Biaxial testing of fibre reinforced composites

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OPTIMAT BLADES

TG 2

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1. Introduction

The prediction of the (residual) strength of fibre-reinforced composites using failure criteria is not easy because of the different failure modes and their complex interactions that may occur. During the last fifty years the failure behaviour of fibre-reinforced composites was studied intensively and various failure criteria were proposed [1]. These criteria can generally be divided into two groups: (i) mechanistic criteria, which take into account the different modes of failure and which are mainly based on micro-mechanical models and (ii) empiric criteria, which predict the strength out of a mathematical model without taking into account what's happening on the micro-mechanical level. A recent worldwide study, which compares for fibre reinforced composites, the currently used failure criteria with each other and with a small number of biaxial experiments [2, 3], shows that both categories of criteria give only an acceptable prediction of failure for a very limited number of specific cases. Furthermore the first group of criteria often seems to be too complicated for real design problems, while the second group is often too easy to be generally accepted.

This worldwide study also pointed out that the failure criteria are mainly validated with uniaxial experiments and hardly with biaxial ones. However, we know that the failure behaviour of uni-axially loaded fibre-reinforced composites is different from biaxially loaded specimens. Moreover in real life applications fibre-reinforced composite components, as for instance wind turbine rotor blades, are usually loaded in more than one direction at once, that is, they are biaxial loaded. Consequently limiting the evaluation of a material characteristic to uniaxial coupon tests may lead to misrepresentation of the behaviour of a material in real constructions. Indeed, using more realistic loading conditions, i.e. introducing biaxial conditions, will lead to a more accurate representation of the expected behaviour of the structure in-service.

Unfortunately, reliable experimental data of the failure behaviour of fibre-reinforced composites subjected to biaxial loading are hard to find and in addition, the limited number of biaxial tests was performed using tubular specimens.

Figure 1: Biaxial test bench for specimens loaded in tension/compression combined with torsion.

Figure 2: Biaxial test bench for cruciform specimens loaded in tension/tension.

A servo-hydraulic test bench (MTS) for combined loading in tension/compression and torsion is shown in Figure 1. This configuration is able to test tubes at a maximum loading capacity of 100kN in tension/compression and 1kNm in torsion.
However, for many applications the materials are used in the form of flat or gently curved panels, so tubular test specimens are unsuitable. Moreover, thin tubes are not easy to fabricate and obtaining a perfect alignment and load introduction are not straightforward. Furthermore premature failure often occurs at the edge due to stress concentrations or local buckling. For this reason, as shown in Figure 2, biaxial testing facilities for planar cruciform test specimens have been developed at the department MEMC (Mechanics of Materials and Constructions) of VUB (Free University Brussels). This planar biaxial test bench has a loading capacity of 100kN in both directions, but only in tension.

2. Description of the planar cruciform test bench

A valid biaxial test for a flat coupon avoids premature failure at the load introduction points and gives a large region of uniform stress/strain at the specimen centre. Additionally the central point needs to be fixed in space during testing. As illustrated in Figure 3 this can not be achieved using only two actuators. Fixing two end points and loading the opposite points, not even by using hinges, is not sufficient to obtain a uniform stress distribution and a central point that will not experience any displacement. The displacements Δx and Δy cause bending of the specimen and a non-uniform stress distribution in the central area of the test specimen.

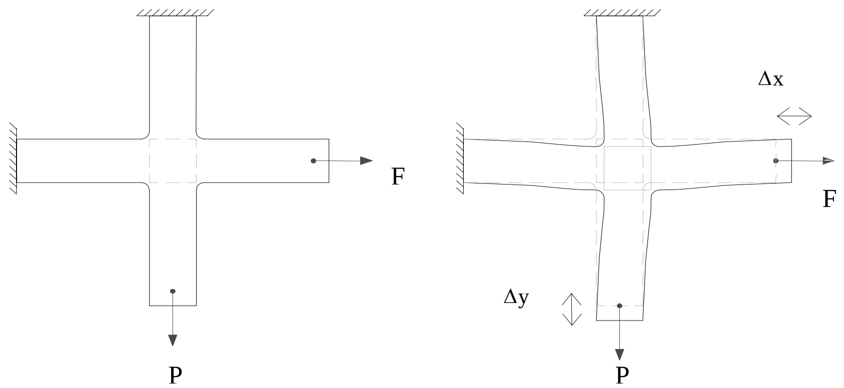


Figure 3: Incorrect configuration to obtain a uniform stress state in the test zone of the specimen.

In order to meet these requirements four servo-hydraulic cylinders were used, but as cylinders with hydrostatic bearings were used, the test frame is limited to tensile loading. Failure or slip in one arm of the specimen will result in sudden radial forces, which could seriously damage the servo-hydraulic cylinders and load cells. To prevent this, hinges were used to connect the specimen to the cylinders and to connect the cylinders to the test frame. Using four hinges for each loading direction results in an unstable situation in compression and consequently only tests in tension-tension can be performed (Figure 4). In addition, the force P has to be equal and co-linear to P', F equal and co-linear to F' and the forces P & P' need to be perpendicular to F & F' (Figure 5).

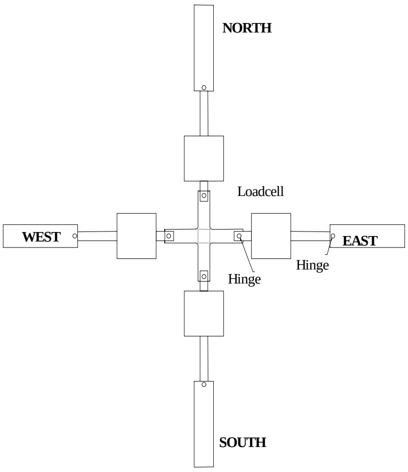


Figure 4: Configuration to obtain a uniform stress state in the test zone of the specimen.

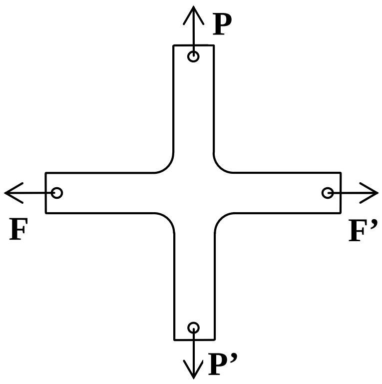


Figure 5: Cruciform specimen.

In this ideal situation (Figure 6a) no displacement of the central point of the specimen is observed. However, during testing a small crack in one arm might generate a small displacement and a small force F_y, in the y-direction for instance, resulting in a system of forces as shown in Figure 6b. From the force equilibrium in the y-direction we obtain:

$$P + F_y = P' \quad (1)$$

Consequently, P is no longer equal to P'. But as four load cells were used we are able to measure this small difference and use it, in order to return to the ideal situation, as a control signal in the y-direction. The same is done in the x-direction.

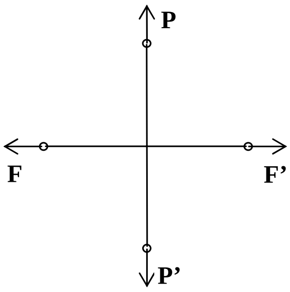


Figure 6a: Ideal situation: forces P & P' and F & F' are equal.

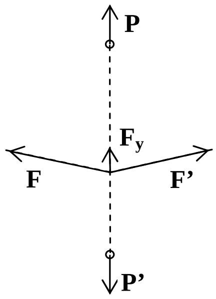
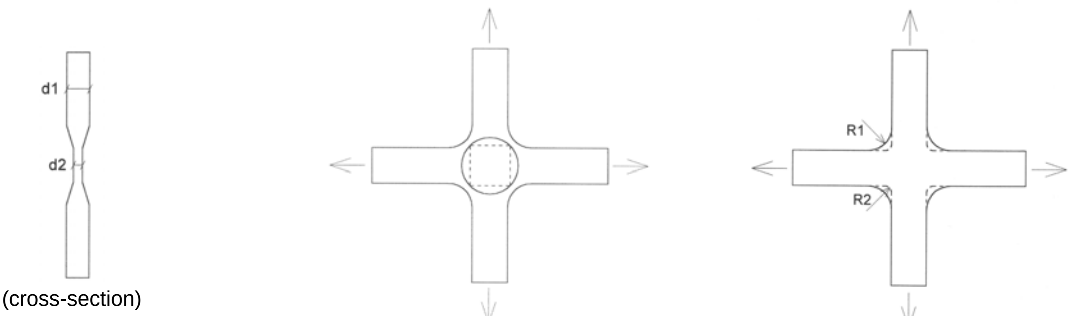


Figure 6b: Real situation: forces P and P' are no longer equal.

3. Design of the cruciform test specimen

In biaxial testing of polymer matrix composites it has proved extremely difficult to design a valid cruciform test specimen as some conditions which have to be met are not easily realizable [4]: (i) there has to be a uniform state of stress/strain in the biaxially loaded test zone, (ii) failure has to occur in the test zone and not in the uniaxially loaded arms and (iii) the results should be repeatable. The design of a cruciform specimen that meets all these requirements is of primordial importance. In addition, we really need a global measurement technique that enables the assessment of the overall behaviour of the complex test piece.
Strains measurements using a strain gauge or extensometer are not sufficient because both give an average value of the deformation along their gauge length and most of the time only in one direction.

Due to biaxial strengthening effects failure is more likely to occur in one of the uniaxially loaded arms than in the biaxially loaded test zone.
Unlike the situation with metals [5], the design of cruciform test specimens has not been studied extensively. For metals it's easily possible to reduce by milling the thickness of the test zone. There's no damage introduced on a relevant level in this manner. For fibre-reinforced composites it's more difficult to reduce the thickness of the test zone. Milling a small area of a laminate can introduce damage since fibres not perfectly horizontal might be cut. Consequently the failure behaviour will be modified.
Besides milling away material in the test zone, as is done for metals other possibilities might be investigated: (i) using for instance end tabs in aluminium will increase the thickness of the arms, (ii) adapting the curvature radius at the intersection of two arms will reduce the stress concentration and will consequently increase the change of failure in the test zone (Figure 7).



a) thickness of the loading arms in relation to the test zone

b) form of the test zone: square or circular

c) rounding radius of the test zone

Figure 7: Parameters to investigate by the design of a cruciform specimen.

4. Photo-elastic study of the stress distribution in a biaxially loaded cruciform test specimen

In order to have a very quick evaluation of the performance (uniformity of the stress distribution, presence of stress concentrations, …) of a proposed test specimen's geometry, a photo-elastic study was carried out.

A model of the proposed test specimen was fabricated out of a sheet of photo-elastic material (Araldite). The width of the vertical arm was 25 mm and the width of the horizontal arm 20 mm. In both directions the total length of the specimen was 220 mm. The curvature radius at the intersection of both arms was 10 mm. Conversely to fibre-reinforced composites this material is isotropic.

Using a circular polariscoop the isochromatic fringes in the cruciform specimen loaded in both vertical and horizontal directions were studied.

As may be observed in Figure 8 the stress distribution (σ_1- σ_2) is reasonably uniform, both in the arms and in the measurement area. Also the stress concentrations in the corners are acceptable.

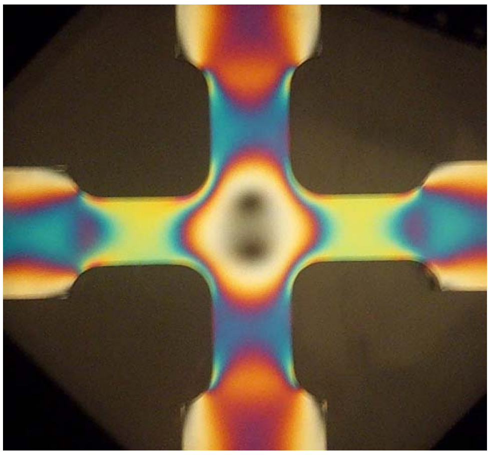


Figure 8: ISOCHROMATICS
Vertical loading: 300N
Horizontal loading: 300N

As it was the intention to protect the arms from premature failure, using aluminium end tabs on the photo-elastic specimen was investigated next.

As can be seen in Figure 9 the uniformity of the stress remains of an acceptable level.

In the upper left corner a slightly higher stress concentration may be observed probably due to small misalignment. This certainly indicates that proper alignment is crucial for keeping stress concentration at an acceptable level.

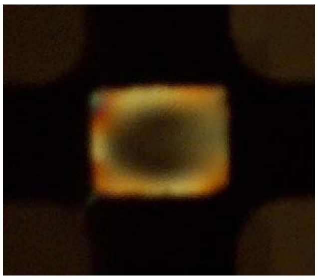


Figure 9: ISOCHROMATICS
Horizontal load = 200N
Vertical load = 200N

5. Proposed geometry of the cruciform test specimen

Based on the previously discussed requirements and the preliminary results of the photo-elastic study, the proposed geometry of the cruciform specimen is shown in Figure 10.

As the stiffness of the specimen in the vertical direction (fibre direction) is much higher compared to the stiffness in the horizontal arm, the width of the vertical arm was determined by the loading capacity of the test bench (100kN) whereas the width of the horizontal arm was limited by the grip size of the clamps.

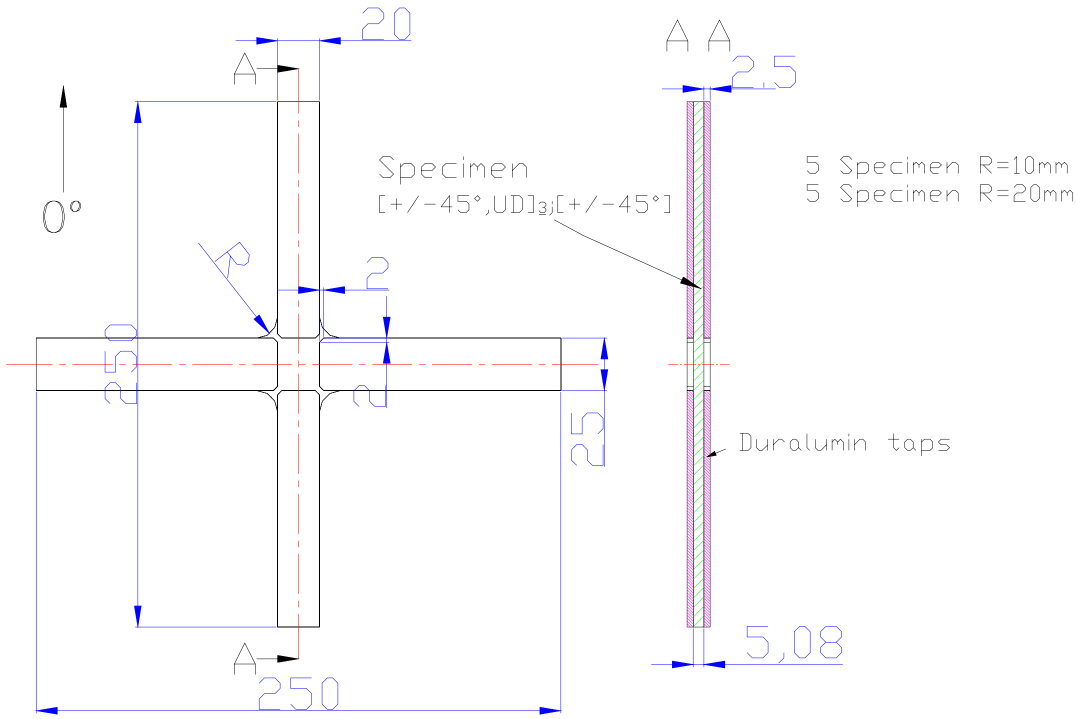


Figure 10: Proposed geometry of the cruciform test specimen.

In order to prevent the arms from premature failure and to carry the load as much as possible directly to the measurement zone the end tabs were made from duralumin with a thickness of 2.5 mm.

6. Conclusions

Many structural components, as for instance wind turbine blades, are fabricated from fibre-reinforced polymers. Although these components, in service, are loaded usually in more than one direction, the evaluation of their properties is mostly limited to uniaxial coupon tests. In order to improve the understanding of their behaviour introducing more realistic loading during the test, i.e. biaxially loading is absolutely necessary for a more accurate representation of their behaviour. For this reason, the biaxial testing facilities for tubes and planar cruciform test specimens have been developed within the department MEMC of the Free University Brussels (VUB).
As it has been proven to be extremely difficult to devise a valid biaxial test for flat coupons, special care was given to the design of the specimen's geometry. A photo-elastic study showed the potentials of the proposed geometry. Certainly detailed Finite Elements Analysis will help to improve the geometry at a later stage.

7. References

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