknowledged in (Linse and Gebekken 2010). Deterministic approaches are widely used, despite such high levels of variability, which leads to under or over-designed masonry structures.

To build a model that can sufficiently capture reality, it is important to understand how masonry structures are likely to behave under the actions to which they may be subjected and how uncertainties in the modelling process may affect forecasting. The current paper identifies key areas where uncertainty quantification and propagation methodologies may be applied in the future, including a state-of-the-art review of modelling approaches.

Section 2 focuses on masonry behaviour (sources of variability and failure mechanisms); Section 3 describes different modelling approaches; Section 4 highlights other sources of variability, Section 5 introduces probabilistic tools that have been used in masonry modelling and Section 6 summarises this paper and proposes future work.

**2. Variability in masonry construction and behaviour**

Masonry units have varied material properties, dimensions and shape. An extensive list of those can be found in (Hendry and Khalaf 2003). Mortar is used to bond masonry units, prevent water penetration and provide an even distribution of stresses (Jones 2015). When masonry structures are subjected to horizontal and/or vertical in-plane actions, failure can occur in the masonry units, mortar or both; depending on the stiffness of the different components. A schematic of the typical failure mechanisms of masonry under in-plane actions (vertical or/and horizontal) is reproduced in Figure 1. The overall strength of a typical masonry wall or building will vary depending on its water absorption capabilities, level of workmanship, weathering processes, the type of masonry components that are used and boundary conditions.

High water content in mortar is desirable in that it enhances workability in its wet state. However, the lower the water content in the mortar hardened state, the higher the compressive mortar strength (CEMEX 2008; Linse and Gebekken 2010) and associated brick-to-mortar interface strength. The brick-to-mortar interface shear strength is also affected by the level of water absorption in masonry units: with 80% saturation value, the mean bond strength reaches its highest value under static loading (Sarangapani, Venkatarama Reddy et al. 2008). Mortar that is stronger than masonry units (i.e. with a higher tensile, compressive or shear strength depending on the mode of failure), is not desirable either, as these masonry units will be prone to cracking when failure occurs, making future repairs costly (CEMEX 2014; Sarangapani, Venkatarama Reddy et al. 2008). An optimal balance is required with regard to mortar water content.

(PCA 1997) detailed standard tests for determining mortar properties under static loading and on site. However, site made mortars are less common due to the need for more accurate mixing processes. Quality assurance guidelines are present, mostly in developed countries, to establish good practice in masonry construction. The application of these guidelines is, however, rather subjective and can be difficult to achieve. Furthermore, weathering processes can also affect masonry strength. If the voids in the fine aggregate are not properly filled with binder, water penetration can reduce durability. The presence of the afore mentioned is responsible for the defects on masonry structures which may lead to changes in masonry strength (Hendry and Khalaf 2003).

Out-of-plane actions, such as those arising from blast or seismic events, subject the affected structure to bending, i.e. the face of application experiences compression whereas the opposite side of the wall or structure experiences tension. If masonry bonds have low tensile strength, very little bending resistance can be achieved (Linse and Gebekken 2010). Boundary conditions influence the ability of masonry to resist out-of-plane actions by developing arching behaviour. For structures subjected to out-of-place actions, stiffer supports and axial loading can reduce the maximum displacement. Failure occurs either by crushing or when rigid bodies separate from each other due to tensile failure in the mortar (see Figure 2 where the blast load is assumed to exert a uniform pressure). The failure of a wall is likely to be a combination of arch compression and tensile splitting of the mortar. This behaviour is generally modelled by splitting the wall into two rigid body elements that rotate about their supports after the first cracks appear. The effectiveness of arching action for eight full scale vertically spanning unreinforced masonry walls under blast loading was investigated in (Abou-Zeid, El-Dakhakhni et al. 2011). All walls were visually inspected after blast shocks - it was found that the out-of-plane resistance was enhanced by the arching conditions. No out-of-plane-shear failure was observed for the walls that developed arching behaviour (one of the specimen walls was used as a control wall, where no arching mechanism developed).

The influence of brick surface characteristics (altered by adding frogs and coatings) on the brick-to-mortar interface strength is shown in (Sarangapani, Venkatarama Reddy et al. 2008). There it was found that weak mortar with a good bond, enhanced by the treatment of the brick surface with coatings such as epoxy resin, can often perform better than stronger mortar with poorer bond strength. Key findings included: 1) flexural bond strength increases with mortar strength for all masonry unit types 2) composite mortars have a better bond strength 3) the moisture content of a brick at the time of layering affects the amount of water absorbed from the mortar. This study was conducted on Indian masonry, where mortar was generally stiffer than the masonry units. A large coefficient of variation in compressive brick strength was found during this work. This was attributed to a lack of quality control in the manufacturing process as well as a large coefficient of variation in the flexural bond strength for walls constructed on site (Sarangapani, Venkatarama Reddy et al. 2008).

The reasons outlined in the previous paragraph lead to variability in brick-to-mortar interface strength and interfaces that are not fully bonded. In (Vermeltfoort and van der Pluijm 1991) it was found that partial bonding influences tensile strength. In (Burnett, Gilbert et al. 2007) numerical models that accounted for 75% fully bonded brick-to-mortar interface surfaces gave closer results to experimental data than models that had a 100% bonded interface.

Masonry components have also been found to exhibit dynamic strength enhancement when subjected to high strain rate loading. High strain rate loadings arise from dynamic or impact loadings and they imply a large rate of deformation in the material under loading. This is generally due to the rapidly applied stresses on the structure. The relationship between strain rate loading and masonry component strength has been investigated by (Hao and Tarasov 2008; Pereira, Dias et al. 2013), where an increase in masonry unit and mortar ultimate strength ocurred when strain rate loadings increased. However, there was high variability present in the testing.

This section has highlighted that masonry has high variability under static and dynamic loading, which is affected by the interaction between its components (water absorption, level of workmanship, etc.) Consequently, to fully characterise masonry behaviour, it is necessary to consider the interactions between the properties of the masonry units *and* mortar as well as incorporating the variability present.

**3. Modelling approaches**

Section 3 highlights the diversity in techniques for modelling masonry under blast and seismic events.

***3.1 Analytical approaches***

The approaches described here generally require low computational times but disregard local behaviour, post-cracking behaviour and degradation effects. Additionally, the aforementioned variabilities with regards to material properties and failure mechanisms are not considered.

Experimental tests on masonry have shown dynamic strength enhancement when subjected to high strain rate loading (Chan and Bindiganavile, Schuler, Mayrhofer et al. 2006; Burnett, Gilbert et al. 2007, Linse and Gebekken 2010, Pereira, Dias et al. 2013). Consequently, a common approach to design for dynamic loading is to conduct a linear static analysis of a structure and apply dynamic increase factors (DIFs) to the static strength of the masonry. Such factors are derived from experimental tests (Linse, Gebbeken et al. 2012). As experiments are generally conducted for individual components, DIFs might not account for interface behaviour and so their applicability needs to be treated with caution.

SDOF models simplify complex systems into equivalent single-degree-of-freedom-systems (see Figure 3). Load and mass transformation factors are defined by equating the work done, strain energy and kinetic energy of the complex system and the equivalent SDOF system for both elastic and plastic behaviour (Cormie, Mays et al. 2012). End rotations and maximum displacements are calculated. Cracks or stresses in the material and brick-to-mortar interface effects are not considered. Such an approach is recommended for masonry design under blast actions by UFC-3-340-02 (USACE 1990), however, only concrete masonry unit (CMU) walls in running bond with single or multiple leaves are considered. Dynamic properties are specified for concrete and reinforcement but not neither for mortar nor grout. Recent updates have incorporated masonry strength, local effects such as spalling and quality of masonry construction (USACE 2014). It should be noted that, similarly, complex systems can be simplified into SDOF models to analyse their behaviour under *seismic loading*. This is done, for example, by using the capacity spectrum, proposed by (Freeman, Nicoletti, et al. 1975), to forecast the maximum displacement of a structure for a given earthquake (where special attention is paid to irregular shaped buildings (Kuramoto, Teshigawara et al. 2000)).

SDOF models are the foundation of some spreadsheets and software packages which are used to design structural elements under air blasts. These include SDOF Blast Effects Design Spreadsheets (SBEDS), developed by Protection Engineering Consultants senior principal Chuck Oswald and distributed by the U.S. Army Corps of Engineers; or Oasys Ergo, developed by Arup. These packages allow the user to define boundary conditions, load time-history data and resistance functions. However, there is currently no accurate method to determine resistance functions for CMU walls. Similarly, the engineer must make judgments with regards to the behaviour and modelling of cavity walls (such as how mass or stiffness is accounted for) (Browning, Davidson et al. 2008)

Pressure – Impulse (P-I) diagrams are iso-damage curves that show the pressure and impulse combination required for a specific level of damage (Cormie, Mays et al. 2012; Baylot, Bullock et al. 2005). They are usually obtained from using simplified elastic SDOF models (Li and Meng 2002), or experimental testing. Any combination of pressure and impulse that falls on the left or below the P-I curve, is considered to be safe for the given structure. P-I diagrams can be divided in three regions: impulse controlled, peak load and impulse controlled and peak load controlled only, depending on whether the duration of the load is longer, similar or shorter than the natural period of the structure (quasi-static loading, dynamic loading or impulsive loading) (Figure 4).

***3.2 Numerical modelling***

There is neither a universal numerical method nor a single classification for the modelling of masonry. This section illustrates the variability in modelling assumptions associated with a number of numerical methods.

A review of masonry modelling approaches under seismic events is presented in (Calderini, Cattari et al. 2010). As part of the Perpetuate programme, which aims to develop European guidance for cultural heritage buildings. Four main categories of models are established, based on the scale of the analysis and the description of masonry continuum. The first consist of two or three-dimensional continuum constitutive laws using a smeared crack approach, plasticity laws, homogenisation procedures or multi-scale analysis. The second are structural element models, which mostly consider in-plane responses (e.g. equivalent frame methods). These two approaches are referred to as macro-models in the current paper (Figure 5a). The third are interface models, where masonry units and joints are modelled separately. These are referred to as detailed (mortar is discretised) and simplified micro-modelling (mortar is not discretised) in this paper (Figure 5b and Figure 5c). Macro-blocks models, which are mostly used for historical buildings, are not covered here.

*3.2.1 Macro-modelling*

Macro-modelling approaches treat masonry as a homogeneous material, either by smearing its properties or by characterising a representative volume element (RVE). A main drawback is the difficulty in obtaining homogenised material properties from testing. The variability present at the brick-to-mortar interface is not accounted for.

The choice of homogenised material model is usually driven by the software used. An elasto-plastic strain hardening model available in ABAQUS was used in (Pandey and Bisht 2014) to investigate the effect of varying contact friction between masonry infill walls and reinforced concrete (RC) frames for structures subjected to blasts. A Mohr-Coulomb yield and failure criterion, characterised by three stress invariants, with non associated plastic flow of cohesive-frictional material with both internal friction and dilatational effects were added into the model. It was found that higher levels of contact frictionreduced the wall’s dynamic reponse. A parametric study for different blast actions and wall thickness was also conducted in (Pandey and Bisht 2014) where variability in material properties was acknowledged but not accounted for. Input and output data were obtained from previous experiments in (Varma, Tomar et al. 1997), where the output was validated against other modelling work (Wei and Stewart 2010).

In (Dafnis, Kolsch et al. 2002) shaker table tests were used to study how the out-of-plane behaviour of infill masonry walls (within RC frame) related to boundary conditions at the top of masonry walls. Masonry was modelled homogenously with linear elastic plane elements, as a concrete slab, using ANSYS. Areas prone to cracking were represented by contact surfaces, with two translational degrees of freedom. Material properties were either measured from the tests or taken from literature (but it was not specified which values were used in the model). Results were in reasonable agreement; however modelling assumptions for the boundary conditions were made after wall testing, i.e. with knowledge of the expected behaviour.

(Wei and Hao 2009) obtained DIFs for strength, Young’s modulus and shear modulus in different directions for a RVE of masonry. This was used to develop a homogenised numerical model that accounted for strain rate effects. No comparison with experimental data was provided and potentially broad assumptions were made (e.g. DIFs the same for compression and tension). The RVE model was validated against the results obtained from a homogenised numerical model.

*3.2.1 Micro-modelling*

*3.2.1.1 Simplified micro-modelling*

Simplified micro-modelling discretises masonry units and assumes a zero-thickness brick-to-mortar interface. These models were originally 2D (Lourenco 1996) although 3D models have become predominant. Efforts have been made with regards to computational efficiency, for example, by partitioning and parallelising the structure. Crack propagation, large displacements, elasto-plastic behaviour as well as energy dissipation, decohesion and residual frictional behaviour have also been incorporated (Macorini and Izzuddin 2011; Macorini and Izzuddin 2013; Macorini and Izzuddin 2014).

In (Dennis, Baylot et al. 2002), eight-noded continuum elements with a rigid slide surface using Drucker Pracker failure criterion, dependent on tensile strength and cohesion of mortar, were used. The results were validated against 5 blast-load tests of one way ¼ scale CMU walls. For static loading, this approach gave slight over-predictions and so lower bound properties were used. On the contrary, for blast tests, typical properties showed a slight under-prediction. This could be due to: 1) ‘typical’ values of mortar properties being used, instead of those obtained through testing, 2) mortar not being scaled. Eight-noded hexahedral elements and trilinear shape functions for masonry units with a Mohr-Coulomb failure surface using the Tresca limit, to allow for brick-to-mortar interface contact and separation, were used by (Eamon, Baylot et al. 2004). This allowed for nonlinear behaviour, large strains and large displacements. Validation was made against 14 CMU ¼ scaled specimens under blast actions. A 10% reduction in density was made to account for voids. It was found that the CMU interconnectivity, contact parameters and mortar strength governed global wall behaviour. Top and bottom blocks were modelled with a finer mesh to better account for boundary conditions. The model was sensitive to material properties, however not all properties were available from tests. The authors acknowledged the uncertainty present in masonry modelling under blast and conclude that it is ‘*unlikely that development of accurate model using nominal material parameters is possible, and data is often unavailable’* (Eamon, Baylot et al. 2004).

(Rafsanjani, Lourenço et al. 2014; Rafsanjani, Lourenco et al. 2015) developed a rate- dependant numerical model using a simplified micro-modelling approach. The brick-to-mortar interface was represented with a tension cut off, Coulomb friction and elliptical cap. The data for DIFs was taken from (Hao and Tarasov 2008) for components tested on their own, not accounting for their interaction. In addition, DIFs for tension and shear were assumed due to lack of data. Several parametric studies were conducted, concluding that tensile strength influences structure displacement. (Rafsanjani, Lourenço et al. 2014; Rafsanjani, Lourenco et al. 2015) validated their numerical model against previous experimental testing conducted by (Gilbert, Hobbs et al. 2002), where 21 unreinforced masonry walls were subjected to impact loading. The numerical model described in (Burnett, Gilbert et al. 2007) was also validated against this data. LS\_DYNA was used to model linear elastic solid elements joined together by a self-developed discrete-crack model, with Mohr-Coulomb failure criterion and tension cap. The material properties were taken from (Beattie 2003). Failure mechanisms were generally well predicted and displacements fell within 10% of experimental test data obtained in most cases; however coefficients of variation of up to 30%, due to variablity in material characterisation, were acknowledged.

*3.2.1.2 Detailed micro-modelling*

This approach discretises mortar *and* masonry units. Models proposed using this approach have not been used for very large structures as per the high computational times required and have generally been validated against small models, such as the triplet and couplet tests under impact loading performed in (Beattie 2003). There, a multi-purpose nonlinear finite element analysis software package was used (LS-DYNA ((LSTC) 2007)), and brick and mortar were discretised using eight-noded fully integrated solid elements. An iterative process was needed to establish the dynamic input properties. Brick and mortar were modelled with bilinear stress-strain behaviour and the brick-to-mortar interface used Mohr-Coulomb failure criterion.

A detailed 3D micro modelling approach is presented in (Linse and Gebekken 2010). For mortar, an isotropic model accounting for tensile bond strength, shear bond strength and compressive strength is proposed. The 4-parameter Ottosen failure criterion for compressive strength and Mohr-Coulomb used by (Lourenco 1996) for the shear state with tension cut off criterion (Rankine criterion) was chosen. Strain rate effects were accounted for by incorporating a damage model. For masonry units, the William – Warnke isotropic model was used to represent triaxial stress combinations with parameters such as tensile strength, compressive strength, ductility, Young’s Modulus and Poisson’s ratio. The Ottosen-Speck fracture model with tension cut off and damage model was proposed (Linse and Gebekken 2010) for which uniaxial compression strength, two dimensional compression strength and uniaxial tensile strength are required. However, most of the input data had to be assumed (Gebbeken, Linse et al. 2012). In (Linse, Gebekken et al., 2012) ANSYS AUTODYN software was employed, but the lack of experimental data for brick and mortar properties under dynamic loads was acknowledged. Two main behaviour characteristics were highlighted with regards to material properties: 1) the tensile strength of bricks is important as bricks experience tensile forces due to the Poisson effect and mortar 2) the Young’s Modulus is different for tension and compression. It is also acknowledged that some parameters cannot accurately be tested without considerable effort.

This section acknowledged the range of modelling approaches available, which adds variability and uncertainty to the masonry characterisation challenge. Engineering judgement is key not only in establishing the material properties (which are highly variable), but also selecting the adequate modelling approach.

**4. Additional sources of variability**

This section discusses assumptions made with regards to blast and seismic load application and scaling.

When modelling a structure subjected to blast loading a uniform pressure is generally applied to in the medium to far field region. However, a finite surface approach, which assumes non-uniform pressure acting on the structure, would be more realistic as it acknowledges uncertainty in blast load parameters (Abou-Zeid, El-Dakhakhni et al. 2011). Additionally, P-I diagrams are pulse shape dependent, i.e. if the same structure is analysed using different pulse shapes, the maximum deflection can occur at different times (Li and Meng 2002). The main discrepancies in P-I diagrams that assume different pulse shapes occur at the dynamic region (Abrahamson and Lindberg 1976). For seismic actions, loading is applied statically when linear (equivalent lateral force method) or nonlinear (pushover analysis) behaviour is assumed. Alternatively, modal and response spectrum analysis and nonlinear time history analysis can also be used. Response spectrum analysis is often used as it accounts for the modal behaviour of the system and its peak responses only (Timur 2016).

Blast and seismic scaled masonry tests are sometimes used to validate numerical models (Baylot, Woodson et al. 2004; Dennis, Baylot et al. 2002; Eamon, Baylot et al. 2004; Macorini and Izzuddin 2014). Scaled masonry is often stronger and more flexible than full scale masonry (Petry and Beyer 2012). The ideal scenario is to target similar mass and stiffness distributions to those of the full scale structure. Artificial Mass simulation adds non-structural mass to scaled masonry to simulate dynamic behaviour of the full structure (Petry and Beyer 2014).

The masonry unit manufacturing processes affect surfaces and water absorption properties, which influence masonry strength, for which scaling is known to be problematic. Scaled modelling, however, can be useful when comparing behaviour, the effects of retrofitting solutions and/or damage patterns (Tomaževič and Weiss 2012; Tomaževič and Gams 2012; Tomaževič, Klemenc et al. 2009; Ersubasi and Korkmaz 2010). For example, (Petry and Beyer 2014) found similar failure modes and damage patterns when comparing full scale and 1/2 scale masonry walls under quasi-static static cyclic loading.

**5. Techniques to account for variability in masonry under blast and seismic events**

The acknowledgement of masonry uncertainties is widely accepted, but is not always addressed with probabilistic/uncertainty methods. This section describes different techniques that can be used to account for the uncertainty present in masonry construction and modelling. Some engineering examples are introduced, where probabilistic methods have been used when dealing with seismic and blast modelling of masonry.

A *reliability analysis* evaluates the failure probability of a system. This can be estimated by generating random samples of uncertain inputs, typically using Monte Carlo (MC) simulations. Due to its consistent performance and simplicity, MC simulations are generally taken as the benchmark to which other techniques are compared (Eamon and Charumas 2011; Patki and Eamon 2014). However, they are computationally expensive, especially when used to evaluate the probability of rare failure events. Consequently, several techniques have been developed to reduce this computational cost. First-Order-Reliability-Methods (FORM) and Second-Order-Reliability-Methods (SORM) use first and second order approximations of the limit state functions (LSF), which define failure, and are effective for linear or quadratic LSFs (Schueller 2003). Other techniques include subset simulation, failure sampling, line sampling and importance sampling. Subset simulation uses nested Markov chain Monte Carlo (MCMC) sampling to estimate low probability failure events, where failure is defined as a product of conditional probabilities of events that are faster to calculate. Failure sampling, which also uses MCMC, was developed as an alternative to subset simulation and was shown to be 30% computationally more efficient (Eamon and Charumas 2011; Patki and Eamon 2014). Line sampling is also computationally efficient and accurate when dealing with finite element analysis and complex systems with small probability of failure. In this case, the multi-dimensional problem is divided into various one-dimensional problems by generating a unity vector pointing towards the failure domain instead of random samples (Schueller 2003). Importance sampling techniques achieve computational efficiency by forcing random samples to be generated in the failure region (Faulin, Juan et al. 2010, Schueller 2003). It should be remembered, however, that assuming variability in *all* input parameters may still be prohibitively computationally expensive. In such scenarios, sensitivity analyses can be performed to show which input parameters have the greatest influence on a model’s outputs (Saltelli 2008).

Reliability analyses were performed on 43 unreinforced CMU infill walls subjected to blast actions in (Eamon 2007). It was found that if geometry, materials and boundary conditions are kept constant; mortar joint strength and contact surface friction are the most influential variables, whereas peak impulse is the most influential parameter with regards to load application. The random variables chosen were the mortar joint modulus of rupture, contact friction, Poisson ratio, compressive strength, tensile strength, modulus of elasticity, shear modulus, bulk modulus and strain rate. Joint strength is affected, however, by a number of other factors, as discussed in Section 2. The quality of workmanship can influence the mortar thickness, which is variable throughout masonry structures, as investigated in (Mojsilovic and Stewart 2015) who performed reliability analyses on 12 existing masonry walls using SORM and MC methods. Incorporating uncertainty at the mortar thickness showed lower failure probabilities, when compared to reliability analysis performed with variability on their material mechanical properties but with mortar thickness kept constant.

The uncertainty at the brick-to-mortar interface strength of a masonry triplet test, used for shear strength characterisation, subjected to impact loading has been also investigated (Mendoza-Puchades, Judge et al. 2016). Uncertainties with regards to the shear and tensile strength of the interface were propagated through a model, leading to a probability distribution over failure loads (see Figure 6).

Research in the 70s was conducted to evaluate civil defence shelters and residential masonry structures in the US when subjected to nuclear air blasts. A SDOF dynamic model was established and resistance functions were calculated using MC and other simulation techniques which accounted for uncertain physical properties. This led to a probability distribution over collapse overpressure (Wiehle 1970).

Bayesian methods allow one to infer probabilistic parameter estimates from observations/measurements. Uncertainty in masonry properties was investigated in (Atamturktur, Hemez et al. 2012), at a full bay of the Washington National Cathedral. Uniform prior distributions, defined by expert judgement on plausible lower and upper limits, were assigned to parameters such as Young’s modulus of limestone ribs, concrete fills, brick walls and limestone piers. Bayesian inference was used to establish the mean and standard deviation of the natural frequencies of the structure. These parameters were taken from numerical models, assuming a linear elastic material, isotropic constitutive behaviour and idealised boundary conditions. Similarly, other researchers have performed inverse analyses and used genetic algorithms to establish properties at the brick-to-mortar interface under static loading for a given observed behaviour (Chisari, Macorini et al. 2015). This type of inverse approach is particularly useful if input distributions are unknown. History matching calibration techniques can also be used to obtain input parameter intervals for a known experimental performance. However, expert judgment is needed to decide upon the input parameters that are required (Andrianakis, Vernon et al. 2015).

A logic tree approach was used in (Lagomarsino, Penna et al. 2016) to assess the variability in engineering judgements made when modelling masonry behaviour. This included uncertainties in the criteria for calculating the effective height of piers, boundary conditions between orthogonal walls and selection of cracked stiffness. These uncertainties, amongst others, were assessed when conducting nonlinear pushover analyses with an equivalent frame macro modelling approach for eight masonry buildings using TREMURI Software in (Bracchi, Rota et al. 2015). In this work, the building capacity was expressed in terms of peak ground acceleration (with its cumulative distribution fitted as lognormal distributions and three limit states defined as a function of displacements that represent a damage threshold). A sensitivity analysis showed that cracked stiffness and boundary conditions between orthogonal walls had the greatest influence on the global stiffness, ultimate displacement, yielding acceleration and ground acceleration for the ultimate limit state.

**6. Conclusions**

This work presents different approaches to modelling masonry under blast and seismic events. High variability is encountered in modelling asssumptions, methodology and/or material resistance. (which is influenced by geometry, workmanship, masonry properties and interactions). This variability is widely acknowledged, but is mostly accounted for using engineering judgement. Moreover, forecasting is often treated as replication (i.e. trial-error is used until known behaviour is achieved). A number of tools can be used to assess this variability (and have been applied to other engineering challenges). It is in our interest to make improvements in the challenging task of forecasting masonry behaviour under blast and seismic actions by incorporating probabilistic/uncertainty approaches, in a manner that it is meaningful to industry. This review paper illustrates the need for future modeling methodolgies and is part of a larger project which aims to develop uncertainty quantification/propagation frameworks for the assessment of masonry structures subjected to blast actions.

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**Figure captions**

Figure 1. Typical failure mechanisms of masonry under in-plane actions: a) Failure due to vertical loading is observed by means of horizontal cracks along the mortar or both the mortar and masonry units, b) Failure due to horizontal loading is observed by means of vertical cracks along the mortar or both the mortar and masonry units, c) Failure due to combination of vertical and horizontal loading is observed by means of diagonal cracks along the mortar or both the mortar and masonry units.

Figure 2. Arching behaviour due to out-of-plane actions: a) Schematic of wall with rigid supports and axial in-plane loading subjected to uniform blast pressure, b) Arching behaviour and failure mechanism of wall in “a”

Figure 3. Examples of Single-degree-of-freedom-systems from complex models subjected to blast actions: a) Mass and spring model, b) Lumped mass model

Figure 4. Pressure – impulse diagrams

Figure 5. Numerical modelling for masonry structures: a) Macro-modelling, masonry modelled as a homogeneous material, b) Simplified micro-modelling, masonry modelled as a heterogeneous material with zero thickness joints, c) Detailed micro-modelling, masonry modelled as a heterogeneous material, both masonry units and mortar discretised.

Figure 6. Uncertainty propagation on a masonry triplet test (Mendoza-Puchades, Judge et al. 2016)