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Acoustic emission based damage limits and their correlation with fatigue resistance of refractory masonry

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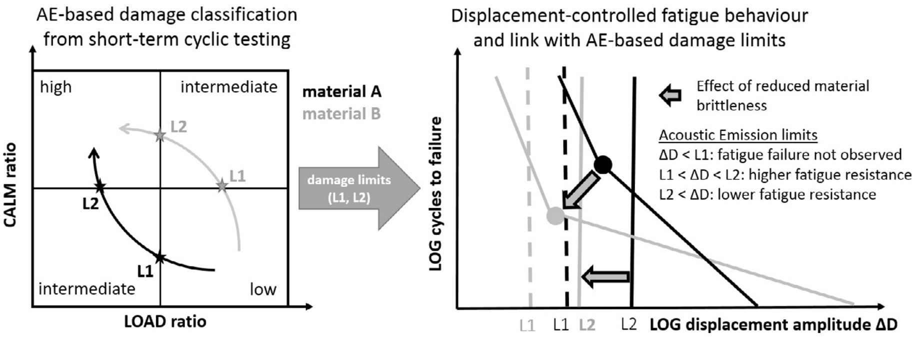
HIGHLIGHTS

- Micro fracture of different refractories is defined from acoustic emission (AE) data.
- AE LOAD and CALM ratios from cyclic testing indicate critical damage limits.
- Displacement controlled tests experimentally quantify cyclic fatigue resistance.
- Lower fatigue resistance zone correlates with AE-based critical damage limit.
- Less brittle material has lower fatigue resistance in broader amplitude range.

GRAPHICAL ABSTRACT



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ABSTRACT

During service in industrial furnaces, refractory masonry is exposed to cyclic thermal strains. Fatigue is a frequent cause of structural failure. In this study, displacement-controlled cyclic tests are applied to quantify the fatigue resistance of two silica-based products demonstrating different brittleness at failure. Limits for displacement producing critical damage were obtained from Acoustic Emission (AE) data. CALM and LOAD ratios, obtained from short-term cyclic tests, were used for this purpose. A correlation was found between experimental fatigue curves and AE-based damage limits. Less brittle material was found to be more susceptible to fatigue degradation in the broader amplitude range.

1. Introduction

Masonry structures of refractory ceramic bricks (refractories) serve in furnaces and high temperature installations in many materials processing industries [1]. Due to the batch nature of the process the masonry is exposed to cyclic loads of predominantly thermal origin. Performance of the refractories is critical for the longevity of the whole installation. Currently the state of the art approach to select the material most suitable for the given application is the indexes of merit that use parameters obtained from monotonic loading tests [2,3]. Owing to increasing life expectancy of producing installations, in recent years the cyclic fatigue failure of refractories has been attracting increased attention

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[4–10]. Fatigue tests performed in force and displacement controlled mode indicated the susceptibility of the refractories for fatigue degradation. As in civil engineering materials [11], in refractories the rates of damage accumulation demonstrate a minimum in the intermediate phase of the fatigue failure process [8,9]. The degradation of the friction and interlocking in the crack wake zone is believed to be the mechanism controlling the fatigue degradation on micro-structural level [9].

The micro-structure of refractories features large grains (up-to 5 mm in diameter) imbedded into a matrix of small grains, pores of different sizes and micro-cracks [12]. In monotonic loading tests, it has been shown that the micro-cracks and pores promote crack-shielding effects, reduce brittleness and, therefore, diminish the risk of undesired sudden failure [2]. For the cyclic fatigue degradation of refractories, the correlation between different elements of the micro-structure and the failure process is yet to be developed. In this respect, one of the major issues is the influence of micro-cracks and brittleness of the material on the fatigue resistance under loads of different intensity.

The Acoustic emission (AE) technique is recognized for its ability of in situ monitoring of the damage developing in materials and structures under loading. The elastic energy released in the form of stress waves from the crack propagation is received by piezoelectric sensors on the surface. The signal is further amplified and processed to deduce information on the fracture process data [13]. AE has a wide range of applications in monitoring the crack propagation in materials such as metals [14], concrete [15], wood [16], rock [17] and masonry [18]. For castable refractory concrete, AE was successfully used to monitor damage accumulation due to changing temperature [19,20] and during different phases of fatigue degradation [8]. In silica bricks, AE was used to detect micro-crack formation due to thermal shock and phase transition [21].

In this study, we analyse the fatigue resistance of two silica refractories demonstrating different brittleness at failure. Tests are performed in displacement-controlled mode. The degradation process is assessed by stress-strain measurements and from AE data. AE data is used to determine the displacement limits for damage to develop during the initial loading. Those are compared with trends obtained in fatigue tests. The study is expected to contribute to the optimisation of the material selection algorithms and the design of refractory masonry structures.

2. Methods and materials

2.1. Materials

Samples of two commercially available silica based refractory bricks have been analysed. The silica brick (SB) is produced from quartz raw materials by pressing and sintering at some 1500 °C. The modular block (MB) is formed by casting of a mixture featuring fused silica grains and calcium-aluminate cement. Before the tests, MB was heat treated at some 1400 °C for 100 h to enable the crystallisation expected to take place in the first several months of service. The materials are used in glass producing units and in coke ovens of the steel industry. For the latter the service life of the masonry is expected to be around 30 years. In this period, the loads resulting from 10000–12000 production cycles will be experienced by the bricks.

2.2. Methods and equipment

The chemical-physical characterisation of the materials was performed utilising established measurement techniques. The chemical and mineralogical composition was determined by XRF and XRD methods. The density and porosity was measured by the water immersion method according to EN993-1. The ultra sound velocity was determined by a devise produced by C.N.S Electronics Ltd. The dynamic Young's modulus was obtained by the impact excitation technique in an apparatus produced by IMCE BV.

Monotonic and cyclic three point bending tests were performed at room temperature in two equipment set-ups at two collaborating labs. At KU Leuven, the tests were conducted in combination with AE monitoring. The tests were done in the frame AG-X Plus from Shimadzu. The loading rate was 0,4 mm/min. The sample geometry was $40 \times 40 \times 150\ \mathrm{mm}^3$. The span for the three-point bending setup was 120 mm. Up to 12 loading-unloading cycles were done. In every new loading phase, a higher maximal displacement value was reached (Fig. 1a). A minimal force of 5 N was maintained upon unloading. In the final loading step, displacement was increased until the ultimate failure of a sample. The amassing size of AE data was limiting the amount of cycles that could be monitored. Four AE sensors were installed, two on the upper and two on the lower side of the sample at a distance of 5 cm from each other (Fig. 2). The set-up of the sensors was symmetrical regarding the main loading axis. AE data was acquired using a Vallen AMSY-5 system with four-channel ASIP-4 AE boards. AEP4 voltage preamplifiers with 230–830 kHz frequency bandwidth and 34 dB gain were used. 375 kHz piezo-electric sensors with 250–700 kHz operation frequency were attached to the specimens by means of a thin layer of hot-melt glue. The noise filter threshold was set to 38,5 dB. AE hits were recorded upon exceedance of the threshold, and subsequently grouped into AE events. An AE event can be either a detection of an AE source by one sensor, or a detection of an AE source by multiple sensors within a limited time interval. To avoid double counting, the latter is still referred to as just one event.

To obtain critical damage levels specific AE-based analysis approaches were used. Those are based on the normalisation of AE data and stress-strain parameters registered during the loading and unloading cycles of growing intensity [22]. The first parameter is calculated as the ratio between the load at the on-set of the AE activity during current loading cycle to the maximal load reached at the previous loading cycle. The parameter is called the LOAD ratio [22]. It allows differentiating between Kaiser and Felicity effects. In case when the LOAD ratio is around 1, Kaiser effect is present, which means the material's micro-structure shows a 'memory' for the previously obtained maximum load level and onset of AE activity coincides with the exceedance of this previous maximum load level. In this condition, the material is stable and has very little damage development. When the ratio drops below 1, the material demonstrates Felicity effect, which means AE activity is registered upon loading before the previously achieved maximum load level is reached. Its condition is seen as critical and prone to progressive degradation. In previous studies on clay brick masonry [18] and concrete [22], a LOAD ratio of 0.9 was taken as the limit between Kaiser and Felicity effects. For more information regarding Kaiser and Felicity effect, the reader is referred to [13].

In this study, to calculate the LOAD ratio, the onset of AE activity was set as the moment when the cumulative amount of events in the current cycle exceeds 20. A limit value of 0.9 is applied to differentiate between Kaiser and Felicity effect.

The second AE parameter applied in this study is called CALM ratio [22]. It is a ratio of AE events registered during un-loading to the AE events for the whole loading-unloading cycle. Structures demonstrating a CALM ratio above 0.05 are expected to possess a critical amount of damage and be unstable [22]. The third parameter combines CALM and LOAD ratios [22,23]. According to the combined parameter, the specimen is expected to have minor damage when both LOAD and CALM ratios are sub-critical. If either of the criterions is in critical range, the damage is intermediate. If both criteria are critical then the damage is heavy [23].