# A COMPARATIVE STUDY OF 3D STITCHED COMPOSITES AND COMPOSITE LAMINATE. PART I: FLEXURAL PROPERTIES

**Lucas Moura Montenegro Reis[a], Vera Lúcia Arantes[a], Arnaldo Carlos Morelli[b]**

[a]University of São Paulo, São Carlos School of Engineering
Ave. João Dagnone, São Carlos and 13563-120, Brazil
lucasreis_27@usp.br, vera@sc.usp.br

[b]Federal Institute of São Paulo, Campus São Carlos
Rd. Paulo Eduardo de Almeida Prado, São Carlos and 13565-820, Brazil
arnaldo.morelli@ifsp.edu.br

**Keywords:** 3D stitched composites, flexural properties, delamination, polymer-matrix composites.

**Abstract.** *In this paper, a comparative study of the flexural properties of 3D stitched composites and composite laminate was carried out. E-glass fibers were reinforced with kevlar yarns with tex 336, inserted parallelly to the length of the samples in a stitch with density of 0.037 mm$^{-2}$. After the stitching process onto the fiberglass plates, the Vacuum Assisted Resin Transfer Molding (VARTM) process was used to infuse the dry preforms with epoxy resin. The samples were tested using a three-point flexural method, then tests were made to determine the specific mass, and a fiber volume fraction was performed to prove the compatibility between composites laminate and 3D stitched composites. Although both materials revealed a brittle behavior when bended, the composite laminate was found to exhibit greater bending strength and modulus compared to 3D stitched composites. It is believed that the reduction in the flexural properties of 3D stitched composites may be caused, partly, by the damage inserted during the sewing process in the fiberglass, such as the breaking and misalignment of the in-plane fibers and resin rich regions.*

## 1. INTRODUCTION

Fiber reinforced polymer (FRP) are composites composed of two or more materials with distinct properties that, when combined, offer enhanced properties compared to the individual constituents. Currently, the application of these materials have exponentially increased in many industry areas, such as: aerospace, aeronautic, naval, civil, chemical processing equipments, sporting, land transport, leisure sectors and automotive [1, 2]. However, composites laminate has some limitations in their interlaminate mechanical properties, for instance, high susceptibility to delamination in several scenarios, such as impact at low speeds and ballistic impact [3].

In order to overcome the composite laminate weakness, scientists and engineers have studied ways to increase the interlaminar fracture toughness, damage resistance and tolerance of composites laminate subject to impact loads, ranging from the use of tough resin (thermoplastic resins) to high strain fibers. The solution to the problem was the development of composite materials reinforced with multi-directional fiber reinforced, giving rise to the concept of preforms or three-dimensional fibers [4].

Three-dimensional fibers consist of in-plane warp and weft yarns layers interlaced in the through-thickness direction by z-binders yarns. Preforms can be described by the type of fiber, number of filaments in each yarn, tex-yarn (g/km), spacing between reinforcement yarns, fiber volume fraction (vf) and preform architecture [5, 6].

Composites reinforced with preforms have several aeronautical and aerospace applications, such as turbine engine thrust reverses, rotors, rotor blades, insulation, structural reinforcement, heat exchangers, rocket motors, nozzles and leading edges to wings [7]. Currently, these materials have applications in the automotive and civil.

With the increasing of the application of three-dimensional composite materials, numerous technics capable of reinforcing in-plane fibers in the through-thickness direction have been developed, such as 3D weaving, 3D braiding, 3D knitting, Z-pinning, tufting and stitching (method used in this research). The first three techniques modify the architecture of the fabric, creating a preform close to the final shape (near net shape) of the part. The last three methods reinforce in the through-thickness direction in a post-stacking process [8].

Stitching reinforcement technique consists of inserting yarns of high resistance (carbon, kevlar, vectran) in fiber fabrics in the through-thickness direction. 3D stitched composites have more attractive interlaminate properties and a higher damage and resistance tolerance under impact. On the other hand, the sewing procedure perturbs the internal configuration of the laminate, causing breakage and misalignment of the fibers in the fabric and regions rich in resin, which act as stress concentration sites. These additional failure modes result in a reduction of intralaminar properties, such as flexural properties [9-11].

The mechanical properties, damage progression and failure mechanisms of three-dimensional composite materials manufactured using the stitching method depend on stitch parameters (stitch density and stitch yarns diameter), on the reinforcement material and on the stitch type. The three types of stitch most common are lock, modified lock and chain, being the modified lock stitch the most used one [12, 13]. Yang et al. [14] developed a type of stitch that differs from the conventional style, capable of decreasing the susceptibility to delamination through self-healing of delamination cracks in the through-thickness direction. Such recovery is generated by the reinforcement yarns and has been proven to increase the interlaminar fracture toughness of composites (Figure 1).

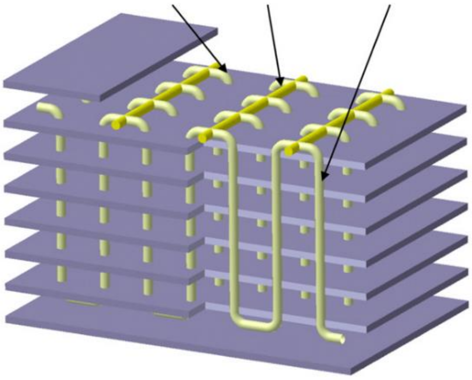


Figure 1 - Sewing performed by Yang et al (Adapted from [14]).

The stitch density (SD) is calculated using Equation (1) and depends on the pitch (p), which corresponds to the distance between the stitch points, and the spacing (s), associated with the lateral distance between the stitch.

$$SD = 1 / (p \times s) \quad (1)$$

Researches have been carried out to determine the flexural behavior of 3D stitched composites. Mouritz [15] has presented a comparison between the behavior of composites laminate and 3D stitched composites under four-point flexural test. The preform was fabricated with E-glass fibers reinforced with kevlar yarns using an industrial sewing machine, then vinyl ester resin was used to consolidate the composites by the Resin Transfer Molding (RTM) technique. The preforms had different values of stitch density and seam orientation and a modified lock type of stitch was used in all composites plates. The flexural strength of composites laminate was 13-16 % higher compared to all 3D stitched composites.

The flexural elasticity modulus of composites laminate was also superior, in a range of 7.1-41.1 %. The study concludes that this reduction in strength and modulus is caused by damage introduced in-plane fibers during the sewing process, such as breakage and misalignment of the fibers.

Chung et al. [16] experimentally evaluated the flexural behavior of 3D stitched composites. Graphite and kevlar fibers were used to fabricate the preforms, reinforced with kevlar yarns. The pitch used was 3.2 mm in all 3D stitched composites. After stitch process, the Resin Transfer Molding technique was used to infuse de dry preforms with epoxy resin. The 3D stitched composites and composites laminate were submitted to the four-point bending test. The study concluded that 3D kevlar-epoxy composites showed flexural strength 21% higher than 2D kevlar-epoxy composites. 3D graphite-epoxy composites displays a fracture energy 66 % higher than 2D graphite-epoxy under flexural test, which indicates that cracks in three-dimensional composites progress at a much slower pace than in composites laminate; in contrast, composite laminate revealed catastrophic failure.

The discrepancy between the literature data on the performance of three-dimensional stitched composites materials under flexural test justifies the necessity for this research. For the validation of the study, both composites types had similar thickness and fiber volume fraction, the same type of resin, and were manufactured using the same technique, making the comparison legitimate.

## 2. EXPERIMENTAL DETAILS

### 2.1. Sample preparation

The preform plates have been fabricated with WR-326 (Texiglass®) fiberglass fabric in the plain weave architecture and reinforced in the through-thickness direction by kevlar yarns with tex 336 (texiglass®). The use of kevlar as a reinforcement material is justified due to its high mechanical strength, low specific mass, and high compatibility with resin system.

Although the reinforcement technique used as a reference was stitching, industrial sewing machines were not used, being the stitch performed manually. When using machines, the magnitude of the stitch tension could not be accurately controlled. Excessive stitch tension can damage the fibers during the reinforcement process, causing perturbs, waviness and breakage of in-plane fibers. It is believed that, when using manual stitch, the introduction of this type of damage is reduced, as the sewing process is more subtle, in addition to being a method capable of reinforcing small pieces of composite material, without the need for machinery and using low costs and easy access inputs.

Kevlar yarns were inserted parallelly to the length of the specimens in pitch and spacing equal to 6 mm and 4.5 mm, respectively, giving the 0.037 $mm^{-2}$ stitch density. Intermediate stitch density values were used for making the sewing process possible and executable and did not cause high disturbances to the fiberglass.

The initial step of the sewing process consists of the sequential stacking of the fiberglass; 14 layers of fiber were stacked so that the sample thickness could be reached. Subsequently, the fibers are fixed to a polystyrene plate containing a template. The template has the function of determining the spacing and pitch, so it is possible to maintain a sewing pattern on the entire plate. The final step is to unmold the polystyrene plate (Figure 2). The seam process developed gives the preform a seam pattern like the one performed by Yang et al. [14].

The composites were infused with epoxy resin (Ephoxal®) by the Vacuum Assisted Resin Transfer Molding (VARTM) technique. The use of this technique is justified for being a promising one in the area of composites processing in addition to allowing the use of low cost tooling while still producing high quality composites parts, being the infusion process used to manufacture naval top-side structures [17]. The strength and stiffness of the composite depends on the amount of existing fiber. Low values of fiber volume fraction are associated with a composite with low mechanical performance; in contrast, fiber volume fraction values between 60-70% are related to structural composites with high mechanical resistance [18], [19].

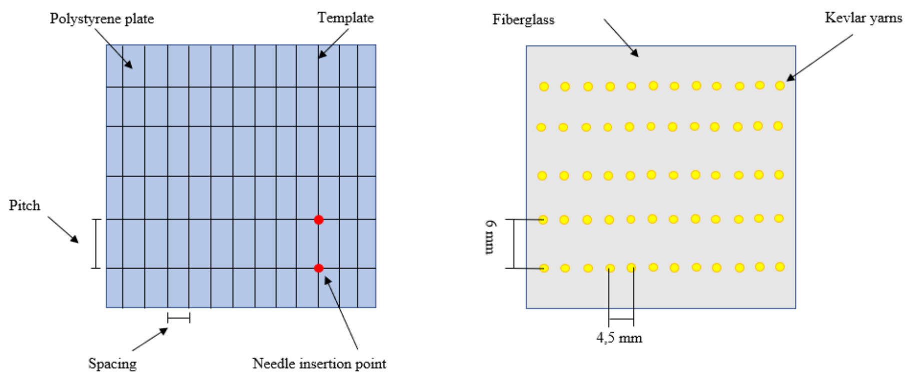


Figure 2 – Stitching process.

## 2.2. Flexural testing

The flexural test has been carried out by using a universal testing machine model EMIC DL 1000 and it followed the guidelines proposed by ASTM D7264 / D7264M-15 - Standard test method for flexural properties of polymer matrix composites materials. The specimens were subjected to the same laboratory conditions of temperature, pressure, and moisture before and during the tests, ensuring the high quality of the samples. Seven samples of each type of composite were manufactured.

The bending properties vary according to which surface of the composite is in compression regime during the test. In composites manufactured using the VARTM technique, there is a difference in surface roughness between the surface that is in contact with the mold and the one that is in contact with the vacuum bag. In order to eliminate this parameter, all samples were tested with the rough surface in contact with the crosshead.

The dimensions of the specimen are determined through 32:1 span-to-thickness ratio. The span used was 116 mm long and the test was performed at a crosshead movement speed of 2 mm/min. Through this test it was possible to determine the maximum flexural stress, flexural modulus of elasticity, and strain.

## 2.3. Validation of the samples compatibility

The high compatibility of the samples depends on similar values among thickness (*t*), specific mass, and fiber volume fraction. A severe difference in the values of these characteristics of the composites would cause misinterpretation of the comparative analysis of the flexural properties.

The final thickness of the composites depends on the compaction of the preform, which occurs during the infusion process. To ensure that the samples had similar thicknesses, the infusion materials used were the same in all experiments as well as the infusion parameters.

In order to validate the comparative study between 3D stitched composites and composites laminate, it was necessary to carry out tests to determine specific mass and fiber volume fraction, which was done accordingly to the guidelines proposed by ASTM D792-13 - Standard test method for density and standards specific gravity (relative density) of plastics by displacement and ASTM D3171-15 - Standard test method for constituent content of composite materials - Procedure G. Technical specifications such as fiber volume fraction ($V_f$), and specific mass ($\rho$) are provided in Table 1.

Table 1 – Samples specifications.

| **Composites** | **$V_f$ (%)** | **$\rho$ (kg/m³)** | **t (m)** |
|---|---|---|---|
| Laminate | 74.79 | 2030 | 0.00348 |
| 3D stitched | 72.66 | 1960 | 0.00369 |

## 3. RESULTS AND DISCUSSION

### 3.1. Validation of the samples compatibility

Composite laminate displayed a specific mass 3.5% higher than 3D stitched composites. This small difference in the specific mass value indicates homogeneity in the infusion process and compatibility between 3D stitched composites and composites laminate, which allows a comparative analysis of their mechanical properties.

Composites laminate exhibited a 2.85% higher fiber volume fraction than 3D stitched composites. The slight difference in the values of fiber volume fraction reiterates the homogeneity of the infusion process and the compatibility between the composites. The fiber volume fraction obtained in this study was higher than the one found in previous researches [15, 20] , although those researches have used RTM as an infusion method, which is a procedure with a higher cost, due to the machinery involved in the process. Fiber volume fraction between 70-75% represents ideal values for structural composites with high mechanical resistance [4]. The composites manufactured in this research displayed similar fiber volume fraction to high performance composites, which confirms the quality of the VARTM technique.

### 3.2. Flexural testing

Table 4 presents the flexural properties of composites laminate and 3D stitched composites and the standard deviation. Composites laminate exhibited values of flexural stress and flexural modulus of elasticity 23% and 20% higher than 3D stitched composites, respectively. The results achieved in this research are similar to those already obtained in previous works [15, 21], the flexural properties of 3D stitched composites were reduced considerably when stitched in the through-thickness direction with kevlar yarns. The decrease in the values of the flexural properties of the 3D stitched composites materials may be associated with the damage caused by the sewing process in the in-plane fiberglass. Breakage and misalignment of fiberglass are types of damage that occur during sewing. These damages inserted in-plane fiberglass leads to the formation of small areas with low content of fiber, which are filled with resin during the infusion process. These regions are called resin rich regions.

The breakage of the fiberglass occurs due to the abrasion caused between the reinforcement needle or stitch yarns, and the in-plane fibers, whereas the fiber misalignment occurs because the needle disturbs the fiber network around the stitches. The amount of distortion depends on the grammage of the in-plane fibers, the stitch density, and the stitch yarns diameter. The regions rich in resin around de stitch become stress concentrators, considerably reducing the flexural properties of composite materials.

Equal deformation values have been found, indicating that the deformation of the composite materials is not influenced by the stitch.

Table 2 – Flexural properties of the composites laminate and 3D stitched composites.

| Composites | Flexural strength (Mpa) | Flexural modulus of elasticity (Gpa) | Strain (%) |
|---|---|---|---|
| Laminate | 433 (±25) | 20 (±0,7) | 2.7 |
| 3D stitched | 334 (±19) | 16 (±0,9) | 2.7 |

Figure 3 shows the typical behavior of 3D stitched composites and composites laminate. Both materials showed similar performance under flexural testing. The total deformation of less than 3% present in the materials suggests a brittle behavior that is associated with the low plastic deformation capacity of the thermoset polymer matrix.

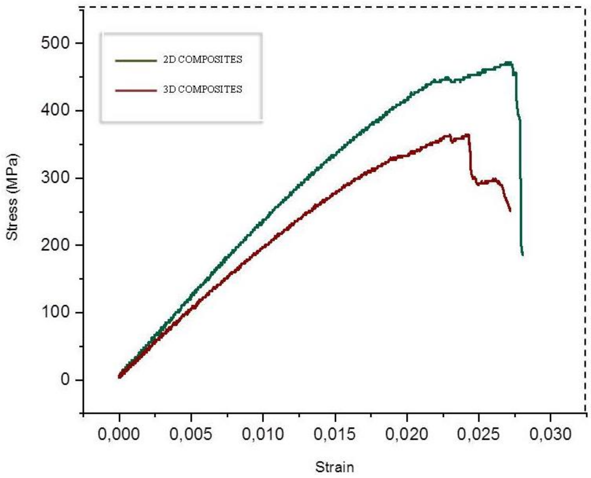


Figure 3 – Stress x Strain curve.

## 4. CONCLUSIONS

In this study, flexural properties of stitched 3D composites made of fiberglass and reinforced with kevlar yarns were investigated. It can be concluded that composites molded using the VARTM technique in this research showed satisfactory values of fiber volume fraction and that the infusion processes performed were strictly controlled, so that the manufactured composites presented high compatibility.

The flexural properties of composites made of fiberglass and impregnated with epoxy resin are reduced when there is the presence kevlar yarns with tex 336 inserted in the through-thickness direction by the manual stitching process.

Breakage and misalignment of in-plane fibers and resin rich regions are the failure mechanisms associated with reduction of flexural strength and flexural modulus of elasticity of three-dimensional composites.

In a future study, images obtained by Scanning Electron Microscopy (SEM) can ensure that the three-dimensional composites failed due to the mechanisms explained in this research, which were also exhibited and discussed by other researchers in previous works.

It is necessary to note that the stitching technique aims at increasing the interlaminate properties of composites laminate, such as impact resistance. Intralaminar properties, such as tensile and flexion, are sought to be at least maintained.

## ACKNOWLEDGMENTS

The authors wish to thank CAPES for support of this research and Texiglass® and Ephoxal® for providing the necessary materials.

## REFERENCES

[1] F. O. Aramide, P. O. Atanda, and O. E. Olorunniwo. Mechanical properties of a polyester fibre glass composite. *International Journal of Composites Materials.* vol. 2, p. 147–151. (2012).

[2] M. Ansar, W. Xinwei, and Z. Chouwei. Modeling strategies of 3D woven composites: A review. *Composite Structures.* vol. 93, p. 1947–1963. (2011).

[3] M. V. Hosur, M. R. Karim, and S. Jeelani. Experimental investigations on the response of stitched/unstitched woven S2-Glass/SC15 epoxy composites under single and repeated low velocity impact loading. *Composite Structures.* vol. 61, p. 89–102. (2003).

[4] F. Neto and L. C. Pardini. *Compósitos estruturais ciência e tecnologia*. São Paulo. Edgard Blücher. 2nd edition. (2006).

[5] S. Rudov-Clark, A. P. Mouritz, L. Lee, and M. K. Bannister. Fibre damage in the manufacture

of advanced three-dimensional woven composites. *Composites Part A: Applied Science and Manufacturing.* vol. 34, p. 963–970. (2003).

[6] L. C. Pardini. Preformas para Compósitos Estruturais. *Polímeros*, vol. 10, p. 100–109. (2000).

[7] A. P. Mouritz, M. K. Bannister, P. J. Falzon, and K. H. Leong. Review of applications for advanced three-dimensional fibre textile composites. *Composites Part A: Applied Science and Manufacturing.* vol. 30, p. 1445–1461. (1999).

[8] D. B. Bortoluzzi. *Desenvolvimento de reforços tridimensionais por meio de costura em compósitos de fibra de carbono/epóxi*. Master Thesis. Federal University of Itajubá. (2013).

[9] F. Aymerich and P. Priolo. Characterization of fracture modes in stitched and unstitched cross-ply laminates subjected to low-velocity impact and compression after impact loading. *International Journal of Impact Engineering.* vol. 35, p. 591–608. (2008).

[10] F. Aymerich, C. Pani, and P. Priolo. Damage response of stitched cross-ply laminates under impact loadings. *Engineering Fracture Mechanics*. vol. 74, p. 500–514. (2007).

[11] J. qian Xuan, D. sen Li, and L. Jiang. Fabrication, properties and failure of 3D stitched carbon/epoxy composites with no stitching fibers damage. *Composite Structures*. vol. 220, p. 602–607. (2019).

[12] K. T. Tan, A. Yoshimura, N. Watanabe, Y. Iwahori, and T. Ishikawa. Effect of stitch density and stitch thread thickness on damage progression and failure characteristics of stitched composites under out-of-plane loading. *Composites Science and Technology.* vol. 74, p. 194–204. (2013).

[13] L. Tong, A. P. Mouritz, and M. K. Bannister. *3D Fibre Reinforced Polymer Composites*. Oxford. UK: Elsevier. 1nd edition. (2002).

[14] T. Yang, C. H. Wang, J. Zhang, S. He, and A. P. Mouritz. Toughening and self-healing of epoxy matrix laminates using mendable polymer stitching. *Composites Science and Technology*. vol. 72, p. 1396–1401. (2012).

[15] A. P. Mouritz. Flexural properties of stitched GRP laminates. *Composites Part A: Applied Science and Manufacturing.* vol. 27, p. 525–530. (1996).

[16] W. C. Chung, B. Z. Jang, T. C. Chang, L. R. Hwang, and R. C. Wilcox. Fracture behavior in stitched multidirectional composites. *Materials Science and Engineering A*. vol. 112, p. 157–173. (1989).

[17] D. Bender, J. Schuster, and D. Heider. Flow rate control during vacuum-assisted resin transfer molding (VARTM) processing. *Composites Science and Technology.* vol. 66, p. 2265–2271. (2006).

[18] H. H. K. Xu, C. P. Ostertag, L. M. Braun, and I. K. Lloyd. Effects of fiber volume fraction on mechanical properties of SiC-fiber/Si3N4-matrix composites. *Journal of the American Ceramic Society*. vol. 77, p. 1897–1900. (1994).

[19] L. Ciprian, P. Radu, and E. Ioana. The effects of fibre volume fraction on a glass-epoxy composite material. *Incas Bulletin*. vol. 7, p. 113–119. (2015).

[20] A. Yudhanto, G. Lubineau, I. A. Ventura, N. Watanabe, Y. Iwahori, and H. Hoshi. Damage characteristics in 3D stitched composites with various stitch parameters under in-plane tension. *Composites Part A: Applied Science and Manufacturing*. vol. 71, pp. 17–31. (2015).

[21] A. P. Mouritz, J. Gallagher, and A. A. Goodwin. Flexural strength and interlaminar shear strength of stitched GRP laminates following repeated impacts. *Composites Science and Technology*. vol. 57, p. 509–522. (1997).

**RESPONSIBILITY NOTICE**

The authors are the only responsible for the printed material included in this paper.