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SHEAR DISTRIBUTIONS AND COAXIALITY STUDY OF PTFE SPECIMENS UNDER SIMPLE SHEAR

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Abstract. *The application of the kinematic vorticity number can be useful to define pure and simple shear for in-plane analysis. In such way, the main objective of this work is to perform an experimental coaxiality study of PTFE specimens under simple shear at large deformations and incremental strain. A time-independent formulation of the kinematic vorticity number is used. The methodology known as the Modified slotted shear test is implemented and displacement fields are measured using the Digital Image Correlation (DIC) method. Moreover, a shear distribution analysis is performed to estimate the shear uniformity in the shear path of the specimens. For large strain, satisfactory and accurate shear distributions were obtained.*

Keywords: *Simple Shear, Kinematic Vorticity Number, Coaxiality, DIC, PTFE.*

1. INTRODUCTION

The kinematic vorticity number, often denoted as w_k, first appeared in fluid dynamics analysis (Truesdell, 1953). However, studies have shown that this number can also be applied to solid analysis, mainly to estimate pure shear and simple shear deformations of rocks (Passchier, 1987, and Tikoff and Fossen, 1995). Considering solid analysis, it was showed that time-independent solutions for w_k were reached for incremental and homogeneous steady-state deformations (Tikoff and Fossen, 1995).

In literature, simple shear is considered to be a non-coaxial deformation (Ghosh, 1987). However, Butcher and Abedini (2017) presented coaxiality assumptions for simple shear condition before and after yield shear stress value. In the elastic regime, materials subjected to simple shear condition undergo a coaxial phase, while in the plastic regime, a non-coaxial deformation is noticed. Normal stresses do not progress in the same rate for elastic and plastic regimes, leading to these assumptions. For small strains, simple shear condition is approximately considered to be a pure shear condition, which is coaxial. According to Schielicke et al. (2016), coaxial deformations are identified when $w_k = 0$ and simple shear when this number is approximately equal to 1. Values above 1 indicate that the rotation has greater influence in the deformed state than the deformation itself. Moreover, values with higher orders ($w_k \rightarrow \infty$) show that only a rigid-body rotational motion occurs.

Polymeric materials have been intensively studied in recent years using different methodologies in literature (Codolini et al., 2018). For instance, Nunes (2015) proposed a modification of the standard ASTM B831, denoted as the Modified slotted shear path, regarding the application in materials subjected to large deformations, such as polytetrafluoroethylene (PTFE). These modifications were introduced concerning the minimization of the rotation, out-of-plane deformations and distortion of the shear path. It is important to emphasize that PTFE has a low coefficient of friction and non-stick surfaces, which can make experimental procedures potentially hard to be executed. PTFE is a thermoplastic polymer widely used in several industrial applications (Filho and Nunes, 2018) and has a complex non-linear behavior, according to Nunes et al. (2011). Therefore, the knowledge of PTFE subjected to several loadings conditions is important, especially in simple shear.

The purpose of the present work is to evaluate the simple shear deformation using the kinematic vorticity number and perform an experimental coaxiality study. Recently, Filho and Nunes (2018) developed a similar study. However, further coaxiality information is important in such analysis. The PTFE specimens were fabricated using the modification of the standard ASTMB831 proposed by Nunes (2015) and displacement fields were evaluated using the Digital Image Correlation method (DIC). Moreover, a recent study has concluded that the Modified slotted shear test has provided a non-uniform strain distribution in the shear path of polypropylene specimens for large deformations (Codolini et al., 2018). Therefore, a new approach using a DIC algorithm with higher accuracy was performed to determine the shear distributions in the shear path of PTFE specimens.

2. MATERIALS AND METHODS

2.1 Specimen

The specimens, illustrated in Fig. 1(a), were manufactured from a thin sheet of polytetrafluoroethylene (PTFE) according to the geometry proposed in the Modified slotted shear test, which is a modification performed by Nunes (2015) of the standard ASTM B831. Their dimensions were 130 × 40 × 2 mm with two 45° angled slots 1 mm thick. The distance between both slots was 16 mm, defining the shear path, and the applied shear loads were distanced in 1 mm, giving the dimensional relation within both distances on the order of 16. According to G'Sell et al. (1983), this relation should be greater than 15 to guarantee the uniformity of the shear deformation distribution. PTFE is a thermoplastic polymer with a low coefficient of friction that increases the difficulty of performing experimental tests. These difficulties are mainly related to mounting the specimen on the testing machine. Therefore, a thin aluminum holder depicted in Fig. 1(b) was affixed in the specimens to minimize sliding effects and distortion, such as out-of-plane displacements of the shear region. Further information on the modified specimen can be encountered in (Nunes, 2015).

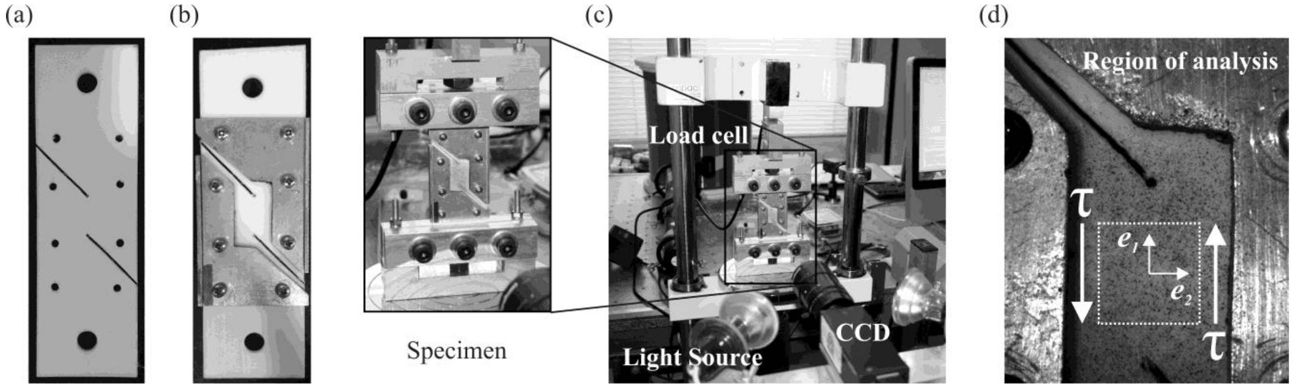

Figure 1. PTFE specimen (a), aluminum holder (b), experimental setup (c) and region of analysis (d).

2.2 Experimental setup

The simple shear tests were performed under a quasi-static loading condition at room temperature of 25ºC. The velocity was set in 8mm/min and load data was obtained using a 100kgf load cell. A bi-dimensional home-made Digital Image Correlation (DIC) method with 0.01 pixel of precision was used to obtain the specimen's full-field displacements. DIC is a noncontact optical method, which code is based on normalized cross-correlation function to extract the in-plane displacement fields. In such way, for improving image correlation, a random speckle pattern was introduced on the specimen's surface. This pattern can be obtained through several approaches and in this study an overspray of black paint was implemented. The application of the DIC method is convenient since PTFE specimens have low coefficient of friction. Therefore, any contact method, such as Strain Gauges, cannot be used not only because of the fixture impossibility, but also because these methods are inappropriate for large deformations. A target subset of 15 × 15 pixels and calibration factor of 24,2 pixel/mm were considered. More information on DIC method is given by Sutton et al. (2009) and Sharpe (2008).

Figure 1(c) illustrates the experimental setup of the simple shear test. It is possible to observe a CCD camera placed perpendicular to the specimen that was mounted on the testing machine. The digital monochrome camera (Sony XCD-SX910), combined with a 1/2″ 13–130mm 10X Close-up Manual Zoom lens, was used to capture images at the beginning and during the experiment. The images were taken at the center of the specimen in view of reducing the distortion generated by the curvature of lens and light sources were used to provide images with better quality. The image capture and load data were obtained simultaneously. Also, in order to reduce the errors of image correlation it was considered incremental motion.

3. KINEMATICS

Figures 2(a), 2(b) and 2(c) illustrate a unit cube subjected to homogeneous pure shear ($\gamma_{12} = 0$, $\delta_1 \neq 0$ and $\delta_2 \neq 0$), simple shear ($\gamma_{12} \neq 0$, $\delta_1 = 0$ and $\delta_2 = 0$) and general shear ($\gamma_{12} \neq 0$, $\delta_1 \neq 0$ and $\delta_2 \neq 0$), respectively. Considering an in-plane strain condition, leading to the simplification $\delta_3 = 1$, the general shear deformation related to the reference configuration X_i to the current configuration x_i can be expressed by the following expressions

$$x_1 = \delta_1 X_1 + \gamma_{12} X_2 \quad x_2 = \delta_2 X_2 \quad x_3 = X_3 \,, \tag{1}$$

where γ_{12} is called the amount of shear, and δ_1 and δ_2 are normal extensions related to the $\boldsymbol{e_1}$ and $\boldsymbol{e_2}$ directions.

Therefore, the deformation gradient tensor, denoted by **F**, is given by

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}}, \tag{2}$$

where

$$\mathbf{F} = \begin{bmatrix} \delta_1 & \gamma_{12} & 0 \\ 0 & \delta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

The displacement gradient tensor, defined by $\nabla\mathbf{u}$, can be expressed as follows

$$\nabla\mathbf{u} = \mathbf{F} - \mathbf{I}, \tag{4}$$

where **I** is the identity matrix.

Note that pure shear is coaxial, because the principal axes remain unchanged, according to Fig. 2(a). By analyzing Figs. 2(b) and 2(c), it is possible to observe that the principal axes change their direction in the deformed states. For this reason, simple shear and general shear are non-coaxi al deformations. However, Butcher and Abedini (2017) exposed coaxiality hypotheses regarding the elastic and plastic regimes of simple shear. A coaxial deformation occurs in the elastic regime, and non-coaxial deformation in the plastic region. These hypotheses were considered since the progression rate of normal stress is different for for elastic and plastic regimes.

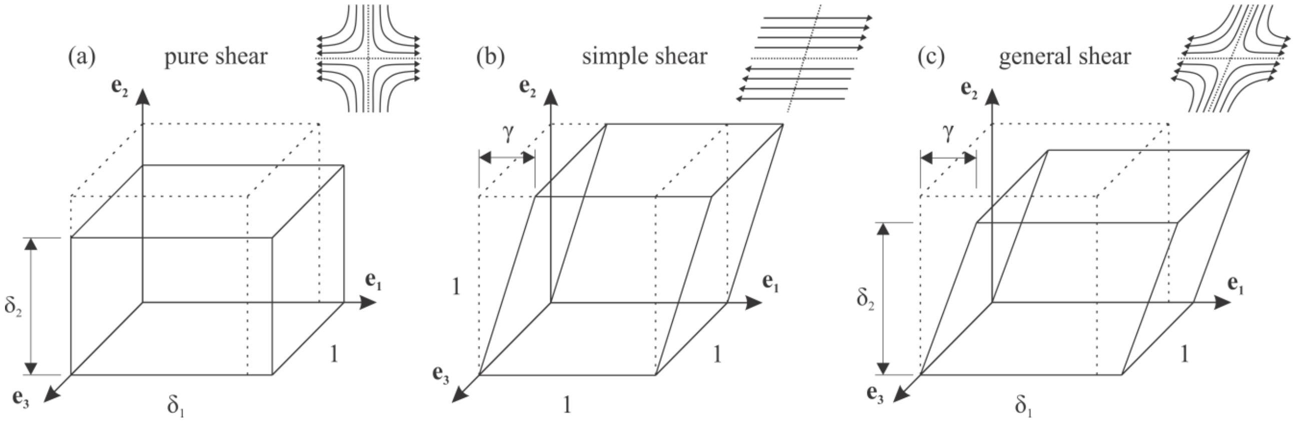

Figure 2. Schematic of pure shear deformation (a), simple shear deformation (b) and general shear deformation (c).

For homogenous steady-deformations and incremental strain, according to Truesdell (1953), Tikoff and Fossen (1995), and Filho and Nunes (2018), the time-independent kinematic vorticity number can be expressed as follows

$$w_k = \frac{\sqrt{\left(\partial u_1/\partial X_2 - \partial u_2/\partial X_1\right)^2}}{\sqrt{\left(\partial u_1/\partial X_1 + \partial u_2/\partial X_2\right)^2 + \left(\partial u_1/\partial X_1 - \partial u_2/\partial X_2\right)^2 + \left(\partial u_1/\partial X_2 + \partial u_2/\partial X_1\right)^2}}, \tag{5}$$

where u_1 and u_2 are the displacement fields related to the $\mathbf{e_1}$ and $\mathbf{e_2}$ directions.

Pure shear, simple shear, their combination and rigid rotation can be identified using such number. The kinematic vorticity number is the ratio between the norm of the vorticity tensor and the norm of the rate-of-strain tensor (Truesdell, 1953 and Schielicke et al., 2016). Both tensors can be obtained using the velocity gradient tensor. However, for time-independent solution, w_k can be evaluated only with the displacement gradient tensor $\nabla\mathbf{u}$, given in (4). The pure shear is defined when a zero internal vorticity is encountered, producing a coaxial strain. The non-coaxiality is reached when the internal vorticity is above 0. Moreover, simple shear is specified when $w_k = 1$ and rigid rotation when $w_k \rightarrow \infty$. For values between 0 and 1, this number indicates that the deformation is more pronounced than rotation.

In order to measure the strain distributions, it is convenient to employ a finite strain tensor, such as the Green-Lagrangian strain tensor, as described by Nunes (2015). This tensor is denoted by

$$\mathbf{E} = \frac{1}{2}\left[\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathbf{T}}\right] + \frac{1}{2}\nabla\mathbf{u}^{\mathbf{T}}\nabla\mathbf{u}\,. \tag{4}$$

The shear component of this tensor is given by

$$E_{12} = \frac{1}{2}\left(\frac{\partial u_1}{\partial X_2} + \frac{\partial u_2}{\partial X_1}\right) + \frac{1}{2}\left(\frac{\partial u_1}{\partial X_1}\frac{\partial u_1}{\partial X_2} + \frac{\partial u_2}{\partial X_1}\frac{\partial u_2}{\partial X_2}\right). \tag{5}$$

4. RESULTS AND DISCUSSION

Figure 3 illustrates the displacement fields for a 8 × 8 mm region located in the center of the specimen, depicted in Fig. 1(d), for loads of 4MPa, 8MPa and 12MPa, approximately. Knowing that the yield shear stress of PTFE is on the order of 8MPa according to Nunes (2015), the approximate loads of 4MPa and 12MPa were chosen in the elastic and plastic regimes, respectively. The displacement fields, obtained using DIC method, were reconstructed in a mesh of 101 × 101 elements in order to evaluate homogeneous deformation tensors at each point in the selected region, making possible the kinematic vorticity number usage. By analyzing Figs. 3(a) and 3(c), on both elastic and plastic regimes a non-coaxiality was observed, contradicting what Butcher and Abedini (2017) pointed out. Moreover, the deformed state rotates near the corners before yield shear stress, according to Fig. 3(a). From the yield shear stress, the rotation is barely noticeable, as illustrated in Figs. 3(b) and 3(c). However, it should be kept in mind that this rigid-body motion can occur for larger deformation states.

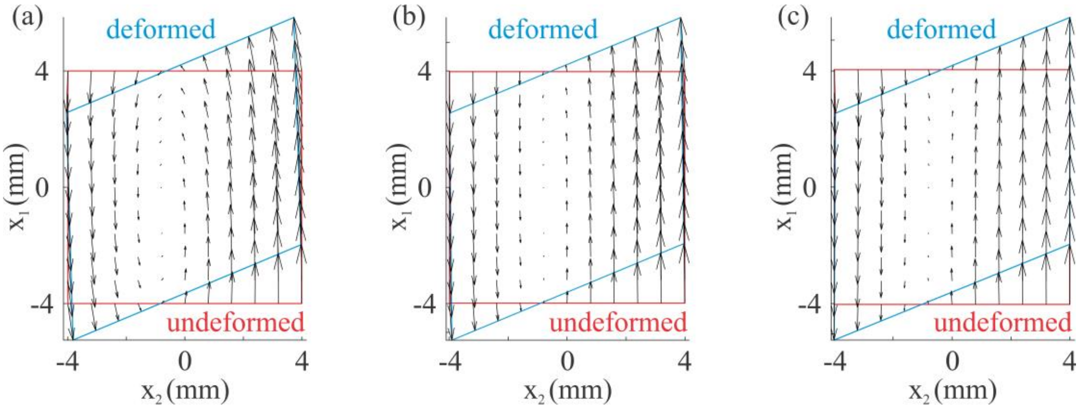

Figure 3. Displacement fields for 4MPa (a), 8MPa (b) and 12MPa (c).

It is evident that simple shear is restricted to the center of the specimen, as depicted in Fig. 4(c), where w_k is close to the reference value of $w_k = 1$. On neighborhoods of Figs. 4(a) and 4(b), this value is greater than $w_k = 1$. Therefore, rigid rotation prevails over deformation on these regions ($w_k > 1$). Coaxial conditions is obtained when $w_k = 0$. However, for any loading condition, the kinematic vorticity number is above 0.95, indicating that non-coaxiality is seen in the elastic, yield shear stress and plastic regimes.

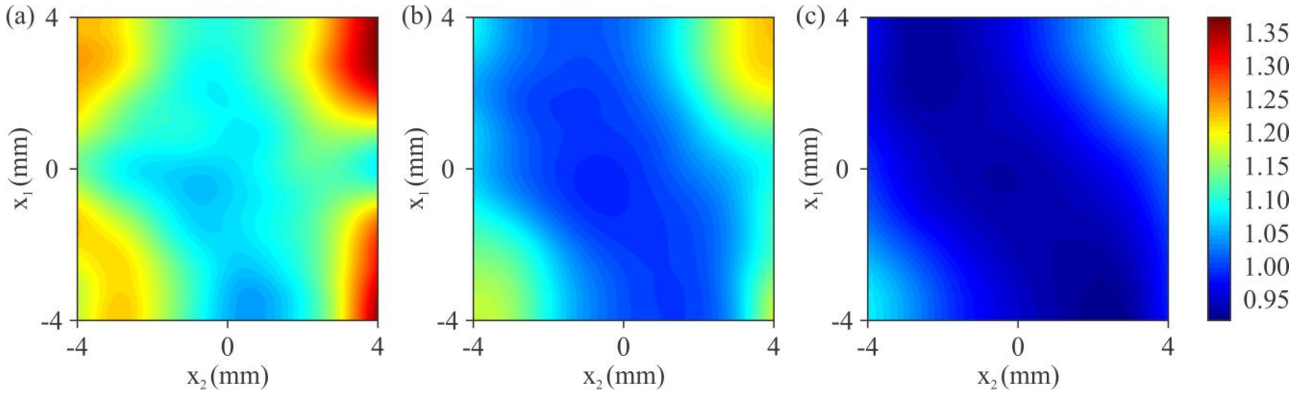

Figure 4. Kinematic vorticity number for 4MPa (a), 8MPa (b) and 12MPa (c).

The evolution of the shear component E_{12} of the Green-Lagrangian strain tensor for applied loads of 4MPa, 8MPa and 12 MPa between both slot ends with their standard deviation is shown in Fig. 5. The study of the shear uniformity was investigated in the shear path. It is remarkable that a uniform shear distribution was reached in the central region employing the methodology proposed by Nunes (2015), and accuracy is seen even for large strains. However, higher E_{12} values were observed near slot ends for higher loads, as these regions holds a stress concentration area. In addition, a small difference can be detected within the curves ends, showing that the shear path rotates. It was observed by Codolini et al. (2018) that the Modified slotted shear test provided non-uniform shear distributions. Nevertheless, in this work a satisfactory shear distribution was evaluated.

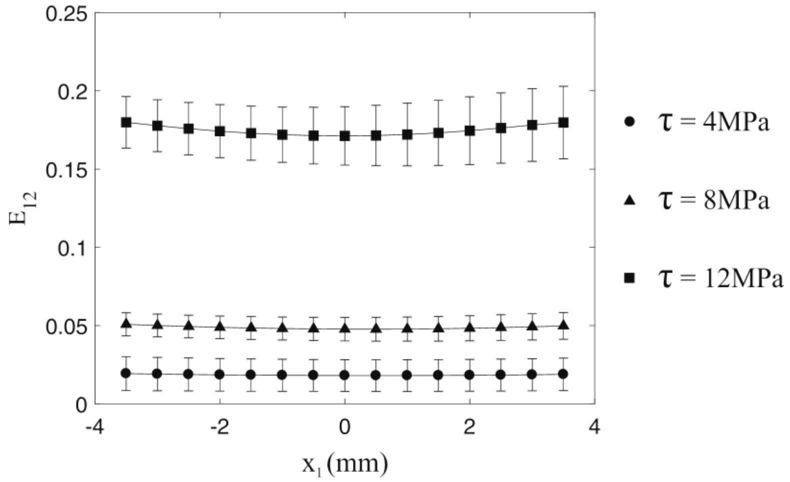

Figure 5. Shear distributions along shear path.

5. CONCLUSION

The kinematic vorticity number can be a tool for estimating the coaxiality condition of materials submitted to any loading process. In this work, the coaxiality and shear distributions of PTFE specimens under simple shear were experimentally studied. In the plastic regime, a small combination of pure and simple shear was seen in the central region of the specimens, where w_k was between 0.95 and 1.05 approximately. In the elastic regime and in the yield shear stress, the w_k values were above 1, showing that rigid rotation influence occurred. In such way, a non-coaxiality was seen in the center of the specimens for small and large strains, confirmed by the displacement fields and the kinematic vorticity number analysis. Moreover, the shear distributions along the shear path were satisfactory and presented accuracy even for large strains. It is important to emphasize that further investigations must be performed regarding the employment of the kinematic vorticity number on solids, mainly in polymer applications.

6. ACKNOWLEDGEMENTS

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