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Sample preparation

Shape optimization of a cruciform geometry for biaxial testing of polymers

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ABSTRACT

The presented literature review of cruciform shapes used for biaxial characterization of materials indicates that the majority of shapes can be divided into two large groups when the following selection criteria are taken into consideration: (i) the shape of the outer boundaries and (ii) the load capacity needed to achieve failure in the biaxial region. Manipulation of the outer shape boundaries appears to be essential to bundle the applied loads to the central zone where failure is intended to be built up. For each group, one particular cruciform design is reported whereby the outer boundaries are based on a single curved shape. Although the use of discontinuous double radii edges should be avoided according to earlier reports [1,2], it is shown here through the construction of an optimization algorithm, that the use of a single curve for the outer boundaries leads to strains in the arms that are strongly dependent on these single curved edges. Numerical simulations based on the finite element method as well as experiments performed on polymeric test pieces in combination with DIC measurements, show good agreement on this matter and demonstrate this sensitivity very clearly.

1. Introduction

From the early seventies, many attempts have been made [3–10] to perform biaxial tests on different kinds of polymer materials. Tubular specimens were the earliest geometrical types that were used to obtain a bidirectional stress state. One of the main reasons why alternative geometries were explored for biaxial testing applications was that the use of internal pressure, in combination with axial or torsional forces, led to significant build-up of stresses in the thickness direction [11,12]. The dominant effect of these through-the-thickness stresses on the overall stress state of the material indicated that these types of tests could only give an insight into tubular-like applications such as pressure vessels. Consequently, this led to the fact that, in other applications where the through thickness stresses and strains are negligible, flat specimens would be more suitable to obtain more realistic stress-strain relationships and, therefore, also better predictions for failure and strength criteria could be assessed. Besides the development of a wide range of loading systems, a variety of cross shaped geometries have been investigated with always the same and obvious requirement in mind: the load has to be transferred in an appropriate way to the central zone of the specimen where the biaxial loading state is intended to be built up. However, it appeared from previous research [10] that this design necessity forms the main difficulty in the biaxial testing of cruciform specimens. It is, therefore, pointed out that a general design philosophy for this type of experiments is difficult to obtain.

In this report, we focus on the influence of the cruciform shape on the strain distribution in the arms of these flat specimens. For this, a generic optimization process based on the finite element model approach is developed

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showing the strains for a polycarbonate cruciform specimen. Experimental results based on the DIC method are in good agreement with the numerical ones.

2. Broad scope of specimens in the literature

Despite the fact that different designs found in the literature for metallic alloys, biological tissues or composite materials appear very similar at first sight, the design approaches that lead to these designs differ fundamentally in many cases. When a general overview is made of these specimens, it can be stated that the differences lie mostly in (i) the way the arms are designed and (ii) the load capacity of the testing equipment used. It is, therefore, important to understand the interaction between these two elements. The manner in which the applied loads are introduced into the material from the clamping area to the place where the material is expected to fail depends largely on the capacity of the load that can be applied and the influence of the load trajectories by the outer shape of the arms. The specimens found in the literature are divided into two categories: (i) cases where the load trajectories are left undisturbed or (ii) where the load trajectories are actively changed through application of geometrical changes to the cruciform arms.

2.1. High loads, straight outer boundaries

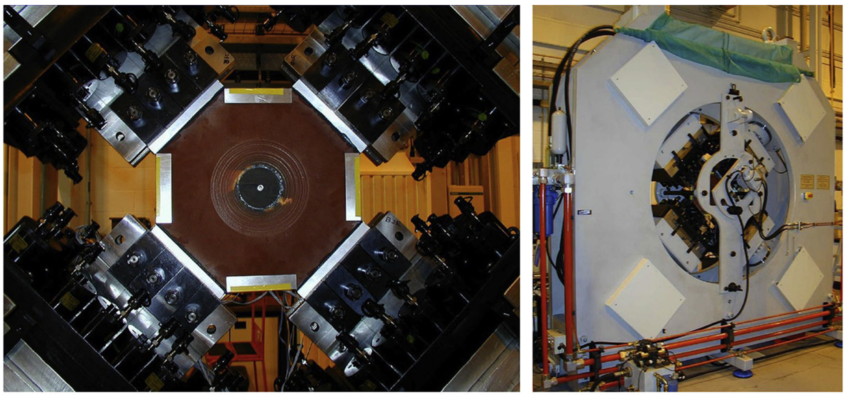
For the first category, where the load trajectories are left undisturbed (by the outer boundaries) and, therefore, no concentration of the load into a certain zone can be achieved, the technique to obtain a biaxial zone is mainly shifted to the application of very high loads in combination with thickness variation by using cladding. An example of this type of geometry can be found in the shape developed by the private company Qinetiq (Fig. 1a-b) [13,14] for which an experimental setup has been built for loads up to 1500 kN. As the focus in this report lies mainly on the study of the sensitivity of the outer boundaries on the strain distributions in the arms, and not on the influence of the load trajectories by variations in the material thickness, one can still understand the use of this kind of specimen by looking at a specimen with straight arms as being one with a curvature having an infinite radius. It is, therefore, an extreme form that will not be encountered often, on the one hand due to the necessity for very large load capacities and, on the other hand, due to the shift in adjustments from the outer boundaries to the use of complicated cladding geometries and materials to reach the biaxial bearing strength of the material.

2.2. Low loads, curved outer boundaries

For a second category of specimen, more moderate load levels of around 100 kN per loading arm are employed. To force the loads into the biaxial zone it is imperative in these cases that the load trajectories are manipulated by changing the geometry of the arms. Different approaches exist for this. Where in most cases straight arms are used to introduce the loads into the materials, the region behind the straight arm sections can have different curvatures: a single rounding radius at the end of the straight arm at the intersection of the two orthogonal directions (Fig. 2a) [15] or as double rounding radii (Fig. 2b) [8]. In other cases, the curvature can be extended to the region where the load is introduced in the specimen, making the straight arms vanish (Fig. 2c). This happens in the shape used by Rochdi et al. [16].

Whereas the main philosophy behind these curvatures is to force the load into the central section, it has been seen in earlier reports [1,2] that for specimens such as those used by Welsh et al. [8,9] and Smits et al. [6] the reverse happens (Fig. 3). The rounding of the arms, with an inner and outer radius, and milling of the central zone led to high stress concentrations making the material fail in these zones before allowing the material to reach its true biaxial strength. Moreover, the effect was so significant that, even for homogeneous and isotropic materials, it was found that the transition zones between the inner and outer radii operate as load attracting poles, leading to the initiation of damage in these zones. Therefore, preference is given to specimens with outer boundaries having only one curvature.

Moreover, one should carefully monitor how the change in curvature influences the change in trajectory. Therefore,



(a) (b)

Fig. 1. The test setup (a) used at Qinetiq for testing of cruciform specimens (b). Picture taken from Ref. [13,14].