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Damage law identification from full field displacement measurement: Application to four-point bending test for plasterboard

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ABSTRACT

Plasterboards are tested in four-point bending up to failure, and digital image correlation is used to follow the kinematics and the progressive degradation of the structure all along the test. Although numerous distinct core cracks are clearly observed, it is proposed to identify the behavior of plasterboard through a homogenized continuum description where the progressive degradation of the bending stiffness is described through a damage law. A specific procedure for the identification is presented where experimental imperfections and symmetry breakdown are accepted and accounted for. The identification procedure is shown to provide constitutive parameters with a remarkably small variability.

1. Introduction

The use of plaster as a building material has a very long and rich history. In their quest for producing a robust, light-weight, insulating structure element for the building industry, the concept of plasterboard was invented as early as in 1894 by two engineers from New York, A. Sackett and F.L. Kane. Plasterboard is nowadays the most commonly used low-cost building plates within the construction industry. This success is mostly due to the fact that plasterboards can be used in many applications, and engineered with enhanced performance for acoustic and fire requirements (Vimmrová et al., 2011). Gypsum board producers are still working for improved properties, or similar properties but with lower densities. Weight has direct commercial consequences, as any density saving impacts directly on production, transport, environmental and economical costs. Moreover, lightweight boards facilitate handling and make installation easier and more secure.

Two main methods are commonly used for the production of porous gypsum. In the first method, gas bubbles are formed in the gypsum paste through chemical additives. The second one consists of foaming by air entrainment in the wet gypsum paste (Vimmrová et al., 2011; Çolak, 2000). The relationship between microstructure and mechanical properties of raw plaster or core of the board (Murat et al., 1974; Coquard, 1992; Meille, 2001), or the evaluation of fire resistance of a partition wall with plasterboards has been thoroughly studied (Sakji, 2006; Sakji et al., 2008). However, plasterboard as such has received only little recognition as a structural part; its mechanical behavior and fracture resistance are scarcely investigated in the literature, although from manufacturing to installation, mechanical properties such as the flexural strength of the boards are crucial. Benouis (1995) showed the orthotropic nature of the plasterboard, which is a consequence of the tensile behavior of the paper. Some studies on the mechanical properties of syntactic foam core sandwich composites are also available. In these studies it is observed that the skin (paper) contributes to an increase of up to 40% in estimated flexural strength, depending on starch content in adhesive between core and skin (Gupta and Woldesenbet, 2005). Other studies on mechanical properties of gypsum sheathing found that the bending strength of gypsum sheathing depends on the strength of the adhesive bond between the facings and the gypsum core (McGowan, 2007).

Therefore, it is critical for the producers to strive to create a board of even lighter weight that still passes the standard tests. To achieve this goal, it is important to make progress on the

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characterization of the failure mechanism in bending tests and to identify the different stages of damage and failure. Progress along these lines opens new pathways for optimized light wallboards, and hence efficient light frame construction.

In the present paper, Digital Image Correlation (DIC) is used to measure the kinematics of the plasterboards during four-point bend tests up to failure. From this measurement, the ambition is to provide an effective constitutive law within the framework of plate theory (*i.e.,* without distinguishing core and facings) to be used for describing wallboard within arbitrary flexural loadings up to ultimate failure.

Since the pioneering works of Sutton et al. (1983); Chu et al. (1985), DIC has been widely used not only in the academic world but also in industry. Recent advances enable the sought displacement field to be decomposed onto a suited library (Hild and Roux, 2006) such as finite element shape functions (Besnard et al., 2006). This type of technique has been used based on beam/plate kinematics (Hild et al., 2009; Réthoré et al., 2009; Leplay et al., 2010). The main interest of this approach is that it provides full kinematic fields expressed in standard form for beam/plate theories. Moreover, because of the reduced number of degrees of freedom, measurement uncertainties are significantly reduced. Because the kinematic description has a direct mechanical meaning the interface with a further modeling for identification purposes is direct and does not involve any projection error. However, it may be noted that if the displacement field significantly deviates from that of elastic plate theory (say because of pronounced damage or cracking), then an integrated approach may reveal inaccurate. For this reason, the motion has been analyzed without specific assumption, and then the two-dimensional kinematic field has been reduced to 1D plate kinematics.

Examples of identification of elastic (or more complex constitutive laws) based on DIC measurement are numerous (Forquin et al., 2004; Hild and Roux, 2006; Périé et al., 2009; Eberl et al., 2010; Leplay et al., 2010; Grédiac and Hild, 2013). However, damage models have been less studied. Chalal et al. (2004) resorted to the virtual fields method to determine the parameters of a linear relationship between the damage parameter and the local shear strain. An alternative route is given by the equilibrium gap method that aims at identifying fields of elastic contrasts (Claire et al., 2002, 2004), which may be reinterpreted *a posteriori* as damage fields (Claire et al., 2007; Crouzeix et al., 2009). More recently, it has been shown that the same type of formalism can be used to directly identify the parameters of the damage law in the case of isotropic (Roux and Hild, 2008) and anisotropic (Périé et al., 2009; Ben Azzouna et al., 2011) descriptions of damage.

Dedicated examples suited to beam-like geometries are less common (Forquin et al., 2004; Leplay et al., 2010; Hild et al., 2011). In particular, Leplay et al. (2010; 2011) used the central section of a four-point bend test to evaluate a damage law of a ceramic material. In that case, the kinematics (*i.e.,* uniform curvature) decouples from the constitutive law, and hence identification is direct. This procedure was shown to be accurate, but it does not tolerate any deviation from the basic hypothesis of constant curvature. Further, to account for local buckling in steel beams (Hild et al., 2011), damage variables have been introduced either in the buckled zone or lumped in a hinge as described in the framework of Lumped Damage Mechanics (Cipollina et al., 1995).

A comparable goal is aimed at in the present study, but with arbitrary test geometry of the plate, namely four-point but also three-point bending, or any arbitrary departure from a perfect test. The inhomogeneous kinematics makes the problem more involved as it calls for a dedicated procedure. Let us stress that the information that can be extracted from DIC is too detailed and spatially resolved for the ultimate goal as the details of core crack inception, their shape size, density, or opening are easily accessed but would drive naturally to a probabilistic approach describing crack initiation in the core, and interface debonding. Although it may appear as paradoxical, the too fine description of the kinematics is challenging for the identification of a homogeneous constitutive law (Gras et al., 2013).

In the following, the methodology is illustrated by analyzing a bending test on plasterboard plate. In Section 2, the experimental conditions are described, and first analyses of kinematic data extracted from displacement measurements thanks to DIC are presented. The identification procedure is summarized in Section 3. First, the identification of the elastic modulus of the plasterboard is proposed. Then, the identification of a damage law is detailed and applied to the experiments on plasterboard plate.

2. Experimental procedure

2.1. Plasterboard

Plasterboard is a material composed of lightweight gypsum core lined with paper coatings. Adhesion between paper and gypsum core is promoted by the addition of starch. The latter has definite advantages over other binders in applications for building interior sandwich panels because it is readily available, environmentally friendly, inexpensive, and renewable.

2.2. Material and sample geometries

Specimens used in the experiment are prepared from industrial plasterboard plates. The tested samples are cut out at a size $160 \times 50 \times 13$ mm^3. They are tested on a four-point bend rig with the following characteristics:

- outer support span, $D_{\text{lower}} = 150$ mm;
- inner yoke span, $D_{\text{upper}} = 40$ mm;
- prescribed displacement speed 5×10^{-2} mm/min until failure.

Load-deflection curves are monitored all along the test.

2.3. Full field measurements

Global DIC is used to measure the displacements of the lateral surface with Correli-Q4 (Besnard et al., 2006). We refer the reader to the latter publication for further details on the specific finite-element DIC code used herein. Let us however stress that although the displacement field is decomposed over finite element shape functions, there is no mechanical modeling involved at this stage. The reference and the last deformed image before failure are shown in Fig. 1. A random speckle pattern has been applied on the sample surface to enhance the image contrast. Digital images are recorded during the deformation process using a digital single lens reflex camera (Canon 40D). The image definition is 3888 × 2592 pixels and stored with 8-bit digitization. The displacement at image n is assessed by correlating the n-th image with the initial image (unloaded state considered as the reference). The acquisition frequency is one image per five seconds. The physical size of one pixel is 37 μm. The size of the Q4 elements has been chosen to be 12 pixels or about 450 μm. A priori estimates of the displacement resolution are 0.04 pixel or 1.5 μm.

After the DIC evaluation of the displacement, the measurement data are projected onto plate theory kinematics by computing the deflection and rotation along any cross section. The ROI is chosen such that its horizontal axis coincides with the neutral axis of the sample. The vertical displacement field is then averaged in each section to determine the displacement field for the neutral axis. The