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Modeling Comparison of Lap Joint Using Finite Element Analysis

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ABSTRACT

Lap joints are commonly used as a method of connecting structural parts. This includes parts that are made by 3D printing technology. Structural simulation using the finite element (FE) method can be used for lap joint analysis purposes. There are two approaches in the analysis of lap joints: actual bolt connection and virtual bolt connection. Although actual bolt connection is ideally used, in some cases it is impractical; for example, when the number of joints and fasteners is huge. Thus, the study is made to understand the behaviour between two different approaches of bolt connection for 3D printed lap joints. The modeling comparison of 3D printed PLA lap joint of these two different connections was studied using FE analysis and carried out using CATIA software to determine the von Mises stress value and displacement for each type of connection. The outcome of this study showed that actual bolts have higher von Mises stress value, while both connection models have similar displacements and different pre-tensions on bolts bring small changes to the von Mises stress values. This shows the significance of the study in understanding the behaviour between two bolt connections of the von Mises stress and diplacement values.

Keywords: FE analysis, von misses stress, 3D printing, pre-tension

Abbreviations

PLA	Polylactic acid
CAD	Computer-Aided Design
FE	Finite Element
Fig	Figure
3D	3Dimensional
VMS	Von Misses Stress

1.0 INTRODUCTION

Single lap joints, scarf joints, tapered joints, and step-lap joints are among the various types of bonded joints available [1] and the usage of adhesive-bonded joints to join structural components is common [2]. In metal structures, a lap joint is a junction in which the edges or ends of two pieces of metal are overlapped and joined together. They are widely utilized, especially when joining thin sheets together. Almost every structure is made up of many parts that are joined. Those structures are either too massive or too complicated to make in one piece. In the design and analysis of structures, joining technology is critical. This applies to composite structures as well. Bolted joints can be used with any material, whereas welding and bonded joints are only used with metallic and composite structures, respectively. To improve the strength of the connection, both bonded and bolted joints can be used at the same time [3]. Some of the fastening methods include bolting, riveting and soldering. For metals to be joined, bolting, riveting, soldering, and arc welding require some additional material. A bonded joint can be manufactured in a number of methods. The strap joint, lap joint, and scarf joint are examples of common layouts, as seen in Fig. 1 [4].

In this paper, lap joints were developed and manufactured using 3D printing with Polylactic acid, PLA material. 3D printing, also known as additive manufacturing, is a computer-controlled method that manufactures 3D objects by depositing a layer on top of another layer to create a 3D item. Computer-aided design, CAD software, or 3D object scanners were used to make the image that benefits this process, as it removes surplus materials by minimizing or eliminating the use of the material in other standard techniques and machining [5]. PLA material is used in this process as it stands out as the most potential biodegradable alternative to petrochemical-based polymers for the production of high-performance materials used in medicine, pharmacy, food, textiles, and electronics sector [6].

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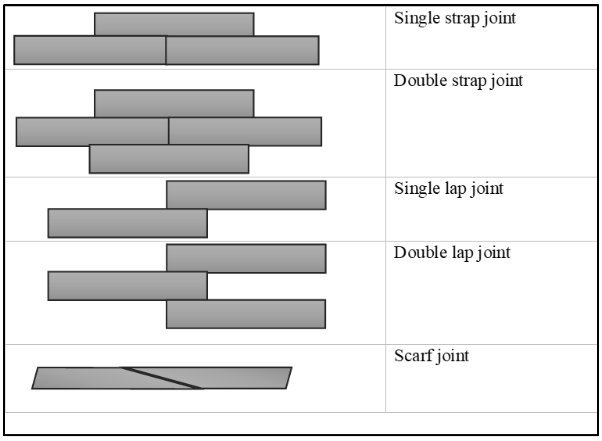

Figure 1: Different configurations of joint [2]

The FE analysis method has been used to analyse stress parameters and adhesive joint strength. FE analysis can be used to determine the stress distribution and it is preferable for complex geometries and elaborate material models [8]. The finite Element Method (FEM) has been used to compare mechanical joints such as bolted and riveted joints, as well as step lap and hybrid joints [3]. Various step lengths have been investigated to determine the ideal step length. The number of bolts and rivets was also adjusted to see how the number of bolts and rivets affected the step lap joint. Rivets and bolts were also studied in terms of hybridization with and without adhesive. In addition, different adhesives and attached materials were compared. FE analysis was also used to compare various joint shapes, and in this research, it was found that the optimum joint type is highly dependent on the adhesive utilized [4]. In [7], a single-lap junction with steel adherends bonded with a commercial epoxy adhesive was studied, particularly on the distribution of normal while the shear stress in the adhesive layer's mid-plane was determined using a 3D finite element (FE) analysis. One approach that is attractive to be used is by employing the so-called virtual bolt, instead of the actual bolts. This is especially attractive to structures with a lot of joints and bolts. However, less study was done on model comparison between the appliance of the actual bolt and virtual bolt, especially for 3D printed structure.

The present work focuses on the model comparison of mechanical joints between virtual bolt and actual bolt through the FE analysis using CATIA Workbench. Different pre-tension load was applied to both models, and the von Mises stress and displacements were observed.

2.0 METHODOLOGY

FE analysis was used to determine the stresses at bolt connections and lap joints. The maximum stress was found after the stresses were created using the finite element approach. The response of the lap joint was assessed by observing the von Mises stress and displacement magnitude, and the results were then compared between two virtual bolt and actual bolt model analyses. Actual bolt brings the term of a 3D designed bolt in comparison of virtual bolt, while virtual rigid bolt tightening connections are used to indicate the boundary interaction between bodies in an integrated system as seen in Figure 2 that ilustrates virtual bolt and actual bolt in CATIA software.

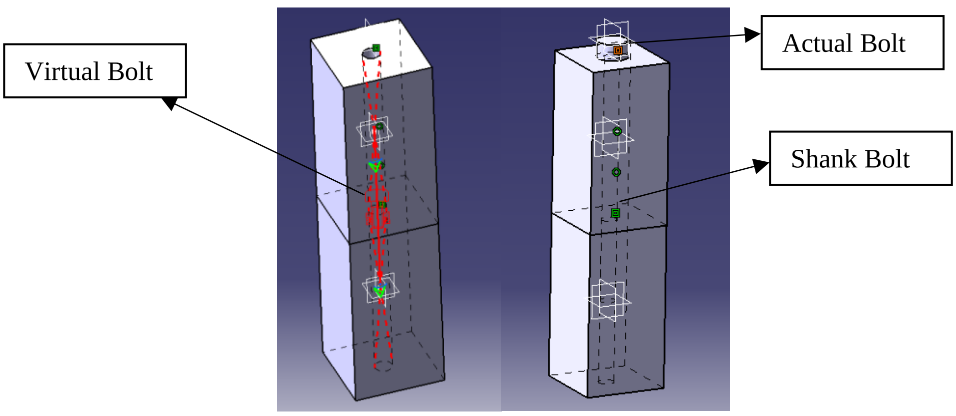

Figure 2: Comparison between virtual and actual bolt

2.1 3D modelling

CATIA Software was used to create a finite element model of the lap joint assembly and perform static analysis. Figure 2 depicts the dimensions in Catia software, which was utilized for 3D modeling. A total of two 3D models with identical length, thickness, and width were created. The lap joint was created using a 3D printer Creality 10S. Fig. 2(a) is the lap joint with the actual bolt, and Fig. 2 (b) is the Lap joint with virtual bolt. The number of bolts is two bolts, with bolt dimensions of 4.5mm bolt head radius with 30mm shank length.

2.2 Finite element method, FEM static analysis

The FE model was then constructed in CATIA software. Fig. 3 depicts the lap joint model utilized in this paper, along with the boundary conditions for the FE analysis. All of the configurations analysed had the same boundary conditions applied to virtual and actual bolt connections. There were two boundary conditions used in this FE model, one was clamped at one end, and another one was restrained motion on Y-axis. The force of 100 N was applied in the -X direction on the opposite end from the clamped end.

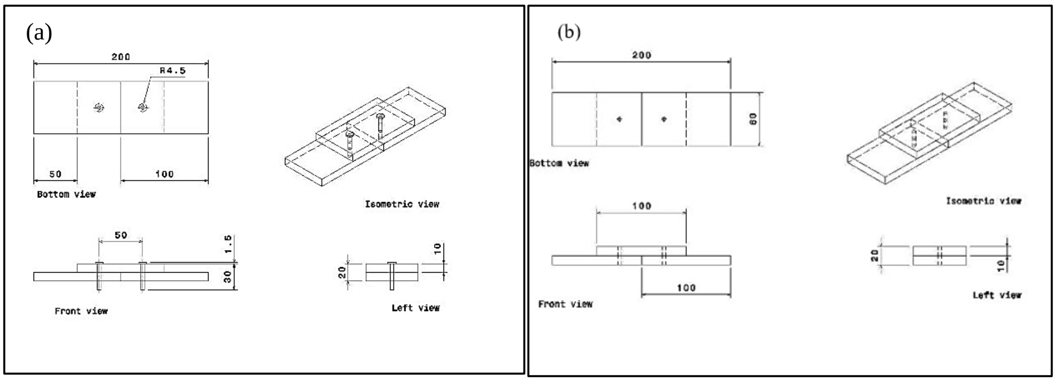

Figure 3: CATIA Drafting with geometry and dimension of (a) Lap Joint with actual bolt (b) Lap joint with virtual bolt

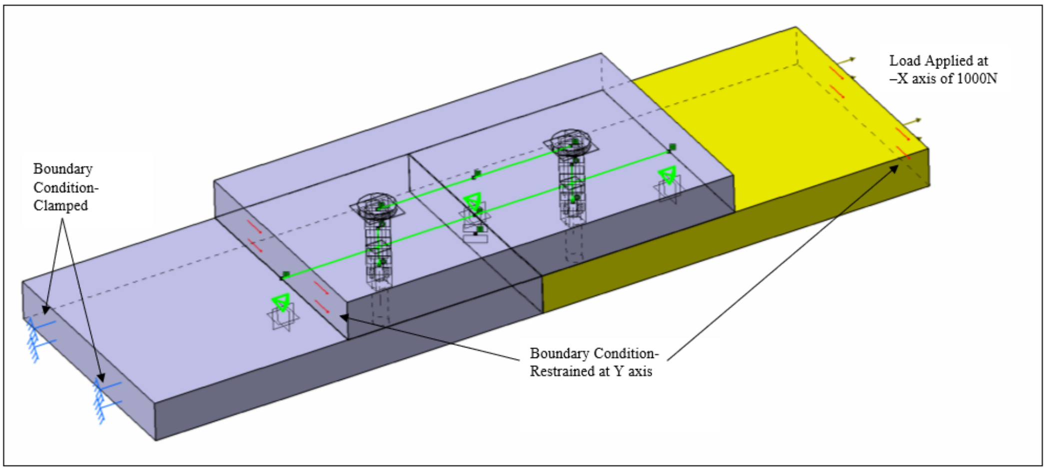

Figure 4: FE Modelling of The Lap Joint

Pre-Tension Bolt was applied during bolt tightening connection as it imitated force exerted on the bolt while tightening it and by applying the pre-tension, it can be seen whether the tension has an impact on the bolt or not. The pre-tension ranged from 0N up to 60N and the direction was the same with bolt direction as presented in Figure 5.

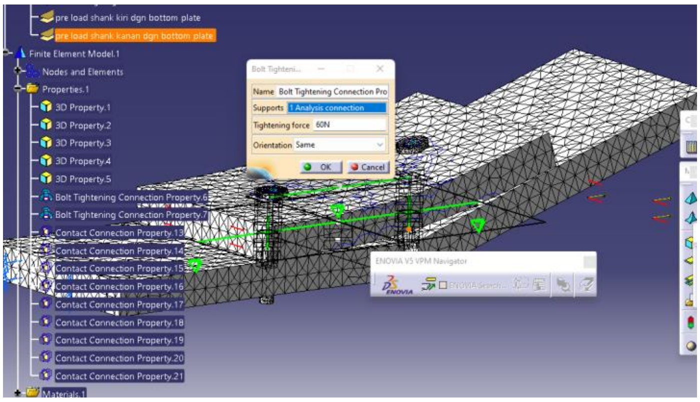

Figure 5: Pre-Tension Bolt application

2.3 Material data

Two materials were used in this joint. The first one was 3D printed PLA material for the plates, and the second one was the steel for the bolt. Table 1 shows the material information below.

Table 1: Material data for PLA [9] and steel

Material	PLA	Steel
Young modulus	1.51e+009 N/m^2	2e+011 N/m^2
Poisson ratio	0.3	0.266
Density	1250kg/m^3	7860kg/m^3
Yield strength	3.12e+007 N/m^2	2.5e+008 N/m^2

3.0 RESULTS AND DISCUSSION

3.1 Finite element model verification

Mesh convergence test was performed to determine the appropriate mesh density, as finer meshes gave more accurate solutions in finite element modeling. The meshing of the lap joint is demonstrated in Fig 4.

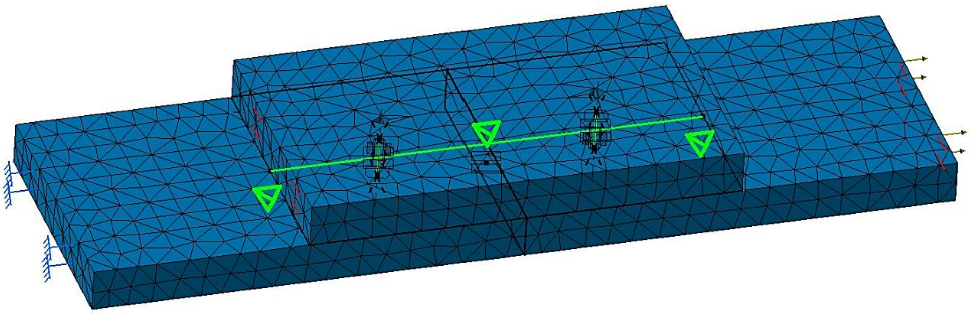

Figure 6: Mesh Visualisation for Lap Joint

Data of the mesh convergence test are shown in Table 2. Figures 7 and 8 show the graph of von Mises stress and displacement from the mesh-dependent test, where the displacement results converged as the mesh density decreased. Based on the mesh tests and using the actual bolt as a reference, the meshing was kept to 4mm element size for the top and bottom plates, and 1mm for bolt meshing. The result of von Misses Stress was 2.91E+06 N/m^2 and 0.304535mm for its displacement on Virtual Bolt Analysis, as compared to 2.55E+07 N/m^2 and 0.323539mm for Bolt Tightening Connection with Actual Bolt Analysis.

Table 2: Mesh Convergence for Virtual Bolt and Actual Bolt analysis

	Virtual Bolt Analysis		**Bolt Tightening Connection with Actual Bolt Analysis**	
Mesh Size	von Misses Stress (N/m^2)	Displacement (mm)	von Misses Stress (N/m^2)	Displacement (mm)
6	2.15E+06	0.297057	2.60E+07	0.313835
5.5	1.69E+06	0.315142	3.43E+07	0.325958
5	1.67E+06	0.300579	2.35E+07	0.317887
4.5	1.48E+06	0.301659	2.51E+07	0.313367
4	2.91E+06	0.304535	2.55E+07	0.323539

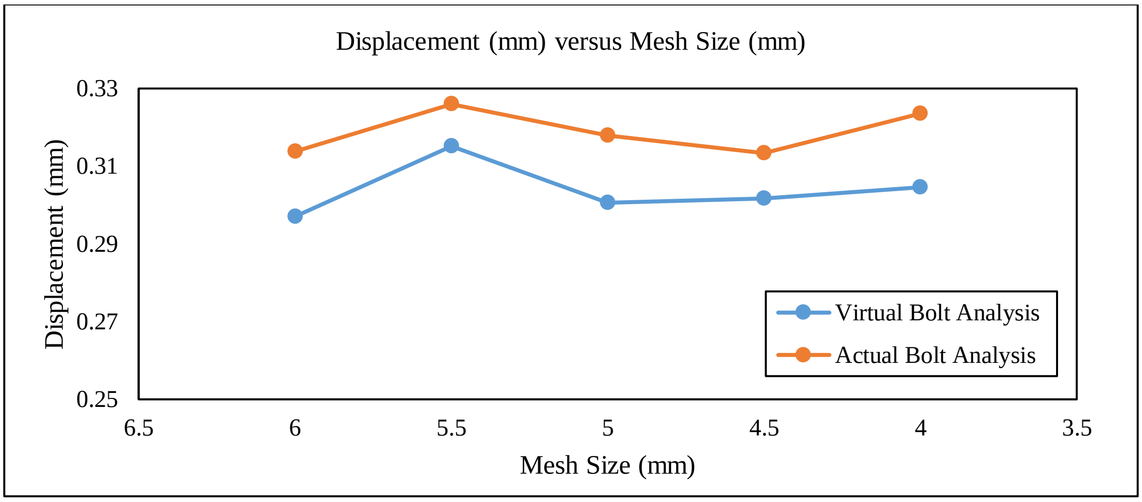

Figure 7: Graph of Displacement (mm) versus Mesh Size (mm)

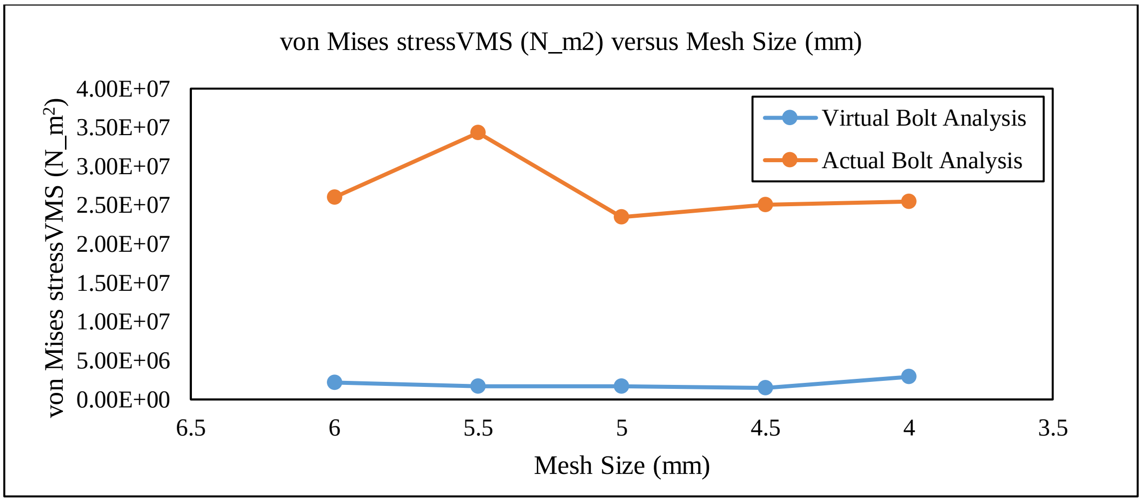

Figure 8: Graph of von Mises stress VMS (N/m2) versus Mesh Size (mm)

3.2 Modelling comparison between virtual bolt analysis and actual bolt analysis

FE analysis on the two connections of lap joints by using Virtual Bolt and Actual Bolt was conducted and the result in the form of von Mises stress (VMS) and displacement was compared. Fig 7. and Fig 8. depict the von Mises stress and displacement of lap joint using the analysis mentioned above with mesh size ranging from 6.5mm to 3.5mm. Meanwhile, Fig. 9, 10 and 11 demonstrate the result analysis of having a Pre-Tension at 0N on actual bolt analysis and Fig. 12, 13, 14 demonstrate the result analysis of having a Pre-Tension at 0N on virtual bolt analysis. The figures show the von Mises Stress, wireframe image and displacement results.

The von Mises stress using Actual Bolt analysis at Pre-Tension of 0N was 2.55E+07 N_m^2 while the analysis for Virtual Bolt was 2.9101E+06 N/m2. The displacement for Actual Bolt was 0.323539 mm and the Virtual Bolt was 0.304535 mm. For Actual bolt analysis, the location for Maximum von Mises stress was at the bolt shank while Virtual Bolt analysis was at the bolt hole. The comparison between the two types of analysis can be seen in Table 3 where in both analyses, different ranges of the pre-tension bolt were applied by ranging it from 0N to 60N.

Bolt Preloading or Pre-Tension Force is the tension created in a fastener when it is tightened. The clamping force is the result of the tensile tension in the bolt creating a compressive force in the bolted joint. The clamping force in an unloaded bolted joint is supposed to be equal to and opposite to the preload for practical purposes. In this study, Pre-Tension forces were applied in the range of 0N up until 60N for both analyses.

From Figure 15, it can be seen that having a Pre-Tension load brings a slight increase in the von Misses Stress. In addition, Figure 13 provides information about von Mises Stress versus Pre-Tension in which both graph analyses move steadily from 0N until 60N, indicating that pre-tension magnitude creates small impact on the von Mises Stress values.

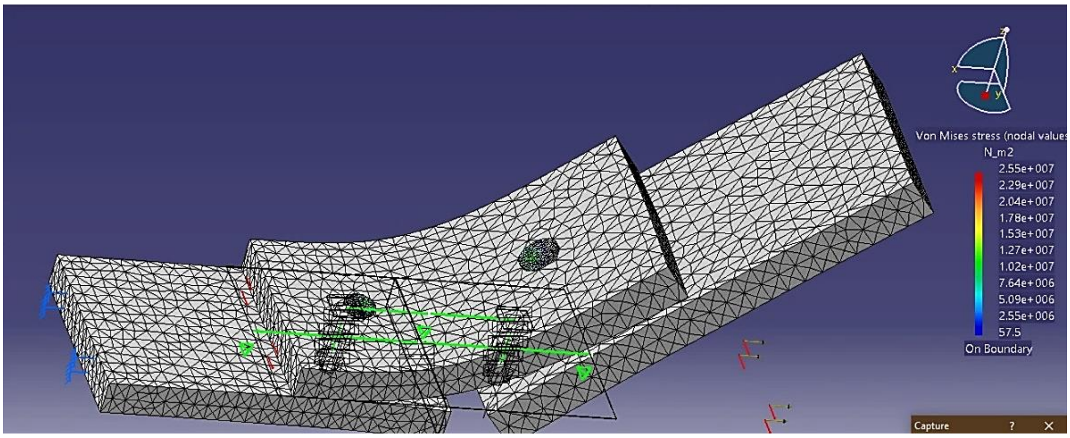

Figure 9: von Misses Stress, VMS of Actual Bolt Analysis at Pre-Tension of 0N

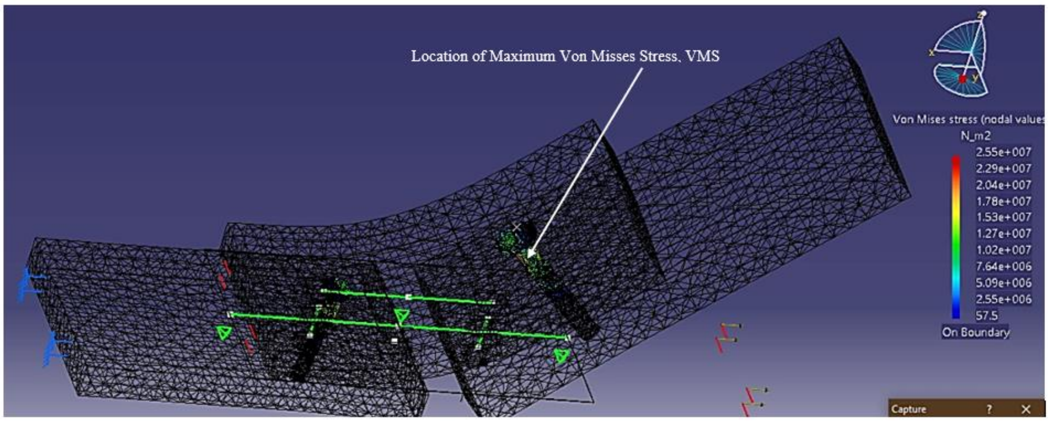

Figure 10: Wireframe image of von Misses Stress, VMS of Actual Bolt Analysis at Pre-Tension of 0N

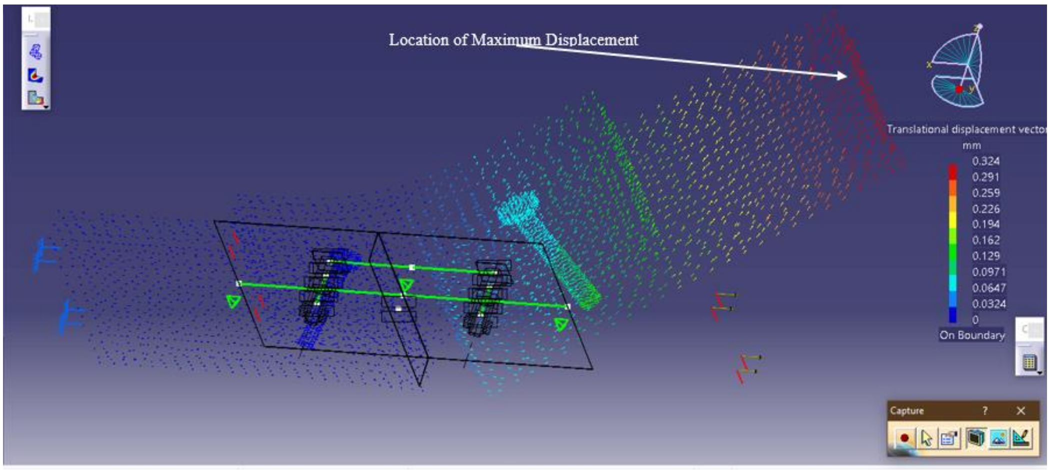

Figure 11: Displacement of Actual Bolt Analysis at Pre-Tension of 0N

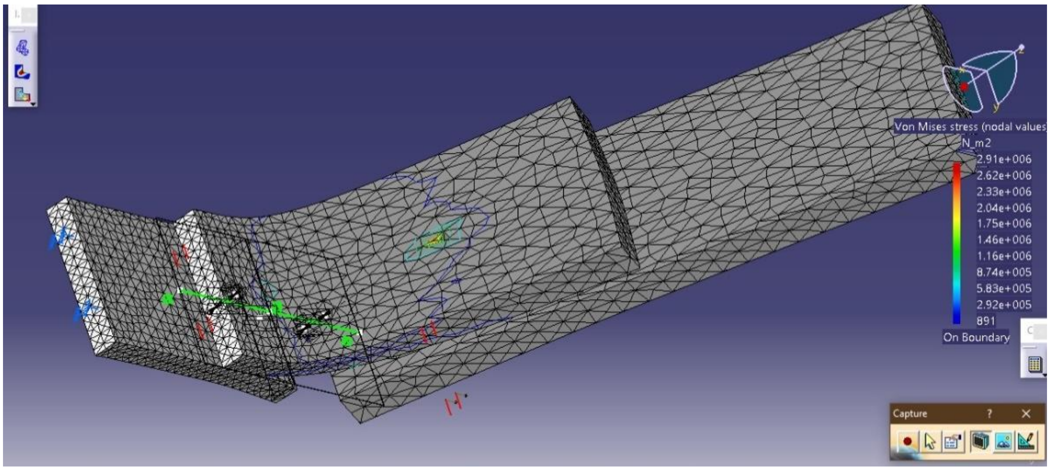

Figure 12: von Misses Stress, VMS of Virtual Bolt Analysis at Pre-Tension of 0N

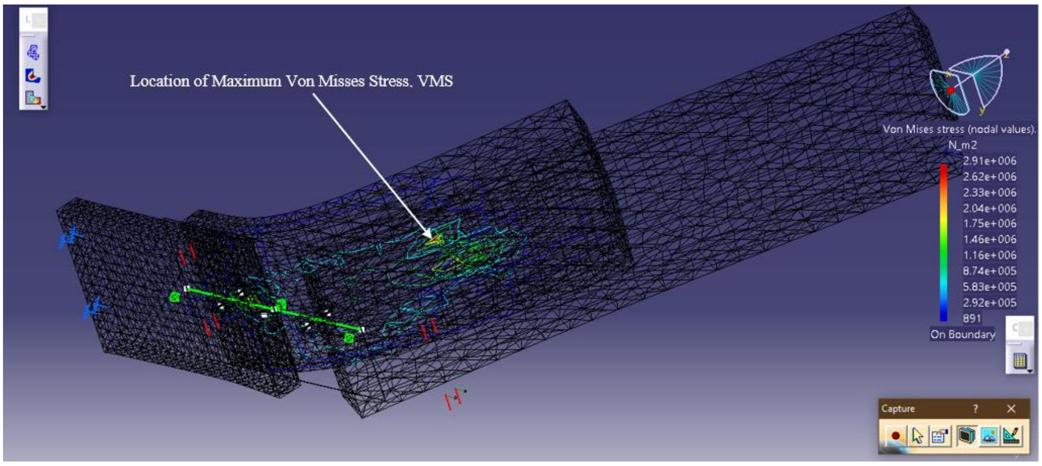

Figure 13: Wireframe image of von Misses Stress, VMS of Virtual Bolt Analysis at Pre-Tension of 0N

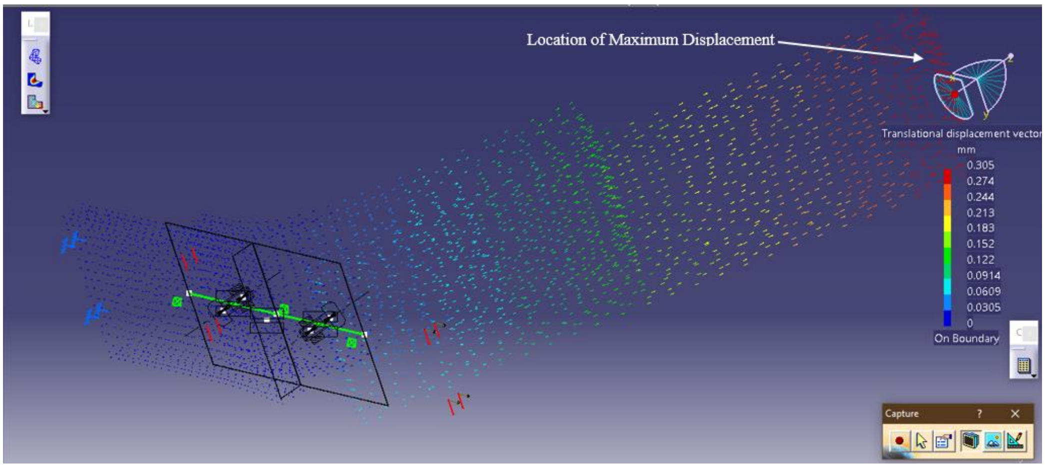

Figure 14: Displacement of Virtual Bolt Analysis at Pre-Tension of 0N

Table 3: Comparison of von Mises stress and displacement under the different pre-tension values of Virtual Bolt analysis and Actual Bolt analysis

	Virtual Bolt Analysis			Actual Bolt Analysis		
Pre-Load (N)	Location of Maximum von Misses Stress	von Mises stress(N/m^2)	Displacement (mm)	Location of Maximum von Misses Stress	von Mises stress(N/m^2)	Displacement (mm)
0	Bolt Hole	2.9101E+06	0.304535	Bolt Shank	2.5500E+07	0.323539
20		2.8906E+06	0.302645		2.5600E+07	0.318432
40		2.9916E+06	0.301011		2.5900E+07	0.313532
60		3.1928E+06	0.29954		2.6200E+07	0.308827
Average		**2.9963E+06**	**0.30193**		**2.5800E+07**	**0.316083**

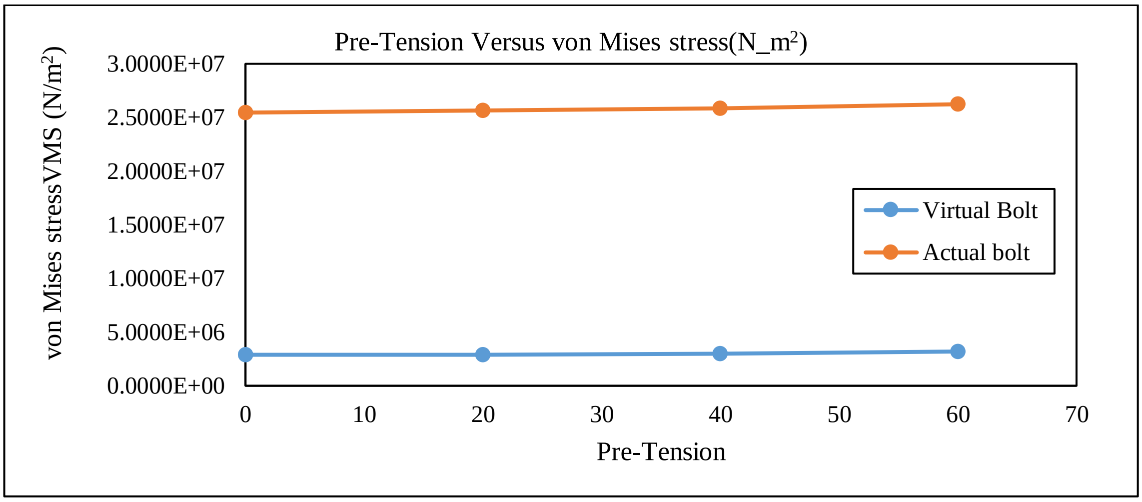

Figure 15: Pre-Tension Versus von Mises stress (N/m^2)

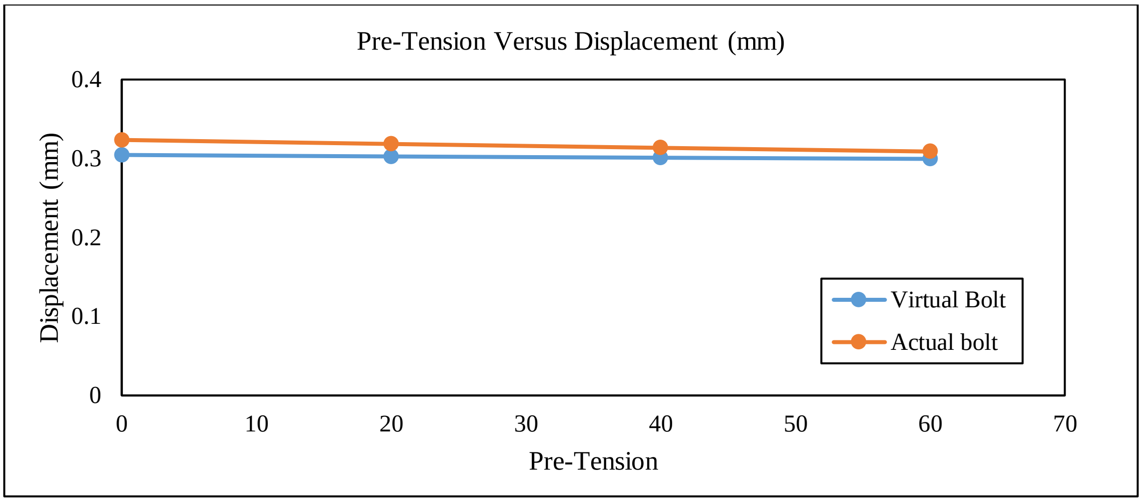

Figure 16: Pre-Tension Versus Displacement (mm)

In Table 3, the overall maximum von Mises Stress for actual bolt analysis was **2.5800E+07 N/m^2** while maximum von Mises Stress for virtual bolt was **2.9963E+06 N/m^2**. The overall maximum displacement value was **0.316083 mm** for actual bolt analysis, whereas the displacement for virtual bolt analysis was **0.30193 mm**. From the data presented above, it can be seen actual bolt analysis with the inclusion of an actual bolt brings a significance result of **158.379% difference.**

4.0 CONCLUSION

The objective of this study, which is modeling comparison of 3D printed lap joint using the actual bolt and virtual bolt, was achieved. FE models of both approaches were built, and analysis was performed. Mesh independence tests were carried out. The effect of Pre-tension on the bolt was investigated. The result showed that the FE model with Actual bolt analysis resulted in higher von Mises stress compared to Virtual Bolt. However, in both analyses, displacement results showed similar values. The effect of Pre-Tension on the bolt in both types of FE models was relatively small.

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