Design of a cruciform specimen for biaxial transverse tests

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ABSTRACT

The objective of this paper is the design of the adequate geometry of the cruciform specimens to be tested under biaxial transverse loads. To this end Finite Element models have been developed. The analysis of the results provided by the FEM models are used to design a cruciform geometry that assures that the failure takes place at the central zone of the specimen (the area really subjected to biaxial load) and minimizes undesirable effects such as stress concentrations.

KEYWORDS: Cruciform specimen, transverse failure, biaxial, FEM models.

1. INTRODUCTION

The significant use of composite materials in the industry has been accompanied, during the last years, by an increase of the responsibility of these materials in the components they are part of. As a consequence, it seems essential to advance in the knowledge of the mechanisms of damage affecting these materials as well as in the prediction of their possible appearance.

This work focuses on the transverse failure, known as matrix/inter-fibre failure at lamina level. This failure may appear in unidirectional laminates subjected to transverse loads or in multidirectional laminates subjected, for instance, to impact loads.

The particular case of the inter-fibre failure under tension has already been studied at micromechanical level by *París et al [1]* by means of BEM models. These numerical studies made it possible to identify the initial phases of the damage growth at micromechanical level as well as its latter growth that leads to the macromechanical failure.

Many of the existing proposals for the prediction of the inter-fibre failure at lamina level are based on the hypothesis that the failure taking place at a plane is governed by the components of the stress vector associated to that plane. This assumption was revised by *París et al [2]* and *Correa et al [3]* for the inter-fibre failure under tension. The results obtained showed that the presence of a secondary tension could alter some aspects of the phases of the development of failure previously detected for the uniaxial case; in particular, it was concluded that the presence of a secondary tension (not associated to the plane of failure) could slightly delay the generation of failure.

It seems necessary to check the validity of the conclusions derived from the aforementioned micromechanical numerical studies by means of macromechanical experimental tests. In particular, experimental studies must be carry out on specimens extracted from unidirectional laminates and subjected to transverse biaxial loads. This task was initiated by the authors in *[3}* (with the development of tension-compression transverse tests), and continued in *Barroso et al [4}* (where the initial steps for the development of tension-tension tests where undertaken).

In loading situation in which both transverse loads are tensile-type the geometry of the specimen required for the development of the experimental tests needs to be cruciform in order to be able to introduce the load along two perpendicular axes. The design of this specimen can be performed using FEM models; these models may reproduce the behaviour of the specimen under the biaxial loading cases to which it would be subjected in the experimental tests. Precisely, the work presented in this paper is a continuation of the investigation presented in *[4]* and is oriented to the development of FEM models that could help in the configuration of the adequate geometry of the specimen. Results from experimental tests based on the geometries proposed in this paper are presented in *Barroso et al [5]*.

1. MODELS

The following aspects must be taken into account for the design of the specimen to be subjected to tension-tension transverse biaxial loads:
- Development of a uniform state of biaxial stresses on the specimen under testing.
- Maximization of the area subjected to biaxial loads.
- Minimization of the possible stress concentrations derived from the geometrical configuration.
- Failure occurrence in the zone subjected to a uniform state of biaxial stresses.

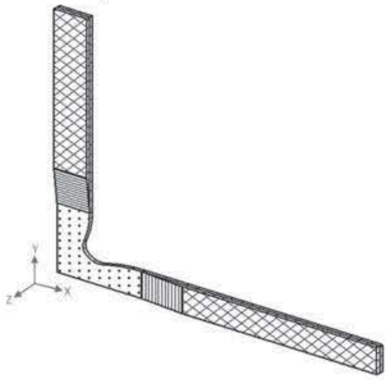
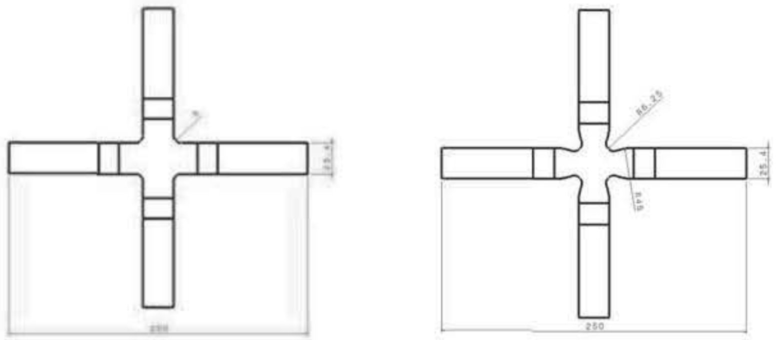


Fig. 1. 3D geometrical model including fibre orientation. (Type D).

The finding of a geometry that fulfils simultaneously with the former requirements is not a simple task. There exists a considerable amount of studies in literature about cruciform specimens though it is not easy to find a specific design for unidirectional laminates to be subjected to transverse loads (i.e. 90° specimens).

In the present work the first geometrical model considered, Type D specimen, is based on *Lamkanfi et al [6}* and is presented in Figure 1 (applying symmetry only an eighth is presented in the plot). The Type D geometry proposed is composed by a main body, which represents the cruciform specimen itself manufactured from a unidirectional laminate, and 8 reinforcing tabs (one at each side of each "arm" of the specimen). The main body presents 2 fillet radii at the central zone and constant thickness; the arms are reinforced with tabs whose slope allows a softer transition with the central zone of the specimen.



Types A (R=l.5 mm), B (R=6.25 mm), C (R=I9.97 mm) specimens

Type D specimen

Fig. 2. Geometrical proposals: Types A, B, C and D specimens.

In order to study the effect of the different geometrical features three alternative and simpler geometries are also proposed (Types A, B and C). These three geometries presenta single fillet radius whose value varies from zero (Type B), to 19.97mm (Type C) passing through the same value adopted for Type D (R=6.25mm, employed in Type A). Figure 2 compares the different geometries proposed.

For all types of specimen considered the unidirectional laminate chosen corresponds to a carbon-epoxy system (AS4/3501-6) whereas tabs are thought to be manufactured from glass fibre +45/-45 fabric.

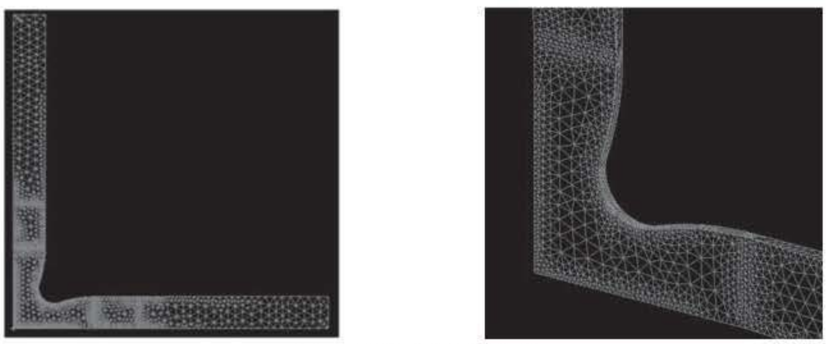


Fig. 3. Mesh employed.

As explained befare, taking advantage of the symmetries, a FEM model has been prepared for each geometry proposed, in order to study the stress state under the combined action of two externa! transverse tensions, correspondingly acting at the ends of the horizontal (x axis) and vertical (y axis) arms. Different loading cases have been considered, all of them corresponding to a fixed value of the external tension a_0 applied at the edge of the horizontal arm, and different portions of, a_0, (characterized by a coefficient *n= 0.25,* 0.5, 0.75 and 1) at the edge of the vertical one. a_0 has been taken equal to the tensile strength associated to the laminate considered, 48 MPa in this case. A view of the mesh employed can be observed in Figure 3 for Type **D** specimen.

2. FEM RESOLTS

The results obtained from the FEM analyses show that a_{xx} is the dominant stress (together with a_{YY} in the T-T limit case, n=1) for all specimens and loading cases considered. By way of an example, Figure 4 presents a_{xx} distribution for Type D specimen.

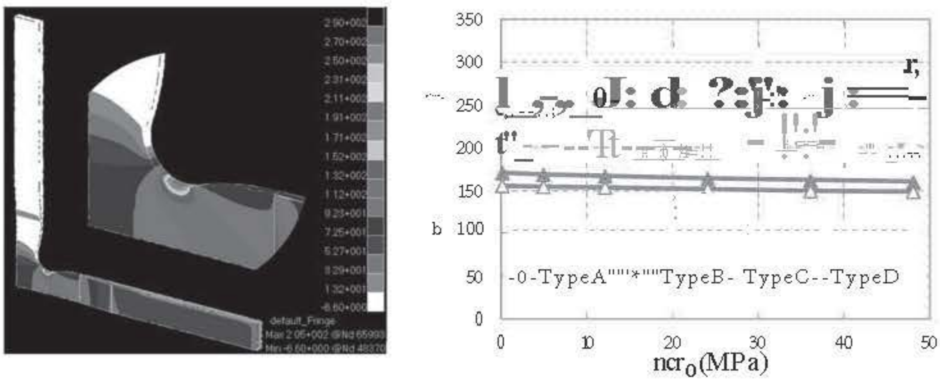
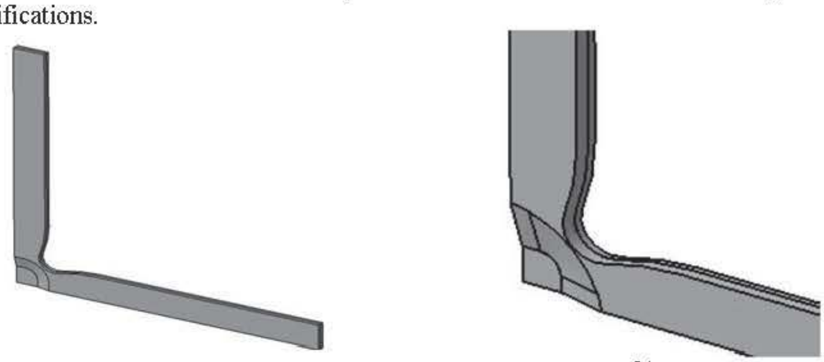


Fig. 4. (a) a_{xx} ditribution for Type D specimen. (b) Maximum values of a_{xx} versus the secondary external tension.

In particular, for the different biaxial cases analyzed the main features are the following:
- Relevant stress concentration is detected for a_{xx} at centre of the free edge, excepting in Type C, where this concentration is located at the joint between the tab and the specimen arm. This stress concentration decreases as n coefficient evolves from n=1 to n=0.
- a_{xx} distribution at the central zone decreases as the secondary tension increases.
- In general, a_{xx} distribution at the central zone of the different specimens is quite uniform.

Figure 5 shows the maximum values detected for each type of specimen versus the value of the secondary external tension. It can be checked from the Figure that the slope of the curves presented is quite low.

Although none of the four types of specimens considered seem to fulfill the objective proposed, mainly due to the high stress concentrations at the free edge, Type D presents the best stress behaviour and thus, it is taken as a basis for further geometrical modifications.



(a) (b)

Fig. 6. Geometrical proposals: (a) Type M1 specimen and (b) Type M3 specimen.

The geometrical modifications pursue the main objective of reducing the stress concentration at the free edge and also making the stress distribution at the central zone of the specimen (the area nominally subjected to biaxial loads) uniform. These objectives are not achieved in a single step, so that several and subsequent models (see Figure 6a where an intermediate proposal, Type MI is presented), were performed until achieving the final model (Type M3 specimen) presented in Figure 6b. This M3 proposal is entirely made on carbon fibre, where the original tabs have been extended to cover the whole specimen. Its thickness is larger excepting in the central zone where the failure wants to be located. The transition between the central zone and the outer one is performed by means of an elliptical area with non constant slope.

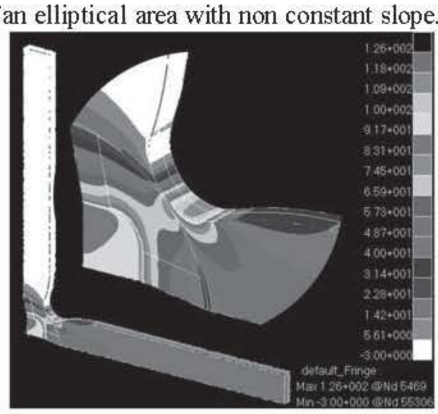


Fig. 7. $\mathbf{u}_{xx}$ distribution for Type M3 specimen.

The results provided by this model are quite satisfactory although this geometry is not able to completely blur the stress concentration at the free edge, see Figure 7. Nevertheless, this stress concentration has been drastically reduced so that the maximum value of $\mathbf{u}_{xx}$ moves from the free edge to the joint between the central zone and the transition one. Specifically, the concentration factor has been reduced to 1.16 versus

2.38 detected in Type D specimen. In addition, the central zone of this Type M3 specimen is subjected to a quite uniform stress distribution whose values identify this zone as the preferential area for failure occurrence.

3. CONCLUSIONS

FEM models have been developed in order to design the specimen suitable for the development oftension-tension biaxial transverse tests.

Four initial models have been considered, Types A, B, C and D. The mechanical analysis showed that the main inconvenience of these designs is the huge stress concentration that arises in all cases.

Based on the former results subsequent geometrical modifications have been performed on Type D specimen. These alterations have mainly consisted in the increase of the thickness associated to the outer part of the central zone; besides, the shape of this central zone has finally turned into an ellipse (Type M3 modification) whose transition zone slope is variable. Stress concentration has been noticeably reduced in this last model, Type M3. In addition, this specimen presents a quite uniform central stress area. Finally, the maximum a_{xx} values take place at the transition zone ofthe central area, and thus, failure occurrence would be presumably promoted at the biaxial zone.

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