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Digital Image Correlation measurements of mortarless joint closure in refractory masonries

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HIGHLIGHTS

- Mortarless joint closure was studied using Digital Image Correlation (DIC)
- DIC optimum parameters were determined to measure the joint behaviour.
- Mechanical behaviour of dry joints is strongly heterogeneous and nonlinear.
- This behaviour is mainly due to roughness and non-planarity of the brick faces.

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ABSTRACT

Understanding the compressive behaviour of mortarless joints is necessary to optimise refractory masonry structures. This study investigates joint closure using Digital Image Correlation, a contactless measuring method. Results show that the gap thickness of the dry joint is mainly due to the non-planarity of contacting surfaces, the surface roughness playing a secondary role. The process of joint closure involves roughness crushing and the adjustment of surfaces, and is strongly heterogeneous, orthotropic and nonlinear. Local joint opening is observed during the first stage of the global joint closure process. This phenomenon is due to rigid body motion which induces a plane rotation of the upper contacting bricks.

1. Introduction

Some vessels used in the steel industry, such as steel ladles, are protected against the hot products they contain by refractory masonry linings made of bricks laid together without mortar. Due to irregular positioning of bricks in the masonry, brick shape defects and brick surface roughness, voids can appear between the bricks. These voids are called dry joints (mortarless joints). The thickness of these joints is generally small, but they play an important role [1,2]. When a thermal load is applied, brick expansion first fills the voids without significantly increasing the stresses [1,2]. In a second step, however, when the joints are closed, the stresses increase as if the masonry were only made of bricks without joints [1,2]. It is therefore crucial to take dry joints into account in thermo-mechanical simulations of vessels containing refractory masonries in order not to overestimate the stresses. To model a masonry, one solution consists in evaluating the effective properties using periodic homogenisation techniques [1,2]. To this end, it is necessary to know the thermo-mechanical behaviour of each component and in particular that of dry joints. In this study, only brick surface roughness and brick shape defects are taken into account. The effect of brick positioning in the masonry (which has an influence on the initial joint thickness) is not studied.

To determine the dry joint behaviour, compression tests on a stack of two bricks can be performed. It is possible to measure the relative displacement of the two bricks to obtain the global behaviour of the joint [3]. Due to the low displacement values reached at joint closure and the nature of the studied areas (dry joints generated by roughness and geometrical imperfections), it seems interesting to determine the local behaviour of the joint in order to highlight the different phenomena that occur. To achieve this, an optical technique such as Digital Image Correlation (DIC) [4–6] can be used. This technique makes it possible to measure both local (on a given point) and global (along the length of a brick) behaviour of the studied joints. Previous studies have used this

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technique to measure the behaviour of masonry structures and specimens with mortar [1,7–10].

The aim of this study was to investigate the local and global compressive behaviour of dry joints using DIC. Compressive tests on two stacked bricks were carried out at room temperature. The temperature effect was not addressed in this paper as the objective was to highlight the dry joint compressive behaviour mechanisms involved and to validate the approach. The measurement method was first validated by parametric studies. The strain and displacement fields up to joint closure were then measured at local and global scales.

2. Method of analysis and studied materials

2.1. Studied materials

Two types of refractory bricks frequently used in mortarless linings were studied. The first are Magnesia-Carbon (MaC) bricks that are predominantly used in converters and electric arc furnaces. The second are Magnesia-Chromite (MCh) bricks which are used in many applications such as vacuum degassers. The material compositions and physical properties are shown in Table 1.

Prismatic specimens were cut using a circular diamond saw from commercially available bricks. The specimen dimensions were 50 * 50 * 120 mm^3. These dimensions were chosen so as to be representative of real bricks. The dimensions of industrial bricks are $700 \times 100 \times 130$ mm^3 and $250 \times 150 \times 80$ mm^3 for Magnesia-Carbon and Magnesia-Chromite, respectively. After cutting, the specimens were cured at 110 °C during 24 h. It is worth noting that the dimensional tolerances of the original commercial bricks are higher for Magnesia-Chromite (±1 mm) than for Magnesia-Carbon (±0.5 mm).

A mortarless joint is formed by two refractory bricks stacked in direct contact with each other. Therefore the dry joint is generated essentially by the roughness of the faces in contact and the geometric imperfections of the two bricks (shape defects, parallelism, planarity, etc.). So, the compressive test must faithfully reproduce the real stress conditions of the bricks in the furnaces. For this purpose at least one rough face (uncut) was left for each sample and used to generate the contact areas of the brick/dry-joint/brick sandwich under the compressive tests.

2.2. Roughness tests

The roughness of the brick faces in contact is one of the reasons for the presence of voids between bricks. It partially defines the dry joint thickness and influences the joint's mechanical behaviour. To compare the two materials, the roughness of uncut faces was measured for some samples using an "SM4" roughness tester equipped with the acquisition software "RUGOSIM".

Fig. 1 shows an example of the roughness evolution of a Magnesia-Chromite (MCh) brick. This measurement was made over a distance of 17.5 mm and shows substantial irregularity of the roughness over this distance. The roughness of the two materials tested (MaC and MCh) was found to be quite similar (see Table 2). The arithmetical mean roughness (R_a) is about $12^{\pm 2}$ μm when the maximum height of the profile between two successive peaks and valleys on the length of measurement (R_y) is about $85^{\pm 15}$ μm.

Table 1
Properties of the studied bricks.

Material	MaC	MCh
Type	Magnesia-Carbon	Magnesia-Chromite
Density, g/cm^3	2.93	3.35
Open porosity, %	10	12
MgO, %	98	52
Cr_2O_3, %	–	27
CaO, %	1	–
Fe_2O_3, %	0.5	10
Al_2O_3, %	–	10
SiO_2, %	0.5	1
Total C, %	14	–

2.3. Equipment used for the compressive tests

Compressive tests were performed at atmospheric conditions on an Instron 4507 mechanical frame with a load cell of 200 kN (Fig. 2). The load accuracy is about ±0.2% of the load attained. To form the joint without mortar (dry joint), two bricks are stacked in the compressive device by bringing the rough faces into contact with each other. In order to better transmit the force and avoid non-contact between surfaces, rubber layers were inserted between the brick specimens and the compressive device parts (upper and lower). The compression tests were performed with a constant displacement rate of 0.033 mm/min. They were stopped when the joint was closed (for higher loads only the brick behaviour is obtained).

2D Digital Image Correlation (DIC) [4,5] was used to measure the compressive behaviour of the dry joint with the 7D correlation software [11]. DIC is an optical method based on grey-scale digital images that can be used to measure the strain and displacement fields of the specimen at each load state. The plane surface of the specimen was observed by a commercial CCD (charge coupled device) camera to record frames of the sample surface continuously during the compressive test (Fig. 2). The maximum image resolution of the camera was 1380×1024 pixels with an 8-bit digitization for grey levels ($2^8 = 256$ grey levels). The maximum acquisition frequency was one frame per second. Images were recorded, digitized and stored in a computer as digital images. During the compression tests, a lamp was installed in front of the samples to light them in order to avoid acquisition being affected by the natural light variations in the room.

Often, for DIC measurements, a random pattern is drawn on the sample surface with special paint to enhance the image contrast. In our case, the natural pattern of the bricks was enough to produce a suitable pattern.

In the present study, measurements were only performed in 2D. This does not enable some possible brick rotations or out-of-plane displacements to be observed. To improve these measurements, it is planned, for future tests, to perform DIC on a second face of the bricks.

2.4. DIC

DIC is a non-contact full field measurement method that was introduced in the 1980s [4,6] and which is now widely used in different scientific fields. The interest of this method is that it can measure both local and global variations of the displacement field of a structure under mechanical loads.

The principle of DIC is to assess the displacement fields, and thus the strain fields (if required), over the surface of a deforming material by comparing two images acquired at different stages of deformation. The first image is referred to as the "reference frame" and the second, acquired after some increment of deformation, as the "deformed frame". Before applying the measuring procedure, a region of interest is manually defined on the initial image and divided into small subsets (quadrilaterals).

Then, the method defines a grid of analysis points over the reference frame. A group of pixels, commonly called a "subset" (Fig. 3), is defined about each node of this grid. Image correlation is performed, for each node, by identifying the most similar subset