SHEAR BEHAVIOUR OF POLYURETHANE FOAM

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Abstract

Polymeric based foams are widely used as insulation or structural core materials. Typically, plastic foams such as polyurethane (PUR) are commercially available in a variety of densities and, consequently, with distinct mechanical properties to fulfil a wide range of uses and applications. Usually, in sandwich construction, PUR foams are used as core material enclosed by two external faces of higher stiffness and strength. Since the lightweight PUR foams are relatively inexpensive, they are prone to be used as core material in sandwich construction, but may limit the ultimate strength of the sandwich panels due to core shear failure. Thus, a detailed characterization of PUR mechanical properties, namely shear modulus and shear strength, is required to efficiently use these materials in structural applications. Thereby, the present study deals with the experimental characterisation of the shear behaviour of a specific PUR closed-cell foam, with density of 70 kg/m^3, in particular, considering the implications of size effect on the obtained results and on the estimation of the material properties. The experimental procedure was based on the standards ISO 1922 and ASTM C273, as well as, other existing publications, considering that this PUR is intended to be used as structural core material in sandwich panels for flooring purposes. Instrumentation included a load cell, LVDTs and digital image correlation. The present work details the experimental program and analyses the main results obtained.

1. Introduction

Polyurethane (PUR) is nowadays one of the most common foam core materials used in sandwich construction. Typically, sandwich panels are composed of two external laminate skins of relatively high stiffness enclosing the core material, providing the panel with both flexural and shear strength. Due to the increasing use of this solution in construction industry, the full understanding of these materials concerning their mechanical properties is required, in particular, PUR foams. In the past few years, several authors have been investigating the mechanical behaviour of foams, such as Gibson and Ashby [1], analysing cellular materials, including different types of foams and sizes. Voiconi *et al.* [2] conducted a series of studies regarding the flexural behaviour and fracture properties of PUR foams, also supported by digital image correlation (DIC). Saha *et al.* [3], Fam *et al.* [4] and Rejab *et al.* [5] studied the experimental mechanical behaviour of PUR foams. However, with the increasing demand of these materials in the construction industry, further studies are required to fully understand their mechanical behaviour, especially in shear. Thus, the present study aims to analyse the implications of the specimen size in the obtained material properties for the PUR, when tested under direct shear. Current recommendations [6,7] suggest that specimens length-to-thickness ratios should be at least 10 to 12, in spite of some researchers, e.g. [8] being using ratios of about 2. Additionally, the PUR foam analysed is intended to be used as structural core material in sandwich panels for flooring purposes in the scope of the R&D Project ‘EasyFloor’. Considering the geometry of the sandwich panels to be developed in ‘EasyFloor’, the length-to-thickness ratio is much lower than 10. In these circumstances, ratios between 2 and 12 will be evaluated in the scope of this study to assess the reliability of smaller ratios, in order to better understand and document the size-scale dependency, as well as the underlying mechanisms that may affect failure and creep behaviours of PUR foam under shear. Therefore, an experimental program using polyurethane closed-cell foam with density of 70 kg/m^3 was performed, using a specimen thickness of 30 mm and length-to-thickness ratios of 2, 4, 6 and 12. A commercial solution was chosen for this foam (Baymer® AL 740 + Desmodur® 44V10L).

2. Experimental Program

The experimental program included four series of PUR closed-cell foam specimens (density of 70 kg/m^3), with fixed thickness (t), width (w), and different length-to-thickness ratios (L/t), as shown in Table 1. Figure 1a shows the test configuration. The developed test configuration was mainly based in the ISO 1922 [6]. Additionally, ASTM C273 [7] and other test configurations existing in the literature were also used for the present proposal. UPN120 steel profiles were used as the supports of the PUR specimens. To avoid moments at the ends of these metal supports, 3-dimensional bearing joints were used, ensuring the verticality of line load and the absence of bending moment transmission at both supports. These specimens were tested monotonically up to failure in shear, in a quasi-static manner with a rate of 0.50 mm/min, using a load cell of 200 kN (± 0.12 kN) and two linear variation displacements transducers (LVDT), with a stroke of +/- 25 mm (± 0.24% F.S.) to record the relative displacements between the two faces of the specimen, i.e. the distortion. Additionally, DIC analysis was used to assess the principal shear strains along the length dimension, in one specimen of each series. Finally, tensile and compressive tests were performed, in accordance with the standards ASTM C297 [9] and ASTM C365 [10], respectively. The geometry of the specimens in both tests was 60×60×60 mm^3. The tensile and compressive tests up to failure of the specimens were carried out in an universal testing machine by displacement control at a rate of 0.50 mm/min.

Table 1. Experimental program carried out.

Series	t [mm]	w [mm]	L [mm]	L/t [-]	Number of tested specimens
PUR_ST_30_60			60	2	3
PUR_ST_30_120	30	120	120	4	3
PUR_ST_30_180			180	6	3
PUR_ST_30_360			360	12	6

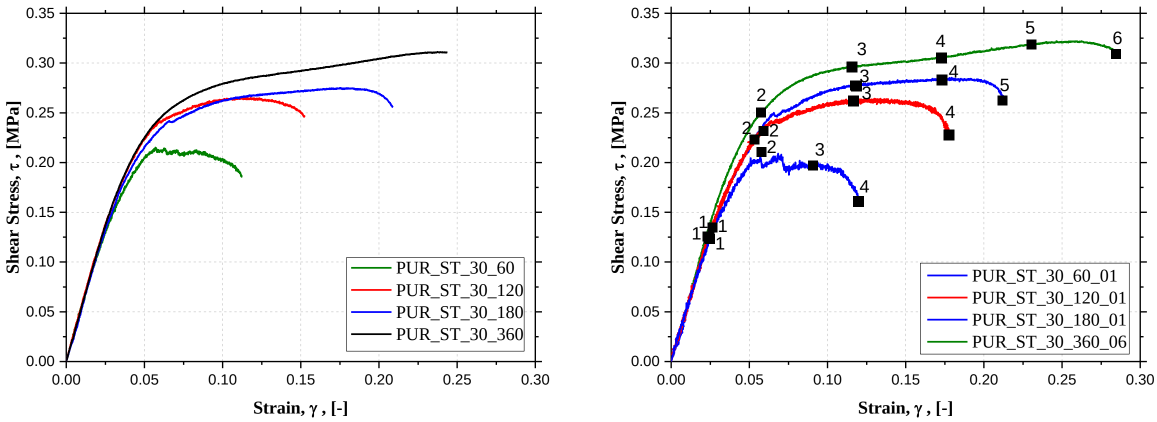
(a) (b) (c)

Figure 1. Quasi-static monotonic tests: (a) and (b) Test configuration; (c) DIC test setup.

3. Results and Discussion

From the tensile and compressive tests carried out, a tensile and compressive strength of 0.32 MPa (CoV: 4%) and 0.33 MPa (CoV: 11%), respectively, were obtained, whereas the Young modulus in tensile and compression attained values of 10.9 MPa (CoV: 12%) and 6.0 MPa (CoV: 8%), respectively.

The average results obtained for each series in the quasi-static monotonic shear tests up to failure are presented in Figure 2a, while the single experimental responses obtained for the specimens tested in combination with DIC are presented in Figure 2b.



(a) (b)

Figure 2. Monotonic test results: (a) Series average curves, and; (b) individual specimens with DIC.

As shown in Figure 2, the mechanical behaviour of the PUR in all the series presented an initially linear-elastic behaviour up to approximately 25 mm/m of the shear strain, followed by a non-linear regime. At this second stage, various factors may contribute to the loss of linearity of the experimental response. One of these is the indentation effects that occur in the vicinity of the loading plates, which cause the foam cells to compress. Another factor is the development of interfacial cracks that occur in the regions of non-uniform shear patterns (see Figure 3). Both effects cause simultaneously a stiffness degradation leading to plateau-like behaviour. Furthermore, it was possible to conclude that the failure was significantly affected by the length-to-thickness ratio, with superior performance being achieved for higher values of *L*/*t*. As expected, the series PUR_ST_30_60 presented an earlier failure, when compared to the remaining series. These results are supported by the DIC analysis, which allowed to obtain the principal strains depicted in Figure 3.

Figure 3 shows that the dominant failure mode was the rupture of the interface PUR-adhesive for the series with *L*/*t* ratios of 2, 4 and 6. This premature failure mode is likely caused by the decreasing of the bonded length of the PUR specimen to the plates during the interfacial crack propagation, thus decreasing significantly the final load carrying capacity. In contrast, in the series with *L/t* ratio of 12, the reduction of the bond length was not so significant, thus higher shear stresses were achieved and consequently a shear failure crack was observed in the specimens. Also, the evolution of the shear strain fields presented in the previous figure vary significantly when different series are compared at the same loading stage (stages 1 up to 6), indicating that the major factor contributing to the differences observed in the shear behaviour between series are indeed due to the stress redistributions. It can be observed that the higher the length-to-thickness ratio, the more uniform the obtained shear strain fields are at the later stages, showing a decreasing effect of the boundary conditions in the overall shear response. This effect is particularly visible in the top and bottom of each series specimens. The boundary conditions produce tensile stress concentrations near the loading plates, causing the development of interfacial cracks, thus leading to a premature failure.

Table **2** presents all the results obtained for each series. It is clear, that by increasing the ratio *L/t* the maximum load, the shear strength, the ultimate shear strain and the shear modulus increase. It should be also highlighted that shear mode failure was only observed for the specimens with a ratio *L/t* of 12.

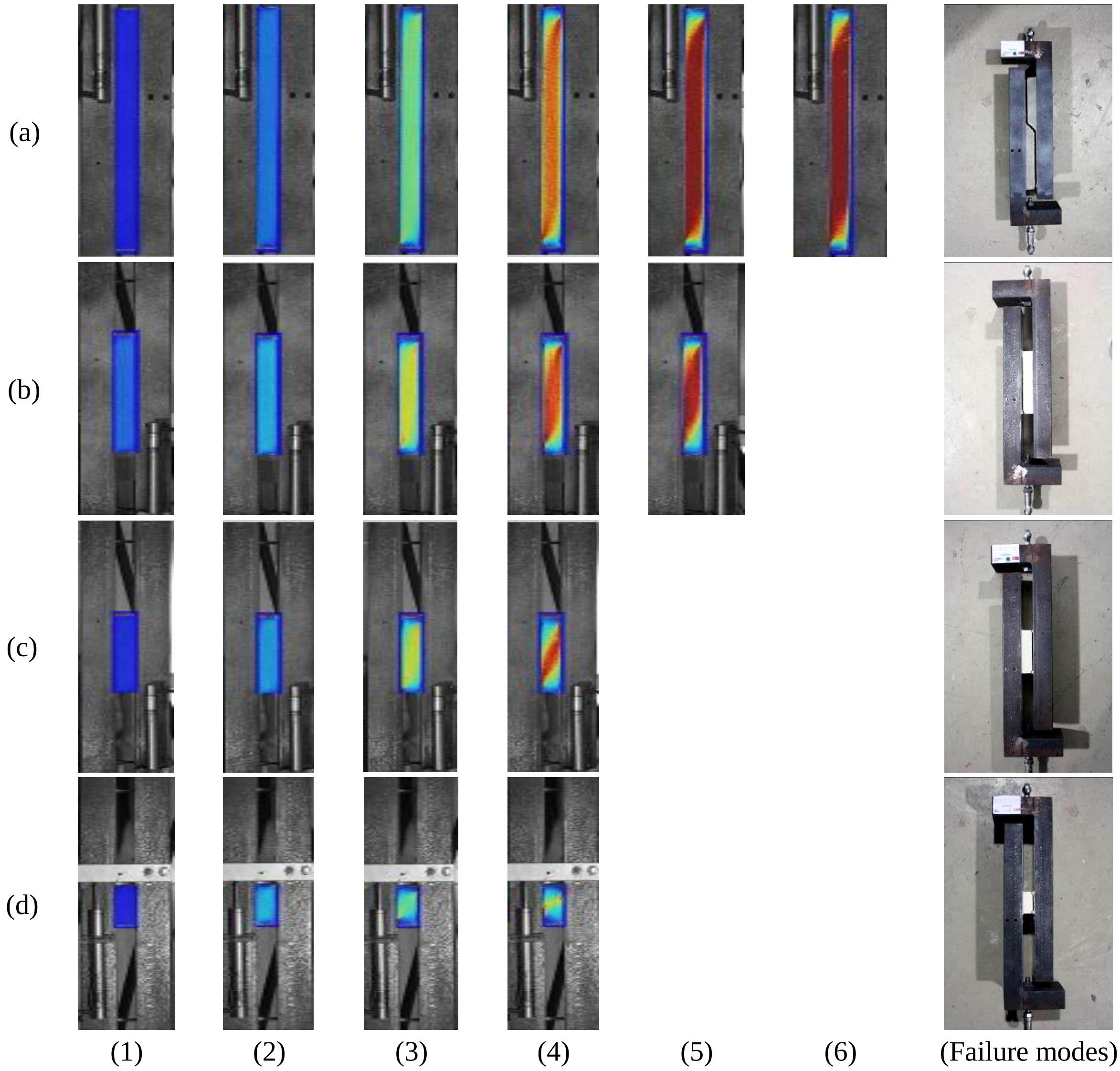


Figure 3. DIC principal strain patterns from stages (1) up to (6) and respective failure modes of the series: (a) PUR_ST_30_360; (b) PUR_ST_30_180; (c) PUR_ST_30_120, and; (d) PUR_ST_30_60.

Table 2. Results obtained for each series.

Series	ρ [kg/m^3]	$F_{max,2\%}$ [kN]	$\tau_{max,2\%}$ [MPa]	$\gamma_{ult,2\%}$ [-]	F_{max} [kN]	τ_{max} [MPa]	γ_{ult} [-]	G [MPa]	FM
PUR_ST_30_60	67.58	1.5	0.21	0.06	1.6	0.22	0.12	4.8	I(3)
(% CoV)	(2.41)	(4.3)	(4.3)	(3.3)	(4.1)	(4.3)	(3.0)	(6.2)	
PUR_ST_30_120	65.84	3.5	0.25	0.07	3.8	0.27	0.17	5.2	I(3)
(% CoV)	(0.00)	(1.6)	(1.9)	(1.1)	(1.2)	(1.3)	(6.5)	(4.0)	
PUR_ST_30_180	66.42	5.2	0.24	0.07	5.9	0.28	0.21	5.2	I(3)
(% CoV)	(0.62)	(2.5)	(2.5)	(2.0)	(2.6)	(2.4)	(0.8)	(1.5)	

PUR_ST_30_360	67.21	11.3	0.26	0.07	13.8	0.32	0.26	5.6	I(2);
(% CoV)	(1.34)	(4.6)	(4.7)	(1.5)	(3.8)	(3.9)	(11.5)	(3.4)	S(4)

ρ – Density; $F_{max,2\%}$ – Maximum load using 2% offset method; $\tau_{max,2\%}$ – Maximum shear stress using 2% offset method; $\gamma_{ult,2\%}$ – Ultimate shear strain using 2% offset method; F_{max} – Maximum load; τ_{max} – Maximum shear stress; γ_{ult} – Ultimate shear strain; G – shear modulus; FM - Failure Mode: I – Failure in the interface between PUR-Adhesive; S – Shear failure; CoV – Coefficient of Variation.

4. Conclusions

A study was conducted with 4 series of shear tests on PUR closed-cell foam material with a density of 70 kg/m^3, using different values of length-to-thickness ratio (2, 4, 6 and 12). The shear strains and shear stresses were evaluated during loading and, additionally, digital image correlation was used to observe the shear strain evolution during testing. The following main conclusions were withdrawn:

- The tested PUR specimens presented a maximum shear stress of 0.32 MPa, an ultimate shear strain of 0.26 m/m and a shear modulus of 5.6 MPa, for the series PUR_ST_30_360 (length-to-thickness ratio, *L*/*t*, equal to 12);
- An increase of 45% in the shear stress and 17% in shear modulus was observed between series PUR_ST_30_60 (*L*/*t* = 2) and PUR_ST_30_360. The series PUR_ST_30_180 (*L*/*t* = 6) presented an increase of 14% for shear stress and 8% for shear modulus in comparison with same series (PUR_ST_30_360);
- DIC results have shown that for increasing values of length-to-thickness ratio the strain fields obtained in the specimen show a much larger area where they are closely uniform, The decrease in the relative size of the non-uniform part of the shear stress fields, together with the decrease in the relative relevance of the delamination cracks which always form at each specimens ends, in general lead to a more objective assessment of the mechanical properties in shear. However similar results seem to be possible to obtain if the failure processes can be simulated accurately for lower length-to-thickness ratios.

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