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Numerical Modelling of Brick-mortar Masonry Structures under Fatigue Loading

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Abstract

Masonry arch bridges are old structures which form an essential part of the transport infrastructure in numerous countries around the world. As such it is crucial to investigate effects of repeated traffic loading to understand the potential fatigue susceptibility of these masonry structures. Although, there have been some efforts towards understanding the fatigue behaviour of masonry structures under repeated loading, this was mainly achieved via various experimental programs, while useful predictive numerical tools are still largely missing. Thus, this study presents a novel numerical formulation at the mesoscale level that can be used to model material damage evolution, specifically cracking, in the masonry brick-mortar interface. The current formulation utilises the elastic-plastic damage mechanics concept and can phenomenologically model the material degradation or cracking behaviour of the masonry brick-mortar interface, which is considered as the weakest region for the majority of masonry structures. The new fatigue formulation is defined by three material properties for the characterisation of the fatigue behaviour of an interface, and it is expected that these parameters can be easily derived from the component-level testing of masonry specimens subject to high cycle fatigue loading. Preliminary numerical investigations show that the current formulation can provide a useful capability to numerically assess masonry structures subject to subcritical damage due to fatigue loading.

Keywords: masonry arch bridges, parametric modelling, fatigue of masonry.

1 Introduction

Masonry arch bridges are old structures which form an essential part of the transport infrastructure in numerous countries around the world. This can be perhaps attributed to their remarkable resilience. Over time, such structures have been subjected to increasing loading leading to the development of damage and cracking in the brick/blockwork. Thus, it becomes crucial to investigate effects of repeated high traffic loading to understand the potential fatigue susceptibility of these old masonry structures.

Although, there have been some efforts towards understanding the fatigue behaviour of masonry structures under repeated loading, this was mainly achieved via various experimental programs, while useful predictive numerical tools are still largely missing. Thus, this study presents a novel numerical formulation at the mesoscale level that can be used to model material damage evolution, specifically cracking, in the masonry brick-mortar interface. The current formulation utilises the elastic-plastic damage mechanics concept and can phenomenologically model the material degradation or cracking behaviour of the masonry brick-mortar interface, which is considered as the weakest region for the majority of masonry structures. Herein, the major components of the proposed elastic fatigue damage formulation for a masonry brick-mortar interface subject to high-cycle fatigue loading regime with negligible inelastic macro-deformations are outlined.

The new fatigue formulation is defined by three material properties for the characterisation of the fatigue behaviour of an interface, and it is expected that these parameters can be easily derived from the component-level testing of masonry specimens subject to high cycle fatigue loading. Preliminary numerical investigations show that the current formulation can provide a useful capability to numerically assess masonry structures subject to subcritical damage due to fatigue loading.

2 Methods

According to the proposed modelling strategy for accurate simulation of masonry structures under fatigue loading, a generic brick/block masonry component is represented using a mesoscale approach, where masonry units are modelled with elastic solid elements and mortar joints by 2D nonlinear interfaces [1]. The proposed material model uses the strain-equivalence principle in continuum damage mechanics [2] and is obtained as an extension of an existing material model for nonlinear interfaces representing mortar joints [3]. A damage parameter D is introduced as an additional internal state variable of the material description for the brick-mortar interface elements. This additional internal state variable represents the average density of various forms of mechanical damage, including material discontinuities contained within an representative volume element of a continuum. For an anisotropic material, characterised by separate normal and in- and out-of-plane shear modes, the nominal stress vector $\boldsymbol{\sigma}$ in the damaged material is related to the prevailing hypothetical effective stress $\tilde{\boldsymbol{\sigma}}$ of the material in its pristine state:

$$\boldsymbol{\sigma} = \left[\mathbf{I} - \mathbf{D}\right] \cdot \tilde{\boldsymbol{\sigma}} \tag{1}$$

By utilising the classical additive decomposition of the total strain $\boldsymbol{\varepsilon}$ into its elastic and plastic components $\boldsymbol{\varepsilon}^{\mathbf{p}}$, the elastic-plastic constitutive material law is expressed as:

$$\boldsymbol{\sigma} = \left[\mathbf{I} - \mathbf{D}\right] \cdot \mathbf{K} \cdot \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\mathbf{p}}\right) \tag{2}$$

The matrix $\mathbf{I}$ is an identity matrix, $\mathbf{D}$ is a second-order damage tensor containing only diagonal elements, and $\mathbf{K}$ is the interface undamaged stiffness. To allow for damage within the elastic loading regime that is representative of material degradation due to high cycle fatigue with negligible inelastic strains in the mesoscale material description, the existing damage evolutions of Minga et al. [3] accrued due to plastic deformations are extended to accommodate additional damage evolutions due to the accumulation of elastic interface opening displacements as a form of strain measures under compressive, tensile, and shearing deformations.

Similar to the form of fatigue damage evolution adopted by Paas et al.[4], Peerlings et al. [5] and Bodin et al. [6], the fatigue damage evolution is defined as a function of the current level of damage component and the equivalent loading function weighted by an assumed material parameter α. The resulting damage evolution is accumulated with respect to the cumulative strain measure under compressive, tensile, and shear deformation modes. Thus, for these respective deformation modes, the fatigue damage evolution takes the form:

$$\dot{D}_a = \alpha_a \cdot \left(1 - D_a\right) \cdot e^{\beta_a \cdot D_a} \cdot \left(\tilde{\sigma}_a - \eta \cdot \tilde{\sigma}_{0,a}\right) \cdot \dot{\varepsilon}_a \qquad \left[0 < D_a < 1; a = 1,3\right] \tag{3}$$

where α, β and η are assumed material constants that can be derived from standard uniaxial fatigue experiments for compression, tension and shear interface opening.

The damage variable D increases up to 1 due to fatigue through the cumulative strain accumulated under cyclic loading, as expressed below. Finally, given the increment of the elastic interface opening and effective elastic stress at a current step $n+1$, ε^{n+1} and $\tilde{\sigma}^{n+1}$, and the damage in the previous step n, D_a^n, the current damage component D_a^{n+1} corresponding to the deformation mode a, can be obtained by solving the following non-linear equation:

$$f\left(D_a^{n+1}\right) = -D_a^{n+1} + D_a^n + \alpha_a \cdot \left(1 - D_a^{n+1}\right) \cdot e^{\beta_a \cdot D_a^{n+1}} \cdot \left(\tilde{\sigma}_a^{n+1} - \eta \cdot \tilde{\sigma}_{0,a}\right) \cdot \dot{\varepsilon}_a^{n+1} = 0 \tag{4}$$

3 Results

In order to provide a preliminary assessment of the proposed formulation, the behaviour of an arch specimen under constant amplitude cyclic loading is considered (Figure 1). This test is based on the recent findings reported in [7]. The experimental setup includes a bare arch 445 mm wide, with span of 3000 mm and rise of 750 mm. The arch is made of two rings with a total thickness of 215 mm. In the considered study, the arch is preloaded by a set of two vertical 10 kN loads acting at one- and three-quarter span, and it is then subjected to cyclic alternating loading at these locations with amplitude of 14 kN and period of 0.5 s.

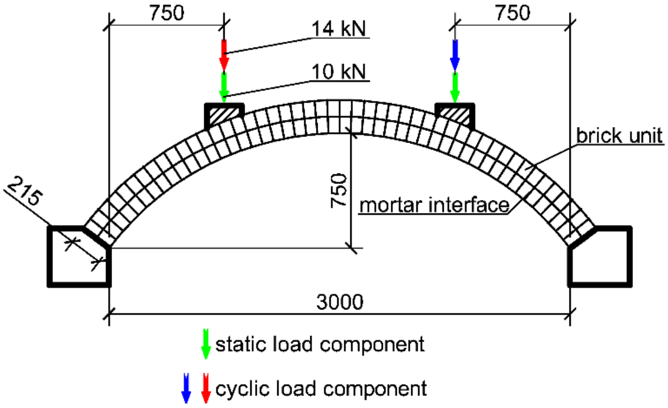


Figure 1. Numerical model setup

Some material properties for the arch are determined according to the data provided in [7]. The other material parameters (e.g. interface stiffness, tensile strength, cohesion, and fracture energy) were determined to achieve the best match against experimental results under monotonic loading. The best fit was observed for the parameter set indicated in Table 1

Brick unit Young's modulus	N/mm^2	16000
Interface normal stiffness	N/mm^3	90
Interface tangent stiffness	N/mm^3	25
Interface tensile strength	N/mm^2	0.2
Interface cohesion	N/mm^2	0.1
Fracture energy in tension	N.mm	0.075
Fracture energy in shear	N.mm	0.12

Table 1. Material properties used in the numerical study

A comparison between numerical and experimental results for the monotonic loading scenario is presented in Figure 2, where the red line indicates the level of cyclic loading (50 % of the arch ultimate static capacity).

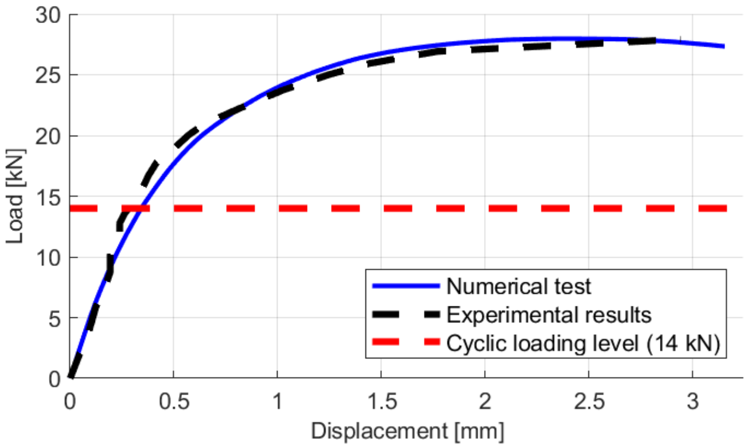


Figure 2. Validation of numerical model against existing experimental data for static loading

To assess the effects on the global structural response of the different fatigue model parameters, a substantial parametric study was conducted by varying the fatigue parameters within the parameter space presented in Table 2.

α	0.01,0.1,0.15,0.2,0.25,0.30,0.35,0.4,0.5,0.60,0.70,0.8,0.9,1.0
β	0.01,0.02,0.05,0.1,0.25,0.5,0.75,1.0,1.5,2.00,2.5,3.0,4.0,5.0,6.0
η	0.01,0.1,0.20,0.3,0.40,0.50,0.60,0.7,0.8,0.90,0.99

Table 2. Parameter space considered in the study

Some results of the conducted study are depicted in Figure 3-Figure 5. The effects of the fatigue parameters on the cycle-displacement response are related to three main aspects: (i) number of cycles before failure, (ii) oscillation amplitude change over time and (iii) oscillation median drift. The later one occurs due to accumulation of plastic deformation/damage in the model.

Fatigue parameters most clearly define the number of cycles before failure, with parameters β and α contributing most substantially. In Figure 3, it can be seen that there is an exponential relationship between parameter α and the number of cycles before failure.

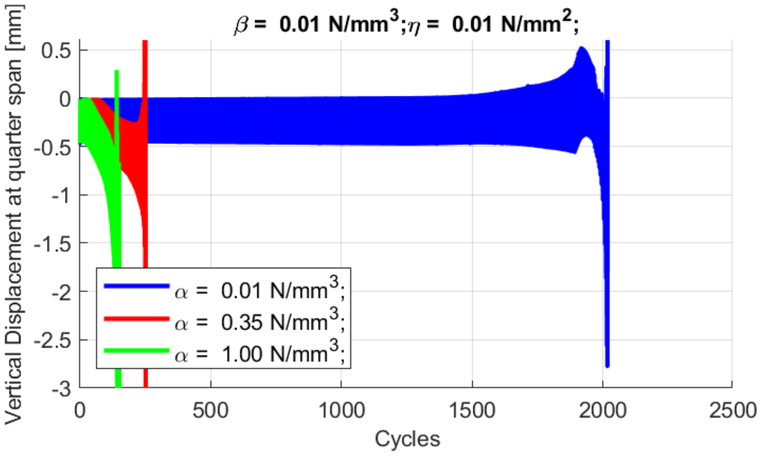


Figure 3. Influence of parameter α on the structural response

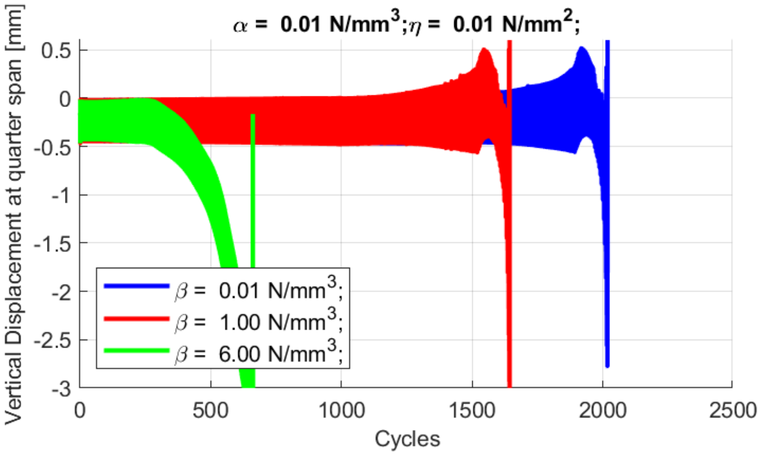


Figure 4. Influence of parameter β on the structural response

Parameter β also significantly affects the number of cycles prior to failure and plays a role in amplitude change over time (Figure 4).

Parameter η, which represents a damage threshold, exhibits only a relatively moderate effect on the number of cycles to failure (Figure 5).

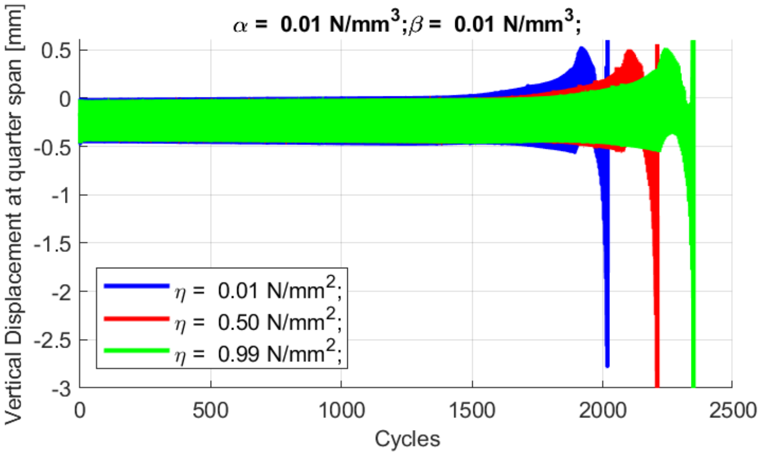


Figure 5. Influence of parameter η on the structural response

All models exhibit similar damage scenarios at initiation of failure (Table 3) which is due to sliding of the loaded bricks (left, right or both loaded bricks). The subsequent mechanism was found to be spurious and heavily dependent on initial conditions; nevertheless, it was always associated with cracks opening at both supports and midspan. For some scenarios (highlighted in red) the failure mode was found to be identical to the one observed in the experiment [7].

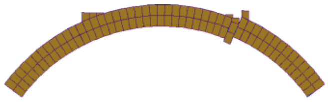
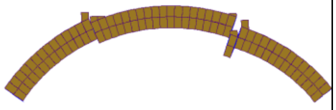
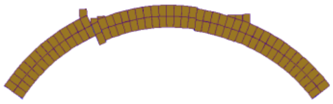
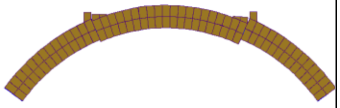
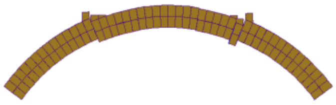
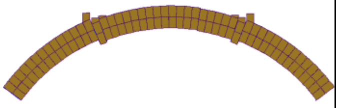
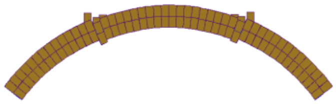
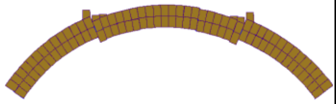
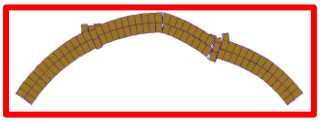
	β = 0.01	β = 1	β = 6
α = 0.01			
α = 0.35			
α = 1.00			

Table 3. Observed failure modes

4 Conclusions and Contributions

A new fatigue formulation is presented in this study for brick-mortar masonry interfaces. It utilises elasto-plastic damage mechanics concepts to model phenomenologically the material degradation at the masonry brick-mortar interface, which is considered as the weakest region in masonry structures. The current formulation requires three fatigue material parameters, α, β and the threshold factors, $\eta_{1,3}$. The crucial parameters are α and β, which model the nonlinear behaviour of the damage evolution and the acceleration of damage with respect to the loading intensity. These parameters can be extracted from component testing of masonry specimens subject to high cycle fatigue loading. The preliminary investigation shows that the current formulation can provide a useful capability for numerically assessing masonry structures subject to fatigue loading.

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