Out-of-plane effect of stacking sequences on crack resistance and energy absorption of glass fiber vinyl ester composite: Experimental

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ABSTRACT

In fiber composites manufacturing, the laminate stacking sequences is one of the most complex design parameters affecting the overall properties of the final parts. However, due to the big number of fibers, matrix, parts geometries, and the number of possible combinations, there is still a need of data on the effect of stacking sequences, on crack resistance and energy absorption capability of fiber composites. Most of the works done so far to understand this effect were made using either carbon or glass fibers combined with epoxy, or with polyester resin while, very few involve the vinyl ester resin, very popular in industries, but mostly in case of filaments winding processes, instead of vacuum assisted resin infusion (VARI) processes, or hand layup processes, as it is the case for epoxy and polyester resin. In this work, we will investigate the out-of-plane effect of stacking sequences, on crack resistance and energy absorption capability of short-beam, made of unidirectional glass fiber vinyl ester composite. We conducted an experimental investigation under three-point-bending loads, with samples of composite manufactured using the VARI process, and according to the following stacking sequences: $[0]_{16}$, $[0_1/90_3]_{2S}$, $[0_2/90_2]_{2S}$, $[0_3/90_1]_{2S}$, $[90]_{16}$, $[90_1/0_3]_{2S}$, $[90_2/0_2]_{2S}$ and $[90_3/0_1]_{2S}$. This work can be part of the database in case of research on out-of-plane behavior of thin-walled structures, made of unidirectional glass fiber vinyl ester composite.

Keywords: Stacking sequences, Crack resistance, Energy absorption, Specific energy absorption.

1. INTRODUCTION

Since their introduction in the market, the design of fiber composite materials has brought many difficulties due to its dependence to several factors such as fiber orientation, laminate stacking sequences, surface waviness and other manufacturing process parameters. Among all these factors, the laminate stacking sequences, which can be defined as the arrangement of plies based on angles, has attracted a lot of interest for researchers [1-6].

Moreover, the crack resistance and the energy absorption capability of structures still have great attention for researchers both experimentally and numerically, because of the complexity of the failure mechanism occurring in the composite structures, due whether to ply stacking sequences and fiber orientation, or to the geometry of the corresponding structure. These challenges gave rise to many works, to study the effect of stacking sequences and fiber orientation, on crack resistance and energy absorption capability of different kind of geometries.

R. Velmurugan et al. [7] studied the influence under axial compression of stacking sequence and fiber orientation, on petal formation and specific energy absorption (SEA) of four and six-ply of $0^o/90^o$ glass/polyester composite tubes. Based on the proportion of axial (0^o) and circumferential (90^o) fiber content and stacking sequence in the tubes, they changed the number of petals formed and the trend of petalling. They noticed that the presence of axial fibers closed to the inner surface, and a proper proportion of circumferential fibers close to the outer surface of the tube wall, lead to higher energy dissipation in the tubes undergoing petalling.

Jiang, H. et al. [8] investigated numerically under axial quasi-static impact, the failure modes and energy absorption characteristics of T700/2510 fabric and unidirectional (UD) composite sinusoidal plates with different stacking sequence, and validated they method with the experimental results. They confirmed the influence of the variation of fiber angles on the crush behavior of composite sinusoidal plate.

Using the experiment, M. Nalla Mohamed et al. [9] investigated the influence under axial compression, of fiber orientation and stacking sequence on petal formation and specific energy absorption (SEA) of composite cylindrical tubes, made of unidirectional and woven layers of glass/epoxy and carbon/epoxy. From their analysis, they recommended for better load capacity and energy absorption, the fiber orientation $0^o/90^o/0^o$ for the crushed composite collapsible tubular.

Basim Mohammed Fadhil [10] analyzed the effect of plies stacking sequences of Cross ply, multi, and angle ply symmetric of E-glass/Epoxy circular and square tubes, under impact loading with low velocity. Using ANSYS-LS-DYNA, he performed the pre-processing and post-processing impact loading procedure and the damage caused. The results showed that the stacking sequences of the plies and the tube geometry play an important role in the mechanical behavior of the tube under impact loading.

Xiaobing Ma et al. [11] studied experimentally and numerically under quasi-static and impact crushing condition, the crash and energy absorption properties of different fiber orientations of 759/5224 woven glass cloth/epoxy. They found that one could improve the crash and energy absorption capability of a composite structure, by choosing the proper fiber orientations and that, this fiber orientation has a significant influence on the crash and energy absorption properties of composite tubes.

E. Mahdi et al. [12] carried out an experimental investigation of composite collapsible tubular energy absorber device under axial crush, in order to optimize the energy absorbed. They performed quasi-static crush test at ambient conditions, using specimens of woven E-glass fiber/epoxy composites of 0/90, 15/-75, 30/-60, 45/-45, 60/-30 and 75/-15, fabricated by the cost effective wet wrapping process. They found advantageous to lay the woven fiber to 15/-75 and 75/-15, in term of the capacity of the pre-crushing loading and the energy absorbed.

A. Esnaola et al. [13] studied the possibility of using basalt fiber composites for automotive crush applications, using different stacking sequences of semi-hexagonal composite structures. They analyzed and compared under quasi-static condition, the specific energy absorption (SEA) capability of basalt fiber composites and E-glass fiber composites. Their results showed that the highest SEA values, around 30 kJ/kg, is found for the samples with unidirectional and bidirectional E-glass fibers presenting however, different deformation mechanisms of energy absorption, while basalt/polyester, exhibiting due to buckling effect during the crush an unstable collapse, is found to not be suitable as composites for automotive crush applications. Moreover, the collapsible problem of basalt/polyester composite is avoidable with the hybrid made of E-glass and basalt fibers with polyester, but present a lower SEA value compare to the one made of E-glass/polyester.

In our work, we are going:

- To study **experimentally** the effect of the stacking sequences, on crack resistance and energy absorption, of short beam made of 16-layers of unidirectional glass fiber reinforced vinyl ester composite;

- To Extract from the load-displacement curves, the following parameters:

Energy Absorption (EA)

The **EA** [14, 15] can be defined as the integration of the load-displacement curve.

$$EA = \int_0^{S_b} P\,dS = \overline{P}(S_b - S_i)$$

Where $\mathbf{P}$ is the cracking/crushing load and, S_b and S_i, are the crack/crush distances.

Specific Energy Absorption (SEA)

The **SEA** [14] is defined as the energy absorbed (EA) per unit mass and can be denoted as:

$$SEA = EA / m$$

Where **m** is the undeformed mass (before crack, crush or impact).

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2. EXPERIMENTAL PROCEDURE

2.1. Materials and laminates fabrication

The samples are made of 16-ply of 430 gsm unidirectional E-glass fiber from Chongqing Polycomp International Corp. (CPIC), combine with the bromide and reactive flame retardant vinyl ester resin of density 1.15±0.02 (25^{o}C) from SWANCOR IND. CO., LTD, known as sw905-2. The resin is prepared using as hardener 0.8 % of methyl ethyl ketone peroxide known as NOROX KP-925H from UNITED INITIATORS and as accelerator 0.8 % of cobalt salt 1305 from SWANCOR IND. CO., LTD. The laminates were manufactured at room temperature using the Vacuum Assisted Resin Infusion (VARI) process **(Figure 1),** and following the stacking sequences $[0]_{16}$, $[0_1/90_3]_{2S}$, $[0_2/90_2]_{2S}$, $[0_3/90_1]_{2S}$, $[90]_{16}$, $[90_1/0_3]_{2S}$, $[90_2/0_2]_{2S}$ and $[90_3/0_1]_{2S}$. From the plates of 250 mm x 250 mm x 5 mm of each stacking sequence, we cut five (5) specimens of dimension 98 mm x 15 mm x 5 mm (Length*Width*Thickness) **(Figure 2).**

The **Table** 1 presents the mechanical properties of E-Glass/sw905-2 lamina.

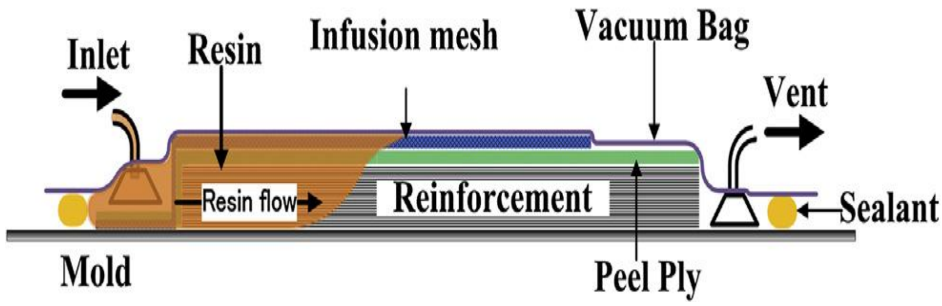

Figure 1: Schematic diagram of the Vacuum Assisted Resin Infusion (VARI) process [16].

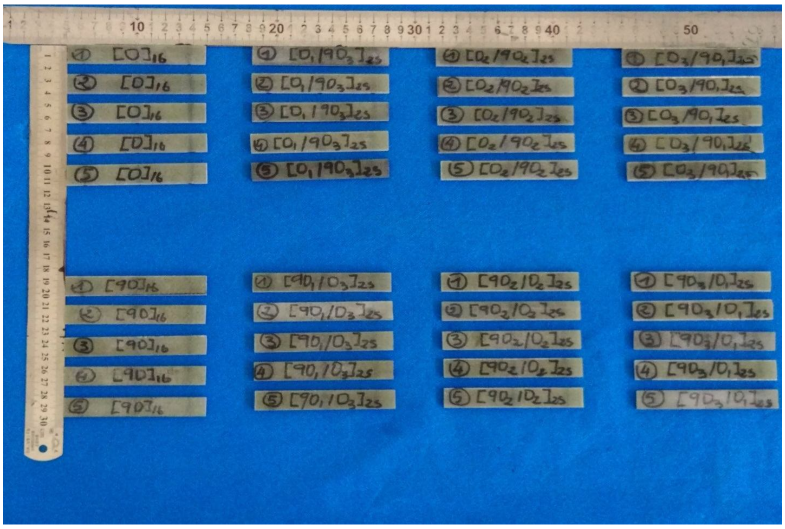

Figure 2: Specimens of three-point-bending test before testing.

Table 1: Mechanical properties of E-Glass/sw905-2 lamina

E_1 GPa	$E_2 = E_3$ GPa	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$ GPa	G_{23} GPa	X_T MPa	X_C MPa	$Y_T = Z_T$ MPa	$Y_C = Z_C$ MPa	$S_{12} = S_{13}$ MPa	S_{23} MPa
45.6	8.20	0.278	0.365	5.83	3.00	566.67	241.38	20.69	82.96	65.26	46.00

2.2. Testing procedure

The tests were conducted at room temperature for the samples of each stacking sequence subjected to three-point-bending test according to the standard test method ASTM D7264/D7264M-07 [17], and using the Universal Testing Machine (UTM) **(Figure 3).** We carried out the test at a speed of 5 mm/min. It allowed us to plot the load-displacement curves from which we computed the energy absorption (EA) and the specific energy absorption (SEA) for each stacking sequence.

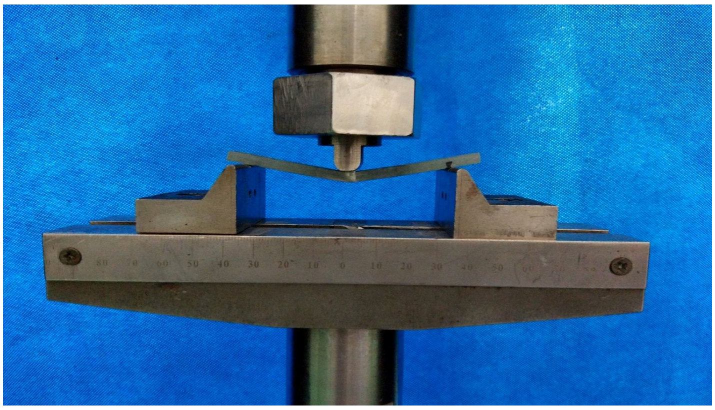

Figure 3: Three-point-bending experimental test of a sample.

3. RESULTS AND DISCUSSION

The tests of the forty specimens (five (5) of each stacking sequence) allow to get the following load-displacement curves, the energy-absorption, and specific energy absorption diagrams**.**

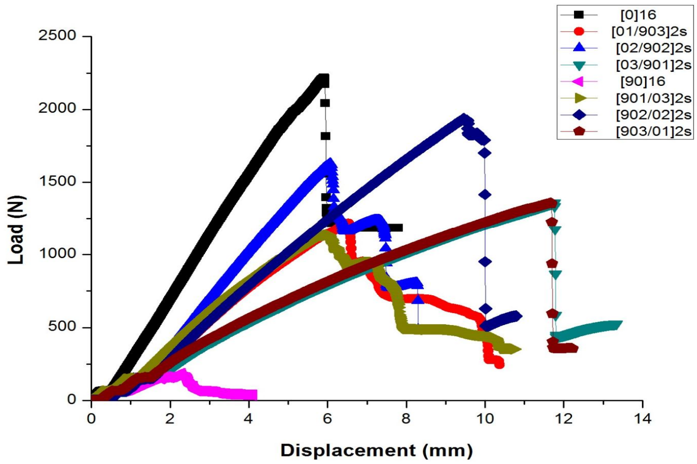

Figure 4: Load-displacement curves of different stacking sequences under three-point-bending test.

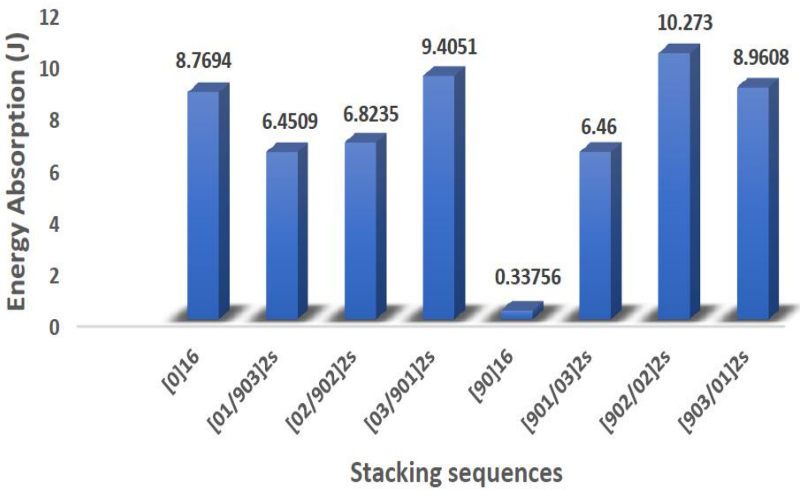

Figure 5: Energy Absorption of different stacking sequences of glass fiber/vinyl ester composite.

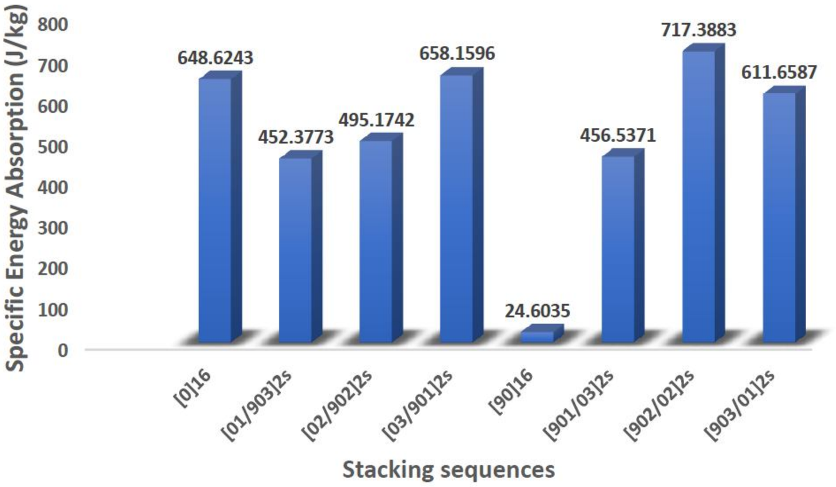

Figure 6: Specific Energy Absorption of different stacking sequences of glass fiber/vinyl ester composite.

In the representations shown, the stacking sequence $[90]_{16}$ exhibits under three-point-bending load, a very brittle behavior compared to the others having a progressive failure mode and a relative high EA and SEA capability. This can be due to the fibers all oriented in 90^o direction, which is not suitable for the flow of the resin whose properties are dominating in out-of-plane tests. Furthermore, the high values of EA and SEA in the others stacking sequences is certainly due to the presence of fibers oriented in the 0^o direction, which is more suitable for the flow of the resin.
Moreover, the highly nonlinear curve observed for $[90_2/0_2]_{2s}$ giving rise to a very big EA and SEA value, can be due to the variation of angle orientation.

4. CONCLUSION AND FUTURE WORKS

The investigation under three-point-bending load of the effect of stacking sequences on crack resistance, and energy absorption capability of glass fiber vinyl ester composite short-beam, was successful. The stacking sequence $[90]_{16}$ exhibits a very brittle behavior giving rise to a very low value of EA and SEA, while the others present relative high values, with $[90_2/0_2]_{2s}$ on top. Further investigation can be conducted numerically using finite element analysis, in order to validate the results obtained; while other experiments can be done under tensile test, mode I or crash loading, using more complex geometries.

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