BITARA
Jurnal Pendidikan Bitara UPSI
Universiti Pendidikan Sultan Idris
Sultan Idris Education University
eISSN 2821-3173

# Stress Distribution Study on Alum-Zinc C-Channel Steel with Multi-Bolted Connections: Numerical Analysis

**Khairi Supar[1]*, Nur'Ain Idris[1], Hilton Ahmad[2], Kasbi Basri[3], Mohd Shafie Nemmang[4], Muhammad Fahmi Hasbullah[5]**

[1]Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, 84600 Muar, Johor, Malaysia
[2]Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia
[3]Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[4]Malaysian Institute of Road Safety Research (MIROS), 43000 Kajang, Selangor, Malaysia
[5]Bridge Department, Sarahill Consultant-Khairi Consult JV, 93100 Kuching, Sarawak, Malaysia

***Corresponding author email: khairis@uthm.edu.my**

**ARTICLE HISTORY**
Received: 10th July 2025
Revised: 3rd August 2025
Accepted: 19th August 2025
Published: 15th February 2026

**KEYWORDS**
Finite Element Analysis
Stress Distribution
Multi-bolted Configuration
Alum-Zinc
Abaqus

**ABSTRACT -** This study employs Finite Element Analysis (FEA) using the ABAQUS software to investigate the stress distribution and structural performance of multi-bolted C-channel steel connections. Multi-bolted connections play a vital role in ensuring the strength and stability of steel structures, yet limited research has focused on the comparative behavior of staggered and non-staggered configurations. In this work, numerical models of C-channel plates with varying bolt numbers and arrangements were developed to evaluate tensile strength, stress distribution, and deformation patterns under a 10 kN tensile load. Material properties of aluminum-zinc (Alum-zinc) for the plates and steel for the bolts were applied and contact interactions were simulated to replicate realistic loading conditions. The analysis revealed that non-staggered bolt configurations exhibited superior load-bearing capacity and more efficient stress transfer, while staggered arrangements showed higher stress concentrations near bolt holes. Additionally, increasing the number of bolts enhanced structural performance, but also led to higher localized stresses. These findings provide valuable guidelines for optimizing bolt placement and quantity in C-channel connections. The study contributes to improving the reliability and safety of steel structures by offering practical recommendations for design optimization through numerical modelling.
.

## INTRODUCTION

The performance of multi-bolted connections, particularly those involving C-channel members arranged in various bolt patterns, remains underexplored despite their widespread application in modern construction. This gap restricts the advancement of optimized design recommendations for such joints. Over recent decades, technological progress has significantly enhanced living standards by fostering innovation across products, engineering practices, and services. In structural engineering, the integration of computer-aided design and numerical simulation tools has empowered engineers to efficiently model, analyze, and optimize building structures (Ye et al., 2022). Ongoing improvements in analytical techniques have deepened insights into structural behavior, shortened design cycles, and elevated architectural quality. Construction materials critically influence the durability, safety, and performance of built structures. Among these, Alum-Zinc (AZ) C-channels are favored for their lightweight nature, favorable strength-to-weight ratio, and manufacturability. Multi-bolted connections within AZ C-channel sections are crucial for maintaining structural integrity in industrial and civil

https://doi.org/10.37134/bitara.vol19.sp.11.2026

applications. However, the ideal bolt configuration and the detailed stress responses of such connections remain insufficiently characterized. Furthermore, the adoption of advanced numerical analyses to predict these behaviors, especially in AZ steel members, has been limited, highlighting an important area for further research.

ABAQUS operates as a Finite Element Analysis (FEA) software within the SIMULIA suite which enables users to perform detailed simulations of complex material behaviors (Mater, Shahat, & AbdelSalam, 2023). The software provides flexible modeling capabilities that enable precise analysis of structural components under load conditions, thus making it appropriate for studying bolted steel connections (Ahmad & Supar, 2020). The software enables users to create digital prototypes that duplicate actual structures for cost-efficient and time-effective structural performance testing through numerical simulation. The research employed Abaqus to analyze the tensile behavior of Alum-Zinc C-channel materials. The steel material meets ASTM A194 standards from the American Society for Testing & Materials which applies to high-strength and high-temperature structural components (ASTM International, 2024). The replacement process for bolted joints proves more precise than welding steel structures. The validated numerical analysis enables researchers to perform parametric study which examines how different factors affect tensile and compressive behavior including material characteristics and bolt dimensions and grades and placement and C-channel dimensions and connection types and loading conditions and environmental elements.

The majority of existing research focuses on traditional mild steel and cold-formed sections with single-bolt or welded joints. The current literature shows a significant lack of research about Alum-Zinc coated C-channel sections with multiple bolted configurations especially when comparing staggered to non-staggered bolt arrangements. The impact of Alum-Zinc coating on stress distribution and load transfer and joint performance under tensile forces remains unclear in scientific literature. The current numerical studies fail to demonstrate how different bolt arrangements affect the behavior of coated steel C-channel members. The research requires additional investigation through advanced numerical methods because of these identified knowledge gaps (Chen et al., 2025). The research aims to address this knowledge gap through Abaqus software-based numerical modeling to evaluate tensile strength and stress patterns in multi-bolted Alum-Zinc coated C-channel steel. The research aims to determine the tensile strength of staggered and non-staggered bolt configurations through two-dimensional finite element analysis while examining stress distribution patterns to identify the most suitable design. The structural behavior of C-channels under different physical loadings becomes possible to predict with high accuracy through Finite Element Analysis (FEA) modeling and simulation. Numerical methods enable designers to optimize structural parameters which result in improved durability and efficiency of their designs (Li, Yan, & Guan, 2021). The results depend on three main elements which include material properties and loading scenarios and connection dimensions.

The research findings enhance design recommendations for Alum-Zinc C-channels through better comprehension of their tensile behavior. The research results enable engineers to create multi-bolted connections which maximize safety performance while minimizing costs and ensuring long-term structural stability in actual engineering applications. geometries.

## MATERIALS AND METHODS

C-channel sections are widely used in structural applications such as bridges and roof trusses. Therefore, continuous efforts are needed to improve the strength and performance of C-channel sections. The purpose of this study is to determine the maximum stress in bolted C-channel connections with different bolt arrangements and to compare their behavior under tensile loading. Numerical analysis offers an effective model approach and evaluates the structural response of such members, providing important insights and analysis of their performance under various loading conditions. Finite Element Analysis (FEA) is a robust computational method for numerically solving structural boundary problems. This study uses Abaqus/CAE, a commercial FEA software recognized for its accuracy and versatility, as it provides advanced meshing, contact modeling, and post-processing capabilities for analyzing bolted connections. Abaqus is part of the SIMULIA suite, which has been widely adopted in engineering research for nonlinear stress and strain simulations.

The material properties used in this study are based on the Alum-Zinc C-channel plate and steel bolts. Alum-Zinc coating was chosen due to its widespread use in mild steel systems for improved corrosion resistance and durability, especially in humid or outdoor environments. The Young's modulus values

https://doi.org/10.37134/bitara.vol19.sp.11.2026

for the Alum-Zinc were set to 85 GPa and 200 GPa for steel bolts, with a Poisson's ratio of 0.2, consistent with values reported in previous studies (Li, Yan, & Guan, 2021; Mater, Shahat, & AbdelSalam, 2023). The friction coefficient was included to simulate realistic contact behavior between the connected surfaces. Figure 1 shows the Alum-Zinc C-channel plates were modeled with three, four, and six-bolt arrangements in both staggered and non-staggered configurations. These configurations were chosen to represent typical multi-bolted connections and evaluate how different bolt layouts influence stress distribution. Figure 2 shows the overall dimensions of the Alum-Zinc C-channel (330 mm × 75 mm) with a thickness of 1 mm. The 80 mm length of the overlap region was designated as the lap joint area for the multi-bolted arrangement.

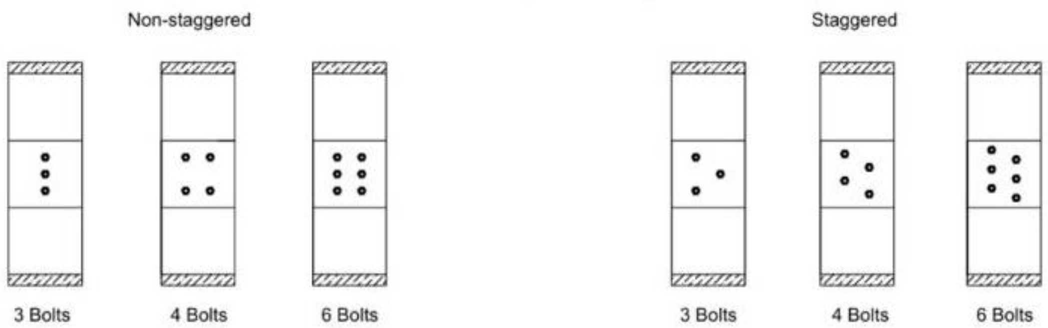



**Figure 1**. Bolt configurations of c-channel Alum-Zinc.

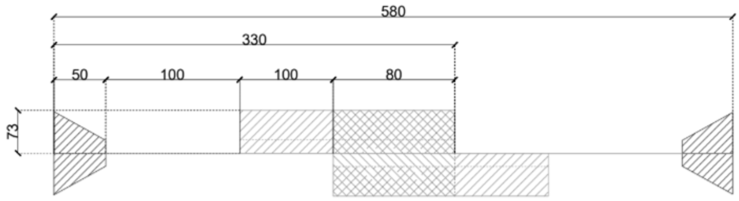



**Figure 2.** Overall dimension

The applied tensile load was set to 10 kN to represent realistic service level load conditions typically experienced by light gauge steel joints in experimental and analytical studies. This load value ensures that the stress distribution in the connection remains within the elastic range of the material, allowing valid comparisons between different bolt configurations while avoiding the effects of nonlinear materials. Numerical analysis in Abaqus follows a standard modeling procedure involving the modules: Parts, Properties, Fittings, Steps, Interactions, Loads, Mesh, Work, and Visualization. The plates and bolts were modeled according to the specified dimensions, with material properties defined and assigned to each component. The plate and bolt were assembled as geometries to analyze the output variables such as stresses, strains, and displacements. The Interaction module modeled the surface contact between the bolts and plates using a defined friction coefficient, and the Load module applied a fixed support on one end of the bolts and a 10 kN tensile load on the opposite end of the plate. The resulting stress and deformation data were analyzed using the Visualization module.

## RESULTS AND DISCUSSION

The stress distribution study has been carried out, and the effects of various parameters were explained in the following section. Stress analysis is an important part of engineering science, as failure of most engineering components is usually due to stress (Supar, Ahmad, & Yussof, 2019). FEA stress analysis study on bolted plates is a detailed examination of the stresses and strains in bolted plate assemblies under various loading conditions using the finite element method. The stress analysis for this study is the effect of the hole boundary and the bolt.

https://doi.org/10.37134/bitara.vol19.sp.11.2026

**Stress Distribution Profile**

FEA is widely used for the efficient analysis of stress distribution in complex structures. By entering geometric parameters, users quickly obtain stress predictions that are important for structural integrity and stability. Figure 3 shows that a higher stress level increases the probability of material failure (Santos, 2013). This study examined the stress distribution in a plate under a 10 kN load, from normal to fracture. This study highlights a significant difference in the stress distribution behaviors between staggered and non-staggered plates subjected to a 10 kN load. The stress distribution graphs indicate a progressive increase in stress from zero to maximum stress, accompanied by simultaneous deformation phases. For plates with staggered bolts, the graph shows a higher maximum stress and a continuous curved line.

In contrast, the graph for the non-staggered bolts showed a crooked line, suggesting a more uneven stress distribution. This difference may be due to the placement of the bolts, which plays a significant role in how the stress is distributed across the plate (Safaei *et. al.*, 2022). Analysis reveals that as the plate is subjected to increasing stress, it enters a plastic deformation phase, resulting in permanent deformation (Santos *et. al.*, 2016). This phase shows that the material will not return to its original shape even if the applied stress is removed. Deformation is evident in both graphs, with the plate stretching and the distance from its normal position becoming measurable. As stress continues to increase with the material reaches its ultimate strength and leads to failure (Supar & Ahmad, 2017).

This analysis highlights the importance of bolt placement in structural design to optimize load-bearing capacity and prevent premature failure (Supar & Ahmad, 2017). The closer a material is to its breaking point, the stronger the material needs to be to prevent catastrophic failure. Material selection, combined with bolt placement, can have a significant impact on the performance and safety of structural components. Therefore, engineers must consider both stress distribution patterns and material properties to design robust and reliable structures (Ahmad, 2016). Analyzing how materials approach their breaking or fracture point under varying conditions is very important to ensure the design of structural integrity and longevity of the components.

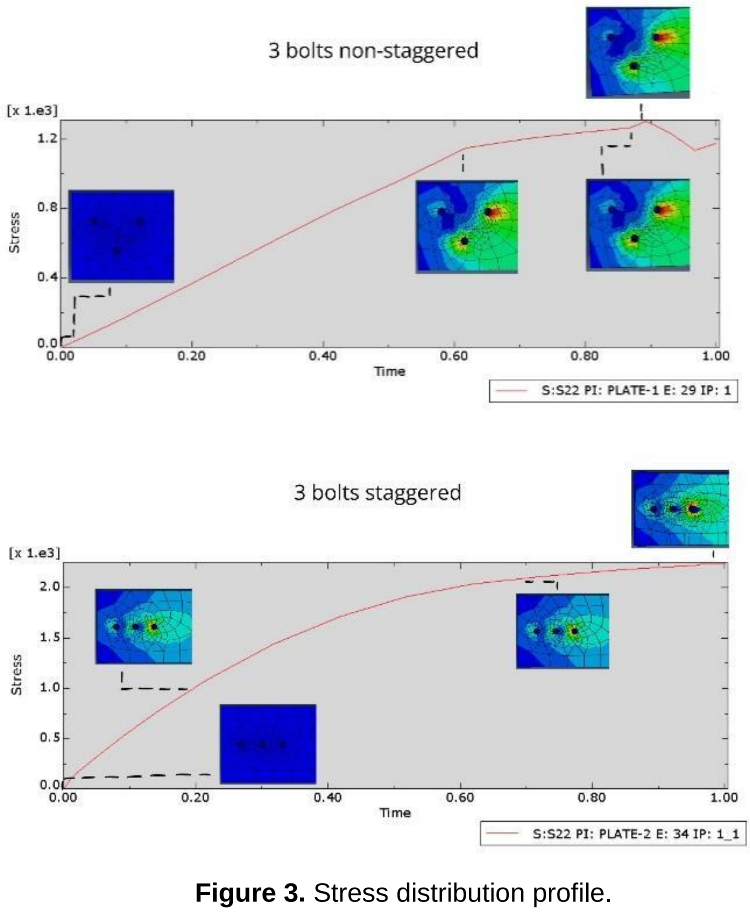
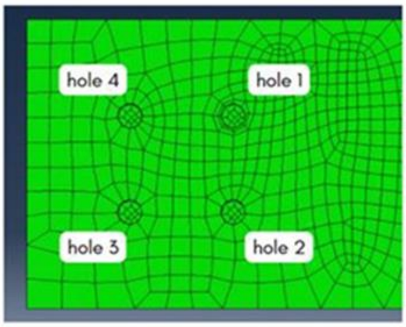



**Figure 3.** Stress distribution profile.

https://doi.org/10.37134/bitara.vol19.sp.11.2026

### Effect of Hole Boundary

The stress analysis of the effect on hole boundaries examines how a structural element's holes affect the distribution and concentration of stress. The stress flow in the material can be greatly changed by holes, and this frequently results in larger stress concentrations near the edges of the holes. The finite element mesh of a plate with four holes labeled as hole 1, hole 2, hole 3, and hole 4 in Figure 4 (a). The mesh is finer around the holes to capture the stress gradients accurately. Figure 4 (b) shows the resulting stress distribution around the hole after application of the load.

(a)


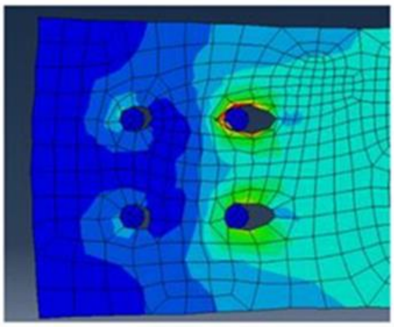

(b)


**Figure 4.** Stress distribution with (a) Meshing of plate alum-zinc; (b) Hole boundary.

From the results obtained in Figure 4, the stress that occurs in hole 1 is symmetrical with hole 2, while the stress that occurs in hole 3 is symmetrical with hole 4, as shown in Figure 5. Holes 1 and 2 have high stress values, which are the holes closer to the applied load. Holes 3 and 4 indicated low-stress values, which are holes that are far from the applied load. Therefore, the higher the distance between the holes and the tension, the lower the stress value obtained.

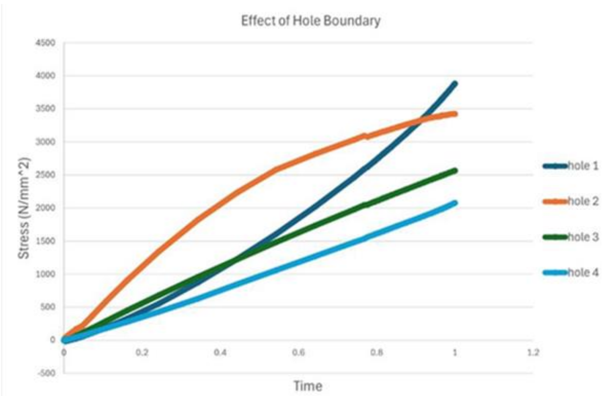



**Figure 5.** Maximum stress on the hole boundary of 4 bolts non-staggered configuration

### Effect Number of Bolts

The bolt hole deforms when the joint experiences an external tensile load. The deformation of bolt may be different based on the non-staggered and staggered arrangement of bolt. This difference may result in dissimilar contact relationships for the bolt and the components during the tensile loading process of the two types of joints (Supar, Ahmad, & Yussof, 2019). The arrangement of the bolt helps distribute the load more evenly across the joint. It reduces the stress concentration on the bolts and the connected plates, which can increase the joint's strength and fatigue resistance. Figure 5 shows the result of the maximum stress value of non-staggered and staggered bolts for three, four, and six bolts. From the result obtained, it is found that the 3-bolt plate has a lower stress value compared to 4 bolt and 6 bolt with a maximum value stress (N/mm$^2$) for non-staggered bolt and N staggered bolt. When there is less bolt, The stress decreased on individual bolt to share the load, and each remaining bolt carry small portion of the total load which cause lower load per bolt. The shear and tensile forces experienced by each bolt are lower, which can lead to a higher likelihood of bolt failure under heavy loading conditions.

https://doi.org/10.37134/bitara.vol19.sp.11.2026

The stress concentration is lower when there are less bolts which causes the plate to fail slowly because the load is evenly distributed across the joint. The lower localized stresses can decrease and accelerate material fatigue, leading to a low risk of crack initiation and propagation around the bolts. As for structural stability, when there is less bolt to distribute the load, it increases the load bearing capacity of the connection. The joint integrity is compromised which means the connection may be less prone to failure under dynamic or fluctuating load. For the comparison between staggered bolt and non-staggered bolt, it is found that non-staggered bolt can withstand greater load than staggered bolt. This is because the lower the stress value, the greater the load it can withstand, which shows it is less prone to failure. From the overall result, the stress distribution profile analysis revealed that the maximum stress occurs at the bolt, indicating potential points of failure under high load conditions. Similar findings were reported by Supar and Ahmad (2017), where larger stress occurred within pitch area in plates with larger holes numbers in double-row configurations. The smaller number of bolts can decrease the value of stress which can improve the load capacity. The staggered configuration distributes stress more evenly, reducing stress concentrations and enhancing load-bearing capacity.

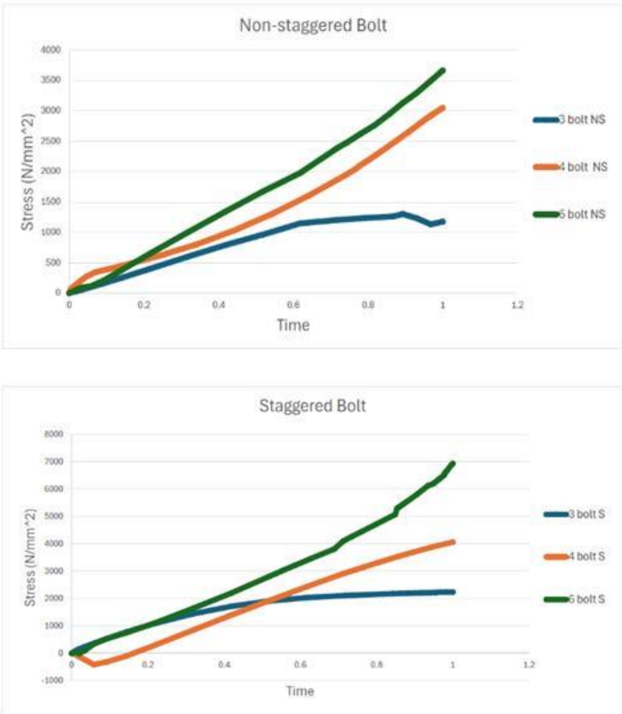



**Figure 6.** Maximum stress on non-staggered and staggered configurations.

## CONCLUSION

In conclusion, this study highlights the effectiveness of using ABAQUS software for numerical modeling and analysis of multi-bolted C-channel connections. By comparing staggered and non-staggered designs, the research identifies key parameters influencing stress distribution. and evaluating their effects on tensile performance and stress concentration. Plates with staggered bolt arrangements show reduced stress concentration and increased joint strength, while plates with a higher number of bolts exhibit improved performance under heavy loading conditions. This indicates that staggered connections are more effective in enhancing load transfer efficiency and reducing localized failure. Moreover, plates with a greater number of bolts exhibited higher load-bearing capacity and improved stiffness, confirming that both the number and arrangement of bolts play critical roles in optimizing joint performance. The findings also verified that Alum-Zinc coated steel provides adequate strength and corrosion resistance, making it a suitable material for lightweight structural systems. The application of ABAQUS FEA proved effective for predicting stress behavior and optimizing design parameters, offering a reliable and economical tool for structural analysis. It should be noted that this study was limited to numerical simulation without experimental validation, and the model adopted simplified

https://doi.org/10.37134/bitara.vol19.sp.11.2026

boundary conditions and linear-elastic assumptions. These simplifications were necessary to reduce computational complexity but may affect the accuracy of stress prediction under real service conditions. Future work should therefore include experimental testing to validate the numerical findings and extend the analysis using three-dimensional (3D) finite element models in ABAQUS to capture out-of-plane effects and more complex stress interactions. High-strength bolts and compatible steel materials should be used to enhance load-bearing capacity and durability, while ensuring material compatibility to prevent issues like galvanic corrosion. Further investigations using screw-type or hybrid connections are also recommended to evaluate alternative fastening mechanisms and their influence on joint performance, durability, and load transfer efficiency in Alum-Zinc C-channel systems.

## ACKNOWLEDGEMENT

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme – Early Career (FRGS-EC/2024/TK06/UTHM/03/4) (FRGS-EC Vot. K562) and Geo-Structural Engineering and Technology (GSET) focus group, Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia in providing financial support.

## CONFLICT OF INTEREST

The authors declare that there are no financial or non-financial conflicts of interest, including political, personal, or professional relationships, that could have influenced the work reported in this manuscript.

## AUTHORS CONTRIBUTION

All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

**Khairi Supar.**: Conceptualization, Methodology, Numerical Modeling, Formal Analysis, Writing – Original Draft Preparation. **Nur'Ain Idris.**: Data Curation, Validation, Software. **Hilton Ahmad.**: Supervision. **Kasbi Basri.**: Methodology Review, Writing – Reviewing and Editing. **Mohd Shafie Nemmang.**: Technical Advisory, Validation, Writing – Reviewing and Editing. **Muhammad Fahmi Hasbullah.**: Industry Input, Practical Interpretation of Results, Writing – Reviewing and Editing.

## AVAILABILITY OF DATA AND MATERIALS

Data available on request from the authors.

## DECLARATION OF GENERATIVE AI

During the preparation of this work, the authors used ChatGPT (OpenAI) to enhance the clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## ETHIC STATEMENTS

Not applicable.

https://doi.org/10.37134/bitara.vol19.sp.11.2026

## REFERENCES

Ahmad, H. (2016). Stress distribution of bolted joints with different lay-up types. In MATEC Web of Conferences (Vol. 74, p. 00003). EDP Sciences. https://doi.org/10.1051/matecconf/20167400003

Ahmad, H., & Supar, K. (2020). Strength predictions of single-lap woven fabric Kenaf composites bolted joints. Journal of Mechanical Engineering and Sciences, 14(4), 7389-7395. https://doi.org/10.15282/jmes.14.4.2020.07.0581

ASTM International. (2024). ASTM A194/A194M-24: Standard specification for carbon and alloy steel nuts for bolts for high pressure or high temperature service, or both. ASTM International. https://doi.org/10.1520/A0194_A0194M-24

Chen, Y., Yamaguchi, T., Hayashi, G., Yamauchi, M., & Ueno, K. (2025). Load transfer mechanism and design strength of hybrid bolted joint with friction-and bearing-type connections. Structures, 71, 108020. https://doi.org/10.1016/j.istruc.2024.108020

Ye, J., Quan, G., Kyvelou, P., Teh, L., & Gardner, L. (2022). A practical numerical model for thin-walled steel connections and built-up members. Structures, 38(4), 753–764. https://doi.org/10.1016/j.istruc.2022.02.028

Li, C. H., Yan, J. B., & Guan, H. N. (2021). Finite element analysis on enhanced C-channel connectors in SCS sandwich composite structures. Structures, 30, 818-837. https://doi.org/10.1016/j.istruc.2021.01.050

Mater, Y. M., El Shahat, A. M., & AbdelSalam, S. S. (2023). Experimental and numerical characterization of EPS using elastoplastic response in ABAQUS. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2023.06.295

Safaei, B., Pezeshki, Z., Kotrasova, K., & Kormanikova, E. (2022). Analysis of stress concentration at the edge of hole in plates with different widths by using FEM. IOP Conference Series: Materials Science and Engineering, 1252(1), 012067. https://doi.org/10.1088/1757-899X/1252/1/012067

Santos, A. (2013). Determination of stress concentration factors on flat plates of structural steel. Journal of Physics: Conference Series, 466(1), 012035. https://doi.org/10.1088/1742-6596/466/1/012035

Santos, A., Guzman, R., Ramirez, Z., & Cardenas, C. (2016). Simulation of stress concentration factors in combined discontinuities on flat plates. Journal of Physics: Conference Series, 743(1), 012014. https://doi.org/10.1088/1742-6596/743/1/012014

Supar, K., & Ahmad, H. (2017). Stress distribution study on multi-holes configurations in woven fabric kenaf composite plates. In IOP Conference Series: Materials Science and Engineering, 271(1), 012005. https://doi.org/10.1088/1757-899X/271/1/012005

Supar, K., Ahmad, H., & Yussof, M. M. (2019). XFEM modelling in multi-bolted joints using a unified bolt preload. Latin American Journal of Solids and Structures, 16(1), e151. https://doi.org/10.1590/1679-78255201

https://doi.org/10.37134/bitara.vol19.sp.11.2026