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# Interlaminar shear strength of marine composite laminates: Tests and numerical simulations

M. Godani, M. Gaiotti, C.M. Rizzo *

*Marine Structures Testing Lab, DITEN, University of Genova, Genova, Italy*

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ABSTRACT

This paper deals with an experimental/numerical comparison of the interlaminar shear stress in typical marine composite laminates manufactured according to two different fabrication processes, namely vacuum infusion and pre-impregnated lay-up. Experimental tests were carried out at the Marine Structures Testing Lab of the University of Genova. Actually, among widely applied empirical formulations for the characterization of composites suggested by Classification Societies rules, the ones for the interlaminar shear strength appear the most scattered because of the complexity in assessing failure phenomena. Composite manufacturers generally carry out rather extensive tests for the complete characterization of the laminates.

Due to non-linearities involved in the captioned study, the support of nonlinear numerical models was required. The aim of the comprehensive use of numerical approaches is the reduction of time-consuming and expensive experimental campaigns.

Three different FE modeling strategies are proposed in order to verify the reliability of the numerical results in comparison with experimental targets. The merits and shortcomings of each are discussed, also comparing different types of finite element formulations and mesh refinement sensitivity.



## 1. Introduction

The evaluation of the interlaminar shear stress distribution inside the layers of a laminate is a challenging task since it depends by many factors such as involved materials, manufacturing processes and their quality.

The first studies on the prediction and analysis of the interlaminar shear distribution date back to the late 60s, Hayashi [1] was a pioneer. Later on, many authors deepened these studies, see e.g. [2–4]. In addition, some authors modified the assumptions of the Classical Lamination Theory (CLT) in order to consider deformations and stresses acting perpendicularly to the layers plane. Such studies were summarized and compared by Carrera and Giuffreda [5].

Nowadays, these theories are often implemented in numerical analyses to more accurately predict the distribution of the interlaminar shear stress in a composite laminate. The present work aims at verifying and validating by experimental tests the numerical evaluation of the interlaminar shear stress as well as at assessing the interlaminar shear strength of typical marine composites obtained by different fabrication methods.

The specimens, originally obtained from larger panels made by both vacuum infusion (named in the following INF-A and INF-B panels) and pre-impregnated fabrics (named in the following PRE-A and PRE-B panels), were manufactured according to the ASTM standard D3846-79 'Test method for in-plane shear strength of reinforced plastics' [6,7], which is the reference test required by most of Classification Societies for the evaluation of the interlaminar shear strength of composites.

An empirical formulation is suggested in various rules of Classification Societies (e.g. Det Norske Veritas, Germanischer Lloyd, Registro Italiano Navale) for the evaluation of the ultimate interlaminar shear strength of typical marine composites, depending on the fiber weight content in the laminate $w_f$: $\tau_{xz} = 22.5 - 17.5W_f$. Lloyd's Register of Shipping provides a similar but more conservative formulation: $\tau_{xz} = 22.5 - 13.5W_f$.

It is worth nothing that the rule value is generally valid for all glass fabric types, except for Germanischer Lloyd who specifies that it is valid for chopped strand mat and woven roving combinations, while this paper focusses on the interlaminar shear strength between unidirectional layers of a laminate.

* Corresponding author. Address: Via Montallegro 1, I-16145 Genova, Italy. Tel.: +39 010 353 2272; fax: +39 010 353 2127.

*E-mail addresses:* mattia.godani@gmail.com (M. Godani), marco.gaiotti@unige.it (M. Gaiotti), cesare.rizzo@unige.it (C.M. Rizzo).

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**Table 1**
Geometrical dimensions of the first set of specimens.

| Specimens | Geometry | | | | | | | Contact area | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $L$ (mm) | $B$ (mm) | $H$ (mm) | $h_{notch\ sup.}$ (mm) | $s_{notch\ sup.}$ (mm) | $h_{notch\ inf.}$ (mm) | $s_{notch\ inf.}$ (mm) | $l$ (mm) | $B$ (mm) | $A$ (mm$^2$) |
| *Infusion* | | | | | | | | | | |
| INF-A Spec. 1 | 76.56 | 10.32 | 18.03 | 9.02 | 1.73 | 9.02 | 1.65 | 6.49 | 10.30 | 66.85 |
| INF-A Spec. 2 | 80.01 | 10.21 | 18.99 | 9.50 | 1.84 | 9.50 | 1.84 | 7.35 | 10.78 | 79.23 |
| INF-B Spec. 1 | 80.01 | 10.21 | 19.77 | 9.89 | 1.77 | 9.89 | 1.78 | 7.40 | 10.21 | 75.55 |
| INF-B Spec. 2 | 80.00 | 10.32 | 19.11 | 9.56 | 1.80 | 9.56 | 1.82 | 7.45 | 10.32 | 76.88 |
| INF-B Spec. 3 | 80.00 | 10.36 | 19.36 | 9.68 | 1.73 | 9.68 | 1.88 | 7.26 | 10.36 | 75.21 |
| *Pre-preg* | | | | | | | | | | |
| PRE-A Spec. 1 | 77.32 | 11.26 | 20.23 | 10.12 | 1.71 | 10.12 | 1.84 | 6.40 | 11.23 | 71.87 |
| PRE-A Spec. 2 | 77.32 | 11.89 | 20.59 | 10.30 | 1.62 | 10.30 | 2.43 | 6.40 | 11.75 | 75.20 |
| PRE-A Spec. 3 | 77.32 | 12.66 | 20.08 | 10.04 | 1.81 | 10.04 | 2.06 | 6.40 | 12.62 | 80.77 |
| PRE-A Spec. 4 | 77.32 | 12.40 | 19.86 | 9.93 | 1.71 | 9.93 | 1.70 | 6.77 | 12.60 | 85.30 |
| PRE-A Spec. 5 | 77.32 | 12.68 | 19.97 | 9.99 | 1.68 | 9.99 | 1.69 | 6.44 | 12.60 | 81.14 |
| PRE-B Spec. 1 | 79.21 | 14.05 | 20.11 | 10.06 | 1.83 | 10.06 | 2.06 | 6.52 | 14.05 | 91.61 |
| PRE-B Spec. 2 | 79.21 | 13.75 | 19.94 | 9.97 | 1.61 | 9.97 | 1.81 | 6.04 | 13.75 | 83.05 |
| PRE-B Spec. 3 | 78.95 | 13.67 | 19.98 | 9.99 | 1.96 | 9.99 | 1.75 | 6.45 | 13.67 | 88.17 |
| PRE-B Spec. 4 | 78.01 | 13.22 | 20.18 | 10.09 | 1.88 | 10.09 | 1.82 | 6.16 | 13.22 | 81.44 |
| PRE-B Spec. 5 | 79.95 | 14.10 | 19.87 | 9.94 | 1.78 | 9.94 | 1.80 | 6.92 | 14.10 | 97.57 |

## 2. Experimental results

As mentioned, the specimens used for the first test campaign were obtained by four vacuum infusion and pre-impregnated lay-up (pre-preg) panels. All have similar stacking sequences, mainly consisting of layers of unidirectional fabrics; some very thin mat layers absorbing the excess of resin and a few ±45° roving layers having the same purpose and placed in between unidirectional layers near the laminate surfaces.

Burn out tests were carried out to obtain the fiber volume fraction, estimated $V_f \approx 0.54$ in all tested specimens, so the fiber weigth fraction is computed using Eq. (1):

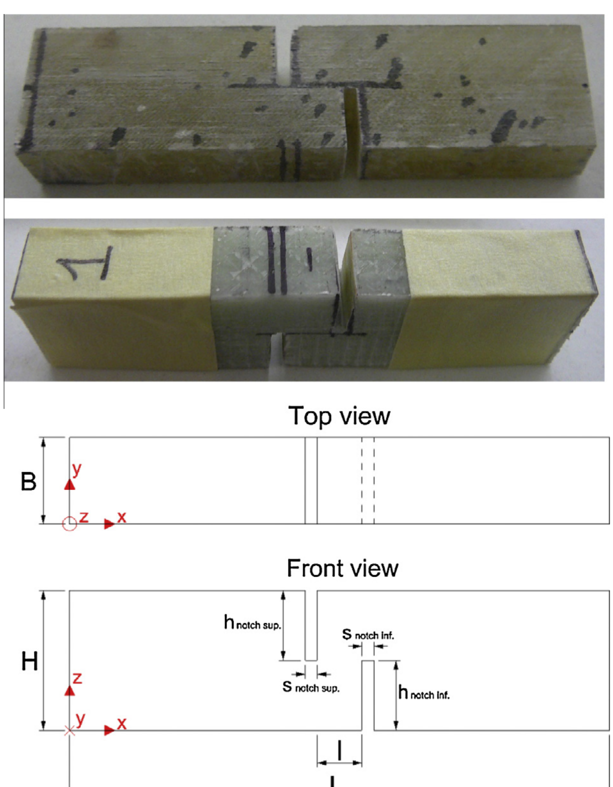


**Fig. 1.** Specimens realization (infusion made panel top, prepreg panel mid, geometry bottom).

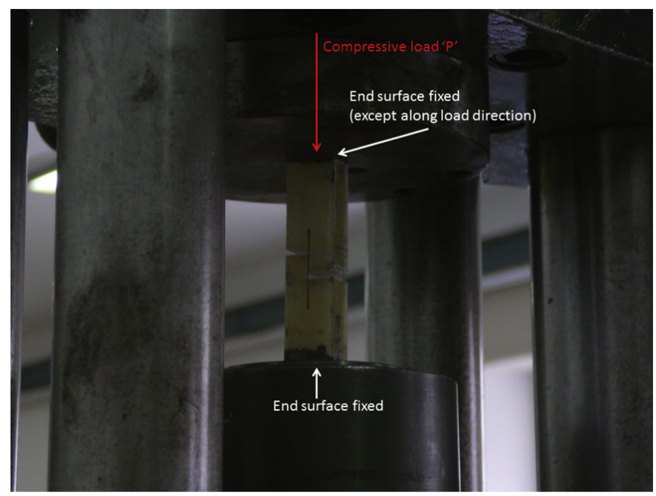


**Fig. 2.** Experimental tests set up.

**Table 2**
Results of the first campaign of experimental tests.

| | Failure load (kg) | Visual inspection |
|---|---|---|
| *Infusion* | | |
| INF-A Spec. 1 | 275 | Fibers compression: to repeat |
| INF-A Spec. 2 | 396 | Fibers compression: to repeat |
| INF-B Spec. 1 | 740 | Specimen OK |
| INF-B Spec. 2 | 560 | Fibers compression: to repeat |
| INF-B Spec. 3 | 940 | Specimen OK |
| *Pre-preg* | | |
| PRE-A Spec. 1 | 480 | Specimen OK |
| PRE-A Spec. 2 | 560 | Specimen OK |
| PRE-A Spec. 3 | 630 | Specimen OK |
| PRE-A Spec. 4 | 950 | Fibers compression: to repeat |
| PRE-A Spec. 5 | 440 | Specimen OK |
| PRE-B Spec. 1 | 350 | Specimen OK |
| PRE-B Spec. 2 | 400 | Specimen OK |
| PRE-B Spec. 3 | 600 | Fibers compression: to repeat |
| PRE-B Spec. 4 | 450 | Specimen OK |
| PRE-B Spec. 5 | 180 | Specimen OK |

$$\textit{Fiber weigth fraction} \quad W_f = (\rho_f * V_f)/[(\rho_f * V_f) + \rho_m * (1 - V_f)] \tag{1}$$

where $\rho_f$ (kg/m$^3$) = 2590 and $\rho_r$ (kg/m$^3$) = 1200 are the fiber and matrix density.