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Experimental evaluation of changes in strain under compressive fatigue loading of brick masonry

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HIGHLIGHTS

- Lower rate of strain evolution for lower stress levels.
- Stress-strain evolution suggests three stages of fatigue deterioration.
- The stress-strain curve configuration changes with increased loading cycles.
- Cyclic loading imposes additional strain compared to quasi-static loading.

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ABSTRACT

Assessing the long-term performance of masonry structures and their response to increased loading conditions are critical to safety and maintenance. A series of laboratory tests have been carried out on brick masonry to assess its performance under long-term fatigue loading. The relationship between stress levels and number of cycles to failure was identified under compressive loading, together with stress-strain evolution at various stress levels. Strain evolution shows distinctive characteristics for the three stages of deterioration and increased strain for increased number of cycles. Experimental results provide useful data for developing analytical prediction models for the fatigue deterioration of masonry structures.

1. Introduction

The longest standing bridges around the world are masonry arch bridges, representing around 40% of the highway, railway and waterway bridge infrastructure in Europe Sustainable Bridges [15]. Due to their age and constantly increasing weight, speed and density of traffic, their assessment and maintenance are becoming increasingly important to ensure their continued safe performance.

High-cycle fatigue loading experienced over 100+ years of service life can lead to significant changes on the material level and deterioration below serviceability or ultimate failure load [5]. Identifying the rate of fatigue deterioration and changes in the material properties for masonry are necessary to enable improved assessment of load capacity, remaining service life, optimising traffic loading and planning maintenance works.

Limited data is however available for assessing the fatigue capacity of masonry structures. Some experimental data is available on SN curves (stress vs. number of cycles) for masonry under fatigue loading [1,7,13,14,16,17] but minimal information has been presented on the evolution of strain under fatigue deterioration.

Abrams et al. [1] performed experimental test series on brickwork prisms to investigate the mechanics of masonry under cyclic compressive stress. Abrams et al. concluded that cyclic loading leads to gradual reduction in the compressive strength of masonry and that the rate of reduction is a function of the mortar strength, amplitude and number of cycles. Greater cyclic stress levels and stronger mortars accelerate deterioration. Clark [7] conducted similar experiments and proposed SN curves for dry and wet masonry, suggesting a fatigue limit for dry brick masonry around ~50% of its quasi-static compressive strength.

Roberts et al. [13] defined a lower bound fatigue strength for dry, submerged and wet brick masonry based on a series of quasi-static and high cycle fatigue tests on brick masonry (Eq. (1.1)).

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$$F(S) = \frac{(\Delta\sigma\sigma_{max})^{0.5}}{f_c} = 0.7 - 0.05\log N \tag{1.1}$$

where F(S) is the function of the induced stress, $\Delta\sigma$ is the stress range, σ_{max} is the maximum stress, f_c is the quasi-static compressive strength of masonry and N is the number of load cycles.

Casas [5] proposed a probability-based fatigue model for brick masonry under compression with different defined confidence levels based on the experimental data reported by Roberts et al. [13] (Eq. (1.2)).

$$S_{max} = A \times N^{-B(1-R)} \tag{1.2}$$

where S_{max} is the ratio of the maximum loading stress to the quasi-static compressive strength, N is the number of cycles to failure and R is the ratio of the minimum stress to the maximum stress $\sigma_{min}/\sigma_{max}$. Coefficients A and B depend on the value of the survival function and were calculated by Casas [5].

Tomor and Verstrynge [17] proposed a joined fatigue-creep deterioration model. A probabilistic fatigue model was suggested by adapting Casas' [6] model and introducing a correction factor C, allowing the interaction between the creep and fatigue phenomena to be taken into account and adjusting the slope of the SN curve (Eq. (1.3)).

$$S_{max} = AN^{-B(1-C\cdot R)} \tag{1.3}$$

where S_{max} is the ratio of the maximum stress to the average compressive strength ($S_{max} = \sigma_{Max}/f_c$), N the number of cycles, R the ratio of the minimum stress to the maximum stress ($R = \sigma_{Min}/\sigma_{Max}$), parameter A is set to 1, parameter B is set to 0.04 and C is the correction factor.

Tomor and Verstrynge [17] identified three stages of fatigue deterioration with the use of an acoustic emission technique to monitor the response of masonry prisms under long-term fatigue in compression. During the first stage (0–75% of the total number of cycles), the acoustic emission levels were relatively low and constant. A small increase in emission was observed in the second stage (75–95% cycles), followed by rapid increase in emission and sudden failure during the third stage (95–100% cycles).

Tomor et al. [16] also identified three distinct stages of fatigue deterioration based on acoustic emission levels. During Stage I, reduction in emission was observed (0–32% of the total loading cycles for compression and 0–58% for shear). During Stage II, emission stabilised (32–67% for compression, not evident in shear) and in Stage III rapid increase in emission was observed, leading to failure (67–100% for compression, 58–100% shear).

Carpinteri et al. [4] performed a series of quasi-static and cyclic tests (8 specimens tested at 70% stress) on brick masonry specimens and walls and suggested a ε-N curve (strain vs. number of cycles) with three distinctive stages. During Stage I deformations increased rapidly for the first 10% of loading cycles, during Stage II deformations increased at a constant rate (10–80% of loading cycles) and during Stage III deformations increased rapidly again, leading to failure. Carpinteri et al. [4] also related the rate of change in vertical deformation during Stage II ($\vartheta\varepsilon_v/\vartheta n$) to the number of cycles at failure (N_f cycles) as shown in Eq. (1.4).

$$N_f = a\left(\frac{\vartheta\varepsilon_v}{\vartheta n}\right)^b \tag{1.4}$$

where ε_v is the vertical deformation, n is the number of cycles and N_f is the number of loading cycles at failure. Parameters *a* and *b* are material constants, that can be evaluated experimentally by applying a number of loading cycles on a prism up to the point here deformation starts to increase at a constant rate (over 10% of the fatigue life).

There are conflicting results for the different stages of fatigue for masonry and a lack of experimental data for identifying appropriate SN curves for different types of masonry and the evolution of strain under fatigue loading. The aim of this study is to i) investigate the stages of fatigue deterioration, ii) investigate the evolution of strain and stress-strain curves and iii) provide test data to develop mathematical models to predict the fatigue life of masonry.

2. Quasi-static and long-term cyclic tests under compression

Based on the work of Roberts et al. [13] and Tomor et al. [16], a series of brick masonry prisms have been tested under quasi-static and long-term cyclic compressive loading to identify changes in the material properties of masonry.

2.1. Materials

The experimental study intends to represent the weakest form of masonry, widely found in the UK waterways network, originating from the 1750s to 1850s. Brick masonry prisms were built using handmade low-strength solid 210 × 100 × 65 mm^3 Michelmersh bricks (B1 bricks). The average compressive strength of the bricks was 4.86 N/mm^2 (1.19 N/mm^2 standard deviation (SD) and 24.48% coefficient of variation) and the gross dry density 1823 kg/m^3. Lime-mortar with 0:1:2 cement: lime: sand by volume (M01 mortar) was used with NHL3.5 lime and 3 mm sharp washed sand and the mortar joins were 8 mm thick.

2.2. Test specimens

Small-scale masonry prisms (B1M01) comprised of five stack-bonded bricks with four 8 mm mortar joints built according to the ASTM standards [2] with total dimensions of 210 × 100 × 357 mm^3 (Fig. 2-1). In order to have systematic building quality,

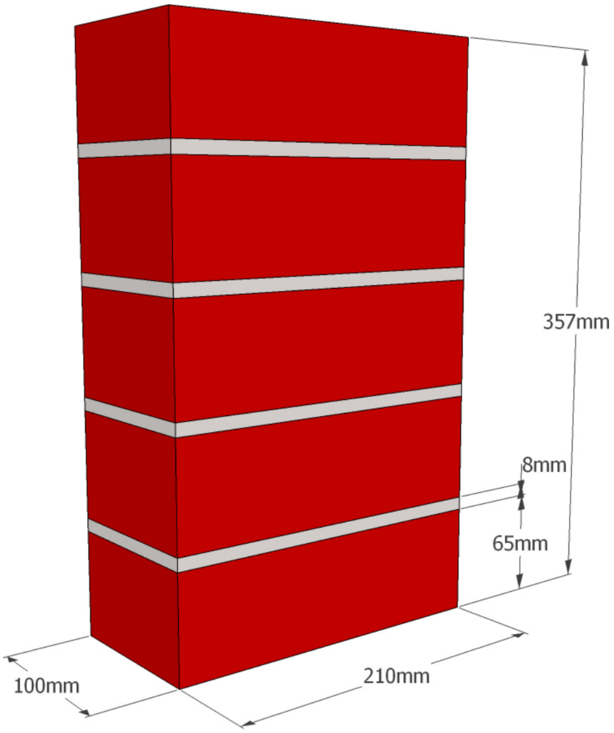

Fig. 2-1. Masonry prism dimensions.