Probabilistic Model for Ageing Masonry Walls

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ABSTRACT: This paper considers a probabilistic model of masonry wall capable to take into account uncertainties caused by ageing and site specific parameters. We define masonry wall uncertainties using random variable representation for geometric, load and mechanical properties and then by introducing specific probabilistic deterioration model. Subsequently, we use probabilistic analysis in ANSYS (APDL) using Monte Carlo simulation method and Latin Hypercube sampling technique with aim to approximate the cumulative distribution function for the von Mises stress and displacement at particular location. It is demonstrated that the likelihood of exceedance of critical parameters such as displacements and von Mises stresses due to ageing could be quantified.

Masonry structures represent a traditional and historically widely used type of construction. Therefore, ageing of masonry structures brings formidable challenges to many infrastructure owners. As a consequence of high variation in quality of masonry between sites, unevenness in mortar joints between and within sites, Mojsilovic and Stewart (2015), but also environmental effects, damage and deterioration over the life cycle, there is a significant uncertainty in ageing of components. Therefore, models for quantification of site specific uncertainties and ageing process would be very useful.

Current deterministic and probabilistic models for masonry behavior are numerous and include so called micro FE models, rheological models, Papa et al. (2001), residual life models, Anzani et al. (2009) etc. however they are not efficient tools to identify ageing effects. Deterministic models cannot include uncertainties in analysis while probabilistic models available so far are limited as they only consider one uncertain parameter Anzani et al. (2009) and Garavaglia et al. (2002).

In this paper we propose a probabilistic methodology for modelling the behavior of ageing masonry hollow block wall, Figure 1 that is based on FE model. Thus, the main objective of this research is to simulate the likelihood of ultimate limit state exceedance for ageing masonry wall at the specific site assuming nonlinear behavior, but enabling flexible probabilistic model that can include site specific information, such as geometry, site-specific load and materials.

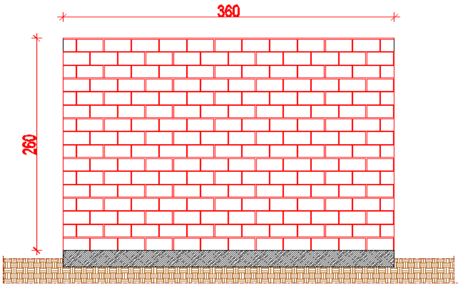

Figure 1: Masonry hollow block wall

1. MASONRY WALL PHYSICAL MODEL

In order to provide FE model validation a physical sample model of masonry wall from a particular site Mojsilovic and Stewert (2015) is adopted. Dimensions of selected wall, built using typical Swiss clay block and standard cement mortar, are 3600x2900x150mm. Furthermore, material properties of wall constituents are assumed to be equal as reported in A. Salmanpour et al. (2013) and Mojsilovic and Stewart (2015). The sample model of masonry wall is not selected from the walls built with special care in laboratory because they exhibit fewer uncertainties than site walls. For instance, all joints thickness of laboratory wall were 10 mm according to design specification, Mojsilovic and Stewart (2015).

2. DETERMINISTIC STRUCTURAL MODELS

Masonry consists of regular units and mortar and exhibits anisotropy. Generally, there are three FE deterministic strategies for representation of masonry assemblage, Lourenco (1996). The most accurate but very complex approach is detailed micro modeling Figure 2 where masonry constituents and interface between them are represented separately. Therefore, units and mortar joints are modeled as continuous elements whereas unit-mortar interface is simulated with discontinuous elements. Detailed micro level model accurately describes real masonry behavior and it is able to simulate all its failure mechanisms.

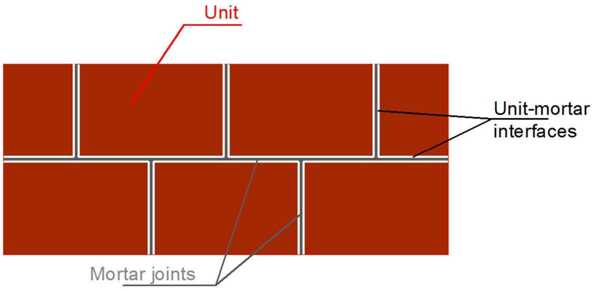

Figure 2: Detailed micro level model

Second alternative for numerical deterministic representation of masonry structures is simplified micro level model Figure 3. This means that mortar joint and unit-mortar interfaces, from both sides of mortar joint are lumped into one interface modeled with discontinuous elements. Furthermore, units are expanded in order to prevent geometry change. These units are simulated with continuous elements. Simplified model is less accurate than detailed model as it cannot take into account Poisson’s effect of the mortar, Lourenco (1996). Evidently, it is computationally less demanding.

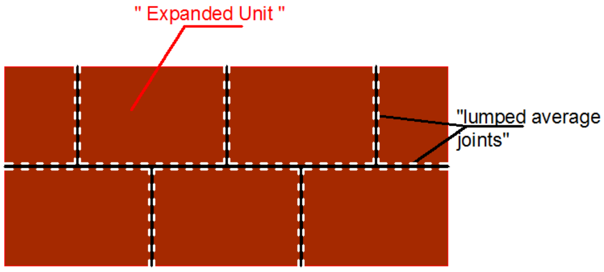

Figure 3: Simplified micro level model

The third, approach for modeling masonry structures is macro level modeling. Macro level model, Figure 4, considers masonry as a homogeneous continuum. In other words, it does not recognize difference between units and joints and cannot simulate all possible masonry failure mechanisms.

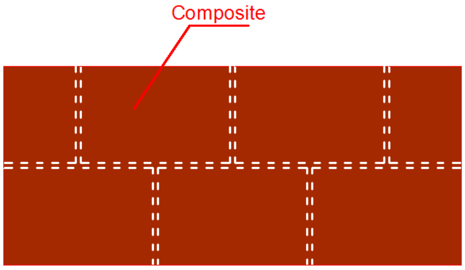

Figure 4: Macro level model

3. AGEING EFFECTS MODELS FOR MASONRY

Historical structures are mainly masonry. And sudden collapse of towers in Pavia and Goch etc. has sparked more research in creep and time-dependent masonry behaviour. An experimental investigation of creep failure has been carried out and a rheological viscoelastic masonry model with damage was proposed in Papa et al. (2001). A model is based on the use of the classical Burger’s rheological model which consists of a

Kelvin element in series with a Maxwell element, Papa and Taliercio (2005). Kelvin element describes primary whereas Maxwell element secondary material creep. Tertiary creep material phase and decay caused by increasing stresses are introduced by damage variables. A rheological model has been validated and calibrated with experimental results, Verstrynge et al. (2011). Furthermore, it has been extended to a three-dimensional version in order to enable implementation in a finite element code Verstrynge et al. (2011). However, acquiring sufficient data for such model is very difficult, and material behavior is usually described as an isotropic model.

4. PROBABALISTIC MASONRY MODELS

Many authors have worked on probabilistic modelling of masonry structures, Anzani et al. (2009), Garavaglia et al. (2002), Masia et al. (2002), Bekker (1999), etc. Anzani et al. (2009) model proposes estimation of the residual life of masonry structures based on horizontal and vertical parameters of the secondary creep strain-rates. The parameters of creep strain-rates are defined as random variables with a certain distribution of values for each corresponding stress level, Anzani et al (2009). Therefore, the purpose of the model was to simulate the probability of the exceedance of limit values of creep strain-rate parameters by vertical stress.

Furthermore, the deterioration test procedure, applied on the full-scale masonry models built in aggressive environment is described and two different stochastic approaches modeling the decay process of masonry over time are proposed in Garavaglia et al. (2002). The first approach considers a masonry deterioration over time as discrete stochastic process $L(l,t)$ with random variable l which presents loss of surface material. The loss of material is measured with a device called a laser profilometar which is able to draw a vertical wall profile in the chosen positions over time. The loss of material, represented with two subsequent wall profiles, is converted to the parameter ΔA, wall cross section change. On the other hand, second approach means that masonry deterioration over time is defined as a stochastic process $L(t)$ where τ is the “lifetime” of the system. In other words, the deterioration is defined as a change of the service-state for the system, described with semi-Markov Processes (s-MP), see Garavaglia et al. (2002). In addition, few probabilistic models of masonry deterioration as transition process from a given performance state to lower state are discussed in Bekker (1999).

A probabilistic model for predicting cracking in masonry walls with foundations on the expansive soil is presented in Masia et al. (2002). By taking into account both the variability in expansive soil movements and the structural response to the movements, this model is able to determine the probability of masonry cracks occurrence and the probability of subsequent crack limit widths exceedance see Masia et al. (2002).

5. PROBABALISTIC MODEL PROPOSAL FOR AGEING MASONRY WALL

In this paper, an advanced two step probabilistic model of ageing masonry wall is presented. In first step, a macro level FE deterministic, Lourenco (1996), model of masonry wall is parametrically defined in ANSYS Parametric Design Language (APDL). In the second step, geometric, material model input parameters, critical resultant stress and vertical displacement parameters are identified as random variables with aim to determine the probability of exceedance of critical values. In addition, a probabilistic analysis of masonry wall is carried out using Monte-Carlo simulation method. Monte Carlo simulation method involves random sampling of input variables and observation results. For example, for each random variable X_i and its randomly allocated value x_i the limit state function $g(x)=0$ is checked. Then, if the limit state condition i.e. $g(x)\leq 0$ is achieved the structural element has failed. This simulation is repeated many times with other random values x_i of random variable X_i. The probability of structural element failure p_f is approximately calculated according to equation Eq. (1)

$$p_f \approx \frac{n(g(x_i) \leq 0)}{N} \tag{1}$$

where n is the number of simulations for which $g(x_i) \leq 0$ is achieved and N is the number of all simulations that depends on desired accuracy.

5.1. A parametric deterministic model of masonry wall

The parametric deterministic model of masonry wall, Figure 5, as isotropic composite is developed using Solid 65 finite element.

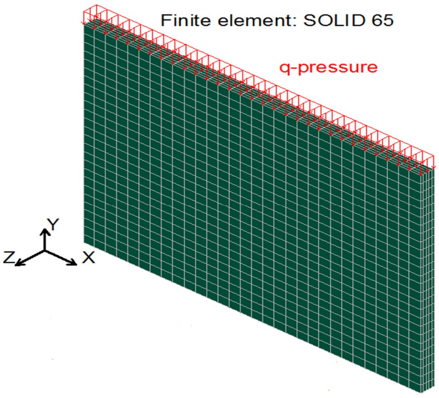

Figure 5: FE model of masonry wall

An eight-node finite element Solid 65 is appropriate for 3-D modeling for brittle isotropic continuum. This finite element supports nonlinear material properties of brittle materials and it is capable of crushing in compression and cracking in tension, ANSYS, Inc (2013). As a result of smearing out of brittle masonry constituents such as mortar joints and clay blocks, we neglect different properties in different directions, masonry brittle isotropic continuum is obtained.

Model mesh consists of 3900 solid brick shape elements and is formed by division into 30 elements along the base of the wall, 26 elements in y direction and 5 elements across the thickness of the wall. With aim to confirm that the fine enough FE mesh is adopted, convergence tests on model are conducted. In other words, the same model with finer mesh (approximately 15 % finer) is created and displacements and stress results are compared with corresponding results of the adopted model. It is found that the difference in stress and displacement results is negligible and analysis with adopted reduced mesh is continued.

In order to simulate accurately the real wall constrains relevant boundary conditions are applied within the model. All displacements on the wall sides and bottom are restricted. On the other hand, rotation constrains along the model sides, bottom and top are not imposed.

Material properties of masonry as an isotropic continuum are derived according to Probabilistic Model Code (JCSS, 2011). Thus, the mean compressive strength masonry is set as f_m=12.84 N/mm^2 taking into account mean compressive strengths of its constituents and compressive determination parameters proposed in Schubert (2010). Bi-linear plasticity stress-strain curve, Figure 6, is defined according to Probabilistic Model Code (JCSS, 2011).

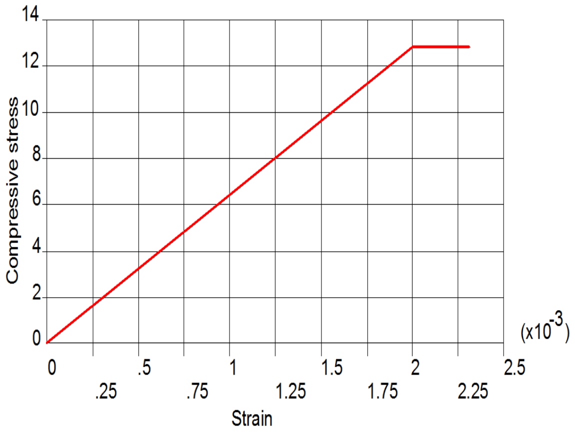

Figure 6: Bi-linear stress strain curve of masonry

Module elasticity, 6420 N/mm^2 is obtained as a ratio of maximum stress and corresponding strain, See Figure 6. Based on mortar and hollow block Poisson's coefficients, Poisson coefficient of masonry, 0.18 is adopted.

All loads including own wall weight, permanent and variable loads are applied on the wall top side through uniform pressure.

5.2. Ageing factors on masonry wall geometric and material properties

Through their life masonry walls are exposed to varying climate conditions which can severely influence masonry durability. Four deterioration mechanisms of brick walls, their consequence and investigation methods are presented in Larbi (2004). In general, sulfate deterioration mechanism is caused by reaction between sulfates in solution and the tricalcium aluminate constituent in Portland cement of mortar joints. This reaction triggers an expansion of masonry wall and in some extreme conditions the mortar joints disintegration, Larbi (2004). Leaching deterioration mechanism occurs when masonry wall gets in contact with acid rain or condensed acid water resulting in loss of cohesion between joints and units, masonry volume changes, surface deterioration, and increasing mortar capillary porosity. Salt crystallisation within both mortar and unit pores can cause an aggressive masonry surface deterioration. If the absorbed water in masonry is frozen, this may lead to the material limit stress exceedance and cause developing cracks, material surface loss. Furthermore, masonry wall exposed to many freezing and thawing cycles can suffer from severe material strength loss, see Larbi (2004).
Ageing tests on eight masonry samples are described in Cultrone et al. (2007). Masonry samples made of different units and lime mortars were put in $C0_2$-saturated climatic chamber for 30 days at constant temperature 25 ^oC and 50 % relative humidity in order to accelerate carbonation process in mortar. Subsequently samples were exposed to ten salt crystallization cycles according to the UNE 7-136-58 standard and to thirty freeze-thaw cycles according to the UNE 67-028-84 standard, Cultrone et al. (2007). Based on the test results it was concluded that salt crystallization processes cause changes in the samples surfaces, developing cracks, loss of material weight, Figure 7. Freeze-thaw test caused less visible changes on the units of masonry samples than salt crystallization test. However, samples suffered significant loss of weight and cracks were visible through mortar joints, Figure 8.

Figure 7: Appearance of deteriorated masonry samples after salt crystallization test., Cultrone et al. (2007)

Figure 8: Appereance of deteriorated masonry samples after freeze-thaw test, Cultrone et al. (2007)

Ageing in-situ tests on Kolizej Palace built in 1847, Kruzan et al. (2012) found that ageing had significant effects on mechanical properties of masonry and its constituents. Therefore, it was concluded that reduction of compressive and tensile masonry strength caused by decay process may be up to 30 % and 36 % respectively. Module elasticity of masonry was very low, particularly for masonry which was exposed to wet conditions, Kruzan et al. (2012).

5.3. Modelling uncertainties associated with ageing masonry

Probabilistic finite element analysis of ageing masonry wall is carried out using the tool ANSYS Probabilistic Design System, Reh et al.

(2006), available within ANSYS (APDL) software. In order to simulate the ageing influences on the wall over time, the wall dimensions and mechanical properties are assumed to be uncertain and represented as input random variables in line with Mojsilovic and Stewart (2015). Input random variables Table 1, are characterized by the joint density functions according to Probabilistic Model Code (JCSS, 2011) and to Brehm (2011).

Table 1: Random input variable specifications

Input variables	PDF	Mean value	Standard deviation
D [mm]	Gaus	150	1.5
H [mm]	Gaus	2600	26
W [mm]	Gaus	3600	36
Q [N/mm^2]	Gaus	10.5	1.05
Y_1 [-]	Lognor.	1	0.21

Wall shape changes associated with its ageing are presented with input variables D, H, W, wall thickness, height and length respectively. In addition, cumulative load is introduced to the probabilistic model with Q random variable. On the other hand, changes in mechanical properties caused by ageing wall and its constituents are described within probabilistic model through:

$$f_{m,j}=f_m \cdot Y_1 \tag{2}$$

$$E_{m,j}=E_m \cdot Y_1 \tag{3}$$

where f_m and E_m are constants, mean masonry compressive strength and mean masonry module of elasticity, respectively whereas Y1 is strength lognormal material variable. Therefore, f_m is 12.84 N/mm^2 E_m is 6420 N/mm^2

Output variables, von Mises stress and vertical displacement are selected for critical location with aim to identify the cumulative distribution function as illustrated in Figure 9 and Figure 10.

Probabilistic simulations are carried out using Monte Carlo method with Latin Hypercube sampling technique. For each simulation (i) the limit states functions of output variables are obtained as functions of input random variables Eq. (4) and Eq. (5)

$$F\sigma = g(D_i, H_i, W_i, Y1_i, Q_i) \tag{4}$$

$$F\delta = g(D_i, H_i, W_i, Y1_i, Q_i) \tag{5}$$

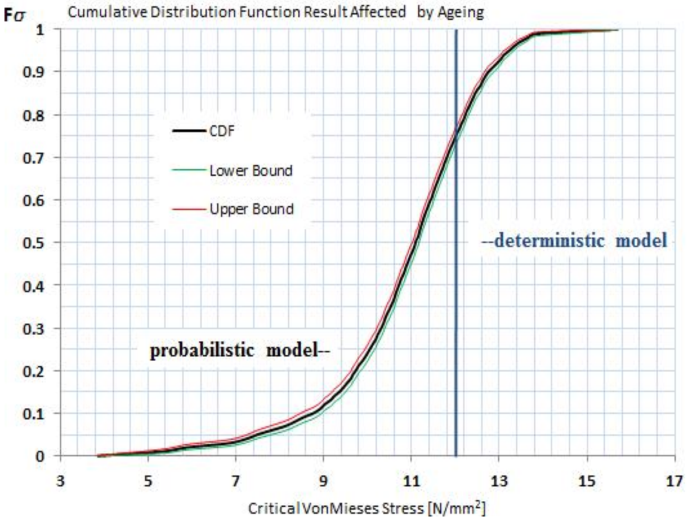

Figure 9: Cumulative distribution function result for the critical von Mises stress

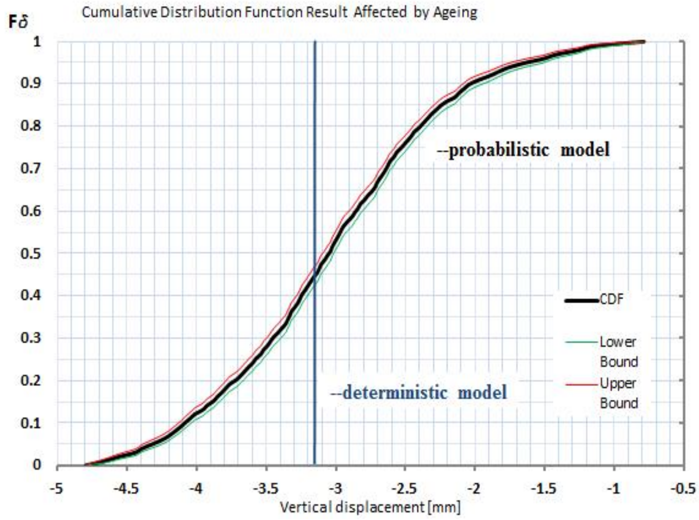

Figure 10: Cumulative distribution function result for the critical vertical displacement

ANSYS tool uses Latin Hypercube sampling technique to ensure more efficient and accurate sampling process, Reh et al. (2006). Probabilistic outcomes such as mean values, standard deviations and histogram plots are derived from Monte Carlo simulation analysis results using statistical methods in ANSYS FE software. Sensitivities shown in Figure 11 and Figure 12 are constructed based on sensitivity factors between all input variables and selected output variables, Reh et al. (2006).

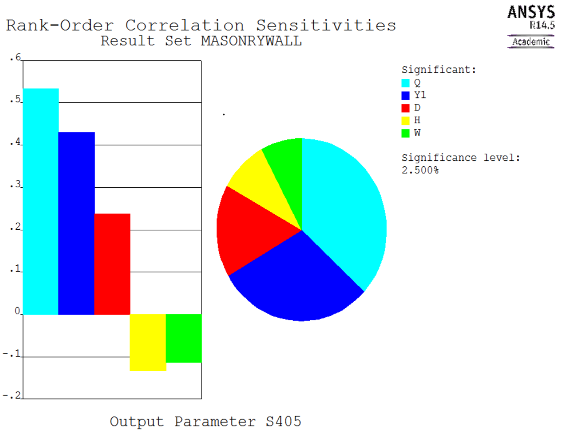

Figure 11: Sensitivities for the critical von Mises stress (random variables defined in Table 1)

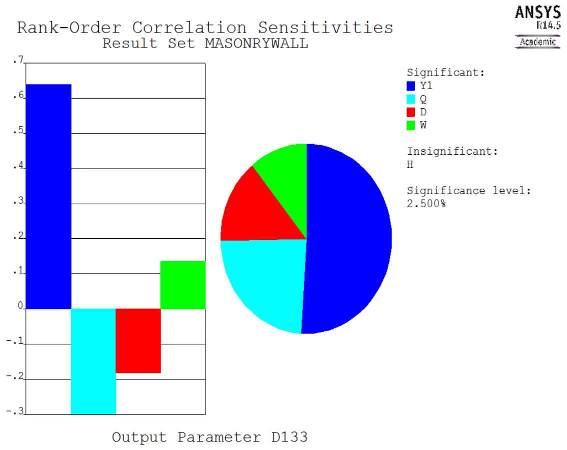

Figure 12: Sensitivities for the critical vertical displacement (random variables defined in Table 1)

In respect to peak von Mises stress, it can be identified that the imposed load is the most important random variable. For displacement it is identified that critical mechanical properties fully correlated, through use of factor Y1 are the most important.

6. CONCLUSIONS / DISCUSSION

Ageing of masonry structures is challenging research area because of masonry popularity as type of building in construction industry and importance of restoration of numerous ancient masonry buildings. In this paper parameters of simply smeared FE masonry wall model are considered as probabilistic variables with aim to simulate influence of ageing effects on the exceedance of the limit states. Two thousand Monte Carlo simulations are carried out using Latin Hypercube sampling technique.

Masonry behavior is modeled as an isotropic continuum i.e. the difference between mechanical properties perpendicular and parallel to bed joints are neglected. In addition, nonlinear behavior is presented with bi-linear stress strain curve and the tension strength of masonry wall is neglected. The proposed probabilistic model is developed as the benchmark study for masonry models for probabilistic ageing evaluation.

Monte Carlo simulation method is very powerful and it is accepted as a benchmark for accuracy verification of other probabilistic methods, Reh et al. (2006). However, there are two main inaccuracy issues related with Monte Carlo method. First issue is related to the number of simulations for low probability events such as civil engineering applications and it is overcome here by increasing the number of simulations. On the other hand, re-meshing inaccuracy of results caused by including geometric variables in probabilistic analysis is not quantified however following from the obtained sensitivity factors this effect can be accepted.

From cumulative distribution functions, seen in Figure 9 and Figure 10 it can be concluded that it is possible to quantify the effect of the ageing process on the probability of exceedance of the ultimate limit state of masonry wall. This is a major advantage over deterministic approach that could not reflect the effect of uncertainties associated with ageing.

Further analysis will be carried out to simulate the changes in mortar joints over the lifecycle and consequent changes in masonry wall reliability. Use of more advanced micro model Lourenco P. (1996), for the bond and between mortar and blocks will be investigated to establish if such (more) accurate physical model for impact of ageing on the wall is suitable due to inevitable high computation costs. Possibility of using microplane damage model for numerical presentation for nonlinear properties of mortar and clay masonry units will be explored in future.

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