

IDENTIFICATION OF THE LOCAL MATERIAL PARAMETER DEGRADATION IN A BIAXIAL FATIGUE TEST ON CRUCIFORM COMPOSITE SPECIMENS

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1 Introduction

Since there is a large demand for biaxial experimental data to evaluate existing failure criteria, a plane biaxial test device was developed at the Vrije Universiteit Brussel. In-plane loads are applied to a cruciform specimen in order to create a known biaxial stress state in the centre of the specimen. The experiments accomplished in the past and present at the author's institution have as main intention the biaxial strength and stiffness characterization of fibre-reinforced composite materials. The results from quasi-static tests have been analysed thoroughly in the past [1,2]. The study of the biaxial fatigue behaviour is however in a less advanced stage.

As pointed out in [3], the investigation of multi-axial fatigue is a very important but little investigated topic. Three different approaches can be used for the study of the fatigue behaviour of composite material systems [4]: (i) the traditional usage of S-N or E-N curves, (ii) the residual strength/stiffness approach and (iii) the progressive damage modelling. Preliminary E/N results of biaxial fatigue tests are presented in [5] and are described in one of the following sections. These can be used for approach (i). The subject of the present paper is the study of the degradation of the mechanical properties of the composite material, which is needed in approaches (ii) or (iii).

If a dynamic biaxial load is applied to a cruciform specimen, the material parameters will degrade with increasing number of cycles. Due to the heterogeneous stress field, this degradation will not

be the same for all locations of specimen (Fig.1). At zones of large stresses in the specimen (the corners between the arms or the centre), the degradation will occur sooner and be more severe compared to zones of low stresses (the arms). The aim of the present study is to identify the material parameters locally and at several stages in the loading process in order to map the parameter degradation at a certain load ratio.

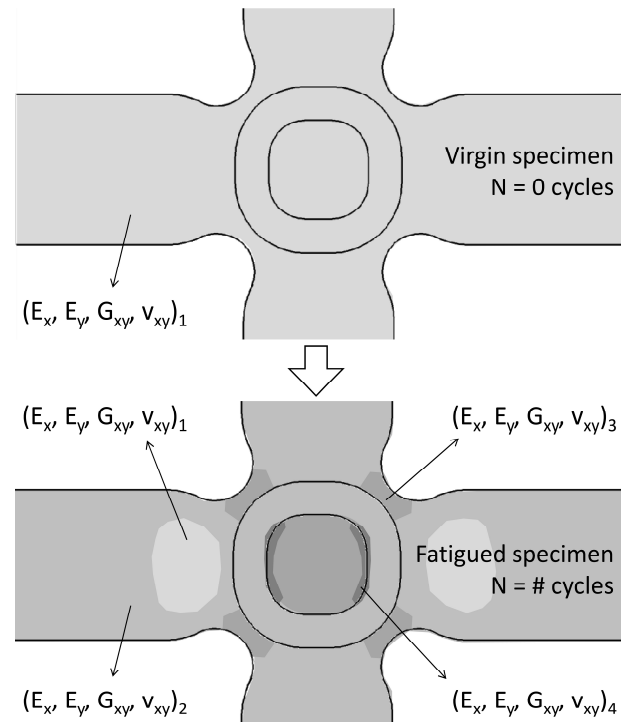


Fig.1. Example of material degradation in the cruciform specimen, after a certain amount of fatigue cycles.

2 Biaxial fatigue testing

2.1 Test equipment

Figure 2 shows the test setup for a biaxial fatigue test, which is similar to the one used for a biaxial quasi-static test. The dynamic load can be applied up to a frequency of 20 Hz and in a variety of waveforms. Unlike with the quasi-static testing, the specimen is clamped in special designed clamps with a pin, in order to reserve the rotation of the specimen. The load is applied mainly due to friction. A more elaborate description of the machine can be found in [1].

The specimen consists of four uniaxially loaded arms and a milled central zone which is biaxially loaded. Tab reinforcements are provided at the end of the arms, where the pin-load is applied. The considered material is in this paper glassfibre reinforced epoxy with a $[(+45^\circ -45^\circ 0^\circ)_4(+45^\circ -45^\circ)]$ layup.

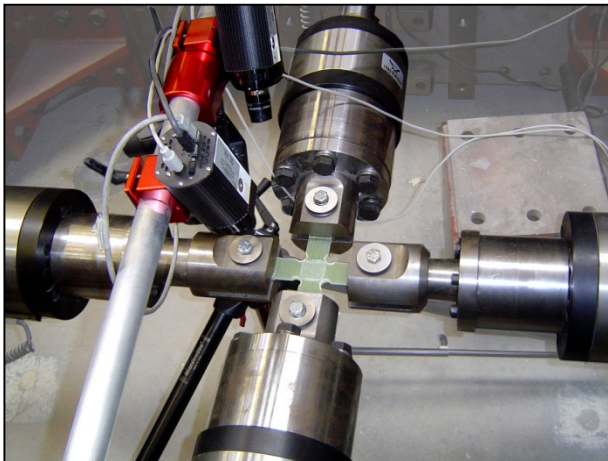


Fig.2. Test setup for in-plane biaxial fatigue tests.

2.2 Preliminar test results

In a preliminary test phase, the cruciform specimens are loaded uniaxially in the x- or fibre-direction and the results are compared with standard uniaxial coupon tests. Through these first tests, the biaxial test bench together with the cruciform specimen are evaluated for fatigue testing.

Fatigue tests with a load ratio of $R=0.1$ are performed. The maximum load is chosen arbitrary and is 30 kN. The load is applied at a low frequency of 2 Hz to limit the heating of the specimen material as this would lead to premature failure. Digital

Image Correlation (DIC), which is a full field displacement measuring technique, is used to monitor the strains during the specimens' lifetime, at several loading stages. E/N curves can thus be obtained. The formulation of S/N curves is not considered, since the stress determination in a cruciform specimen is not straightforward.

Comparing the E/N curves obtained from uniaxial coupon tests with these from the uniaxially loaded cruciform specimens showed a good agreement between both specimen types. Consequently, the suitability of the test bench, the test procedure and the specimen are considered to be suitable for biaxial fatigue tests.

2.3 Biaxial test results

In the next step, biaxial fatigue loading is applied. To study the influence of the biaxial load on the failure and failure behavior of the specimen, the load in the x-direction is kept constant at 3-30 kN while the fatigue load in the y-direction is varied from 0.5-5 kN up to 1.5-15 kN.

Figure 3 shows the evolution of the number of cycles according to increasing biaxial ratio. The biaxial loading seems to have an effect on the lifetime of the specimen. Applying more load in the y-direction increases the lifetime, up to the moment where the failure mode changes from failure in the x-direction to failure in the y-direction.

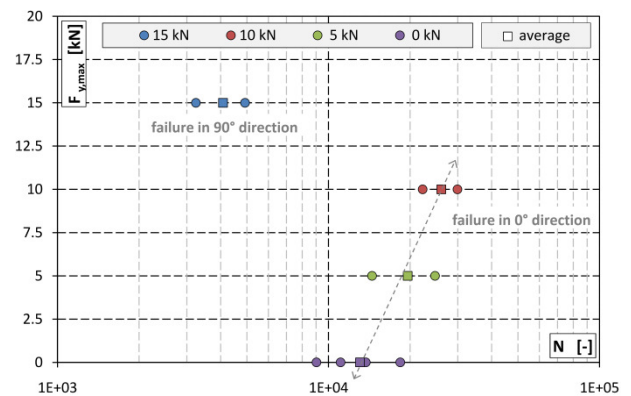


Fig.3. Evolution of the number of loading cycles N according to increasing F_y ($F_x = 3-30$ kN).

Each 1000 cycles, the strains in the centre of the specimen are measured with DIC. The increase of the strains can be followed with this method. Table 1 gives the results for the various test cases. The

increase in strain in the centre of the specimen, and thus also the degradation of the material parameters, is more severe if more load is applied in the y-direction.

Tab.1. Percentage of strain (ϵ_x) increase (percentage of $\epsilon_{\max,0}$) for the different biaxial ratio's.

| F_x [kN] | F_y [kN] | Biaxial ratio | N_{failure} [-] | $\epsilon_{\max, \text{centre}, 0}$ [%] | $\epsilon_{\text{increase}}$ [%] |
|---------------|---------------|------------------|-----------------------------|--|-------------------------------------|
| 3 - 30 | 0 | 1/0 | 13729 | 0.94 | 16.1 |
| 3 - 30 | 0.5 - 5 | 6/1 | 14475 | 0.87 | 24.1 |
| 3 - 30 | 0.5 - 5 | 6/1 | 24715 | - | - |
| 3 - 30 | 1 - 10 | 3/1 | 29900 | 0.67 | 40.4 |
| 3 - 30 | 1 - 10 | 3/1 | 22250 | - | - |
| 3 - 30 | 1.5 - 15 | 2/1 | 4920 | 0.62 | 9.3 |
| 3 - 30 | 1.5 - 15 | 2/1 | 3241 | 0.60 | 17.0 |

2.4 Further testing

Some conclusions can already be drawn, but an extensive test program has to be executed in order to have more insight in the biaxial fatigue behavior of the material. This will be the topic of a future research program.

The aim in this paper is the determination of the material parameters in the biaxially loaded specimen, after a certain amount of fatigue cycles. As already seen in Table 1, this degradation is dependent of the applied loading ratio. To be able to determine the degradation of the material parameters in this specific specimen would be very interesting since several stress states are present in the specimen and can thus be examined. The heterogeneous strain field prevents the use of standard analytical relations for the material parameter determination, but does allow the use of inverse methods. The authors already applied these techniques successfully in the past to obtain the elastic orthotropic material properties in quasi-static tests [6].

3 Identification procedure

3.1 The principles

A “mixed experimental-numerical technique” or “inverse method” will be developed to determine the apparent material parameters of the fatigued composite material. The principle of the method is

similar to the one described in [6]. In the present paper however, the stresses are used as sensitivities. This straightforward approach is known as a “stress based” inverse method, which is described more elaborate in [7].

Figure 3 depicts the working principle of the method. The experimental strains are measured with Digital Image Correlation, when a known load is applied to the arms of the cruciform specimen at a certain lifetime. A numerical model is made in order to retrieve the calculated strains and stresses. Starting values for the material parameters are implemented. When the numerical and experimental strains do not match, the implemented material parameters are not correct. The updated parameters are found by using the previously calculated stresses and the measured strains, from which an improved estimation of the material parameters can be made. New strains and stresses can next be calculated by implementing the updated material parameters. This iterative procedure, which is represented by the dashed line in the picture, is repeated until the final parameters are found. The material parameters are considered as correct if the difference between the calculated and measured strains reaches a minimum.

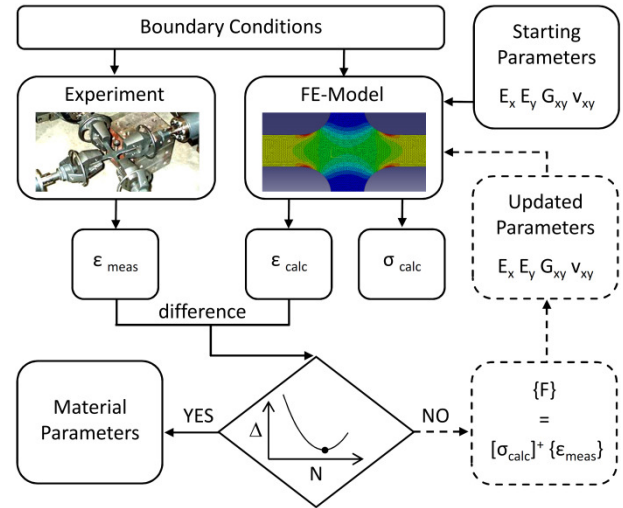


Fig.4. Scheme of the identification procedure.

In the present study, the difficulty is the local identification of the material parameters. Similar studies were done by other researchers ([8],[9]) but using different methods and for other purposes.

The material updating is based on the constitutive laws. Zones with equal material parameters are

considered. For every element, the stress-strain relation in Equation 1, where $\{\varepsilon\}$ is the strain vector, $[\sigma]$ is the stress matrix and $\{F\}$ is a vector containing the orthotropic material properties, is valid.

$$\{\varepsilon\} = [\sigma]\{F\} \quad (1)$$

Since this equation gives us only 3 equations for 4 unknown parameters $\{F\}$, additional information is needed. This same equation can be written for every element which has the same material parameters $\{F\}$, leading to Equation 2.

$$\{F\} = \begin{bmatrix} [\sigma]_{element1} \\ [\sigma]_{element2} \\ [\sigma]_{element3} \\ [\sigma]_{element4} \\ \vdots \end{bmatrix}^+ \begin{Bmatrix} \{\varepsilon\}_{element1} \\ \{\varepsilon\}_{element2} \\ \{\varepsilon\}_{element3} \\ \{\varepsilon\}_{element4} \\ \vdots \end{Bmatrix} \quad (2)$$

By taking the measured strains in an element as $\{\varepsilon\}$ and the calculated stresses -which will change in every iteration- as $[\sigma]$, the material parameters $\{F\}$ will converge to a constant value.

3.2 The application

The application of the parameter identification procedure on a given strain field and thus loading stage results in one set of apparent material properties for every stress state or considered zone in the specimen. For the determination of the degradation curves, the procedure needs to be repeated several times in the lifetime of the specimen.

In this procedure, the material parameters are considered to be homogeneous through the thickness. Damage in one of the lamina will thus be considered as a reduction of the material parameters in the whole thickness.

In order to preserve the stability of the parameter determination procedure and decrease the influence of the noise which is present in the experimental strain fields, zones of equal material parameters will be determined, mostly according to their related stress state. The determination of the material parameters in each element separately is not possible.

4 Test cases

4.1 Preliminar test cases

In a first stage of the research, only virtual experiments are performed to verify the performance of the technique. Some simple cases are considered in order to build up the procedure step by step and detect possible difficulties in an early stage of the developing process.

Tab.2. Starting and degraded material parameters.

| | E_x [GPa] | E_y [GPa] | ν_{xy} [-] | $G_{xy} = G_{xz} = G_{yz}$ [GPa] |
|----------|----------------|----------------|-------------------|-------------------------------------|
| start | 39.10 | 14.44 | 0.294 | 5.39 |
| degraded | 14.43 | 11.36 | 0.485 | 4.93 |

Abaqus is used to develop the models needed for numerical part of the procedure. An elastic orthotropic material is implemented in the 2D model and the material can be applied to every element of the model. The undamaged, starting material parameters can be found in Table 2. The degraded parameters are the ones used in the virtual experiments.

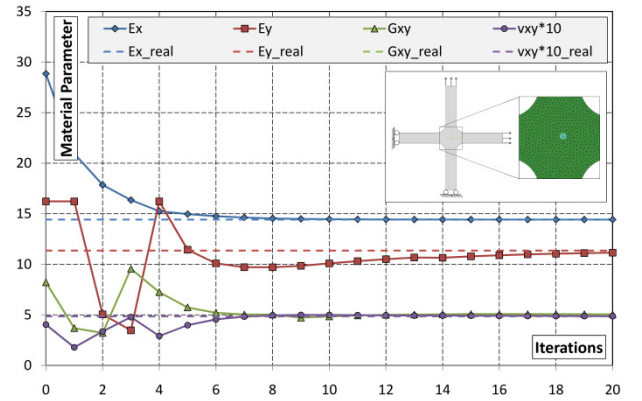


Fig.5. Convergence of the material parameters after several iterations, for 6 central elements.

As a first application of the method, a flat cruciform specimen is considered. The degradation is only applied on a small number of elements, surrounding one node. The material parameters of the other elements are not adapted. The aim is to verify the updating procedure for elements in several zones of the specimen. As can be seen in Figure 5, the procedure is able to find the correct material parameters of the considered elements after several

iterations. Applying the technique on different zones, varying from the arms, the centre or the corner of the specimen, reveals that attention should be paid to the sensitivity of each zone to specific parameters. For example, an element in the x-arm will mostly be sensitive to the stiffness variations in this x-direction and less or not to variations of the shear stiffness. The focus in this zone will be thus on the determination of E_x .

In a second case a rectangular specimen is considered where in one zone E_y is degraded and in the other not. The degradation of the other parameters is not considered, since E_y is the most sensitive parameter in this loading case. The aim is to determine the parameters for both zones simultaneously. As can be observed in Figure 6, the parameters are already found after a few iterations.

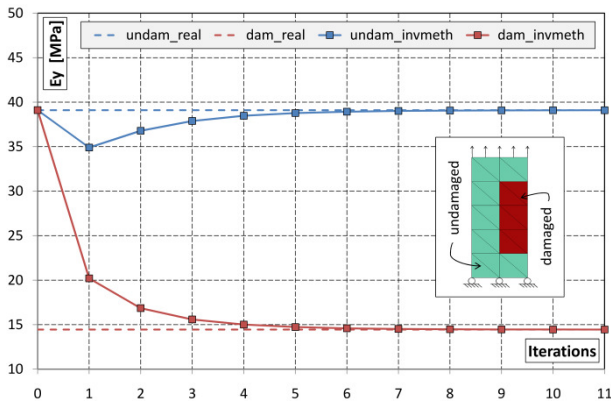


Fig.6. Convergence of E_y after several iterations, for 2 zones in a rectangular specimen.

4.2 Virtual experiment

After these simple test cases, the method will be used to identify the material parameters in a flat cruciform specimen. As in Figure 7, zones will be selected which will have more or less the same material parameter degradation. The degradation in the virtual experiment will be applied by implementing a damage law in the finite element model. An evaluation of computation time and stability of the procedure has to be carried out in order to know how small the “zones of equal material parameters” can become. The results of this study will be shown on the ICCM18 conference.

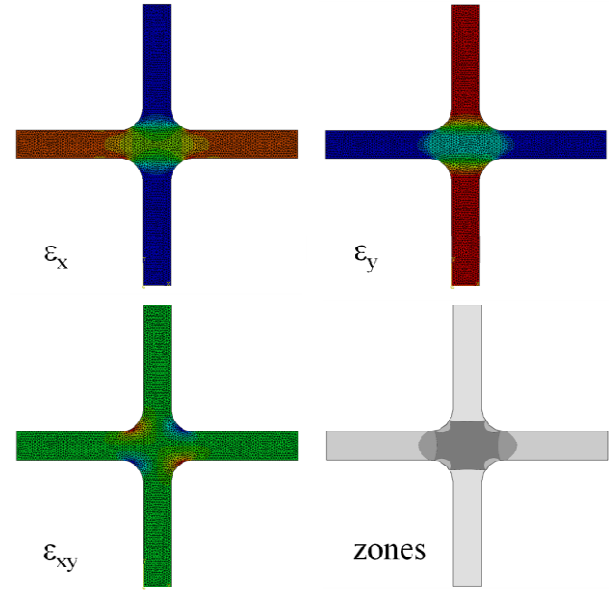


Fig.7. Strain fields for an undamaged flat cruciform specimen and the considered degradation zones.

Future work

Working with virtual experiments is a first step in the evaluation of the inverse procedure. However, the application of the method on real experimental data brings extra difficulties which have to be taken into account. The noise on the strain fields, obtained by DIC, will have an effect on the stability of the parameter updating. At the same time, the numerical model will never be a perfect reproduction of the real experiment : misalignments or small variations of the geometry will not be taken into account. The inverse method will thus be applied on strain data from a biaxial test of a cruciform specimen. In a first stage, a flat cruciform specimen will be considered. In a second stage, the cruciform specimen with milled central area will be considered and degradation curves will be composed.

5 Conclusions

Biaxial fatigue tests on cruciform specimens were accomplished successfully. ϵ/N curves were obtained for several biaxial ratios and a biaxial strengthening effect was noticed. To define the biaxial fatigue behaviour more elaborate, not only ϵ/N information is needed, but also the degradation curves of the material parameters should be known. To accomplish this, an inverse method is being developed. In a first stage, virtual tests were

performed to investigate the performance of the procedure. This gave promising results. In a later stage, the inverse method will be used to identify the material parameters in a real experiment.

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