

Comparative Analysis of Corner Joint Designs for Modular Housing Structures

Muhamad Syafiq Aiman Mohd Zamzuri¹, Mohammad Sukri Mustapha^{2*},
Mohd Rasidi Ibrahim²

¹ Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, MALAYSIA

² Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Johor, MALAYSIA

*Corresponding Author: sukri@uthm.edu.my

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Abstract

This study examines the structural performance of three modular house joint designs using SolidWorks for CAD modelling and ANSYS for static analysis. Emphasizing modular housing's benefits in emergency scenarios, the joints were evaluated for equivalent stress, shear stress, deformation, and safety factors using A36 carbon steel, stainless steel, and aluminium alloy. Results indicate Joint 2 as the optimal choice for roof and base connections, with A36 carbon steel emerging as the best material overall. These findings highlight the importance of joint design and material selection in enhancing the resilience and adaptability of modular structures.

1. Introduction

The rising demand for efficient and sustainable housing solutions has led to significant advancements in the field of modular construction. Modular houses, constructed off-site and assembled on location, offer numerous advantages over traditional building methods, including reduced construction time, lower costs, and minimized environmental impact. These benefits make modular homes particularly attractive for addressing urgent housing needs in emergency situations, such as natural disasters and refugee crises.

The structural integrity of modular houses heavily relies on the design and performance of their joints, which connect the prefabricated modules. Proper joint design ensures the structure's stability, durability, and safety. Various joint designs have been proposed and studied, focusing on self-aligning mechanisms, interlocking systems, and high-strength materials like carbon steel (A36). These designs aim to enhance the ease of assembly, reduce labour costs, and improve the overall performance of modular houses.

This study investigates the performance of three distinct joint designs used in modular housing structures. Each joint was modelled and subjected to static analysis using ANSYS simulation software, focusing on key parameters such as equivalent stress, shear stress, deformation, and safety factors. By comparing these parameters, the study aims to identify the most effective joint design for modular houses regarding structural integrity and resilience under load.

Furthermore, the study also explores the role of bolts in joint assembly, examining the impact of different bolt types and sizes on joint performance. Bolts are a critical component in ensuring the secure connection of modular units, and their selection can significantly influence the overall safety and reliability of the structure.

In the context of emergency housing, modular houses must meet stringent standards for rapid deployment, adaptability, and robustness. This research contributes to the body of knowledge by providing insights into the optimal joint designs and material selections for modular homes, thereby supporting the development of more resilient and sustainable housing solutions for those in need.

2. Literature review

2.1 Introduction to Modular Construction

Modular construction has garnered significant attention recently as an environmentally friendly and efficient alternative to traditional on-site building methods. A vital aspect of modular house design is the joint system that connects the individual modules to create a unified structure. This literature review delves into current research on joint design for modular houses, emphasizing the significance of joints, design considerations, and recent advancements in joint technologies [1][4][6].

2.2 Importance of Joints

Joints are crucial for the strength and performance of modular houses. A well-designed joint ensures that the modules are securely connected and can effectively transfer loads and forces between them [1]. On the other hand, poorly designed joints can result in structural failures, leaks, and other issues, jeopardizing the safety and longevity of the modular house [1].

2.3 Design Considerations

When designing joints for modular houses, we need to consider several factors. These include load-bearing capacity, ease of assembly, and accessibility for maintenance [3]. The joint design should also account for potential movements and deformations caused by factors such as wind, seismic activity, and temperature changes [1]. Additionally, the joints should be designed to minimize the risk of water infiltration and air leakage, ensuring the energy efficiency and comfort of the modular house [5].

2.4 Material Selection for Modular House Joints

Carbon steel is a highly preferred material for modular building structural components and joints. It is used to form the portal steel frame system and load-bearing elements in modular construction [4]. Carbon steel is preferred over hot-rolled steel in modular buildings as it can enhance the sustainable performance of the modular building system [4].

2.5 Recent Advancements in Joint Technologies

Researchers have been exploring various approaches to improving the design and performance of modular joints. One such approach is the development of self-aligning joints that facilitate faster and more accurate module assembly [1].

2.6 Structural Analysis Techniques for Joint Design

Ensuring the integrity of modular house joints necessitates rigorous structural analysis. The Finite Element Method (FEM) is a numerical technique widely used for this purpose, capable of simulating complex structural behaviours under various load conditions. ANSYS software, a leading tool in FEM analysis, provides comprehensive capabilities for assessing the performance of joint designs. Previous studies have explored the structural response of modular buildings, with research focusing on the design and mechanical properties of new modular joints. These findings underscore the importance of structural analysis in developing reliable and robust joint designs [5].

2.7 Applications and Challenges in Emergency Housing

Modular housing is vital in providing quick and efficient solutions to emergencies, such as natural disasters and refugee crises. Case studies highlight the deployment of modular housing in disaster relief efforts and refugee camps. However, challenges remain in terms of logistics, resource availability, and infrastructure. Robust joint design is essential to ensure the stability and safety of modular houses in these applications, emphasizing the need for thorough research and development in this area.

2.8 Summary

This literature review has explored various modular house joint design aspects, including material selection, structural analysis techniques, and optimization methods. Key gaps in existing research have been identified, particularly in using advanced materials and optimizing joint strength. The current study aims to address these gaps by exploring innovative joint designs and materials, contributing to developing more resilient and adaptable modular housing solutions.

3. Methodology

Throughout the design and development of the corner joint design for the modular housing structure, the research flowchart shown in Figure 1 is used to represent the overall workflow. This comprehensive workflow follows a systematic and detailed process, ensuring each phase is meticulously executed for optimal results.

Initially, the task clarification phase is critical, as it ensures a clear and precise understanding of the requirements and objectives of the project. All relevant parameters, design criteria, and performance goals are thoroughly discussed and documented during this phase. This foundational step sets the stage for the subsequent phases by establishing a solid framework based on the specific needs and constraints of the project. Following task clarification, the next phase involves the conceptual design and preliminary analysis. Here, various design concepts are generated, evaluated, and refined. These preliminary designs are subjected to basic stress and load calculations to determine their feasibility. The goal is to narrow down the potential designs to those that show the most promise in meeting the established requirements.

The preliminary designs undergo detailed structural analysis using advanced simulation software like ANSYS Workbench to assess structural integrity and safety. Analysis focuses on key performance metrics, including Von-Mises stress, total deformation, shear stress, and factor of safety. Results are reviewed and compared against design criteria, and modifications are made to enhance performance. The final phase involves validation and verification through rigorous testing and validation under real-world conditions to meet safety standards. This systematic workflow ensures a thorough and methodical approach to designing and developing the corner joint for the modular housing structure.

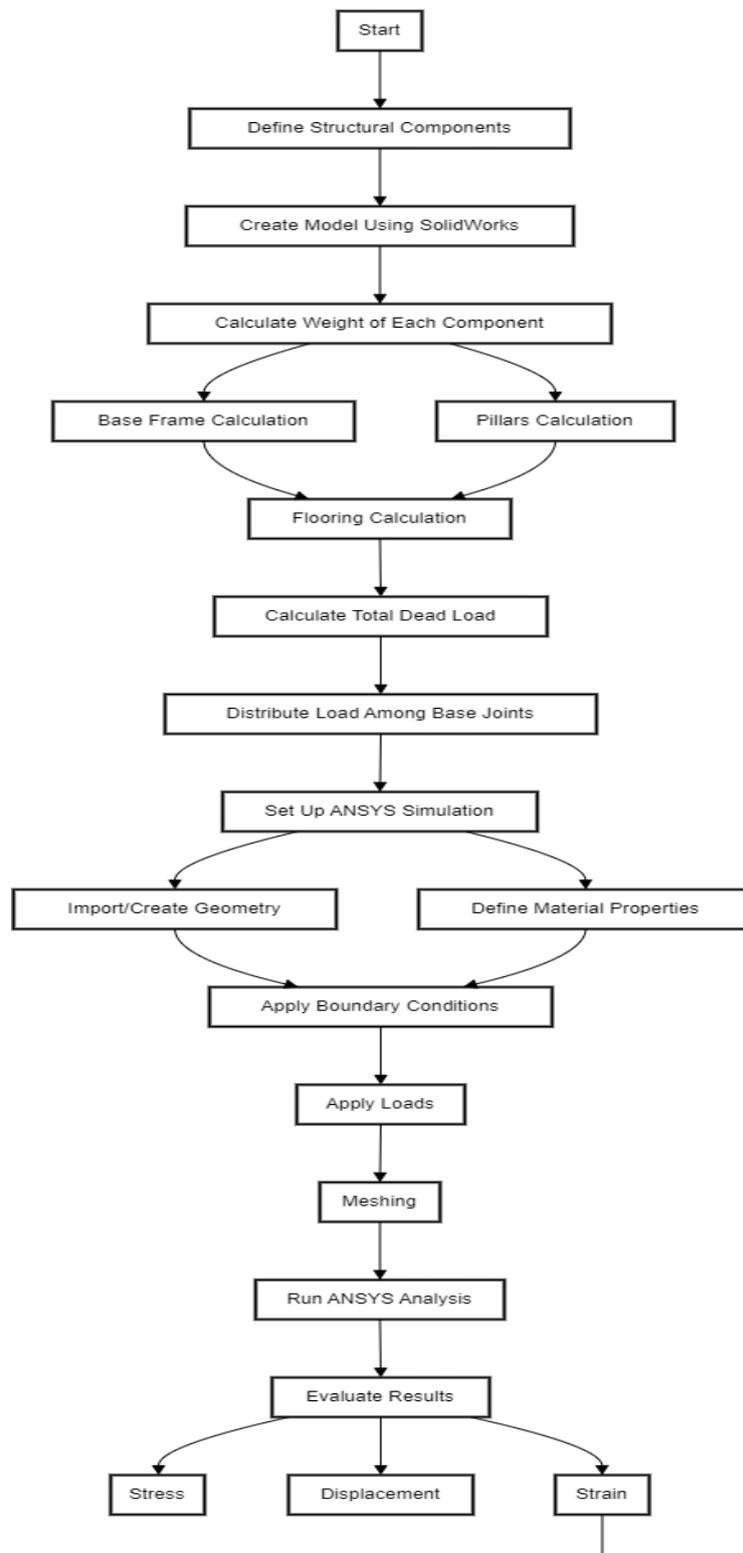


Figure 1 Flowchart

3.1 Structural Analysis

Before initiating any of the simulations, the first critical step is calculating the load that will be applied to the joint. In this project, the dead load is the primary load, which is uniformly applied to each joint design.

Each joint design is prepared with fixed supports to ensure accurate and consistent analysis. These fixed supports are applied to all the bolt holes, securing the joint and preventing movement. Additionally, for the base face of each joint, a fixed support is applied to simulate the real-world conditions accurately and maintain structural stability during the simulation process. This setup ensures that the simulation results reflect the actual performance and behaviour of the joint under the calculated load conditions.

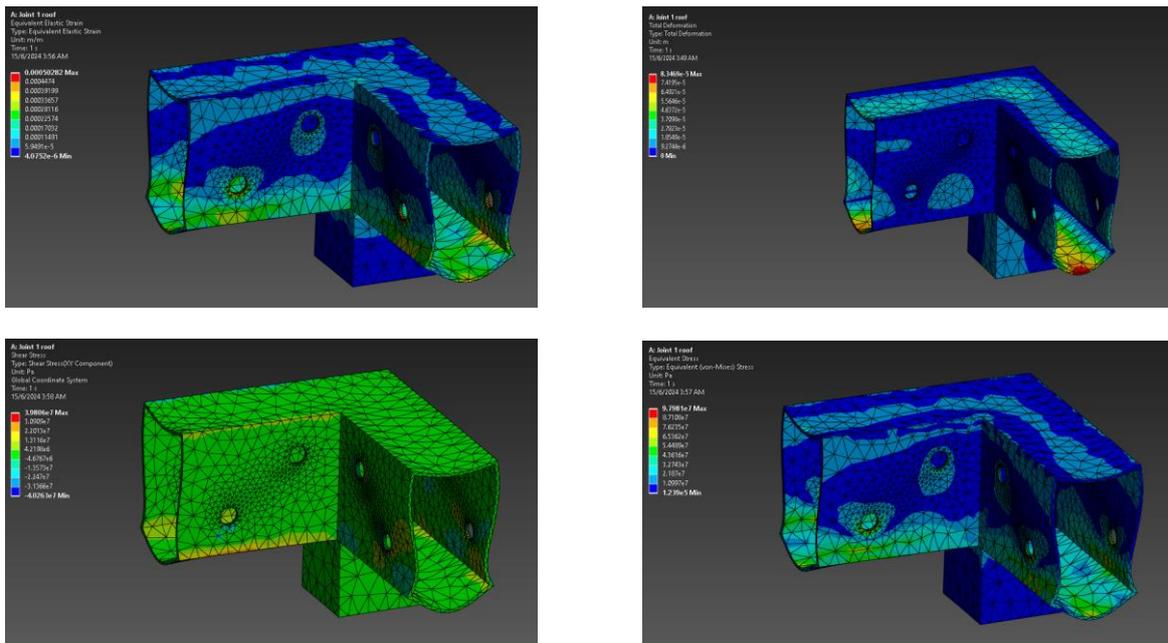
Based on the detailed static structural analysis of all three joint designs, we have evaluated the total deformation, equivalent elastic strain, equivalent (von-Mises) stress, and shear stress for both the roof and base joints. The comparison indicates that Joint 2 stands out as the best design.

Table 1 Load Distribution

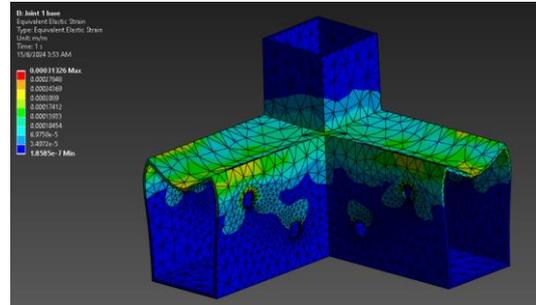
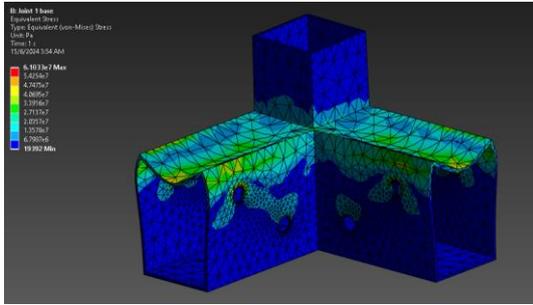
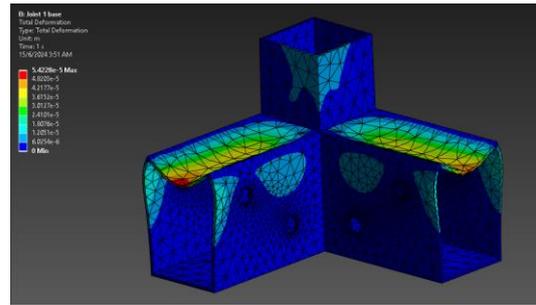
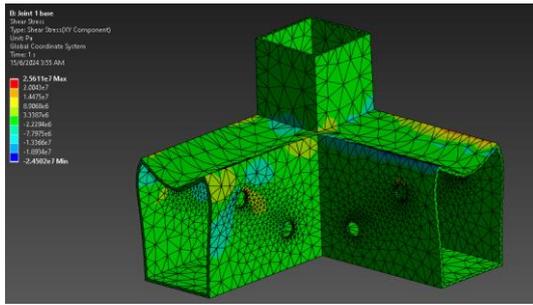
Component	Dimensions (m)	Volume (m3)	Weight (kg)	Force (N)
Base Frame	2" x 3" x 2 mm	0.18288	1435.6	14078.1
Upper Frame	2" x 2" x 2 mm	0.146304	1148.50	11267
Roof (Zink + C channel steel)	18.58 m2 (area)	0.082442	640.862	6300
Total Dead Load	N/A	N/A	N/A	21505
Load Per Roof Joint	N/A	N/A	N/A	4392
Load Per Base Joint	N/A	N/A	N/A	7917

4. Result and Discussion

Joint 1 Roof & Base Analysis:

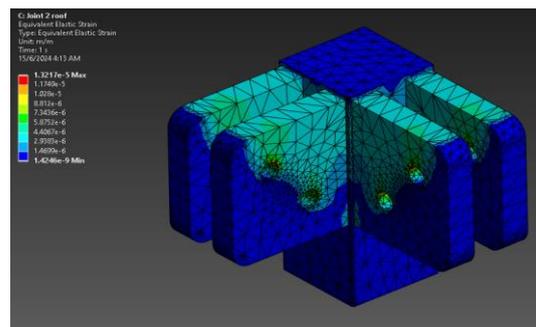
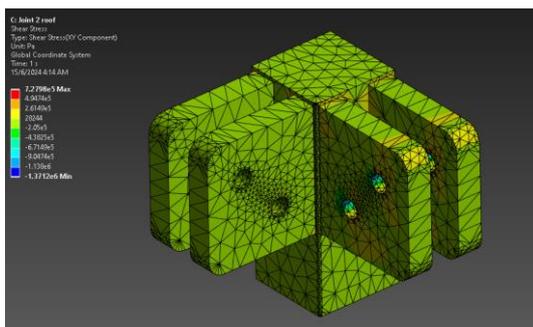
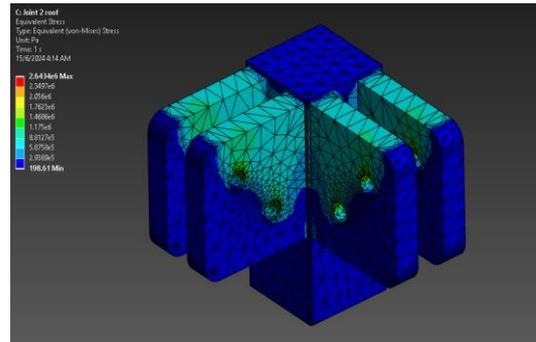
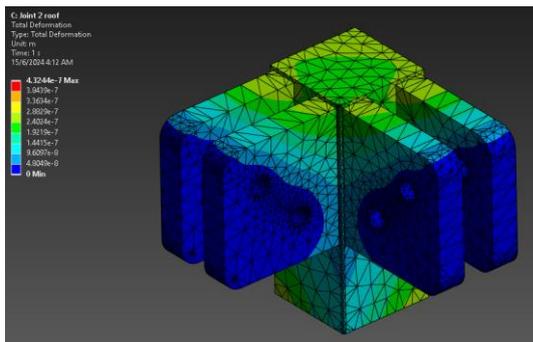


Joint 1 for the roof shows a maximum total deformation of 8.3469e-05 meters, which is relatively high compared to the other joints. The maximum equivalent elastic strain recorded is 5.0282e-04 m/m, indicating a higher likelihood of elastic deformation under load. The equivalent (von-Mises) stress reaches a maximum of 9.7981e+07 Pa, while the shear stress is 3.9806e+07 Pa. The safety factor for the Joint 1 roof has a minimum value of 2.3849, suggesting a moderate margin of safety under the applied load.



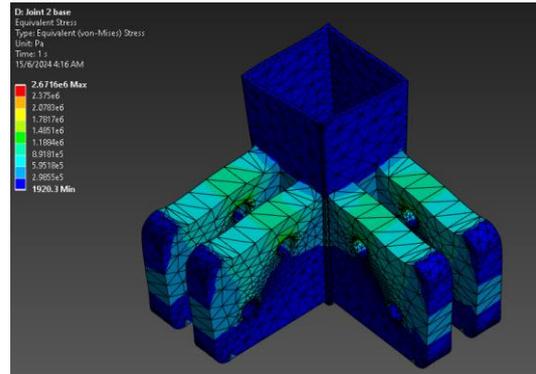
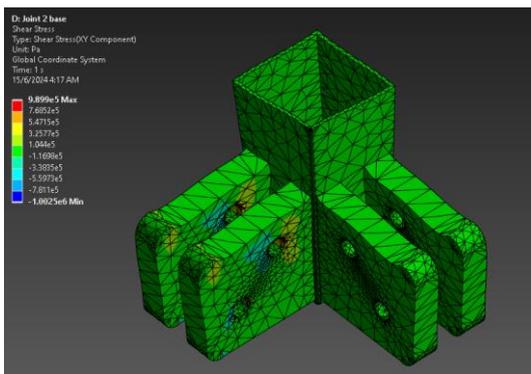
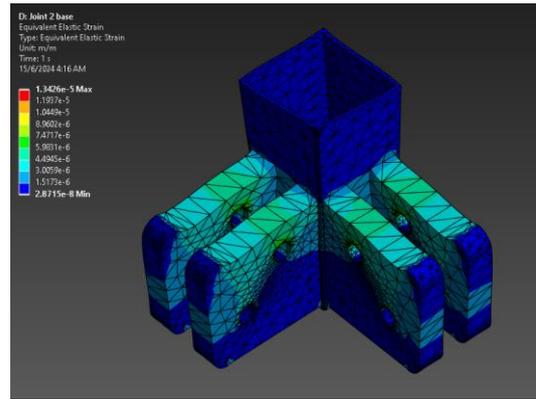
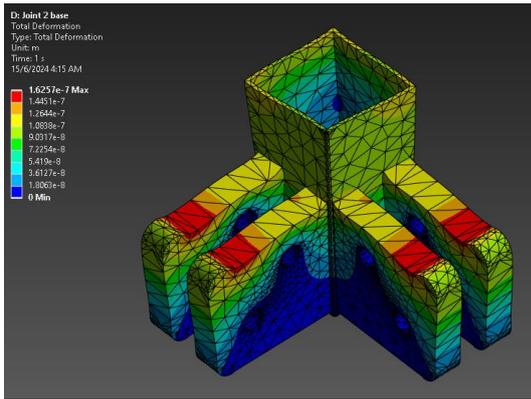
For Joint 1 at the base, the maximum total deformation recorded is 5.4228×10^{-5} meters. The maximum equivalent elastic strain is 3.1326×10^{-4} m/m. The equivalent (von-Mises) stress and shear stress are 6.1033×10^7 Pa and 2.5611×10^7 Pa, respectively. The minimum safety factor is 2.2714, indicating a similar safety margin to the roof joint but higher stress values than the other joints.

Joint 2 Roof & Base Analysis:



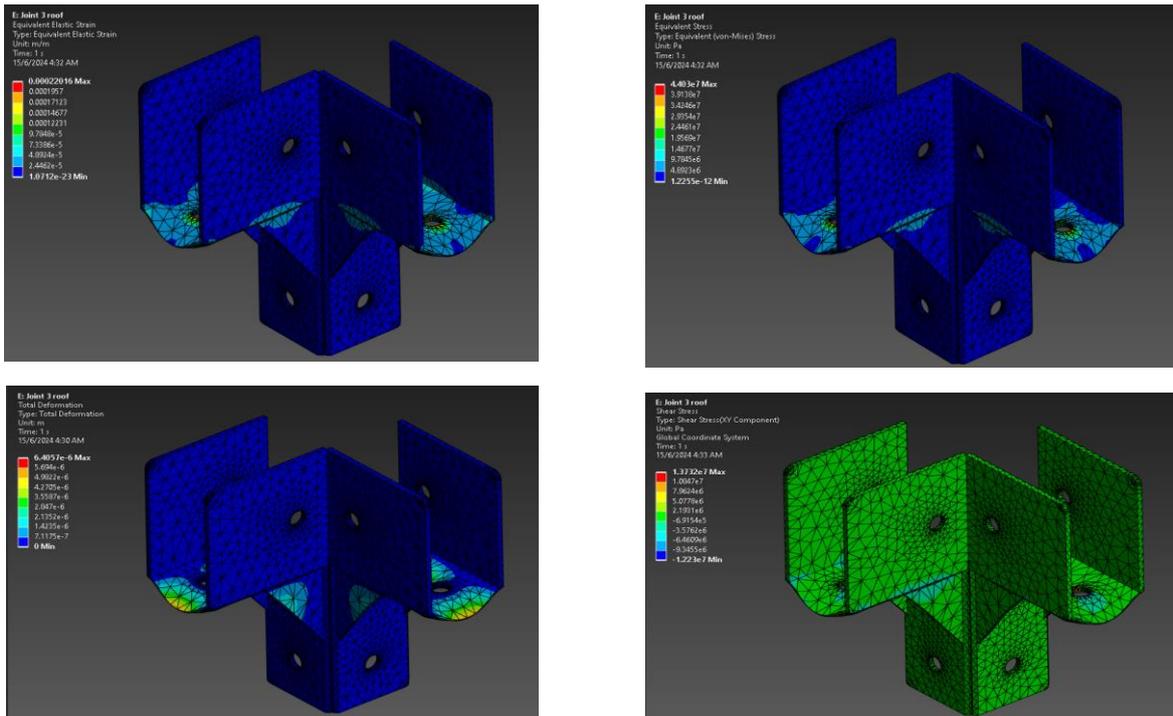
Joint 2 for the roof demonstrates superior performance with a maximum total deformation of just 4.3244×10^{-7} meters. The maximum equivalent elastic strain is significantly lower at 1.3217×10^{-5} m/m. The equivalent (von-Mises) stress and shear stress are also much lower, with maximum values of 2.643×10^6 Pa and 7.278×10^5 Pa, respectively.

7.2798e+005 Pa, respectively. This indicates that Joint 2 undergoes minimal elastic deformation and stress under applied loads.

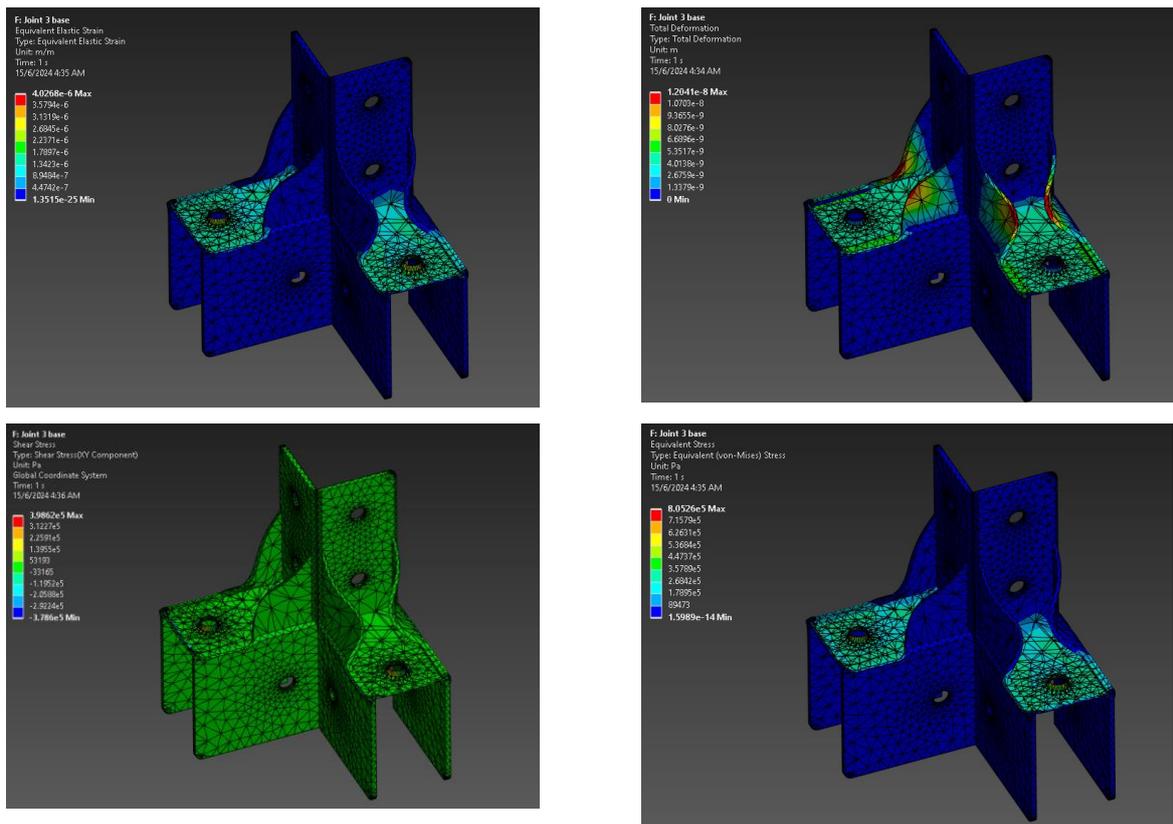


For Joint 2 at the base, the performance remains strong with a maximum total deformation of 1.6257e-007 meters and a maximum equivalent elastic strain of 1.3426e-005 m/m. The equivalent (von-Mises) stress is 2.6716e+006 Pa, and the shear stress is 9.899e+005 Pa. These values confirm that Joint 2 maintains a lower stress and strain profile, contributing to its stability and reliability.

Joint 3 Roof & Base Analysis:



Joint 3 for the roof shows a higher maximum total deformation of 6.4057e-06 meters. The equivalent elastic strain reaches 2.2016e-04 m/m, while the equivalent (von-Mises) stress is 4.403e+07 Pa. The maximum shear stress recorded is 1.3732e+07 Pa. These values suggest that Joint 3, while performing better than Joint 1, still falls short of the performance seen in Joint 2.



The base analysis for Joint 3 indicates a maximum total deformation of 1.2041e-008 meters. The equivalent elastic strain is 4.0268e-006 m/m, and the equivalent (von-Mises) stress and shear stress are

8.0526e+005 Pa and 3.9862e+005 Pa, respectively. Joint 3 shows improved performance over Joint 1 but does not surpass Joint 2.

5. Conclusion

Conclusion and Justification:

Best Joint Design: Joint 2

The best joint design is Joint 2 due to its superior performance across critical factors. Firstly, it shows the lowest total deformation for the roof and base, indicating better stiffness and minimal displacement under load, improving structural integrity and stability. Moreover, it exhibits lower maximum equivalent elastic strain values, suggesting that the material stays within the elastic range, avoiding significant plastic deformation. Additionally, Joint 2 has the lowest maximum equivalent (von-Mises) stress values, indicating lower yield risk and higher safety under applied loads. Furthermore, it demonstrates the lowest shear stress values, implying better resistance to internal shear forces, which is crucial for joint stability. Even though the exact minimum safety factor for Joint 2 was not provided, all other criteria strongly indicate that it maintains high safety margins under operational conditions. Overall, Joint 2 is the best choice for ensuring the structural integrity and safety of the modular house joints, thanks to its excellent performance across all crucial parameters, including deformation, strain, stress, and shear resistance.

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