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Comparison of simple and pure shear for an incompressible isotropic hyperelastic material under large deformation

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ABSTRACT

The concepts of simple and pure shear are well known in continuum mechanics. For small deformations, these states differ only by a rotation. However, correlations between them are not well defined in the case of large deformations. The main goal of this study is to compare these two states of deformation by means of experimental and theoretical approaches. An incompressible isotropic hyperelastic material was used. The experimental procedures were performed using digital image correlation (DIC). The simple shear deformation was obtained by single lap joint testing, while the pure shear was achieved by means of planar tension testing. Classical hyperelastic constitutive equations available in the literature were used. As a consequence, the results indicate that simple shear cannot be considered as pure shear combined with a rotation when large deformation is assumed, as widely considered in literature.

1. Introduction

The shear stress-strain response has been extensively studied in recent years. Basically, there are two ways to interpret shear deformation, which are defined by simple shear and pure shear. In the case of small deformations, pure shear may be considered as simple shear followed by rigid rotation. In addition, the two states of deformation have often been assumed identical in classical literature [1,2]. Despite the fact that these concepts are also well known in continuum mechanics [3,4], the correlation between them is not well defined. Jones and Treolar [5,6] assumed that "*Simple shear differs from pure shear only by a rotation*" in an investigation of a rubber sheet under biaxial strain.

The first experiment for providing pure shear on a thin sheet of rubber-like material was proposed by Treloar [7]. Rivlin and Saunders [8,9] developed an experimental and theoretical investigation on pure and simple shear states of incompressible isotropic material under large elastic deformations. In 1964, Mooney reported a series of measurements using a thin-walled hollow cylinder instead of a flat sheet [10]. The characterization of hyperelastic rubber-like materials by means of planar testing has also been performed by Sasso et al. [11].

Recently, there has been growing interest in the state of simple shear [12–14]. Rajagopal and Wineman [15] have developed a study of new universal relations for a nonlinear isotropic elastic block subjected to simple shear deformation superposed on triaxial extension. Some investigators have concluded that: "*simple shear is not so simple*" [16,17]. Nunes [18,19] has studied the nonlinear mechanical behavior of a hyperelastic material under small and large simple shear deformations. According to Horgan and Murphy [17], "*A simple shear deformation reflects essentially a conceptual experiment that would be extremely difficult to replicate in a laboratory*". Despite all the contributions, there is a need to clarify both simple and pure shear states when large deformations are taken into account.

The purpose of this paper is to investigate simple and pure shear states on a hyperelastic material under large

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deformations. The two states of shear deformation were compared by means of experimental [5,18,19] and theoretical [8,9] analyses, used to verify the validity of the assumption made by Jones and Treloar.

2. Material and methods: experimental setup

Two different experimental tests were performed to investigate the states of simple and pure shear under large deformations. Simple shear was obtained by single lap joint testing, while pure shear was carried out by means of planar tension testing [20]. The material used for manufacturing the single lap joint and thin sheet specimens was an adhesive based on silane modified polymer (Flextec®FT 101). This adhesive is suitable for many types of construction materials and presents high flexibility and elasticity.

The single lap joint specimens were made with adherends of steel A36 and FT 101 adhesive, being a suitable configuration to provide a simple shear deformation [18–20]. They had an overlap length of 50 mm and a joint width of 25.4 mm. The adherend and adhesive thicknesses were 1.6 mm. It is important to note that the adherend stiffness is much greater than the adhesive, in order to guarantee that the adherends do not deform and the adhesive only deforms in shear. Fig. 1 shows the experimental arrangement with the single lap joint specimen mounted on the load apparatus. The apparatus was used to ensure that the adherends remained parallel as the load was applied.

In order to provide pure shear, a planar shear test was carried out [6,7,20]. This test is based on a rectangular sheet of FT 101 adhesive under tension in its plane normal to the clamped edges. Fig. 2 illustrates the rectangular specimen under tension. Thin sheets with dimensions of $150 \times 70 \times 3.4$ mm^3 were employed, the effective area being 150×10 mm^2 due to the clamped edges. It is important to emphasize that the width of the effective area was at least 10 times greater than the length in the stretching direction. As a result, the specimen must remain perfectly constrained in the lateral direction while specimen thinning occurs only in the thickness direction.

The digital image correlation (DIC) method was employed for measuring the displacements of the polymer. DIC is a powerful optical-numerical method developed to estimate full-field surface displacements, being well documented in the literature [21,22]. The basic principle of DIC is to match maximum correlation between small zones (or subsets) of the specimen in the undeformed and deformed states.

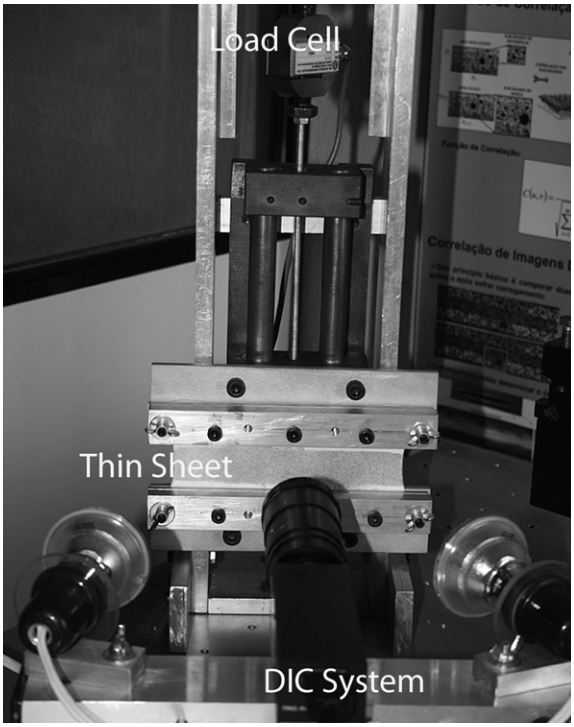

Fig. 2. Experimental arrangement for pure shear.

The specimens were sprayed with black paint to obtain a random black and white speckle pattern in order to perform the correlation procedure. A CCD camera (Sony XCD-SX910) set perpendicularly to the specimen was used for capturing the images. All images were acquired using a $10 \times$ Zoom C-Mount lens. It is important to emphasize that the experiments were carried out in quasi-static conditions and at room temperature, i.e., 25 °C. The images of the undeformed and deformed specimen were captured and processed using a DIC program (home-made DIC code), in order to estimate the displacement fields. The size of the measurement field was 1280×960 pixels and the reference and target subsets equal to 31×31 and

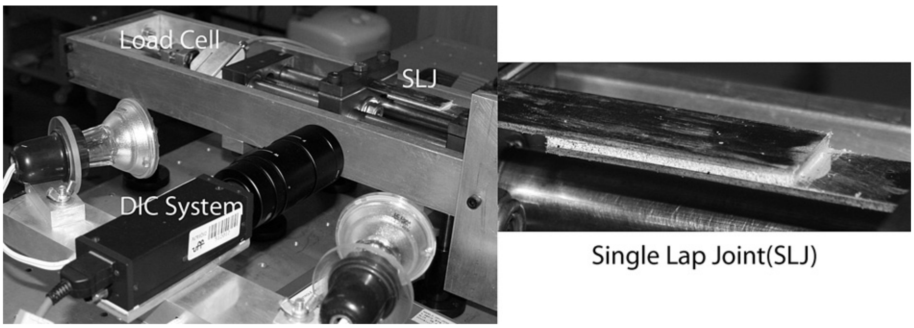

Fig. 1. Experimental arrangement for simple shear deformation.