CHARACTERISATION OF HIGH STRAIN RATE DEPENDENCY OF 3D WOVEN CFRP MATERIALS

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Abstract
New composite materials are increasingly used in aviation to reduce the mass of structures. Aeronautic structures have to be designed so as to be able to sustain a broad range of mechanical loadings during their operational life. These loading cases need also to account for low to high loading rates. The main objective of the present work is to establish and characterize the rate-dependency of the visco-elastic behaviour of polymer reinforced composite materials. More specifically, new generations of 3D carbon/epoxy composite materials are of interest because of their high mechanical performances, which require specific experimental developments to be done. Due to the large size of their textile Unit Cell and carbon fibre high strength and stiffness, unusual dynamic test capabilities are required, which lead to revisit the test protocols, specimens definition and instrumentation. The experimental method described in this work is applied to analyze the strain rate sensitivity of the mechanical behaviour of such a 3D woven composite material. The experiments were performed with a dynamic servo-hydraulic testing machine (ONERA) for a strain rate range varying between 10^{-4} s^{-1} and 10 s^{-1}. The linear mechanical behaviour of the material in warp, weft and 45° directions is characterized. These tests, together with the new experimental protocol, permit to accurately reveal and measure the material behaviour strain rate sensitivity, which proved to be large in the 45° direction.

1. Introduction

Currently, different woven composite material configurations exist. Woven architecture can be made in different textile types (taffeta, twill, 3D, 4D, 5D, ...). This study focuses on an epoxy reinforced by layer/layer unbalanced carbon fibres woven developed by SAFRAN Snecma. This Unit Cell, described in Figure 1, has a significant size compared to classic 2D woven composites. The composite volumetric warp/weft fibres ratio studied is low unbalanced.

This composite is made of two weaving directions, called warp and weft. Warp yarns weaving with different layers interlocks each layer together. This woven composite particularity prevents the fragile delamination phenomenon to appear.

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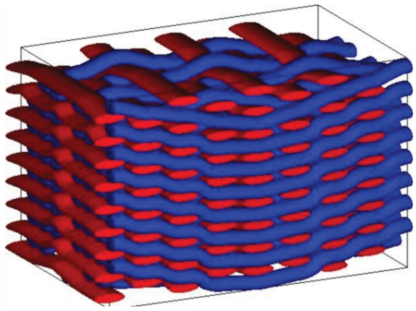

Figure 1. Representation of a complex 3D woven fabric composite Unit Cell

As J. Schneider [1] shows in quasi-static tensile tests ($\dot{\varepsilon} \simeq 10^{-4}\ s^{-1}$), mechanical behaviour of the 3D carbon/epoxy woven composite is orthotropic. This mechanical behaviour presents two domains, firstly a linear one in which the damage is assumed to be negligible at the macroscopic scale. The second one is a non linear domain due to the potential development of damage (matrix cracks, fibre yarn cracks, fibre yarn/matrix decohesion).

The in-plane mechanical behaviour of this specific 3D woven composite has been mainly studied under quasi-static or fatigue loadings [1–4]. In structure life-cycle, particularly for aeronautic applications, a wide loading speed range could be experimented for many reasons (bird strike, ice strike, ...). It is thus important to study the loading speed influence on materials mechanical behaviour in order to design the structure. The present study focuses on the first part of the mechanical behaviour, assumed to be linear, in various directions and for different strain rates.

1.1. Dynamical testing machine

A servo-hydraulic testing machine, developed by ONERA, was chosen for the dynamical experimentations. This device is particularly used for materials characterisation from quasi-static ($10^{-5}\ m.s^{-1}$) to dynamic loadings up to 10 $m.s^{-1}$, for lower loads than 40kN. In order to measure the mechanical load, a ±200 kN piezo-electric force cell (Kistler 9071A) is fixed to the specimen grip.

In order to characterize the 3D woven composite quasi-static behaviour, It was proposed specific dog-bone tensile specimen geometry in warp and weft directions. The large size of the Unit Cell and the high strength and stiffness of the carbon fibres lead to high load levels. The chosen dynamic experimental device cannot reach such load levels. Tensile specimens geometry has to be minimized for dynamic tests. This dimensional change must not impact the intrinsic material properties characterisation.

2. Dynamic tensile specimen

Rather than performing a costly and time consuming experimental campaign for designing the tensile specimen geometry, a numerical approach has been preferred. The numerical approach is based on numerical Finite Element (FE) tensile test simulations in warp and weft directions, directions in which the load levels are critical. The influence of the specimen dimensions was studied with respect to the Young modulus.

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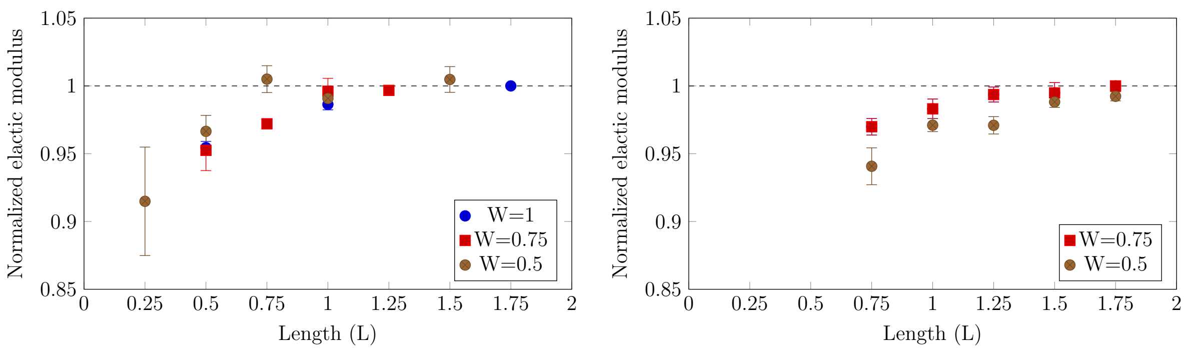
2.1. Minimization of the tensile specimen geometry

The mesh was realised with a modelling chain tool developed by SAFRAN Snecma [5]. From the reference specimen Zone Of Interest (ZOI) μ-tomography, a textile architectural mesh was made. This specific mesh takes into account possible heterogeneities generated by the manufacturing processes. In this case, carbon fibre yarns are considered elastic orthotropic, and epoxy matrix is considered elastic isotropic.

The ZOI width (W) and length (L) influences on the elastic modulus characterisation were studied. The virtual specimens thickness is constant because of the interlocking pattern between each layer in this direction. In each case, displacement boundary conditions representative of a tensile test are applied to the faces orthogonal to the loading direction. The other faces are free in displacement and loading.

Elastic modulus obtained with warp tensile tests for different ZOI dimensions are described in Figure 2(a). Error bars correspond to the dispersion linked to the sample positions. Elastic moduli are normalized by the value obtained with the quasi-static tensile specimen test result (L=1.75 ; W=1). Volume dimensions are normalized by the Unit Cell ones.



(a) Warp tensile tests (b) Weft tensile tests

Figure 2. Evolution of the normalized warp elastic modulus with the size and position of the specimen

For W=1 (●), warp elastic modulus converges quickly to the value obtained with the tested specimen assumed as the reference one. By decreasing the specimen width, W=0.75 (■) and W=0.5 (●), convergence to the reference solution is also observed. A decrease in virtual specimen length by 43% (L = 1) does not significantly alter the elastic modulus identification (error < 1.5%). If the considered ZOI is too small (L=0.25 and W=0.5 for example) elastic modulus varies a lot (± 4.4% different from the mean value). In this case, a significant position sensitivity was noticed.

Elastic modulus obtained with weft tensile tests for different ZOI dimensions is described in Figure 2(b). In this case, weft virtual tests corresponding to the Unit Cell width (W=1) were not studied, due to the largest μ-tomography available in this study (W=0.75). Weft elastic moduli are normalized by the value obtained with the largest virtual specimen (L=1.75 ; W=0.75).

For W=0.75 (■), weft elastic modulus converges quickly to the assumed reference value. As observed in warp direction, by decreasing the specimen width, for W=0.5 (●), the convergence to the reference solution is observed. Virtual specimen length decrease by 14% (L = 1.5) does not significantly alter the elastic modulus, with a 1.1% difference compared to the current reference value.

In both cases, it was observed that weft elastic modulus obtained with smaller width and length specimens compared to the references may be admissible (error < 1.5%). The width reduction of the tensile specimen limits the maximum load to apply. In the present study, a 0.75 Unit Cell specimen width in warp and weft directions allows to perform tensile tests with the dynamic servo-hydraulic machine. Dynamic tensile specimen dimensions are summarized in Table 1.

Direction	Length of the ZOI (L)	Width of the ZOI (W)
Warp	1.4 Unit Cells	0.75 Unit Cell
Weft	2.3 Unit Cells	0.75 Unit Cell

Table 1. ZOI dimensions of the warp and weft dynamic tensile specimens

2.2. Experimental validation

Dynamic tensile test specimen geometries, designed by FE simulations, have to be experimentally validated before characterising the 3D woven composite mechanical behaviour strain rate sensitivity.

Quasi-static tensile tests (10^{-4} s^{-1}) of the dynamic specimens geometry were realised with the servo-hydraulic machine. Longitudinal strain was evaluated by strain gauge, and transversal strain by Digital Image Correlation (DIC). The transversal strain is obtained by a ZOI virtual gauge size. As defined by the Snecma protocol, warp and weft elastic moduli are obtained by linear regression between 0.1% and 0.4% longitudinal strain. Warp and weft elastic moduli obtained with the dynamic specimens geometry are described in Figure 3(a) and 3(b) (respectively ○ and ○).

Quasi-static tensile tests (10^{-4} s^{-1}) of the quasi-static specimens geometry proposed by J. Schneider [1] were realised with a electro-mechanical machine. Warp and weft elastic moduli obtained with the quasi-static tensile specimens geometry are compared to the dynamic ones in Figure 3(a) and 3(b) (respectively ⋆ and ⋆). The tensile specimen dimensions decrease has no impact on the 3D woven composite elastic modulus characterisation. This experimental comparison also proves a good correlation with the numerical approach.

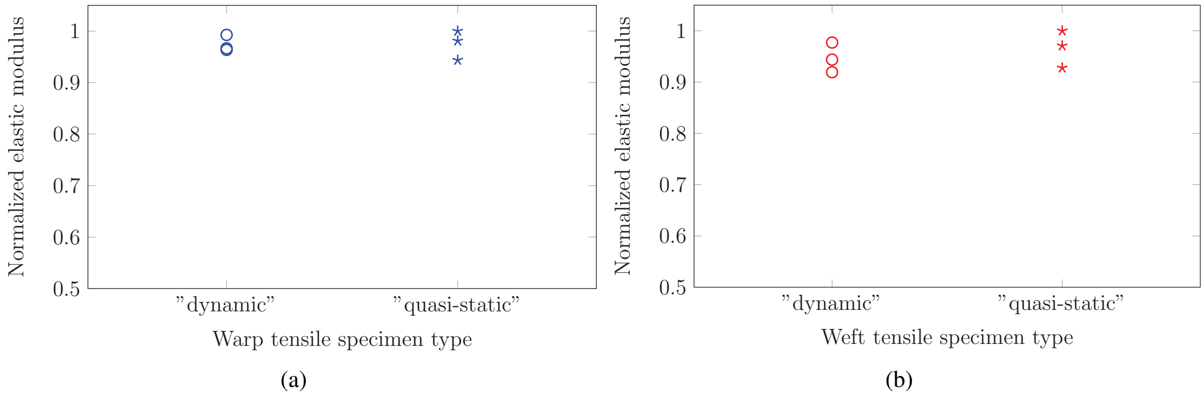


Figure 3. Comparison of elastic moduli obtained with the reference specimens geomtries and the dynamic ones, (a) in warp direction and (b) in weft direction

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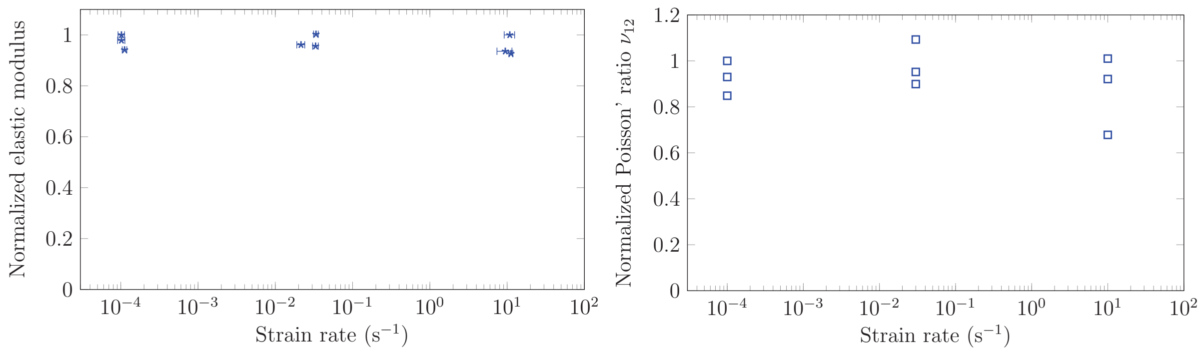
3. Experimental dynamic tensile tests

3.1. Warp tensile tests

Tensile tests on the dynamic warp and weft specimens were realised with the servo-hydraulic machine from quasi-static to dynamic strain rates. Tensile tests were done for 3 speeds : $1.7 \cdot 10^{-3}$ $m.s^{-1}$, 0.01 $m.s^{-1}$ and 1 $m.s^{-1}$, 3 tensile tests for each speed were carried out to evaluate the dispersion.

Elastic moduli obtained for different speeds in warp direction are plotted in Figure 4(a) with respect to the mean strain rate, calculated in the [0.1% ; 0.4%] strain range. Horizontal error bar in Figure 4(a) represents the dispersion in strain rate in the strain range. Error bars are never significant for warp tensile tests. Warp elastic modulus is normalized by the highest one at 10^{-4} s^{-1}. In warp direction, elastic modulus is independent of the strain rate between 10^{-4} and 10 s^{-1} and the dispersion is quite constant.

Poisson's ratio ν_{12} obtained in each warp tensile tests is plotted in Figure 4(b) with respect to the strain rate. Poisson's ratio was evaluated by DIC in the same strain range as the elastic modulus. Poisson's ratio ν_{12} dispersion is higher than the one of elastic modulus. In the Poisson's ratio measurement range the mean value of the transversal strain is relatively low and closed to the measurement uncertainty. Given these low measurement levels, the Poisson's ratio obtained is qualitative. An insensitivity of Poisson's ratio ν_{12} relatively to the strain rate was observed. In this case, warp mechanical behaviour under $\varepsilon_l < 0.4\%$ of the 3D carbon/epoxy woven composite can be considered linear elastic. Daniel et al. [6], Harding et al. [7] and Welsh et al. [8] have studied strain rate dependency of the Young modulus in fibre direction, respectively for UD laminated CFRP and for a 2D woven laminated CFRP composite materials. They all observed insensitivity between 10^{-4} and 10 s^{-1}. Warp carbon fibres weave in woven CFRP does not seem to introduce more strain rate sensitivity of the Young modulus in this fibre direction.



(a) Warp elastic modulus (b) Poisson's ratio ν_{12}

Figure 4. Dynamic warp tensile tests results

3.2. Weft tensile tests

Tensile tests on the dynamic weft specimens were realised with the servo-hydraulic machine from quasi-static to dynamic strain rates. Three tensile tests per speed were performed for $1.7 \cdot 10^{-5}$ $m.s^{-1}$, 0.01 $m.s^{-1}$ and 1 $m.s^{-1}$. Weft elastic moduli, normalized by quasi-static warp elastic modulus, are plotted in Figure 5(a). As shown in warp case, dispersion in weft elastic modulus is also negligible. The strain rate sensitivity of weft elastic modulus is not significant between 10^{-4} and 10 s^{-1}. Poisson's ratio also evaluated by DIC allows to get the same observation. In warp and weft directions, the mechanical behaviour of the 3D woven CFRP under $\varepsilon_l < 0.4\%$ can be considered linear elastic.

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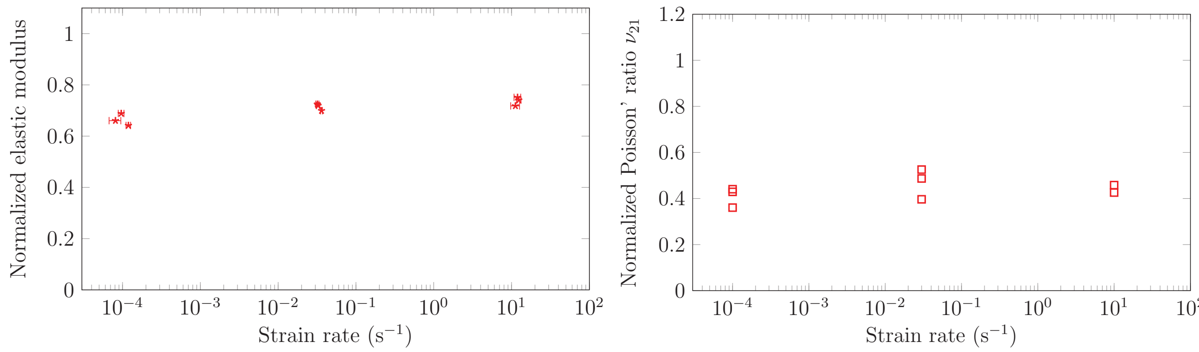


(a) Weft elastic modulus (b) Poisson's ratio ν_{21}

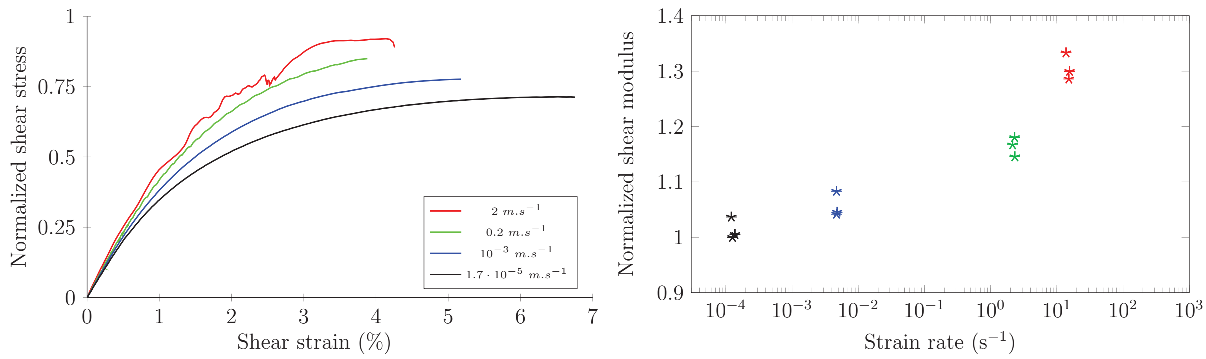
Figure 5. Dynamic weft tensile tests results

3.3. Off-axis tensile tests at 45°

In order to study the strain rate sensitivity of the in-plan mechanical behaviour of the 3D woven CFRP, off-axis tensile tests were performed. Currently, there is no experimental standard for characterising the 3D woven shear mechanical behaviour. Because of their relative architectural simplicity, laminated composite materials benefit from shear experimental standards, based on off-axis tensile test at 45° (ISO 527-5:1997, NF EN 2597:1998, AITM 1-0002:1998).

Many authors proposed to study off-axis behaviour of 3D woven CFRP from the 45° tensile test [1–4, 9]. This test presents a simplicity of implementation and analysis of results. In this study, a 45° tensile specimen, including one Unit Cell in the ZOI width (W) and three in the ZOI length (L), is proposed. In these conditions, maximum load to apply at 45° is lower that maximum load in warp and weft directions.

45° tensile tests were realised with servo-hydraulic machine from quasi-static to dynamic strain rates. Three tensile tests per speed were performed for $1.7 \cdot 10^{-5}$ $m.s^{-1}$, 10^{-3} $m.s^{-1}$, 0.2 $m.s^{-1}$ and 2 $m.s^{-1}$ speeds. Longitudinal and transversal strains were measured with strain gauges. Shear stress-strain curves of the 3D woven CFRP are plotted in Figure 6(a) for different speeds (one curve per speed). Shear stress-strain curves evolve significantly with the change of loading speed.



(a) linear domain (b) shear modulus

Figure 6. Dynamic 45 tensile tests

It was proposed to calculate the 3D woven CFRP shear modulus by linear regression between 0.05% and 0.2% shear strain. In this interval the strain rate is relatively constant for all the tests. Shear moduli obtained for different speeds are described in Figure 6(b) with respect to the mean strain rate, calculated in the identification strain range. Shear modulus is normalised by the quasi-static one at 10^{-4} s^{-1}. An

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important increase of the elastic shear modulus is observed from 10^{-4} s^{-1} to 10 s^{-1} ($\simeq$30%). This result has also been observed in [10] and[11], respectively for a UD CFRP and a 2D woven CFRP composite materials.

4. Conclusions

Quasi-static warp and weft 3D carbon/epoxy woven composite tensile specimens geometry lead to load levels that cannot be reached with ONERA dynamic servo-hydraulic testing machine. Specific dynamic specimens were then developed in order to adapt the specimens strength to the dynamic testing machine capacity.

Reference tensile specimens geometry are one Unit Cell width. Dimensional and positional sensitivities of the elastic modulus characterisation were studied by Finite Element tensile test simulations. In warp and weft cases it was observed that the elastic modulus quantification could be properly performed when reducing the reference width (W) and length (L). Elastic modulus obtained in both cases, with a 0.75 Unit cell width (L=1 in warp direction and L=1.5 in weft direction) is less than 1.5% different from the numerical reference, and relatively independent on the virtual specimen position. A length reduction specimen permits to reach higher strain rate levels than the reference one.

Elastic modulus obtained with the quasi-static and the dynamic tensile specimens geometry at 10^{-4} s^{-1} exhibit a good correlation with respect to the virtual testing approach.

From specific dynamic warp and weft tensile specimens geometry, quasi-static to dynamic tests were performed in order to characterise the stain rate sensitivity of the composite material linear mechanical behaviour. Young modulus and Poisson's ratio obtained in both cases show no dependence on the strain rate between 10^{-4} and 10 s^{-1} as could been observed in the literature for other CFRP composite materials (UD and 2D)

Due to the lack of shear characterisation standards adapted to 3D woven CFRP, off-axis tensile tests at 45° were proposed. The tests were performed for different speeds between $1.7 \cdot 10^{-5}$ $m.s^{-1}$ and 2 $m.s^{-1}$. A significant increase in shear modulus of about 30% was observed between 10^{-4} and 10 s^{-1}. The strain rate sensitivity is primarily driven by the visco-elastic behaviour of the resin in CFRP material, as observed in UD and 2D woven laminated CFRP materials.

In conclusion, warp and weft mechanical behaviour under $\varepsilon_l < 0.4\%$ of the 3D carbon/epoxy woven composite can be considered linear elastic between 10^{-4} and 10 s^{-1}. In the same strain rate range, linear off-axis mechanical behaviour is strain rate dependent and has to be considered in numerical models.

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