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DEVELOPMENT OF INDENTATION FIXTURE FOR PRESTRESSED COMPOSITE

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ABSTRACT

This paper explores the utilization of prestressed composite materials, offering insights into their application across various industries. Prestressed composites offer another degree of freedom in the design process. They improve strength, modulus, fiber volume fraction, while reducing void volume fraction and fiber waviness. This paper also introduces a novel method for applying high levels of prestress in multiple directions using a custom indentation fixture equipped with a shop press and clamping frame. A Finite Element Analysis (FEA) model is developed to predict yarn stress levels during the prestressing process. The study investigates mesoscale models and boundary conditions to replicate real-world scenarios, highlighting the challenges and advantages of different approaches. Results suggest that the indentation fixture can achieve significant prestress levels, while also revealing limitations of solid elements in simulating fabric bending behavior. The work concludes with recommendations for future research, emphasizing the potential of layered solid elements to address these challenges effectively.

1 INTRODUCTION

Composite materials offer a high strength-to-weight ratio, making them increasingly appealing across various industries, from aerospace to chemical transportation and storage. It provides engineers with an added Degree of Freedom (DoF) in the design process, enabling adjustments not only in component geometry but also in the layup sequence, opening numerous possibilities. Recent advancements have introduced prestressed composites as another added DoF. Engineers can control the strength and modulus of composite materials by modifying the fabric tension during curing process. This allows them to adjust the flexibility of composites without altering the reinforcement or matrix. However, a practical method for prestressing the composite at high levels is currently lacking. Therefore, this paper introduces a novel approach for applying significant prestress in multiple directions simultaneously. This method involves a shop press equipped with a custom clamping frame capable of securing the fabric in various orientations to simulate diverse prestressing scenarios. Additionally, a Finite Element Analysis (FEA) model of the fabric has been developed to predict yarn stress levels during the prestressing process. This paper discusses the design of the indentation fixture alongside the FEA model's insights.

2 LITERATURE REVIEW OF PRESTRESSED COMPOSITE

2.1 Prestressed Composite

Composite materials consist of reinforcement and matrix components [1]. The reinforcement may comprise materials such as glass, carbon fiber, aramid, or natural fibers, while the matrix can be thermoset or thermoplastic.

During matrix solidification, tension can be applied to the fabric. This tension becomes locked within the composite as the matrix cures, inducing compression on the matrix [2] [3]. Apart from enhancing the composite's modulus, this induced compression also inhibits crack initiation and propagation, thereby increasing the material's strength and modulus [4]. The benefits of prestressed FRP are extensively documented, encompassing higher tensile strength, modulus, fiber volume fraction, reduced void volume fraction, and fiber waviness [5] [6].

In this study, prestressed composites were classified based on the direction of prestress. If the reinforcement fabric is stretched in either the waft or weft direction, it falls under the category of 1-D prestress; whereas, if stretched in both directions, it is labeled as 2-D prestress. While the indentation fixture can achieve 2-D prestress, this paper focuses mainly on 1-D prestress for building the fixture's foundation.

2.2 Prestress Methodologies

Various methods exist for applying prestress to fabric. The deadweight method involves hanging a weight at one end of the fabric, suitable for low prestress levels in 1-D scenarios [7] [6]. Another method employs V-shaped clamping, stretching fabric between indenters as the load is applied [8]. While this method can produce multiple specimens simultaneously, predicting and maintaining consistent prestress levels is challenging. To address low prestress (below 100 MPa), some researchers use hydraulic jacks with fabric stretching frames, offering accurate levels and directions but are impractical for manufacturing due to complexity and size limitations [9] [10] [11]. The filament wound method addresses high prestress accurately but is limited to 1-D prestress and specific geometries [12]. With traditional methods facing limitations, additional approaches are needed for diverse scenarios and part geometries.

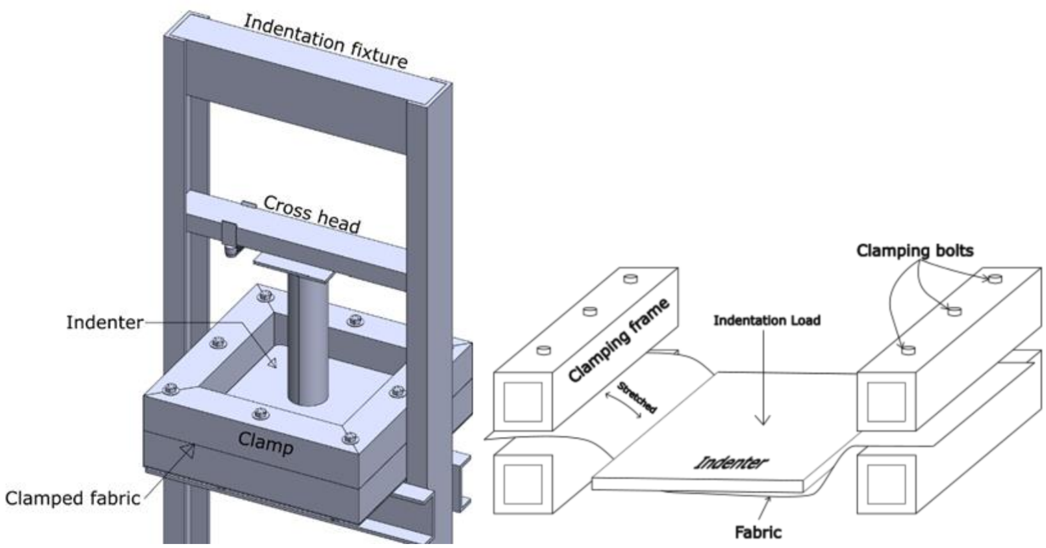

Figure 1: (Left) Indentation Fixture components. (Right) Mechanism of applying 1-D prestress.

The indentation method proposed in this work offers a practical solution, achieving high prestress for complex geometries. The indentation fixture has three basic components, namely the Torin 20 ton shop-press, the indenter, and the clamping frame (Figure 1 - Left). The shop-press includes a metal frame with a hydraulic bottle, with a 20-ton capacity, that provides an indentation load on the fabric. Depending on the clamping conditions, this indentation load will be converted into the fabric's tension (Figure 1 - Right). The indenter consists of a square 11"x11"x 3/8" steel plate welded to a pipe. The indenter's purpose is to evenly transfer the shop-press's load onto the fabric. Finally, the clamping frames are made of 3"x3"x1/8" tubes. The frame has a 12" x 12" opening to allow the indenter to pass through. The reinforcement fabric is clamped in place by three ½"-20 threaded rods on each side, with neoprene gaskets to enhance friction between the clamping frames and the fabric.

3 FINITE ELEMENT ANALYSIS OF PRESTRESSED COMPOSITE

3.1 Meso-scale model

The Finite Element Analysis (FEA) process plays a pivotal role in developing the indentation fixture. An Ansys APDL (Version R2023) model with orthotropic material properties was constructed for this purpose. This model is based on three layers of plain weave fiberglass fabric with a weight of 24 oz/yd^2 (Figure 2). An elastic modulus of 73 GPa was utilized for the yarn axial direction, while other moduli were set to insignificantly small values. This FEA model estimated fabric prestress levels and the corresponding load required. Moreover, it studied stress distribution across the fabric layers and yarn surfaces. Considering the study's objective and the minimal strength of the wet resin, the matrix was not modeled in this study.

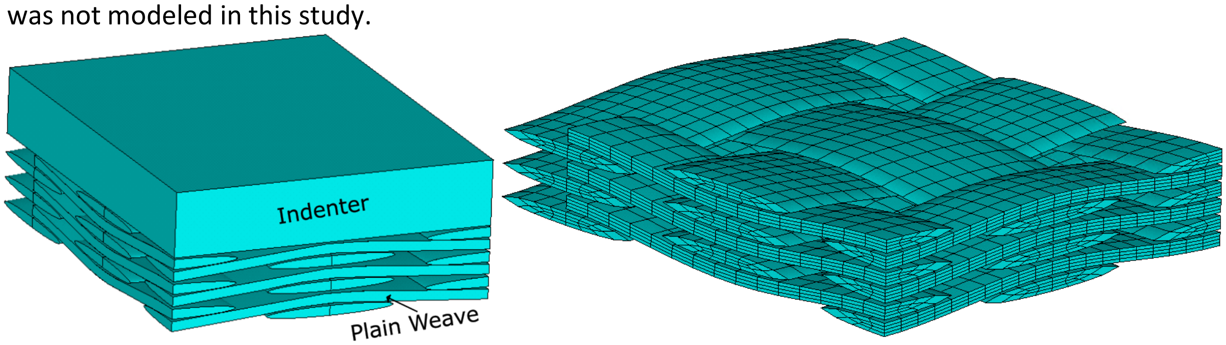

Figure 2: (Left) Solid model of the RVE with a section of indenter. (Right) Mesh of the RVE.

Solid elements were employed to achieve the objective due to their ability to represent stress distribution through yarn thickness and simulate yarn-to-yarn contact. Additionally, solid elements better represent yarn cross-sections compared to shell elements, despite demanding more computational resources. On the other hand, solid elements struggle to replicate bending effects. In the mesoscale model, these challenges associated with solid elements were exacerbated by boundary conditions. The interactions between the indenter's edge and fabric at distant ends influence middle representative volume element (RVE) behavior significantly. Consequently, symmetrical boundary conditions and geometric simplifications were extensively applied to replicate these effects while keeping the model size minimal (Figure 3 - Left).

3.2 Boundary conditions

Symmetrical boundary conditions (B.C.) were enforced in both the x and y directions, effectively quadrupling the size of the RVE. As the indenter and clamps exerted downward force, it was translated into tension within the fabric (Figure 1 - Right). To replicate this condition, the warp yarns at one end of the quarter model were extended to the clamp's edge, while the indenter section was extended to its full length. To replicate the behavior of the free weft yarns, a set of Simulated B.C. was applied to the weft yarn cross-sections (Figure 3 - Right).

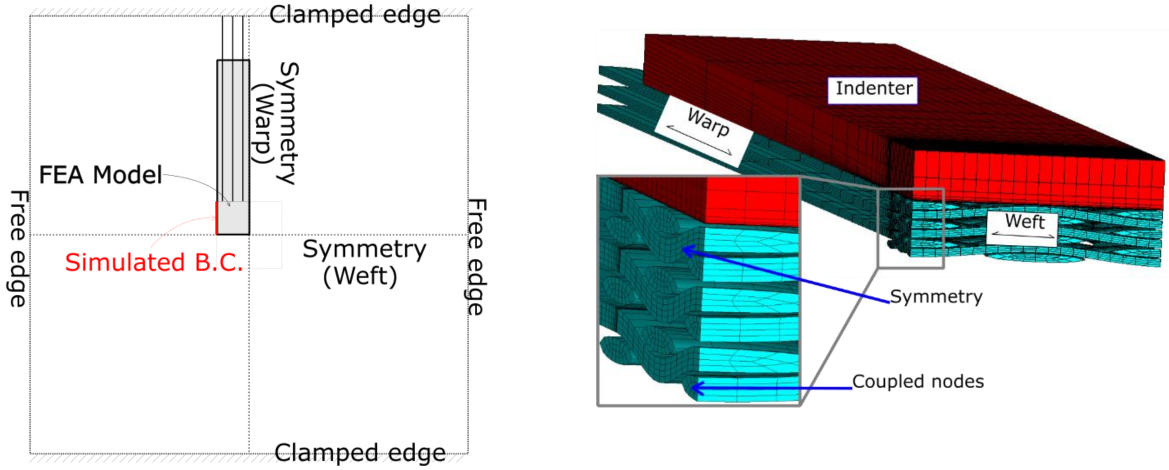

Figure 3: (Left) The RVE position on the fabric. (Right) The mesh of the RVE, its extended warp yarns, and the indenter with Simulated B.C.

All nodes on *each* face of *each* weft yarn were coupled to move together. These coupled nodes allow the weft yarns' cross-sections to translate but restrict their rotations, mimicking long yarns. Even though this method did not replicate the crimp effect, it did not significantly affect the result because the weft yarn's tension contributed insignificantly to the 1-D prestress. Lastly, symmetry conditions were applied to the warp yarns in this set to simulate the full yarns. Due to the characteristic of the model, the contact between the yarns to yarns and the indenter to yarns was modeled as sliding without separation contact. The warp and weft yarns were expected to contact each other while the indenter was expected to contact only the top of the fabric. The friction coefficient between the yarns to yarns and the indenter to yarn was modeled as 0.2 [4]. This coefficient was justified by the lubricating effect of the wet resin. A displacement of 4 mm was applied to the indenter. The displacement control method was selected to help the contact surfaces engage at the beginning stage of the solving process.

3.3 Stress results

The stresses x and y in the RVE were plotted in Figure 4.

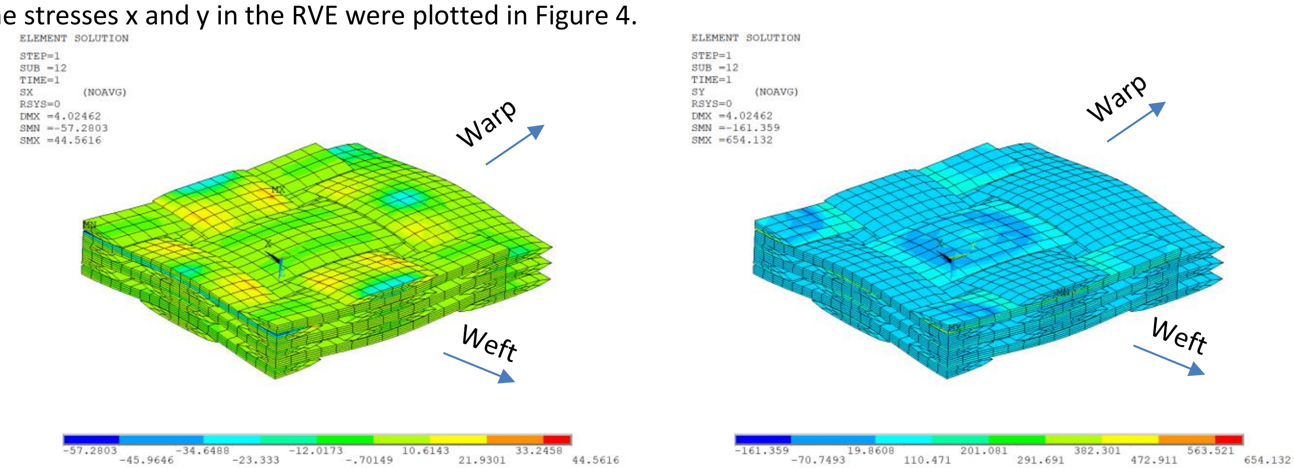

Figure 4: The stresses in the x (weft) and y (warp) directions of RVE.

The stress in the y direction was in the warp direction; thus, it was significantly higher than the x direction which was in the weft direction. This fact agrees with the 1-D prestress assumption. The symmetrical stress shown in Figure

4 (Left) also indicated that the boundary conditions were appropriate to represent the REV away from the indenter's edges. In addition, the y-direction stress in the weft yarns was more uniformly distributed compared to the warp yarns. This difference arose from the bending stress experienced by the warp yarns. As a result, the stresses in the warp yarn were plotted in Figure 5.

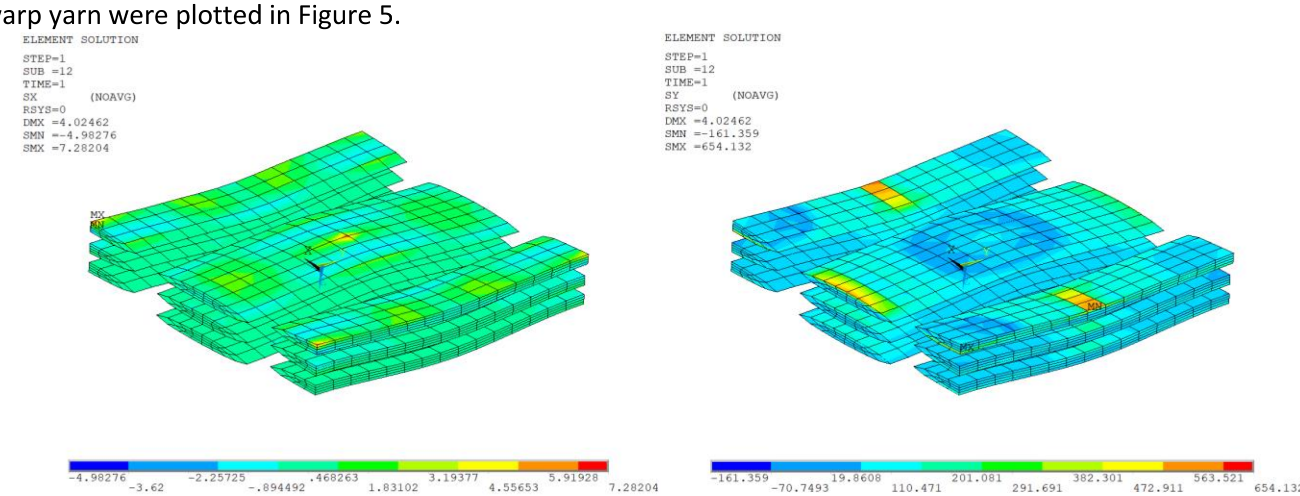

Figure 5: The stresses in the x (weft) and warp (weft) directions of warp yarns.

The FEA indicated that the prestress of approximately 110 MPa would be achieved with 4 mm of indentation. Based on the reaction force in the FEA model, the bottle jack needs to apply a load of approximately 700 N. It also indicated that the weft yarns should see minimal stresses. This model confirms the ability of the indentation fixture to reach a prestress level of above 100 MPa. Previously, achieving this prestress level required a complex stretching frame attached to the tensile test machine. Additionally, the indentation method promotes the nesting of the fabric, indicating that it can replicate the filament winding process. Consequently, it generates specimens similar to filament wound specimens without winding a large-diameter pipe. As these specimens are flat, they can undergo tensile tests in both the warp and weft directions. This capability is particularly valuable for studying filament wound hoop tensile properties, which are impractical due to the specimen's curvature. This model also highlighted the disadvantage of the solid elements when used to simulate the bending behavior of the fabric. The top of the fabric was observed to be in compression due to the indentation. This problem stemmed from the fact that solid elements behave more like curve beams than flexible yarns. Even though this phenomenon was not a true representation of reality, it indicates that the fabric could become dislocated and deformed during the indentation process. The dislocation and deformation are dependent on the type of weave of the fabric [13]. Other researchers overcame this disadvantage by using three layered shell elements [14]. The top and bottom layers are used to replicate the bending behavior of the shell element while the middle layer replicates the tension behavior. This method could be utilized for solid elements to eliminate the bending stiffness problem.

4 CONCLUSION

The design of the indentation fixture was developed, and its capacity was estimated using FEA. The fixture can archive at least 110 MPa prestress with 4 mm indentation and 700 N indentation force. Based on various literatures, this prestress level will exceed the optimum prestress level for fiberglass and carbon fiber fabric [2] [5] [15]. Since the maximum displacement of the fixture was 70 mm and the bottle jack capacity was 20 tons, the fixture should be able to prestress multiple layers of fabric at a high prestressing level. The FEA model also indicated the disadvantage of the solid elements in representing the bending behavior of the fabric. Future study on the feasibility of using layered solid elements to overcome this disadvantage is highly recommended.

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