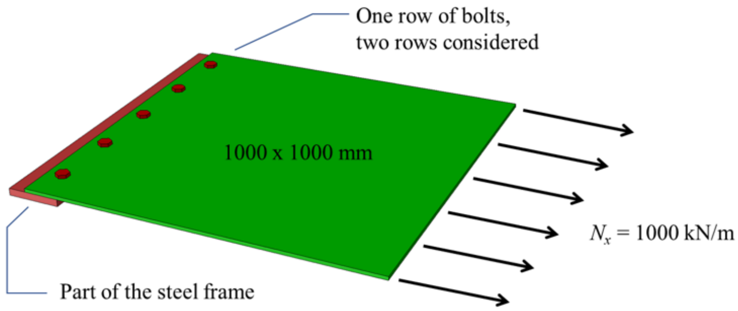
Bolted joints

Commissioned by Steel & Heavy Stuff Engineering A/S



Introduction

Steel & Heavy Stuff Engineering A/S is working on a project involving the connection of a composite structure to a steel frame. Due to a lack of previous experience from working with composite engineering, in addition to an unfortunate bankruptcy, Steel & Heavy Stuff Engineering A/S have reached out to have a feasibility study done on their behalf. The composite being used is a T300 vacuum infused UD carbon, with single-lap bolted joints.

This report will cover a viable solution for the composite metal joining, and relevant theory. Analytical models will be provided as a means to calculate baseline measurements. Parameters such as the layup geometry, local reinforcements, the number of bolts, the bolt diameter, the bolt positioning, and the amount of rows will be tweaked to find a viable solution. A recommended set of specifications will be delivered to Steel & Heavy Stuff Engineering A/S.

Defining the Problem

The dimensions of the structure is a square 1000 x 1000 mm laminate with its layup described in Figure 1. We are analyzing and designing for a distributed load of 1000 kN/m. Table x contains the material properties of vacuum infused UD carbon (T300) that is used in the laminate. In the case of the bolts, we choose to conduct a thorough assessment using high-strength alloy steel.

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Figure 1, initial layup provided by Very Fast Composite Design A/S

Table 1, material properties of vacuum infused UD carbon (T300), units: MPa-mm-Mg

E1	***E2***	***E3***	***Nu12***	***Nu13***	***Nu23***	***G12***	***G13***	***G23***
130000	10000	10000	0.28	0.28	0.5	4500	4500	3500
a1	***a2***	***a3***	***XT***	***YT***	***ZT***	***XC***	***YC***	***ZC***
-0.5E-6	3E-5	3E-5	1400	30	30	900	120	120
S12	***S13***	***S23***	***f12***	***f13***	***f23***	***Vf***	***Rho***	-
60	60	30	-0.5	-0.5	-0.5	0.55	1600E-12	-

Theory

This report will be exploring different types of shear bearing-type joints. Further exploration of eg. adhesive joints might be of interest depending on the problem at hand.

In metal joints, bolts are typically pre-tensioned to ensure that the main shear load is carried by friction between the plates, while the bolt itself is primarily subjected to normal tension stresses. Composites tend to experience significant stress relaxation over time, leading to a loss of clamping force. As the clamping force diminishes, the shear load can no longer be effectively transferred through friction, resulting in increased shear stresses within the bolt itself. Thus making pre-tensioning less of a viable method.

Failure types for shear-loaded joints

This section presents relevant failure modes for shear-loaded joints illustrated in Figure 2. In practice, failure often occurs as a combination of multiple modes. The laminate layup and the ratio between hole diameter (d), specimen width (w), and edge distance (e) play a major role in determining which failure mode is most likely to occur. The mode with the lowest strength will typically govern the overall strength of the joint.

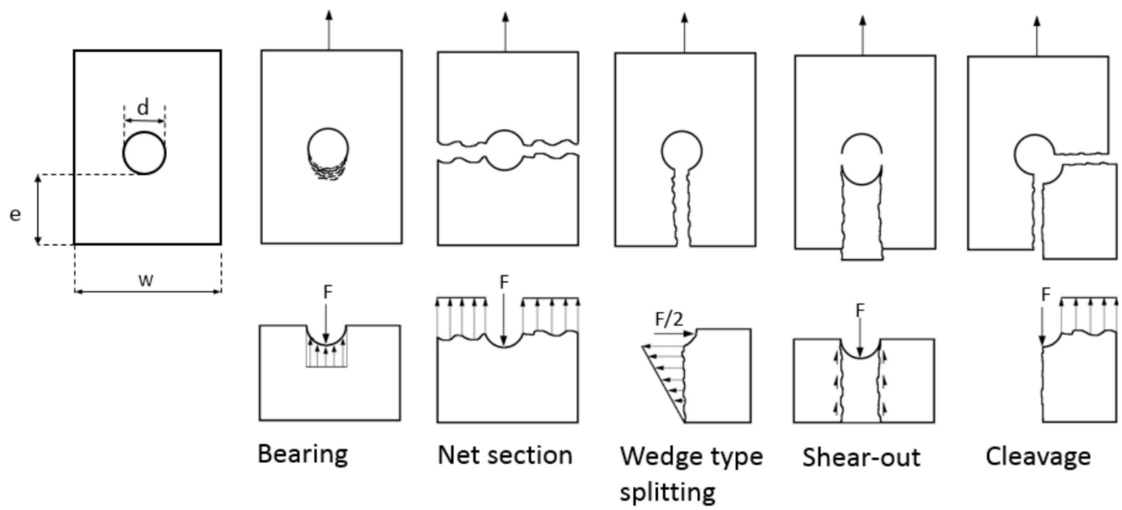

Figure 2, an overview of relevant failure modes

Bearing failure

Bearing failure is characterized by local crushing at the bolt–hole contact interface. It commonly occurs when the d/w ratio is small, as this leads to high contact stresses. A viable solution is to increase the hole diameter to enlarge the contact area. Bearing failure is often considered a desirable failure mode because it develops gradually, allowing for visual detection and corrective action before catastrophic failure.

Net-section failure

Net-section failure is characterized by tensile fracture across the narrow section of the joint, transverse to the loading direction. This failure mode typically occurs when the d/w ratio is large, that is when the bolt diameter is high relative to the width of the specimen. The risk of net-section failure can be reduced by increasing the amount of fibers aligned in the loading direction.

Shear-out

Shear-out failure occurs when the material adjacent to the bolt is sheared off, typically due to insufficient edge distance. It is most common when the distance from the bolt hole to the end of the specimen is small. Orthotropic laminates with a high percentage of fibers in the 0° direction are particularly susceptible. The risk of shear-out can be reduced by introducing ±45° plies, and by increasing the edge distance (e).

Cleavage

Cleavage failure involves longitudinal splitting in combination with net-tension, causing the end of the joint to split. This failure often occurs at low edge distances and may appear as chunks of material breaking off near one or both corners of the joint. Adding 90° plies or increasing the edge distance (e) helps to mitigate the risk of cleavage.

Bolt shear

Bolt shear occurs when shear stress in the bolt exceeds its structural limit, causing the bolt to fail. This is more likely to occur when the bolt is improperly pre-tensioned (metals), or when the bolt diameter is too small. Bolt shear is often accompanied by bearing failure and tends to occur at the threaded section of the bolt, where the cross-sectional area is at its lowest.

(Lasn, 2024)
(Vedvik, 2025)

Method

Initial Assessment Using an Analytical Model

As an initial assessment we use a simplified analytical model of the bolted joints. Assuming uniform load distribution along a single direction, where n is the number of bolts, we get the following expressions for the internal loads q1 and q2 (Figure 3).

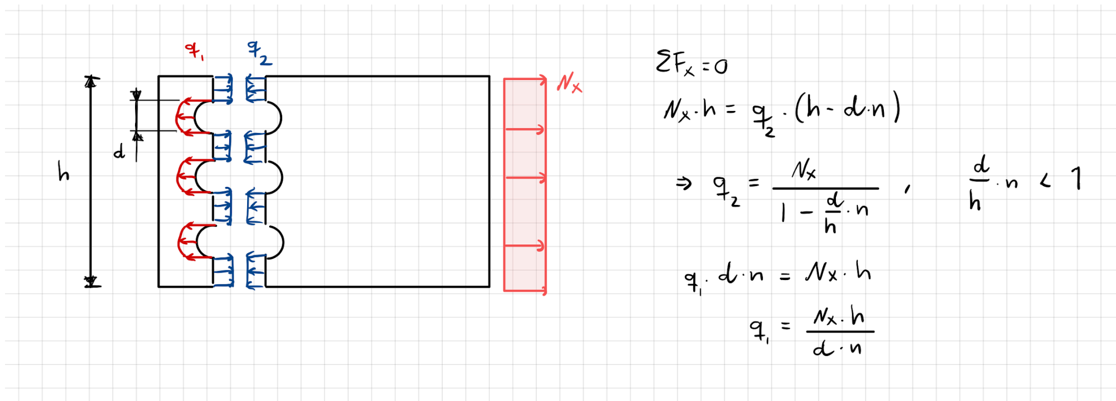

Figure 3, loads for analytical model.

By computing the ABD-matrix we can solve for the deformations and use Hooke's law to obtain the critical stresses in each layer (see Appendix for code). The stresses are then used in combination with the material data of the carbon fiber composite to calculate the exposure factors. For the analytical assessment, we set h = 1000 mm, Nx = 1000 N/mm and d = 20 mm.

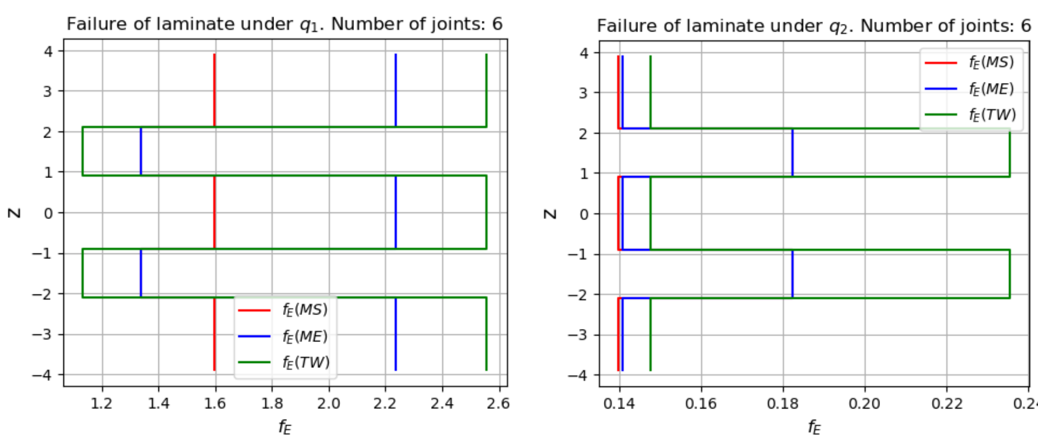

Figure 4, exposure factors through the laminate thickness (num. bolted joints = 6)

From Figure 4 we see that the effect from the compressive load q1 is dominating for 6 bolted joints. Finding the ideal number of bolted joints is a matter of balancing the tensile and compressive loads.

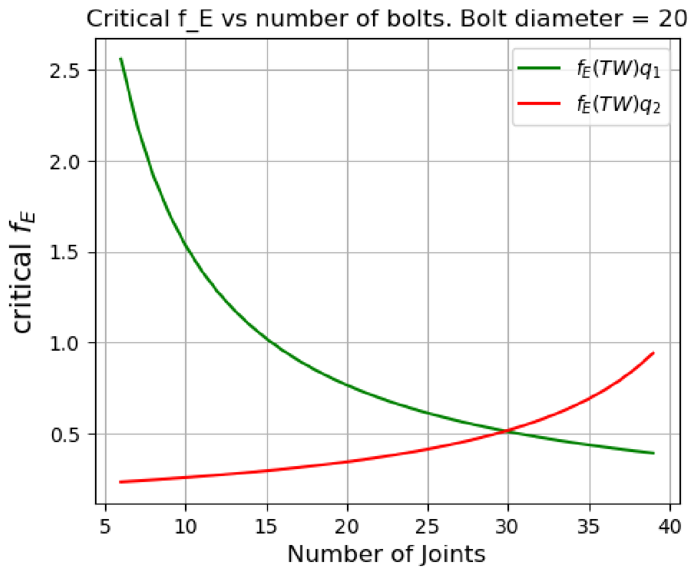

Figure 5, critical Tsai-Wu exposure factor for various numbers of joints.

Using the simplified model, we find solutions where the critical exposure factor is around 0.5 at n = 30 (Figure 5). Due to the highly idealized model we do not have insight into any local effects. A best exposure factor of 0.5 therefore suggests a high likelihood of failure. It is worth noting that varying the number of bolted joints captures the same effect of joint size in this model, making it unnecessary to explicitly investigate different bolt diameters.

Exploring Bolt Positions

We are looking to find out if Very Fast Composite Design was right in suggesting that using two rows of bolted joints doesn't make much sense. We therefore need to compare the effects of adding another row of bolted joints to the effects of adding it to a single row. To explore this, we run simulations in Abaqus (see Appendix for script).

For the case where an extra joint is placed in the transverse direction (along the single row), it is modeled by simply reducing the width of the section in half. We find this reasonable as it captures the influence of having two adjacent joints without introducing unnecessary complexity into the model, while maintaining the same global loading conditions per unit width.

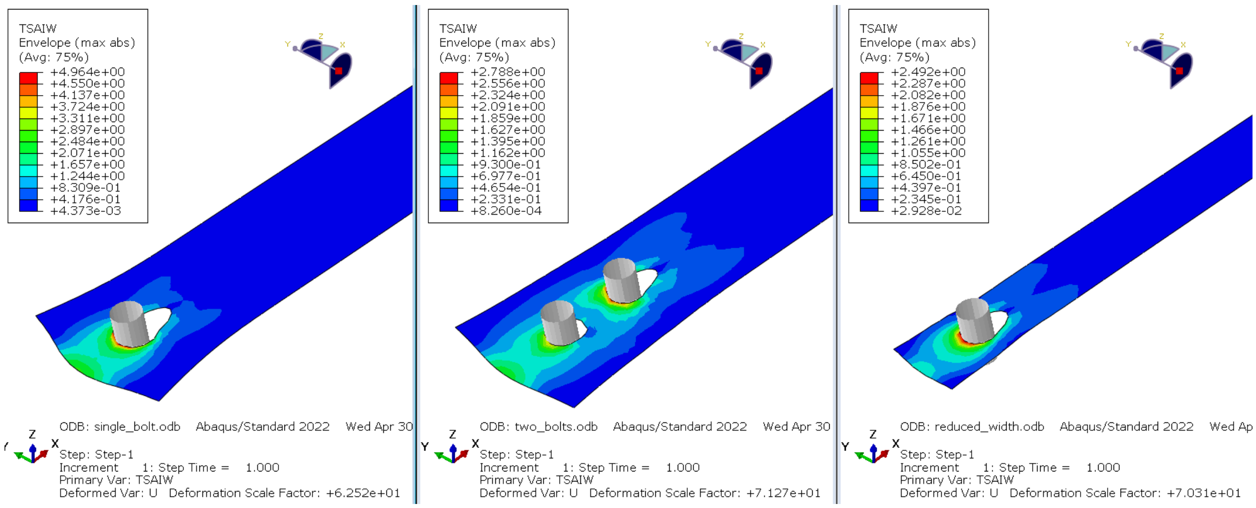

Figure 6, comparison of adding a bolt in the longitudinal direction vs transverse direction.

Looking at the Tsai-Wu exposure factors from Figure 6, we can conclude that both methods effectively reduce the failure stress drastically. However, the maximum exposure factor is slightly higher for the configuration with the added row (2.79) compared to the single-row configuration (2.49). In unidirectional composite materials, load transfer is much more effective along the fiber direction. Adding more bolts in the same direction does less to further distribute the load as it is already efficient in that direction. Looking at the layup by Very Fast Composite Design A/S from Figure 1, we see that around 70 % of the fibers are oriented in the load direction, making the option of adding a second row less viable.

Using two or more rows of bolts does not necessarily benefit the structural integrity of the joint or provide greater protection against failure modes. In an imperfect world, load sharing between the bolts are not uniform and the first row often carries the majority of the load. Bearing damage might initiate, but unlike metals that redistribute the load through yielding, composites distribute and respond unpredictably which can cause catastrophic failure such as net-section or shear out. A study conducted on multi-bolt composite joints found that net-section failure was the dominating failure always occurring in the first hole, while the other holes showed little damage or were even unaffected (Cheng et al., 2017). Additionally, adding several rows increases the number of holes which weakens the laminate due to fiber disruption. Ultimately, there are better ways to improve the joint than simply adding another row of bolts.

Required Number of Bolts and Positioning

The number of bolts required to prevent bolt yielding and the bolt positioning relative to the laminate edge were estimated using simplified analytical methods, supplemented by numerical verification. Firstly, the yielding in bolts must be estimated. The bolt failure mode is assumed to be in pure shear, removing any clamping effects to simplify the calculations. This is also considered a more conservative approach, as bolts are not used as pins to only absorb shear. To calculate the yielding in the bolts, the following equations are applied for a circular, compact cross section:

$$\tau_{max} = \frac{4F}{3A} = \frac{16F}{3\pi d^2 * n}$$

Where n is the amount of bolts required, and d being the bolt diameter. Von mises equivalent stress is then used to calculate the shear in the bolt, reducing the expression to the following:

$$\sigma = \sqrt{3} * \frac{16F}{3\pi * d^2 * n}$$

Where σ is the yield stress of the bolt. Using 12.9 bolts, the minimum yield stress is 1080 MPa. Since the main composite failure mode comes from compressive loads from pretensioning the bolt, smaller but more bolts are preferred to distribute the load. Using M10 12.9 bolts, the required number of bolts from eq() comes out to be >28 bolts to prevent bolts yielding in pure shear. To minimize stress concentrations, each bolt will be fitted with ISO 7093 washers (FastenersEU, n.d.).

Abaqus Model Description

The FEA model is limited to shell elements to avoid unnecessary computational complexity.
In addition, the model is reduced to a single bolted joint. Using 28 bolts, the width of the model is therefore set to 1000/28 mm. The length is reduced from 1000 mm to 300 mm as it virtually has no effect on the stresses around the joint.
The bolts are modeled as an analytical rigid with a diameter of 10 mm (M10).
The global element size (mesh size) was set to 3 for the simulations.

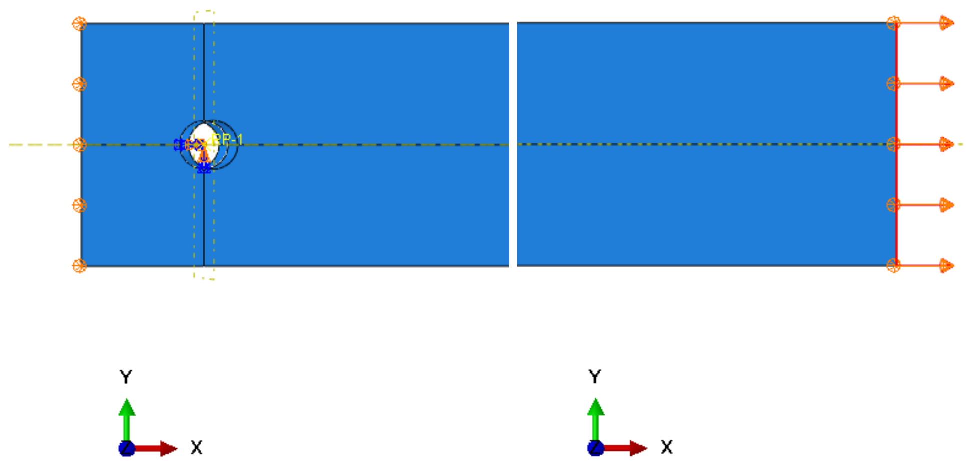

Figure 7, Abaqus load and boundary conditions for both ends of the model.

A distributed load of 1000 N/mm is applied as shown in Figure 7. For the boundary conditions, both ends are fixed in U3 (z-direction), while the bolt has a rigid body connection to RP-1 with no degree of freedom.

Composite Design

Several layups were tested in Abaqus to identify where the stresses peaked, and where failure according to Tsai Wu would first occur. Additional plies were added around the hole with a rotation to best absorb the stresses and keep the Tsai Wu exposure factor within a reasonable limit. The final design consists of the layup shown in Figure 8, where the initial plate has a total thickness of 7.8mm and the reinforced area around the bolts has a total thickness of 25.8mm. The reinforcement is approximately 230% thicker.

		Ply Name	Region	Material	Thickness	CSYS	Rotation Angle	Integration Points
1	✔	Ply-1	faces-at-bolts	CFRP	3.6	<Layup>	0	3
2	✔	Ply-2	faces-at-bolts	CFRP	1.8	<Layup>	-45	3
3	✔	Ply-3	faces-at-bolts	CFRP	1.8	<Layup>	45	3
4	✔	Ply-4	faces-at-bolts	CFRP	1.8	<Layup>	90	3
5	✔	Ply-5	faces-all	CFRP	1.8	<Layup>	0	3
6	✔	Ply-6	faces-all	CFRP	0.6	<Layup>	-45	3
7	✔	Ply-7	faces-all	CFRP	0.6	<Layup>	45	3
8	✔	Ply-8	faces-all	CFRP	1.8	<Layup>	0	3
9	✔	Ply-9	faces-all	CFRP	0.6	<Layup>	45	3
10	✔	Ply-10	faces-all	CFRP	0.6	<Layup>	-45	3
11	✔	Ply-11	faces-all	CFRP	1.8	<Layup>	0	3
12	✔	Ply-12	faces-at-bolts	CFRP	1.8	<Layup>	90	3
13	✔	Ply-13	faces-at-bolts	CFRP	1.8	<Layup>	45	3
14	✔	Ply-14	faces-at-bolts	CFRP	1.8	<Layup>	-45	3
15	✔	Ply-15	faces-at-bolts	CFRP	3.6	<Layup>	0	3

Figure 8, Layup used in FEA

Final Results

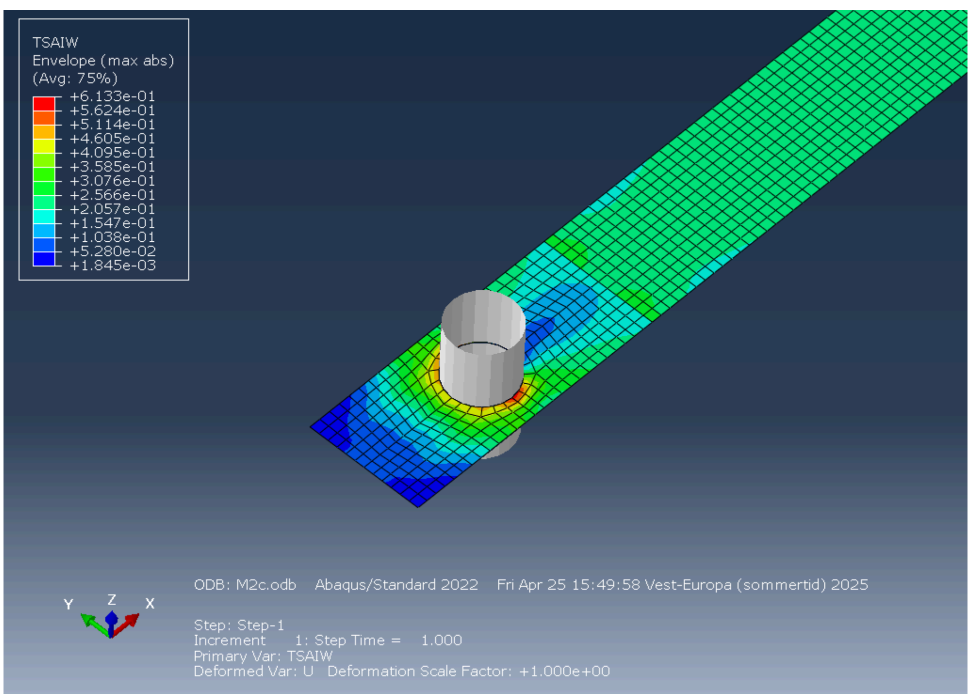

Figure 9, Tsai Wu of the model reduced to one hole.

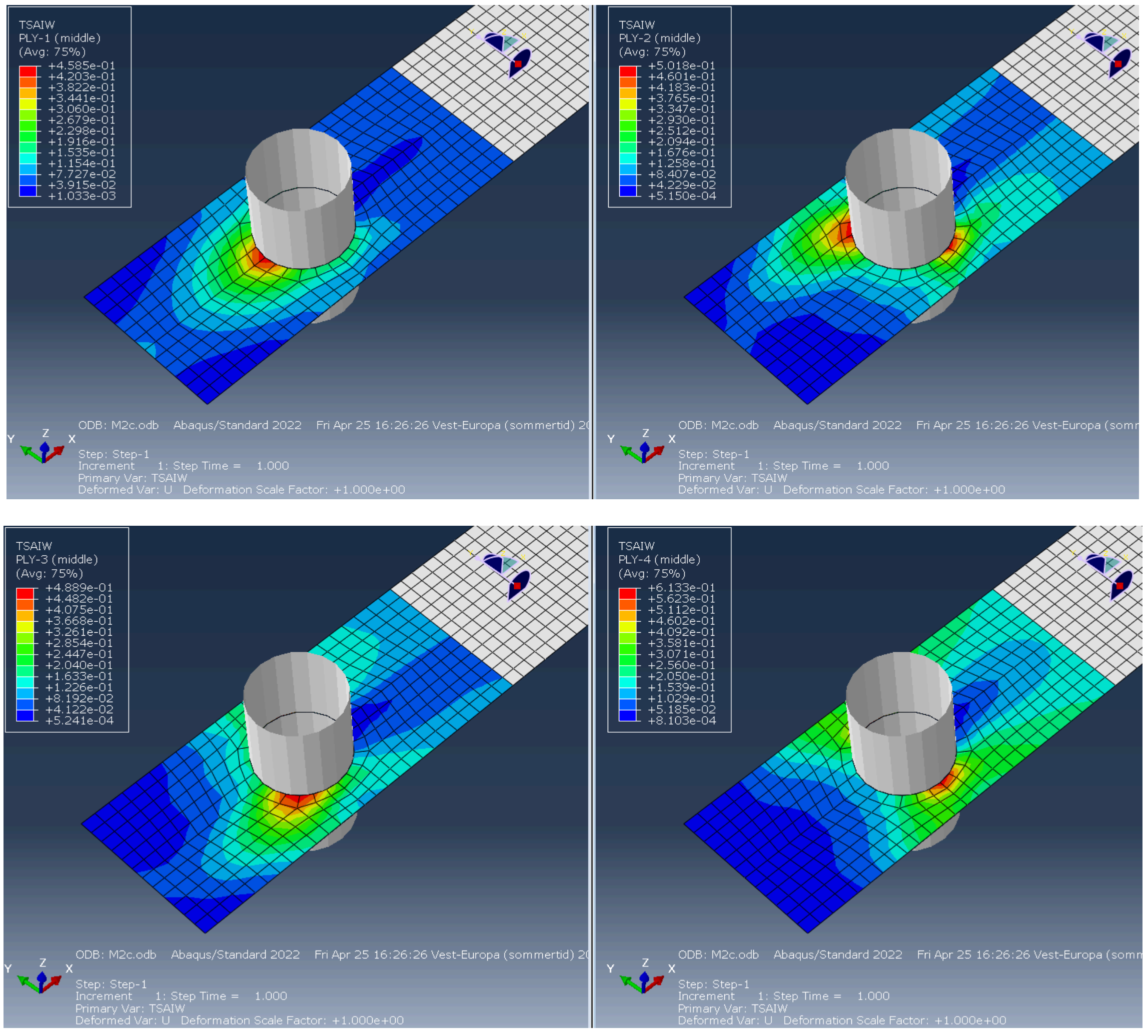

Figure 10, Tsai Wu of reinforcement plies 1, 2, 3, and 4 with rotation angles 0, -45, 45 and 90 displaying the critical areas.

Discussion

The evaluation of the CFRP-metal single-lap bolted joint under a tensile section force of 1000 kN/m highlighted the challenges of joining composite materials with mechanical fasteners. Initial analytical calculations using a simplified method provided an indication that the laminate could, in theory, support the load with sufficient numbers of bolts. However, the critical Tsai-Wu exposure factors approached 0.5 already under idealized assumptions, suggesting that the design was operating close to its material limits even before considering local effects. The laminate's strong bias toward 0° plies provided excellent tensile stiffness, but made it vulnerable to shear-out and bearing failures around the bolt holes.

Initial finite element simulations captured the local stress concentrations and confirmed that the unreinforced laminate would likely fail prematurely under the applied loads (see Figure 6). The simulations revealed that single-row bolted configurations were superior to two-row alternatives, as the latter would have introduced undesirable transverse loading and inefficient load paths. Practical considerations also favored a single row: easier manufacturing, inspection, and lower risk of premature failures due to uneven load sharing.

To mitigate the risk of bearing and shear-out failures, local reinforcements were introduced around the bolt holes. These reinforcements included additional ±45° and 90° plies, as well as extra 0° plies placed directly around the bolts. The final layup, resulting in local thickening to 15 plies, was selected based on engineering judgment and simple analysis rather than detailed optimization. The stacking sequence was designed to enhance resistance to critical failure modes by evaluating local stresses in each ply using the Tsai-Wu criterion in the simulations. The combined use of analytical estimates and numerical simulations enabled a sound, practical design solution without extensive refinement, in line with the project's objective to provide a reliable and efficient joint configuration.

The study demonstrates the limitations of relying solely on global stress estimates when designing joints in composites. Local effects dominate the failure behavior, and without careful modeling and reinforcement strategies, lightweight composite joints risk catastrophic failure even when global strength margins appear sufficient. The combined use of analytical estimates and numerical simulations enabled a sound, practical design solution without extensive refinement, in line with the project's objective to provide a reliable and efficient joint configuration. Any Major Dude Will Tell You: in composite joint design, it's the local details in addition to the global estimates that determine whether the structure holds.

Conclusion

The design of bolted joints in composite materials presents a complex interplay between load transfer mechanisms, material anisotropy, and multiple competing failure modes. In this assignment, both analytical and numerical methods were applied to evaluate the performance of a CFRP-metal single-lap bolted joint subjected to a tensile section force of 1000 kN/m.

Based on the findings from the highly simplified analytical model, it was initially assessed that the baseline laminate configuration could be viable with a sufficiently high number of bolts, but with very limited safety margins. This emphasized the need for further investigation. Numerical simulations revealed stress concentrations around the bolt holes, posing a high risk of failure particularly through bearing and shear-out mechanisms, unless reinforcements were introduced.

The study demonstrated that a single row of bolts was preferable to two rows, both from a mechanical and practical standpoint. Reinforcement of the laminate around the bolts, through the addition of ±45°, 90°, and 0° plies, proved to be essential for achieving a robust and reliable joint configuration. Viable parameters for the final joint design included a single row of at least 28 M10 bolts of strength class 12.9, each fitted with ISO 7093 washers and significant local laminate thickening. Ultimately, the assignment highlights the necessity of combining global analytical assessments with local detailed simulations when designing composite joints.

References

Cheng, X., Wang, S., Zhang, J., Huang, W., Cheng, Y., Zhang, J. (2017). *Effect of damage on failure mode of multi-bolt composite joints using failure envelope method*. 8-15. Retrieved April 24, 2025, from https://www.sciencedirect.com/science/article/pii/S0263822316313022

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Appendix