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► **To cite this version:**

N. Tran, J. Berthe, M. Brieu, G. Portemont, Julien Schneider. Characterization of high strain rate dependency of 3D CFRP materials. 2016 SEM XIII International Congress, Jun 2016, Orlando, FL, United States. hal-01388137

**HAL Id: hal-01388137**

**<https://hal.science/hal-01388137>**

Submitted on 26 Oct 2016

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# Characterization of high strain rate dependency of 3D 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 with respect to a broad range of mechanical loadings during their operational life. These loadings are considered in the design by numerous cases, from low up to high speeds. The motivation of the presented work is to establish and characterize the high strain rate dependency of the linear behavior of composites 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 fiber high strength and stiffness, unusual dynamic test capabilities are required, which leads to revisit the test protocols, specimens definition, instrumentation and exploitation techniques. The experimental method described in this work is applied to analyze the strain rate sensitivity of the mechanical behavior of such a 3D woven composite material. The experiments are done with a servo-hydraulic testing machine (ONERA) in a strain rates range varying between  $10^{-4} s^{-1}$  and  $10 s^{-1}$ . The linear mechanical behavior of the material in the warp, weft and  $45^\circ$  orientations is characterized. These tests, together with the new experimental protocol, permit to accurately reveal and measure the material behavior strain rate sensitivity, which proved to be large in the  $45^\circ$  direction.*

**Keywords :** *composite, interlock, strain rate, experimental, characterization*

## 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 fibers interlock woven developed by SAFRAN Snecma. This Unit Cell, described in Figure 1, as a significant size compared to classic 2D woven composites. The composite volumic warp/weft fibers ratio studied is low unbalanced. A change in warp/weft volumic ratio is made by spacing warp and weft vertically weaving columns differently.

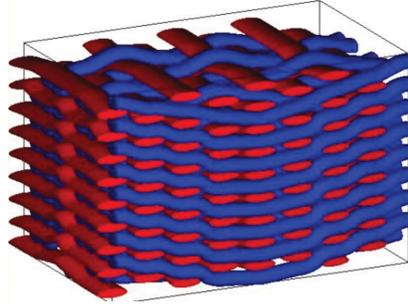


Fig. 1. Representation of a complex 3D interlock woven fabric composite Unit Cell

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

The in-plane mechanical behaviour of this specific 3D interlock woven composite has been mainly studied under quasi-static or fatigue loadings [1–4]. In structure lifecycle, 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 behavior in order to design the structure. The present study focuses on the first part of the mechanical behaviour, assumed as linear, in various directions and for different strain rates.

### 1.1 Dynamical testing machine

A servo-hydraulic testing machine was chosen for the dynamical experimentations. This device is particularly used for materials characterization from quasi-static to dynamic loadings up to several  $10 m.s^{-1}$ .

In order to characterize the 3D woven composite quasi-static behavior, J. Schneider [1] proposed specific dog-bone tensile specimen geometry in warp and weft directions. The large size Unit Cell and the high strength and stiffness of the carbon fibers would lead to apply high load levels. The current dynamic experimental device can not reach such load levels. Tensile specimen geometry have to be minimized for dynamic tests. This dimensional change must not impact the intrinsic material properties characterization.

## 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 specimen dimensions influence was studied with respect to the elastic modulus.

### 2.1 Minimization of the tensile specimen geometry

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

The ZOI width (W) and length (L) influences on the elastic modulus characterization 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 to a tensile test are applied to the faces orthogonal to the loading direction. The others 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.

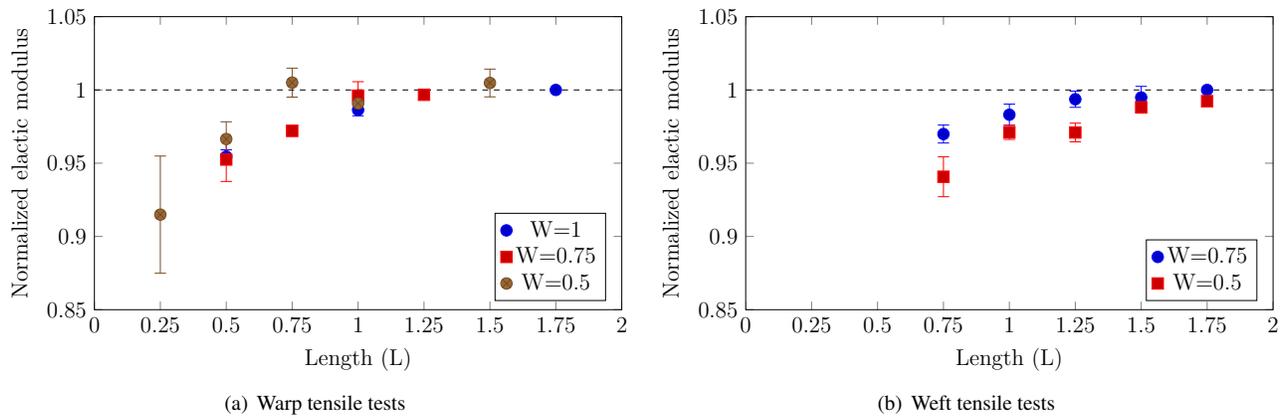


Fig. 2. Evolution of the normalized warp elastic modulus with the size and position of the specimen

For  $W=1$  (●), elastic moduli converge quickly to the value obtained with the tested specimen assumed as the converged one. By decreasing the specimen width,  $W=0.75$  (■) and  $W=0.5$  (●), convergence to the reference solution were 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  $W=0.5$  as example) the elastic modulus identification varies a lot ( $\pm 4.4\%$  different from the mean value). In this case, a significant position sensitivity were noticed.

Elastic modulus obtained with weft tensile tests for different ZOI dimensions are described in Figure 2(b). In this case, virtual tests corresponding to the reference specimen width ( $W=1$ ) were not studied. Elastic moduli are normalized by the value obtained with the largest virtual specimen ( $L=1.75$  ;  $W=0.75$ ).

For  $W=0.75$  (●), elastic moduli converge quickly to this reference value. As observed in warp direction, by decreasing the specimen width, for  $W=0.5$  (■), the convergence to the reference solution were observed. Virtual specimen length decrease by 14% ( $L = 1.5$ ) does not significantly alter the elastic modulus, with 1.1% different compared to the current reference value.

In both cases, it was observed that elastic modulus obtained with smaller virtual specimens width and length than the references may be admissible (error < 1.5%). The tensile specimen width reduction limits load levels 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)
<b>Warp</b>	1.4 Unit Cells	0.75 Unit Cell
<b>Weft</b>	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 specimens, designed by FE simulations, had to be experimentally validated before characterizing the 3D interlock woven composite mechanical behavior strain rate sensitivity.

Quasi-static tensile tests ( $10^{-4} s^{-1}$ ) of the dynamic specimens were realized with the servo-hydraulic machine. Longitudinal strain was evaluated by strain gage transversal strain by Digital Image Correlation (DIC). ZOI virtual gage dimension was used to identify the elastic modulus. 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 are described in Figure 3(a) and 3(b) (respectively  $\circ$  and  $\circ$ ).

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

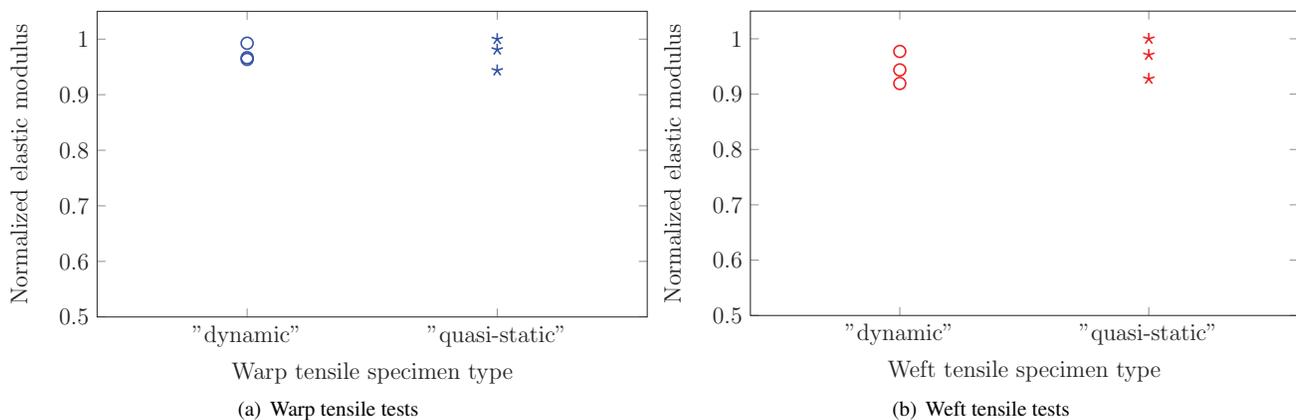


Fig. 3. Comparison of elastic moduli obtained with the reference specimens and the dynamic ones

## 3 Experimental dynamic tensile tests

### 3.1 Warp tensile tests

Tensile tests on the dynamic warp and weft specimens were realized with the servo-hydraulic machine from quasi-static to dynamic strain rates. Tensile tests were made 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 modulus obtained for different speeds in warp direction are described in Figure 4(a) with respect to the mean strain rate, calculated in the elastic modulus measurement gap. Horizontal error bar in Figure 4(a) represents the dispersion in strain rate in the elastic modulus measurement gap. Error bars are not significant for all 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' ratio  $\nu_{12}$  obtained in each warp tensile tests is described in Figure 4(b) with respect to the strain rate. Poisson' ratio was evaluated by DIC in the same measurement gap as the elastic modulus. Poisson' ratio  $\nu_{12}$  dispersion is higher than the one of elastic modulus. Low transversal strain levels in the Poisson' ratio measurement gap are close to the measurement uncertainty. Given these low measurement levels, the Poisson' ratio obtained is qualitative. An insensitivity of Poisson' ratio  $\nu_{12}$  relative to the strain rate was observed.

In this case, warp mechanical behaviour under  $\epsilon_l < 0.4\%$  of the 3D interlock carbon/epoxy woven composite could be considered linear elastic.

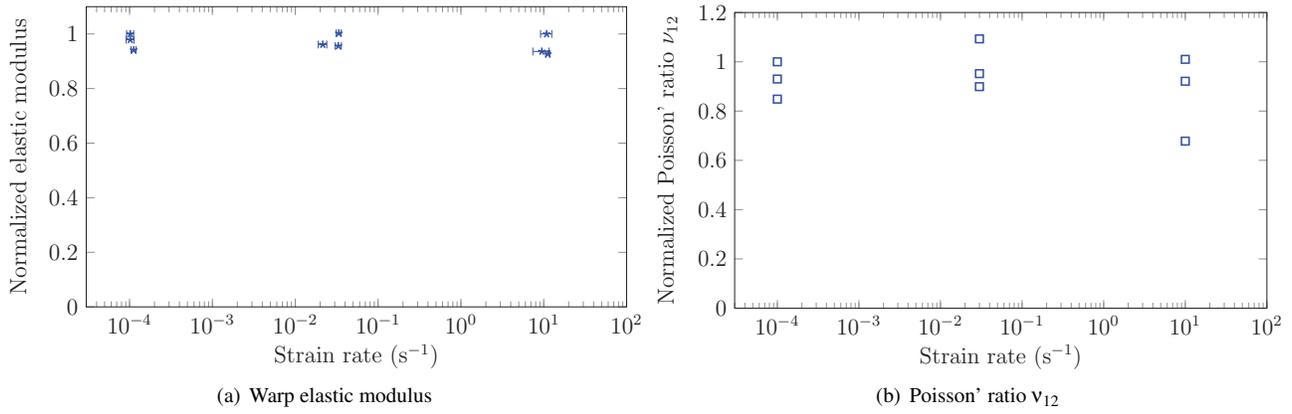


Fig. 4. Dynamic warp tensile tests

### 3.2 Weft tensile tests

Tensile tests on the dynamic weft specimens were realized with servo-hydraulic machine from quasi-static to dynamic strain rates. 3 tensile tests per speed were ran for  $1.7 \cdot 10^{-3} \text{ m.s}^{-1}$ ,  $0.01 \text{ m.s}^{-1}$  and  $1 \text{ m.s}^{-1}$ .

Weft elastic moduli, normalized by quasi-static warp elastic modulus, are described in Figure 5(a). As shown in warp case, dispersion in weft elastic modulus is negligible. Weft elastic modulus strain rate sensitivity is not significant between  $10^{-4}$  and  $10 \text{ s}^{-1}$ . Poisson's ratio also evaluated by DIC allows to make the same observation. In warp and weft directions, 3D interlock carbon/epoxy woven composite mechanical behaviour under  $\epsilon_l < 0.4\%$  can be considered linear elastic.

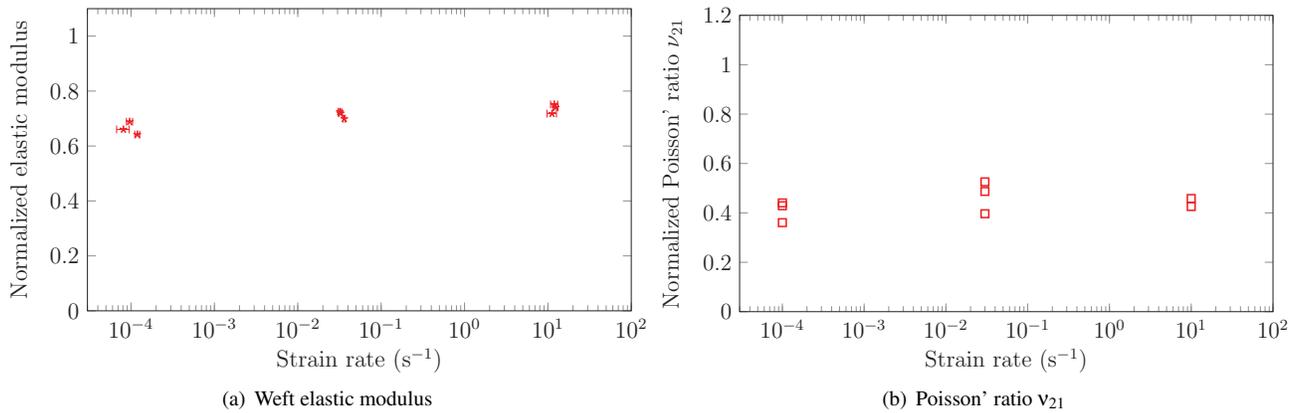


Fig. 5. Dynamic weft tensile tests

## 4 Conclusions

Quasi-static warp and weft 3D interlock carbon/epoxy woven composite tensile specimens require to apply load levels that could not be reached with 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 characterization 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 by 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 reference, and relatively independent of the virtual specimen position. A length reduction specimen permits to reach upper strain rate levels than the reference one.

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

From specific dynamic warp and weft tensile specimens, quasi-static to dynamic tests were ran in order to characterize the strain rate sensitivity of the 3D interlock carbon/epoxy woven composite linear mechanical behaviour. Elastic modulus and the Poisson' ratio obtained in both cases show a independence to the strain rate between  $10^{-4}$  and  $10 s^{-1}$ .

In conclusion, warp and weft mechanical behaviour under  $\epsilon_l < 0.4\%$  of the 3D interlock carbon/epoxy woven composite can be considered linear elastic.

## Acknowledgements

This research was supported by SAFRAN Snecma. We thank our colleagues from SAFRAN (Y.WIELHORSKI, T.FIXY, ...), ONERA (M.RAGONET, A.DEDON, ...), Centrale Lille and LML who provided expertise and technical support that greatly assisted the research.

We thank E.Deletombe (ONERA) for assistance with particular scientific methodology and for comments that greatly improved the manuscript.

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