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Finite element analysis and design optimization of composite T-joints for enhanced maritime and aerospace applications

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ABSTRACT

Composite marine structures are crucial for maritime and aerospace applications due to their strength-to-weight ratio and corrosion resistance. To ensure their reliability and durability, a methodology to predict the damage criticality and service life of composite marine T-joints is essential. Finite Element Analysis (FEA) has emerged as a powerful tool for preliminary design and structural evaluation of complex structures, reducing the need for extensive experimental work and leading to substantial cost savings. This research project aims to conduct a comprehensive FEA of composite T-joints, considering alternative skin, core, and infill materials. Structural analyses under various loading conditions will evaluate overall deflection and stress levels, aiming to enhance the design and reliability of composite marine constructions, ultimately improving their performance and extending their service life in demanding maritime and aerospace environments.

1. Introduction

Composite marine constructions play a pivotal role in modern maritime and aerospace applications due to their extraordinary strength-to-weight ratio and corrosion resistance (Toftegaard & Lystrup, 2005). The dependability and durability of these structures are essential. To accomplish this, it is essential to develop a method for estimating the service life and reliability of composite marine T-joints by predicting their damage criticality (Mostafa et al., 2013).FEA has emerged as a potent instrument for the preliminary design and structural evaluation of complex composite structures (Kim et al., 2006). It has been demonstrated to precisely predict the behaviour of composite structures, thereby reducing the need for extensive experimental work and resulting in significant cost savings. The implementation of FEA prediction methodologies extends beyond maritime applications to the aerospace sector as well.In the past ten years, advances in FEA technologies have revolutionized stress analysis by providing precise and effective solutions. Nevertheless, the complex geometry of composite T-joints poses unique challenges to their analysis. Various Finite Element Method (FEM) programs offer optimized meshing techniques and accurate simulation of boundary conditions, which are essential to the success of Finite Element Analysis (FEA) in investigating critical stresses in composite T-joints. FEM enables the identification of critical stress concentrations and enables quantitative evaluations of stress distributions and deformations under varying loads (Shohel et al., 2023). Accurately conducting these investigations requires a comprehensive comprehension of FEM theory and intricate meshing procedures. In addition, it is crucial to ensure that actual boundary conditions are replicated accurately to avoid erroneous results. Addressing large-scale FEM problems necessitates a substantial amount of memory and disc space.

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The primary objective of this project is to conduct a comprehensive FEA of composite T-joints, taking into account alternative skin, core, and infill materials. Under various loading conditions, structural analyses will be conducted to evaluate overall deflection and stress levels. This research aims to improve the design and reliability of composite marine constructions, thereby augmenting their performance and extending their service lives in the demanding maritime and aerospace environments.

1.1 Overview of T-Joint

The T-junction, a common structural element used to connect bulkhead sections with multiple compartments and the hull (as depicted in Fig. 1), serves an important role in marine engineering. This integral component is constructed from composite over laminates atop a contoured fillet by meticulously layering laminates and applying a filler constituted of chopped fiber-reinforced resin. The primary purpose of the T-joint is to facilitate the transmission of flexural, tensile, and shear loads between the hull and bulkhead while maintaining the watertight integrity of the compartments separated by the bulkhead (Dharmawan et al., 2008).

There are two distinct varieties of T-joints, distinguished by the shape of their laminate covers: triangular and circular (Rahm & Evegren, 2016). Notably, more research has been conducted on circular T-joints than their triangular counterparts. The structural integrity of the T-joint is dependent on the load transmission path established by the overlaminate and resin filler in the fillet, rendering the joint's strength dependent on both constituent elements. T-joints are subject to the following two primary stress conditions:

a) Hull pressure-induced compression at the interface of the hull and the over laminates.
b) Stress at the same interface caused by the weight of hefty machinery.

Typically attributable to differences in interface quality and the presence of defects, delamination can frequently originate in the over laminate.The bulkhead and hull are the primary structures responsible for maintaining a vessel's structural integrity under varying pressures (Wang et al., 2021). Therefore, the dependability of these structures is highly dependent on the T-joint that connects the two segments. Given that a T-joint is a bonded connection, it necessarily represents the system's weakest link. Several factors, including the following, contribute to the occurrence of defects in T-joints:

a) Differences in interface quality
b) The existence of structural defects

This manuscript analyzes composite T-joints in ship hull structures, focusing on their strength, load transfer mechanisms, and overall dependability. Understanding the subtleties of T-joint behaviour is essential for improving the efficacy and safety of marine vessels.

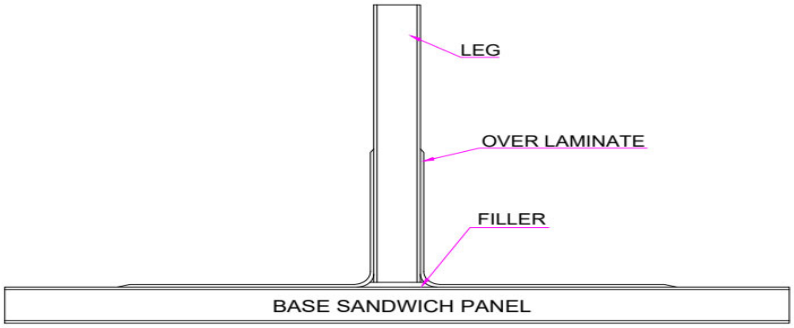


Fig. 1. A Typical Composite T-Joint (Caliskan et.al 2019)

1.2 Design Parameters for T-Joint

The following part provides a summary of the conclusions derived from an extensive analysis of the literature. This review serves as the basis for the creation of a novel composite T-joint design. The variables and criteria that have been established will play a crucial role in the development of this novel T-joint. The salient characteristics of the suggested design are delineated as follows (Mostafa et al., 2013; Caliskan & Apalak, 2019; Akrami et al., 2019; Fathallah & Helal, 2019; Smith & Shivakumar, 2001; Khalili & Ghaznavi, 2011; Juliyana & Krishnan, 2016).:

a) The dual-skin configuration of the T-joint design contains additional skin layers on both the vertical and horizontal plates, so augmenting its structural integrity.
b) Integral overlaminates play a crucial role in reinforcing both the vertical and horizontal plates, while also serving as the major bonding zones within the joint.

c) The core material employed in this application consists of lightweight PVC foam, which is reinforced with a layer of fibreglass to enhance its tensile strength.
d) The supporting core pieces play a crucial role in maintaining the perpendicular alignment of the vertical and horizontal plates. Additionally, they contribute to the expansion of the bonding surface area and provide protection for the filler material. This methodology aims to reduce the amount of resin necessary for the bonding of the two plates.
e) The design's lack of curvature contributes to the simplification of the production process and improves usability. The entirety of the assembly displays symmetry with respect to the Y-axis.
f) Enhanced Contact Area: In order to promote a strong and reliable connection, the design incorporates a generous width of 150 mm, so guaranteeing an augmented contact surface and cross-sectional area.

In order to fabricate this composite T-joint, it is necessary to utilize a PVC foam sheet with dimensions of 700 mm × 150 mm × 30 mm. Nevertheless, it is important to acknowledge that PVC foam sheets of 30 mm in thickness are infrequently encountered and not easily accessible within the commercial sphere. Typically, the highest thickness that is often offered is 18 mm. As a result, it was determined that a revision to the initial design was required.In order to overcome this constraint, the modified methodology incorporates the utilization of two PVC foam sheets, each measuring 18 mm in thickness. These sheets are then glued together utilizing the identical epoxy adhesive that was applied for the primary filler material. This alteration aligns with the core principles of composite materials, which prioritize the incorporation of numerous components. In this particular instance, the incorporation of an epoxy resin layer between the PVC foam sheets effectively fulfills the criterion for achieving optimal thickness while maintaining the integrity of the composite material.The utilization of existing research findings in the development of this novel T-joint design demonstrates a creative approach, offering potential for the construction of resilient composite T-joints with enhanced structural capabilities.

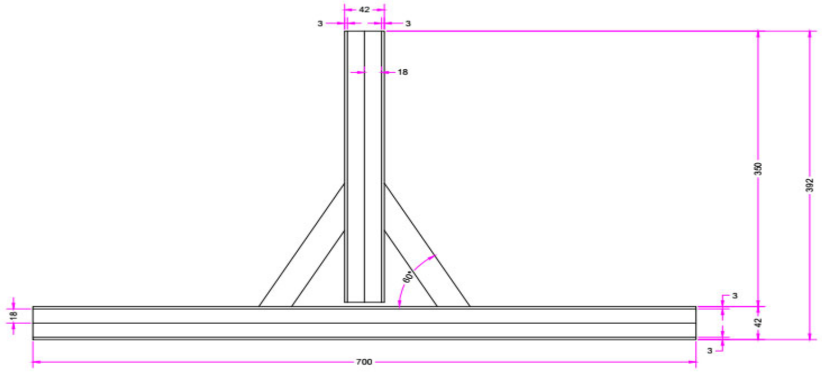


Fig. 2. Conceptual composite T- joint outline

2. 3D Modeling of the Composite T-Joint

The Composite T-joint was meticulously designed and 3D modeled in CATIA V5 R21, with due consideration to material properties and appropriate constraints (Sharma & Obaid, 2021). The process involved the utilization of various CATIA workbenches, including Sketcher, Part Design, and Assembly, to create a comprehensive representation of the composite T-joint.

2.1 Sketcher Workbench

The initial step involved the use of the Sketcher tool to create the foundational sketch of the T-joint. CATIA's Sketcher offers an array of essential commands, such as profile, rectangle, line, axis, trim, corner, chamfer, among others, to aid in the precise construction of the T-joint geometry.

2.2 Part Design Workbench

Proceeding from the Sketcher, we transitioned to the Part Design workbench. Before initiating any part design actions, it was necessary to exit the Sketcher workbench. Within the Part Design environment, the sketch served as the basis for creating the T-joint's 3D structure.We employed the "Pad" command within Part Design to extrude an open or closed profile, effectively generating the T-joint's primary body. The "Pad" command offers various options, including drafted filter pad, multi-pad, shaft, groove, and more, which allow for intricate detailing and customization. Additionally, the "Pocket" command was employed to create pockets within the structure by removing material, contributing to the overall design.

2.3 Assembly Design Workbench

To finalize the composite T-joint assembly, the Assembly Design workbench was employed. This stage involved utilizing the constraint tool, which offers a range of constraint options such as coincidence constraint, contact constraint, offset constraint, fix component, quick constraint, and others. Specifically, we utilized the “contact constraint” to effectively assemble the components of the T-joint, ensuring proper alignment and functionality.The meticulous design and 3D modeling process in CATIA V5 R21 ensured that the composite T-joint was accurately represented, considering material properties and adhering to the required constraints, setting the stage for further analysis and evaluation.

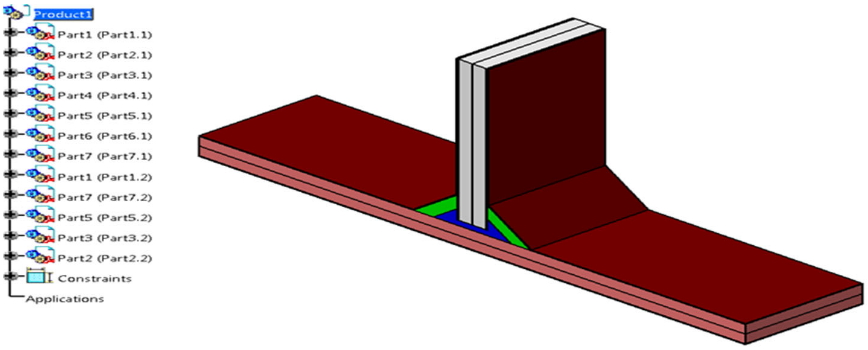


Fig. 3. 3D Modelling of Composite T-joint

3. Materials Selection

Composite materials, often referred to as composites, represent a distinct class of materials composed of two or more constituent materials, each possessing unique physical or chemical properties (Jeykrishnan et al., 2016). These materials are intentionally engineered or can occur naturally, and they maintain their distinctive characteristics at both macroscopic and microscopic scales within the ultimate structure. Composites are aptly described as hybrid materials, as they amalgamate the advantageous mechanical and physical properties of fibers with the aesthetic appeal, bonding capabilities, and physical attributes inherent to polymers (as illustrated in Fig. 4).

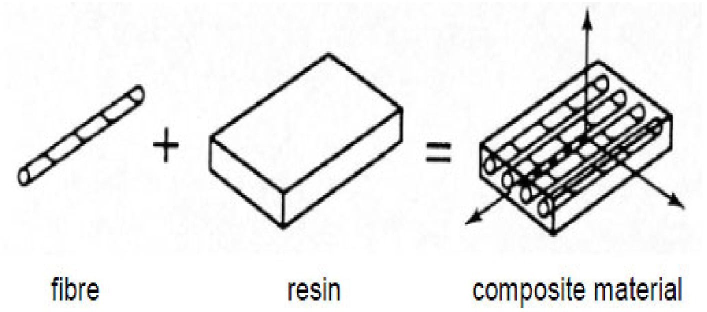


Fig. 4. Model of a perfectly bonded lamina (Caliskan et.al 2019)

3.1 Resin: Epoxy Resin 520 / Hardener: Epoxy PAM

Epoxy resins have established a significant presence in the domain of construction materials, primarily serving as binders . These resins are conventionally deployed in a two-component system, comprising liquid epoxy resin, diluents, fillers, thickening agents, and curing agents. Their versatile utility spans various applications, including the bonding of concrete and composite materials, as well as the formulation of robust thin-set terrazzo flooring for industrial purposes. Over time, their utilization has expanded to encompass road construction, building construction, and the sealing of cracks in concrete structures.

3.2 Fiberglass

Fiberglass emerges as a highly advantageous material selection, primarily owing to its lightweight characteristics, exceptional strength, and remarkable durability. Fig. 5 shows the typical studies on the in-plane elastic constants present the effect of fiber undulation and lamina thickness.Although it may exhibit slightly lower strength properties when compared to carbon fiber and lacks the same rigidity, it effectively offsets these aspects by offering significantly enhanced resilience and cost-effectiveness in terms of raw materials. Furthermore, in contrast to metals, fiberglass presents a favorable combination of attributes encompassing a superior strength-to-weight ratio and reduced overall weight. Moreover, its manufacturing process is characterized by simplicity, employing molding techniques that streamline and enhance production efficiency.

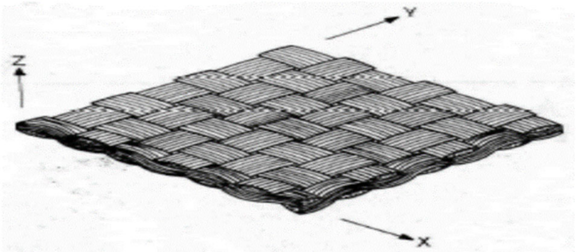
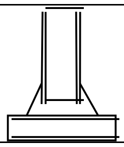
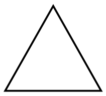
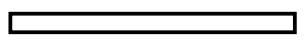
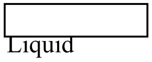


Fig.5. A general plain weave fabric lamina (Jeykrishnan et.al., 2016)

3.3 Foam Cores

Foam cores are extensively employed as core materials, and they can be manufactured from diverse synthetic polymers, including polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PU), polymethacrylamide, polyetherimide (PEI), and styrene-acrylonitrile (SAN). These foam materials are available in a broad spectrum of densities, ranging from less than 30 kg/m³ to over 300 kg/m³. In the realm of composite construction, the commonly adopted densities typically fall within the range of 40 to 200 kg/m³. Furthermore, foam cores are accessible in various thicknesses, spanning from 5mm to 50mm. Based on the findings derived from this comparative study, the following composite materials have been selected for consideration.

Table 1. T-joint materials and specifications

Sr. No.	Part Name	Materials	Dimensions	Value (mm)	Quantity	Shape
1	T-Joint	See below	Overall length Total length Total height	150 700 400	-	
2	Triangular Fillets	PVC Foam	Base length Height Angle of base	90 40.70 60^0	2	
3	Skin laminates	Glass Fiber	Thickness	2	4	
4	Core A and B	PVC Foam	Thickness	43	2	
5	Filler	Epoxy Resin 520	Thickness around the fillet	3	-	Liquid

4. Analysis of Composite T-Joint

The static analysis of the T-joint is conducted following a well-defined methodology, as outlined below. The T-joint is initially modeled using CATIA V5, a design software that seamlessly interfaces with the simulation software ANSYS 12.The CAD model is subsequently imported into the simulation software, and a systematic process plan for the T-joint analysis is established.

Table 2. Material characteristics in multiple configurations for each section

Part No.	Description of Part	Material description	EX (*10^6 Pa)	EY (*10^6 Pa)	Gxy (*10^6 Pa)	S (*10^6 Pa)	Vxy
1	A skin bottom	Glass fiber	26,100	11,500	4,400	31.4	0.14
2	A skin top	Glass fiber	26,100	11,500	4,400	31.4	0.14
3	B skin	Glass fiber	26,100	11,500	4,400	31.4	0.14
4	A Core	PVC Foam	104	104	40	1.4	0.3
5	B core	PVC Foam	104	104	40	1.4	0.3
6	Filler	Epoxy Resin 520	500	500	170	8.7	0.47

This comprehensive process plan encompasses several critical steps, including the creation of the CAD model, determination of boundary conditions, examination of material properties, and characterization of loading patterns.A table is meticulously compiled to detail the material properties and orientations pertinent to each component involved in the analysis.

Within this table, each part is described, and vital material attributes are enumerated. These attributes encompass the elastic constants (EX, EY, Gxy, Vxy), tensile strengths (X and Y) in the local X and Y directions, and the respective orientations in the local coordinate system. It is assumed that the material behaves as linear elastic and possesses orthotropic properties.The model relies on a specialized element, namely the PLANE82 element, which is a plane 8-node orthotropic element. To ensure accurate computations, a 2 × 2 Gauss integration scheme is employed. An automated meshing technique is employed, initially generating a mesh comprising approximately 10,000 elements. The dimensions of the elements vary: the upper skin and filler of panel A exhibit a side length of 1mm, while the core of panels A and B features a side length of 3mm.Finite Element Analysis serves as a pivotal tool in unraveling the complex structural failure mechanisms inherent in the T-joint. It enables the identification and refinement of critical points within the structure. As depicted in Fig. 6, the stress distribution along the Y-axis direction (y) is illustrated for a displacement of 8mm. Notably, the corner of the joint emerges as the focal point with the highest stress values, signifying a substantial concentration of tension within this particular region. Fig. 7 provides a visual representation of how shear stresses are distributed throughout a structure through contour plots. The maximum stress value of 3.527 MPa was obtained through the contour plot when applying the maximum tensile load.

In Fig. 8, it is observed that the maximum stress, as indicated by the color difference in Von Mises stress, is measured at 116.829 MPa and is developed in the overlaminate. This information can help to identify areas of high stress concentration, which may be critical for design considerations. In Fig.9 shows the stresses on a path along the border of the triangle and the filler. The nodal solution within the filler triangle provides valuable information about how the composite T-joint behaves under load and can help in optimizing its design and material choices. The maximum stress value is obtained 0.8Mpa through the analysis. Fig.10 find that SY/SY-yield decreases as path distance increases, indicating a negative relationship. Also find that Sx-yield remains relatively constant over a range of path distances. The obtained value of Sx-yield is 2.4 MPa, with a maximum path distance covered of 168 mm, while the value of SY yield is -0.126.

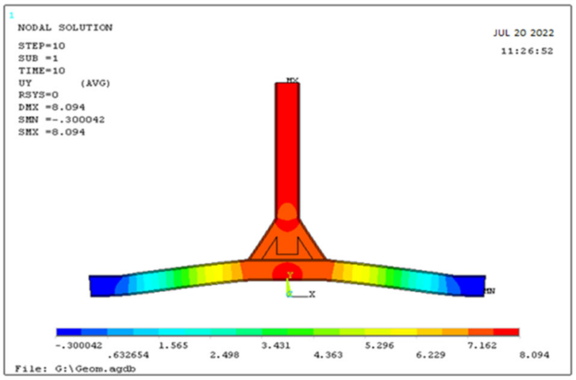


Fig.6. Deflection Plot of composite T-joint

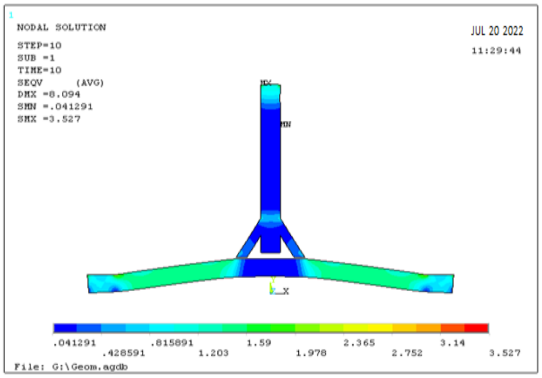


Fig. 7. Counter plot showing shear stresses. Because each plot was created separately (to maximize resolution), the counters are not comparable between segments.

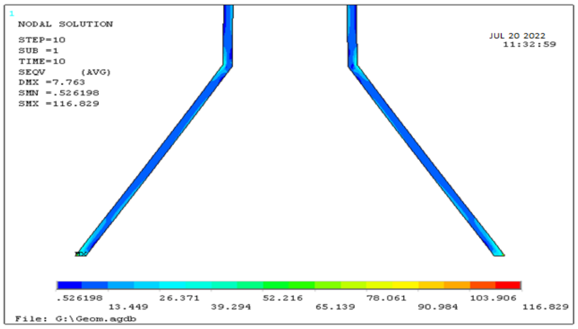


Fig.8. Von-misses stresses of fibre glass (skin)

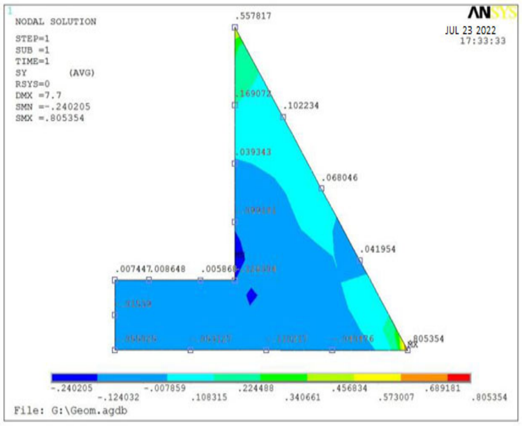


Fig.9. Nodal solution of Filler triangle

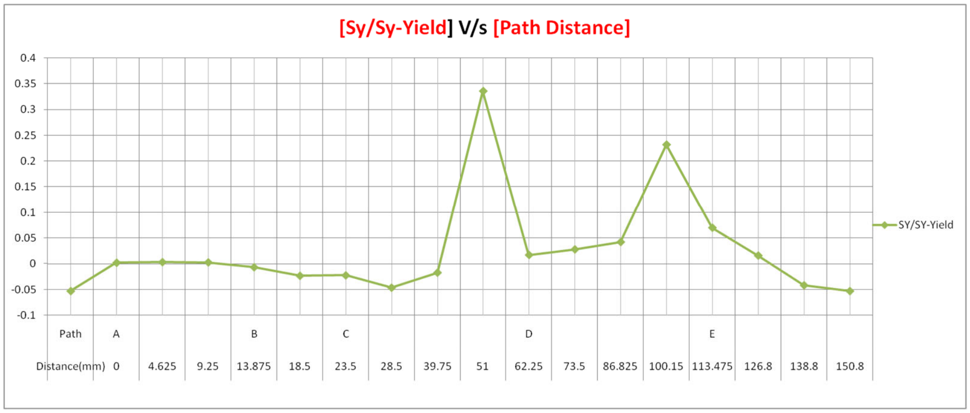


Fig. 10. Plot of Sy/Sy-yield V/S Path Distance

Table 3. Shear value in X and Y direction through path and distance travelled

SY (MPa)	Sx-Yield (Mpa)	SY/SY-Yield	Distance (mm)	Path
-0.126	2.4	-0.0525	0	A
0.0058	2.4	0.002416667	4.625	
0.00864	2.4	0.0036	9.25	
0.0075	2.4	0.003125	13.875	B
-0.0154	2.4	-0.006416667	18.5	
-0.055	2.4	-0.022916667	23.5	C
-0.053	2.4	-0.022083333	28.5	
-0.1102	2.4	-0.045916667	39.75	
-0.0404	2.4	-0.016833333	51	
0.8055	2.4	0.335625	62.25	D
0.0419	2.4	0.017458333	73.5	
0.068	2.4	0.028333333	86.825	
0.1022	2.4	0.042583333	100.15	
0.557	2.4	0.232083333	113.475	E
0.169	2.4	0.070416667	126.8	
0.0393	2.4	0.016375	138.8	
-0.099	2.4	-0.04125	150.8	
-0.126	2.4	-0.0525	162.8	A

5. Conclusion

The T-joint design focuses on achieving lightweight characteristics, specifically catering to sandwich panels composed of two 18mm thick PVC foam cores and three 3mm thick fiberglass skin laminates. Additional components include filler material and two supporting core pieces made of PVC foam, facilitating panel attachment. Finite Element Analysis, executed using ANSYS, plays a pivotal role in subjecting the T-joint to static loads, enabling a comprehensive assessment of its structural behavior. Comparative analyses involving similar joint configurations were conducted, relying on the examination of relative stresses across different sections of the joint. Von Mises stress distribution was employed as the primary basis for these comparisons. The investigation discerned that both the thickness of the hull and the orientation of the over laminate exert influence on critical strains experienced within the over laminate hull. Therefore, these factors are deemed critical considerations during the design phase of such joints. The loading process exhibited a linear increase in applied load until it reached approximately 1982N, accompanied by a displacement of about 0.7mm. Subsequently, with continued load increment, the response curve displayed a change in slope, indicative of base element deformation. Ultimately, a load of approximately 19800N was achieved, resulting in a displacement of 8.4mm, visibly manifesting as bending of the base element. These results highlight the importance of accurately predicting the maximum load capacity and potential deformation of joints in order to ensure their structural integrity. Additionally, it is crucial to consider the material properties and geometry of the base element to prevent excessive bending and failure. Consequently, engineers must carefully assess the loading conditions and select appropriate materials and dimensions to design robust joints that can withstand the anticipated forces and minimize deformation.

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