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Modeling and Simulation of Two Plates Connected Via a Single Riveted Lap-Joint

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ABSTRACT

Rivets and riveted lap joints are important mechanical fasteners that are used in a large variety of applications, and their performance depends on many parameters. The goal of this study is to model and simulate two plates joined together by a riveted lap joint. Four configurations were used, which are 2-vertical, 2-horizontal, 4-inline and 4-staggered configurations, and diameters of 0.2 cm to 0.4 cm were also used. The plate was subjected to forces ranging between 2000 N to 8000 N. Results have shown that the 4-inline configuration was the best due to its lower stresses than the other configurations, followed by the 2-vertical configuration. The 2-horizontal and 4-staggered configurations had the worst performance and had similar performance. Stresses produced by the forces had a linear relationship with the magnitude of force. Finally, the results showed that the best rivet design was the 4-inline configuration with a diameter of 0.4 cm, since increasing the diameter beyond that had a much lower benefit.

Keywords: : single lap-joint, finite element analysis, stress distribution.

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نمذجة ومحاكاة لوحين متصلين عبر مفصل حضني مفرد البرشمة

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ملخـــــــص البحـــــــث

تعتبر مسامير البرشام والمفاصل المثبتة ببرشام من المثبتات الميكانيكية المهمة وتستخدم في الكثير من التطبيقات ويعتمد أداؤها على العديد من العوامل. الهدف من هذا البحث هو نمذجة ومحاكاة لوحين مرتبطين ببعضهما البعض بواسطة مفصل مثبّت ببرشام باستخدام برنامج المحاكاة (ANSYS Static Structural v15) ودراسة تأثير قطر البرشام وتوزيعه تحت أحمال قوة مختلفة ودراسة الإجهاد المكافئ المتولدة من هذه القوة. تم استخدام أربعة توزيعات وهي 2-

عمودي و2–أفقي و4–مضمنة و4–متداخلة وقطر برشام يتراوح من 0.2سم إلى 0.4 سم. تعرضت اللوحة لقوى تتراوح بين 2000 نيوتن و800 نيوتن. تم اختيار التشبيك المستخدم في هذه الدراسة بناءً على دراسة استقلالية التشبيك لضمان اختيار الشبكة الأكثر كفاءة. أظهرت النتائج أن توزيع 4–مضمنة كان أفضل توزيع نظر لوجود إجهادات أقل من التوزيعات الآخر متبوعًا بالتوزيع 2–عمودي. كان لتوزيع 2–أفقي و4–متداخلة أسوأ أداء وكان أدائهم متماثل. كان للقطر تأثير إيجابي على أداء البرشام حيث أدت زيادة القطر إلى انخفاض في الإجهادات المتولدة. الإجهادات المتولدة لها علاقة خطية بشدة القوى القوة. أخيرًا أظهرت النتائج أن أفضل توزيع للبرشام كان التوزيع 4–مضمنة بقطر 0.4 سم نظرًا لأن زيادة القطر إلى ما بعد ذلك كان له فائدة أقل بكثير.

الكلمات الدالة: مفصل حضني مفرد البرشمة ، تحليل العناصر المحدودة ، توزيع الإجهاد.

1. Introduction

Rivets are permanent, non-threaded one-piece fasteners that join two components of an assembly by placing the rivet into a pre-drilled hole and deforming the head of the rivet on one side mechanically to hold the components together. Rivets have a wide range of applications, such as joining aircraft, boilers, ships and car components among other things [1]. Rivets tend to be used over other joining methods, such as bolts, because they are far cheaper to install, and the process can be automated with a single automated riveting machine that can install thousands of rivets every hour. Rivets are made out of three main components, which are made up of a head and shank, which are placed into the material that are to be joined and a second head that fastens the other side of the hole. The act of forming the second head is called setting the rivet [1]. When it comes to manufacturing of rivets, ductile materials such as carbon steel, aluminum and its alloys and brass are used. The chosen material for the rivet is usually matched to the component to lower the corrosion rate and achieve maximum strength [2, 3]. The joints that are connected via rivets are known as riveted joints and there are two main types, which are lap-joints and butt-joints. For lap-joints, the components to be joined overlap each other, while for butt joints, an additional piece of material is used to bridge the two components to be joined. A riveted joint, in larger quantities, is sometimes cheaper than the other options, but it requires higher skill levels and more access to both sides of the joint, which can be difficult for some applications. When the rivets and the components are undergoing different loads, they can fail by shearing through one cross-section known as single shear, shearing through two cross-sections known as double shear, and crushing and riveted plates can fail by shearing, tearing and crushing [1]. There are a variety of factors that affect the performance of rivets, which include their size, type, material joint type, spacing between joints, and their configuration [4]. To ensure that the right rivet and joint are selected, it is necessary to understand the effect of the rivet design parameters and their configuration in a joint, as well as their significance, which is what this study aims to address. Since rivets and riveted joints have a large variety of applications, there have been many studies conducted to show the affect of the rivet parameters as well as their performance. A study conducted by Balbudhe and Zaveri [5] performed a stress analysis on the performance of a riveted lap-joint using both analytical calculations and finite element structural analysis using ANSYS Static Structural. The lap-joint used was a simple two plate single rivet joint with a simple compressive force applied to one of the plates. The results of the study showed that the results gained from the finite volume analysis had results that were in agreement with the analytical results. Another study conducted by Ming Li et al. [6] focused on the shear properties of riveted lap joints with different hole diameters that are used in aircraft fuselage. For this study, a 2D axisymmetric finite element model was established, and the validity of the finite element model was verified by experimentation. The results show that all the specimens had both brittle and plastic mixed fracture modes of rivet shank, and the shear strength of the rivet increases with the increase in hole diameter. The study concluded that, compared with increasing the squeeze force, increasing the hole diameter can effectively improve the shear strength of the riveted lap joint. Kerong Ren et al. [7] studied the impact of rivet arrangement on the strengths of riveted lap joints, the failure modes and failure mechanisms of riveted lap joints using finite element analysis software. The study then continued to study the effects of the number of rivets, rivet rows, rivet arrangement, and row spacing on the lap joint strength and the peak load was used as the evaluation index. The results show that when multiple rivet rows are used, higher stress concentrations cause the plate to first fracture at an outer rivet row with more rivets. Results also show that when the total rivet strength is greater than the remaining strength of the plate, the number of rivets and rivet rows has limited effects on the lap joint strength. The study concluded that the rivets should be arranged such that there are more rivets in the middle and fewer rivets on both sides, and that the rivet row spacing has no significant effect on the lap joint strength.

The goal of this study is to model and simulate two plates joined together by a single riveted lap joint using ANSYS Static Structural V15.0 and study the effect of the force acting on the plate and rivet's diameter and configuration on the equivalent stress produced. There will be four configurations that will be used, which are 2-vertical, 2-horizontal, 4-inline and 4-staggered configurations. This study will then aim to determine which of these configurations has the best results i.e., lower stresses and which rivets face the highest stresses.

2. Physical model

The physical model used in this study is a representation of two plates joined to one another in a riveted lap joint. Each plate has a length (L) of 100 mm, a width (W) of 40 mm and a thickness (t) of 2 mm, Figure 1 shows a schematic of the plate used in this study with the main dimensions marked on it. The plates will overlap with one another at their half-point when being joined, as shown in Figure 2.

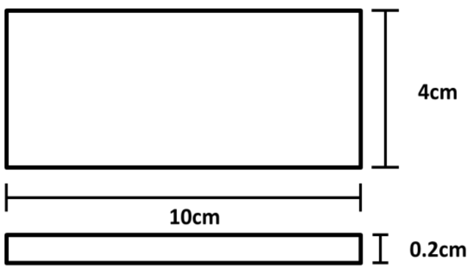


Figure 1. Plate schematic with main dimensions

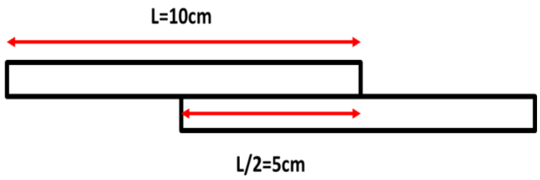


Figure 2. Plate overlapping schematic

As for the rivets that are used for the study, they are cylindrical rivets with a hemispherical head. The rivet's shaft will have varying diameters (D) ranging between 2 mm and 8 mm and length (L_r) equal to twice the plate's thickness, i.e., $L_r = 2t = 4$ mm, while the rivet's head had a radius (r_H) equal to double the shaft's radius, i.e., $r_H = D$, as shown in Figure 3 for a shaft diameter of 4 mm.

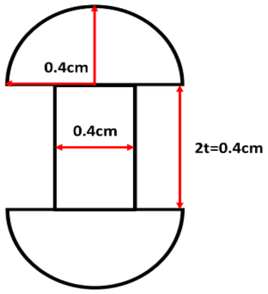


Figure 3. Rivet schematic and dimensions for a rivet shaft diameter of 4mm

For this study, the rivets will be placed in four different configurations, which are the 2-vertical, 2-horizontal, 4-inline and 4-staggered configurations. The rivets will be placed so that all rivets are equally spaced from the center of the plates overlapping area. The center of the rivet is located at the halfway point between the center of the plate overlapping area and the edge of each plate, as shown in Figures 4-7 for the 2-vertical, 2-horizontal, 4-inline and 4-staggered configurations.

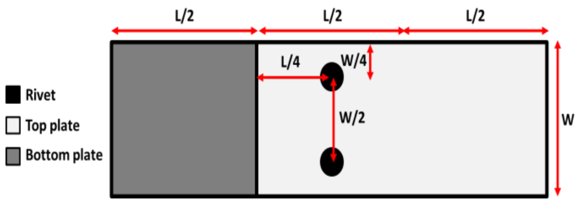


Figure 4. 2-vertical configuration

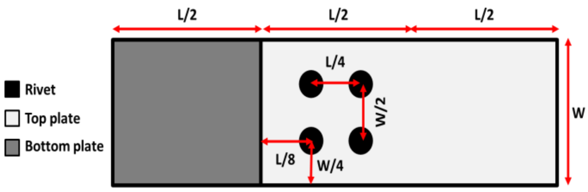


Figure 5. 4-inline configuration

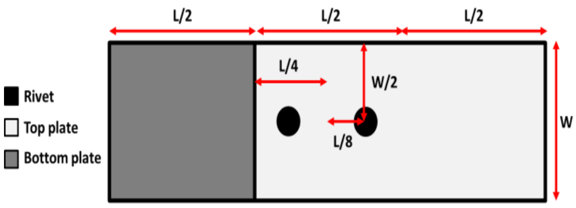


Figure 6. 2-horizontal configuration

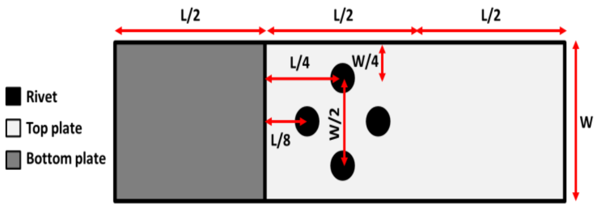


Figure 7. 4-scattered configuration

As for the plate and rivet material, the plate and rivet will use different aluminum alloys. The plate will use aluminum alloy 2024-T3, which is an aluminum alloy with copper as the primary alloying element. It is used in applications requiring a high strength-to-weight ratio, as well as good fatigue resistance; however, it is only weldable through friction welding [8], which makes rivet jointing an excellent choice for this type of material and is the reason for adopting it for this study. As for the rivet, it uses aluminum alloy 2117-T4, which is also an aluminum alloy with the main alloying addition of copper. An aluminum alloy was chosen since, to achieve maximum strength and minimum corrosion, rivets should be made of materials that match the materials of the parts being joined [2, 3]. Since 2117-T4 is often used for the manufacturing of rivets [9], it was chosen for this study. The T3 and T4 in the name refer to the level of tempering the alloy has undergone, which affects its mechanical properties. The mechanical properties of each material are shown in Table 1.

Table 1. Material properties of 2024-T3 (plate) and 2117-T4 (rivet) material [10]

Mechanical property	Material	
	2024-T3	2117-T4
Density [kg/m^3]	2780	2780
Yield strength [MPa]	345	165
Compressive yield strength [MPa]	345	165
Tensile ultimate strength [MPa]	483	296
Compressive ultimate strength [MPa]	483	296
Young's module [GPa]	74	71.7
Poisson's ratio	0.33	0.33

3. Boundary conditions

For this study, there are two main boundary conditions that are applied, which are a fixed frictionless support at the heads of the rivets and a varying compressive force from 2000 N to 8000 N at the opposite side of each plate, as shown in Figure 8.

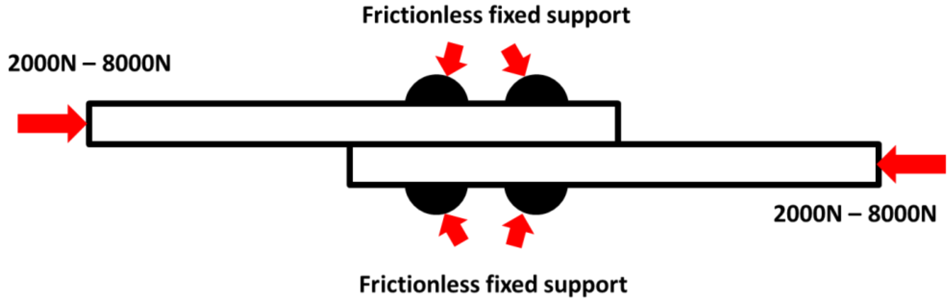


Figure 8. Boundary conditions

4. Meshing process

As with all finite element solvers, ANSYS Static Structural requires the setup of a mesh to perform the simulation and obtain results. This means that the meshing process is extremely important for the accuracy and stability of the simulation. Generally speaking, having a mesh with smaller cell sizes and therefore a larger cell count gives more accurate results; however, this also means that it would require more computational resources and time and can affect the stability of the simulation [11]. To verify that the chosen mesh is suitable, provides accurate results, and requires less computational power, a mesh dependency study is conducted. In a mesh dependency study, the mesh cell count is increased steadily and the results are recorded. Once the results no longer change or the percentage of change is acceptable enough, a lower cell count is chosen. Figure 9 and Table 2 show the results of the mesh dependency study. Based on the mesh dependency study, it is clear that once the mesh element size was decreased from 0.5mm to 0.25 mm, the mesh element count increased by nearly 7 times, but the change in the equivalent stress was only 12%, which is very acceptable considering the burden that the mesh with an element count of 1525219 places on the computer. Based on the mesh study, a mesh with an element size of 0.5 mm and an element count of 208981 will be chosen, as shown in Figure 10.

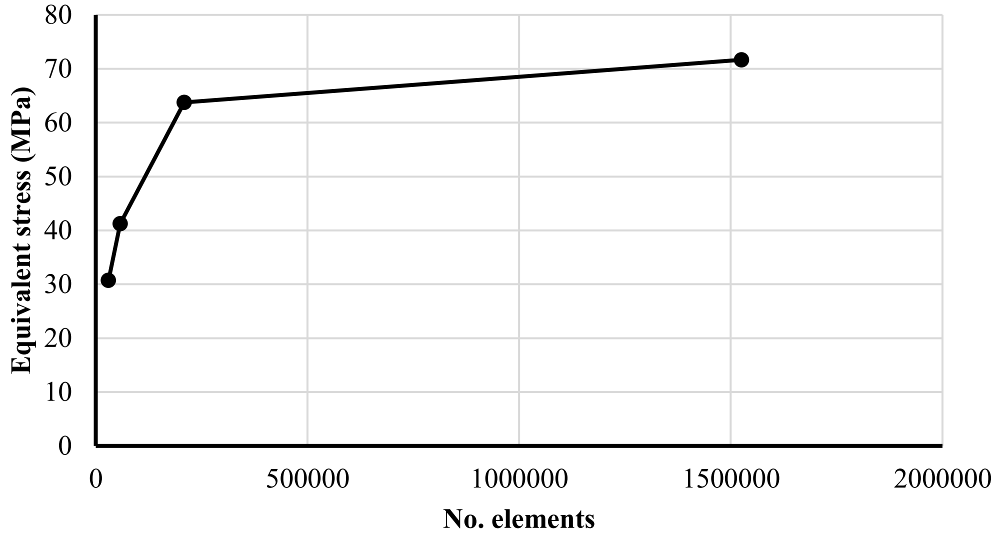


Figure 9. Mesh dependency study

Table 2. mesh dependency

Element size	No. elements	Equivalent stress	Change
1	30117	30.7	-
0.75	57665	41.24	34.33
0.5	208981	63.78	54.66
0.25	1525219	71.67	12.37

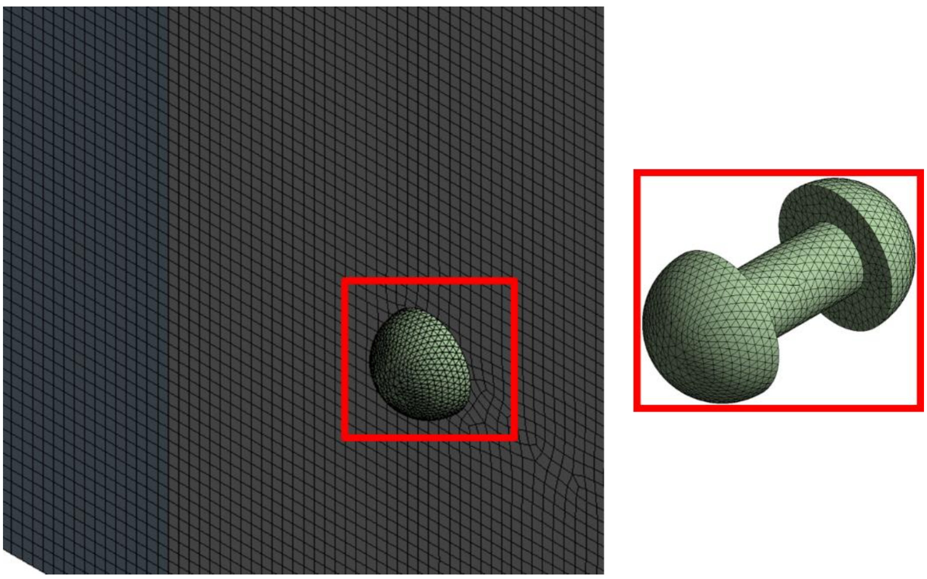


Figure 10. Meshing of plate and rivet

5. Result analysis and discussion

5.1 Verification of results

To verify the results obtained from this study, they were compared to theoretical calculations. For this study, the crushing stress experienced by the 2-horizontal and 4-inline configuration models will be used. The equation for calculating the crushing stress (σ_c) is presented in Equation (4.1) [5]:

$$\sigma_c = \frac{\frac{F}{N}}{D \times t} \qquad (1)$$

where F is the force experienced by the plate, N is the number of rivets facing the direction of the force (2 for 4-inline and 1 for 2-horizontal) and t is the thickness of the plate. Using this equation, the data obtained from the results can be compared to the theoretical data, as shown in Figure 11, for a rivet

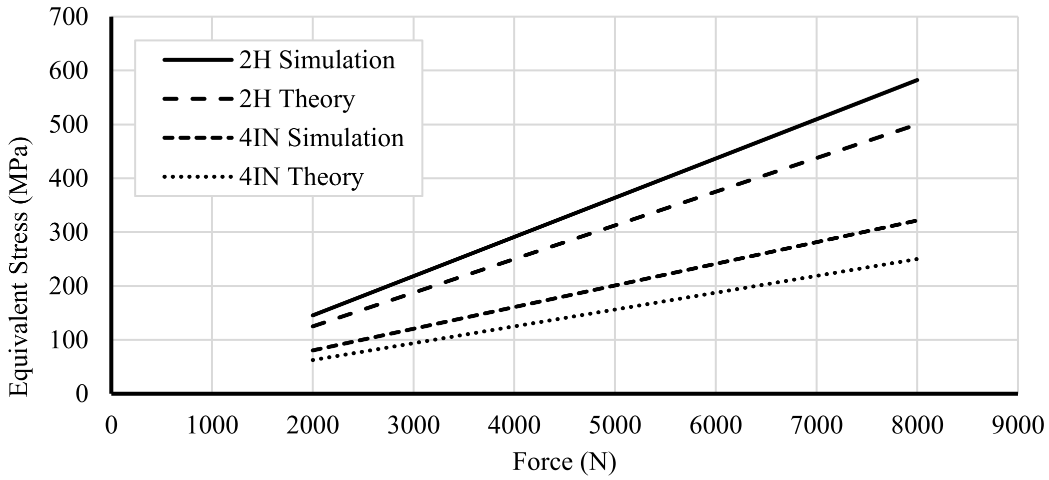


Figure 11. Comparison between the theoretical results and simulation results

diameter of 0.4 cm. The results show that there is a slight deviation between the simulation results and the theoretical results, which is to be expected, since the theoretical results use simpler equations and don’t take all parameters into account. The percentage of error for the 2-horizontal model was 14% and for the 4-inline model it was 22.25%, both of which are extremely favourable and therefore the simulation results can be accepted.

5.2 4-inline rivet results

The results show that the equivalent stress experienced by the rivets increases linearly with the increase of the force acting on the plates, and this is observed for all four of the rivets at each rivet diameter. This can be seen in Figure 12 for a rivet diameter of 0.2 cm. The results also show that there is a slight deviation between each of the four rivets; however, as the diameter of the rivets increases, the differences between them start to decrease, and at a diameter 0.8 cm, the differences become very small. For a rivet diameter of 0.2 cm, all the rivets have stresses surpassing the yield strength of the material (165 MPa) at forces of 4000 N to 8000 N and for a rivet diameter of 0.4 cm, only the front right side rivet (FR) didn’t enter plastic deformation at 4000 N. As for diameters 0.6 cm and 0.8 cm, all the rivets didn’t surpass the yield strength of the material for forces of 2000 N and 4000 N and therefore no plastic deformation occurred. To illustrate the effect of the rivet diameter more clearly, Figure 13 shows the equivalent stress for the back left side rivet for each rivet diameter and at each force, the Figure clearly shows that increasing the rivet diameter from 0.2cm to 0.4cm significantly decreased the stresses. However, when increasing the diameter beyond 0.4 cm, the effect of increasing the diameter quickly dissipated and there is very little gain from increasing it beyond 0.4 cm.

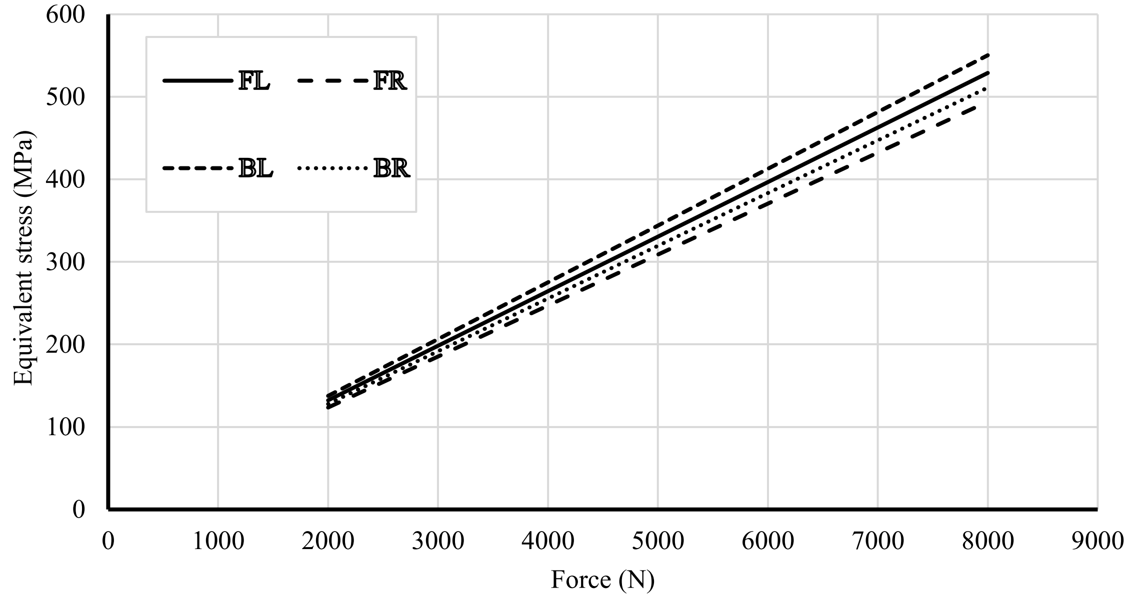


Figure 12. Equivalent stress for each rivet for rivet diameter of 0.2cm at each force (4-inline configuration)

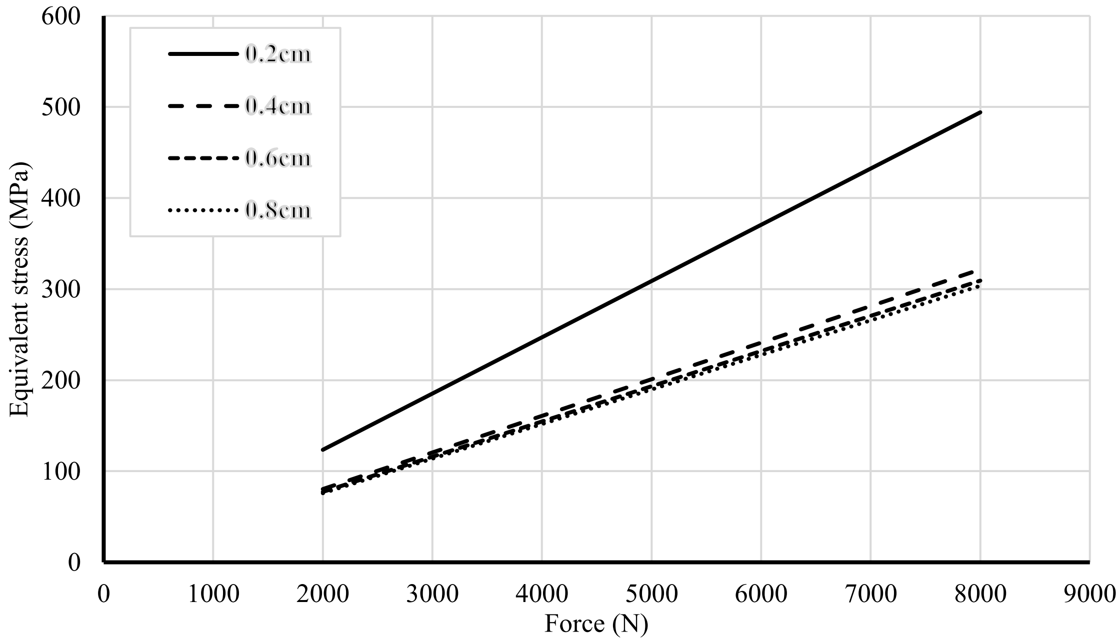


Figure 13. Equivalent stress for each rivet diameter for rivet BL at each force (4-inline configuration)

As for the distribution of these stresses across the rivets, Figures 14 show the equivalent stress distribution for (a) the front left rivet (FL), (b) the front right rivet (FR), (c) the back left rivet (BL) and (d) the back right rivet (BR) at 0.2 cm diameter and 2000 N force.

5.3 4-staggered rivet results

For the 4-staggered rivet results, the equivalent stress increased linearly with the increase in the force applied to the plate. However, unlike the 4-inline configuration, which had relatively similar stresses for each rivet, there is a significant difference between the stresses experienced by each rivet. As Figure 15 shows, the back (B_S) and front (F_S) rivets had significantly higher stresses than the left (L_S) and right (R_S) rivets, with the back rivet being the highest of the two. This is expected since the front and back rivets are closer to the force source than the left and right rivets. Another reason for this is that the left and right rivets share the forces acting on them between them, which means that they experience less stress and will have extremely similar values. As for the effect of increasing the rivet diameter, increasing the rivet diameter decreases the equivalent stress steadily; however, the rate of decrease decreases with each increase in rivet diameter, although it isn't a significant decrease. Figure 16 shows the effect of rivet diameter on the equivalent stress for the back rivet (B_S) at different forces, respectively. Finally, these results show that for a force of 4000 N to 8000 N, all rivet diameters had stresses exceeding the yield strength of the material. As for a force of 2000N, none of the rivets at every diameter entered plastic deformation, and therefor, the staggered configuration can only handle a force of less than 4000 N.

As for the distribution of these stresses across the rivets, Figures (17) show the equivalent stress distribution for (a) the front rivet (F_s), (b) the back rivet (B_S), (c) the left rivet (L_S) and (d) the right rivet (R_S) at 0.2 cm diameter and 2000 N force.

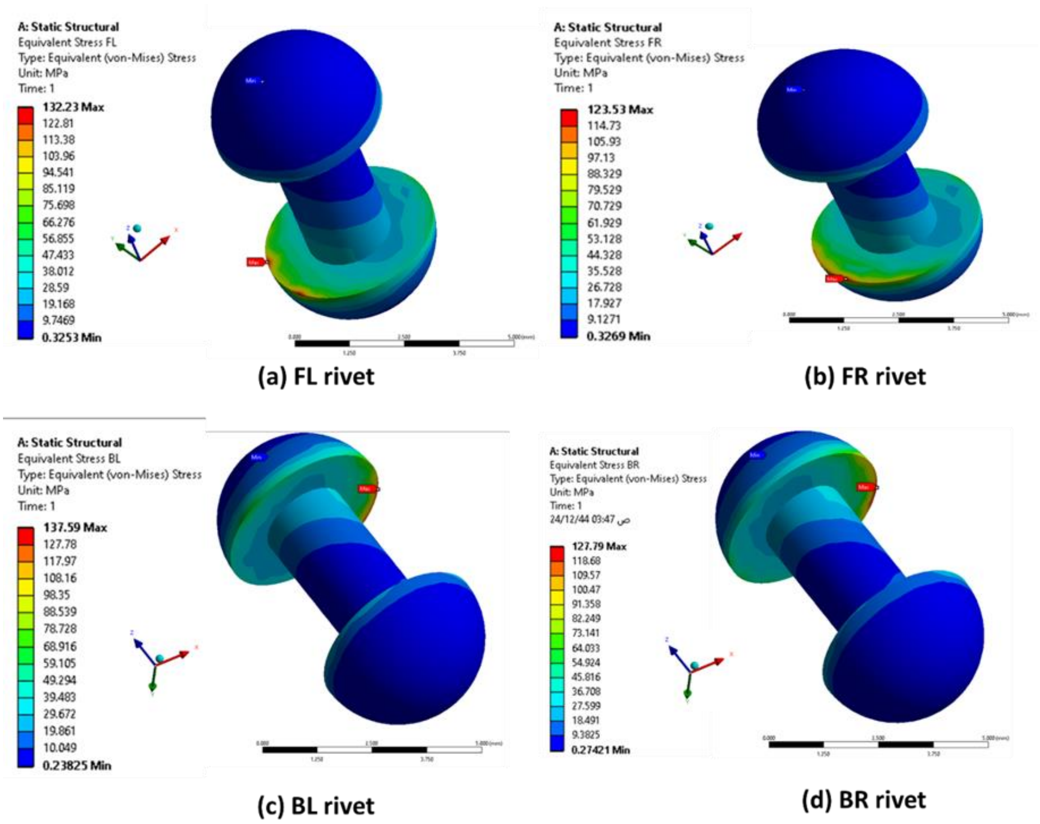


Figure 14. Equivalent stress distribution for (a) the front left rivet (FL), (b) the front right rivet (FR), (c) the back left rivet (BL) and (d) the back right rivet (BR) at 0.2 cm diameter and 2000 N force (4-inline configuration)

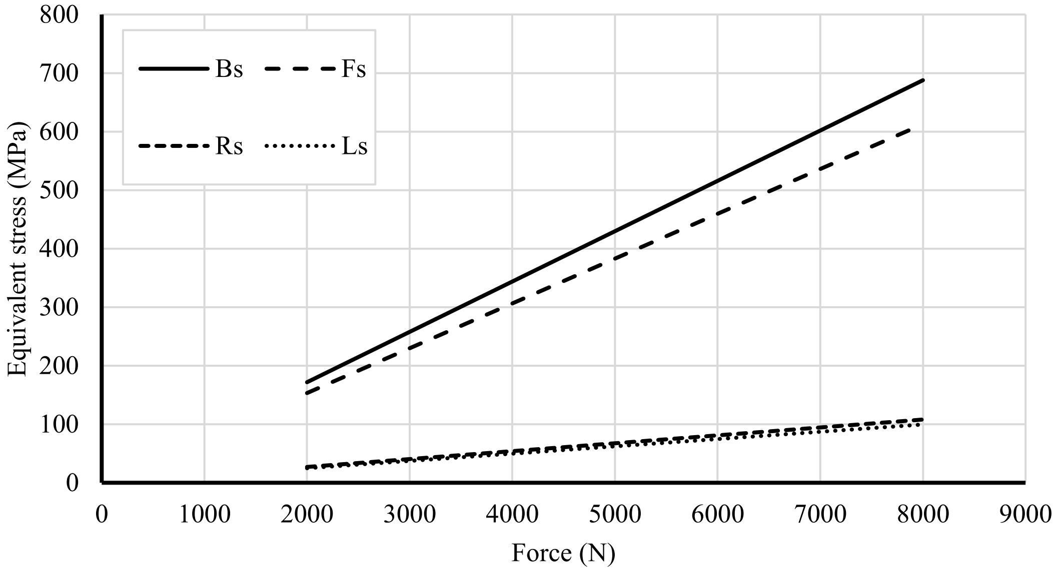


Figure 15. Equivalent stress for each rivet for rivet diameter of 0.2 cm under different forces (4-staggered configuration)

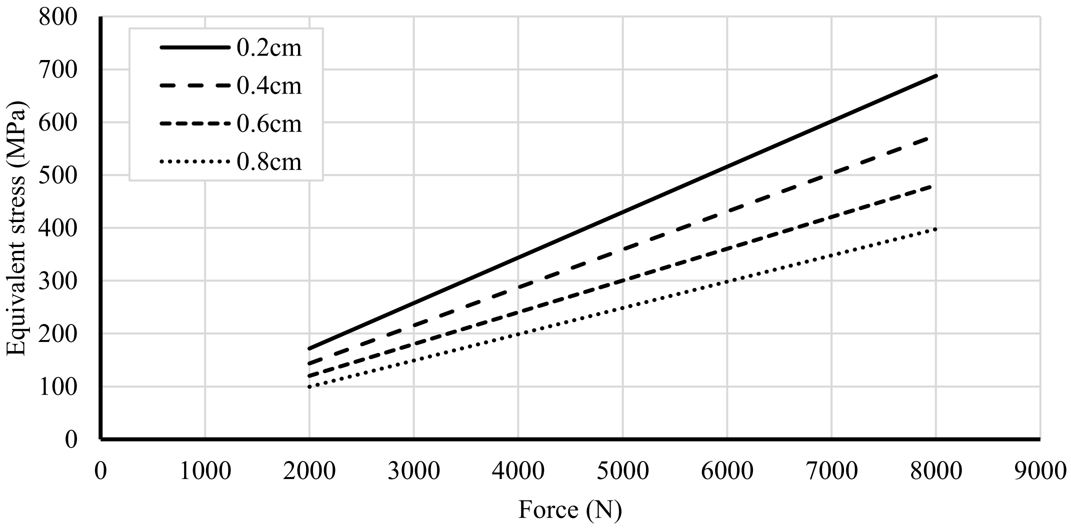


Figure 16. Equivalent stress for each rivet diameter for rivet B at each force (4-staggered configuration)

5.4 2-vertical rivet results

Figure 18 shows the equivalent stress for both left (L) and right (R) rivets at a rivet diameter of 0.2 cm under different forces. These results show that the equivalent stress behaved similarly with the increase in force, i.e., increased linearly and both the right and left rivets had very similar results, which is expected since both rivets should be experiencing similar forces due to them being located the same distance away from the source of the force. To show the effect of increasing the rivet diameter, Figure 19 shows the equivalent stress of each rivet diameter for the right rivet (R) under different forces. Results clearly show that increasing the rivet diameter leads to a decrease in the equivalent stress; however, the rate of decrease also decreases with each increase in diameter, i.e., the

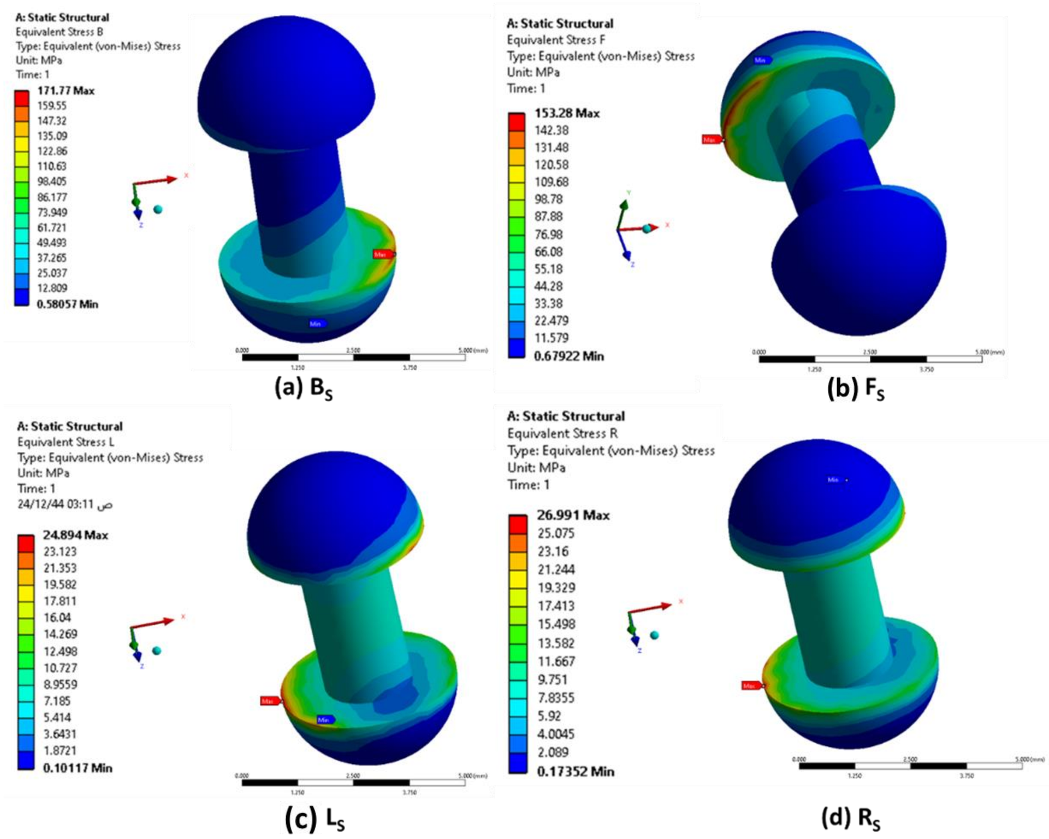


Figure 17. Equivalent stress distribution for (a) the front rivet (Fs), (b) the back rivet (BS), (c) the left rivet (LS) and (d) the right rivet (RS) at 0.2 cm diameter and 2000 N force (4-staggered configuration)

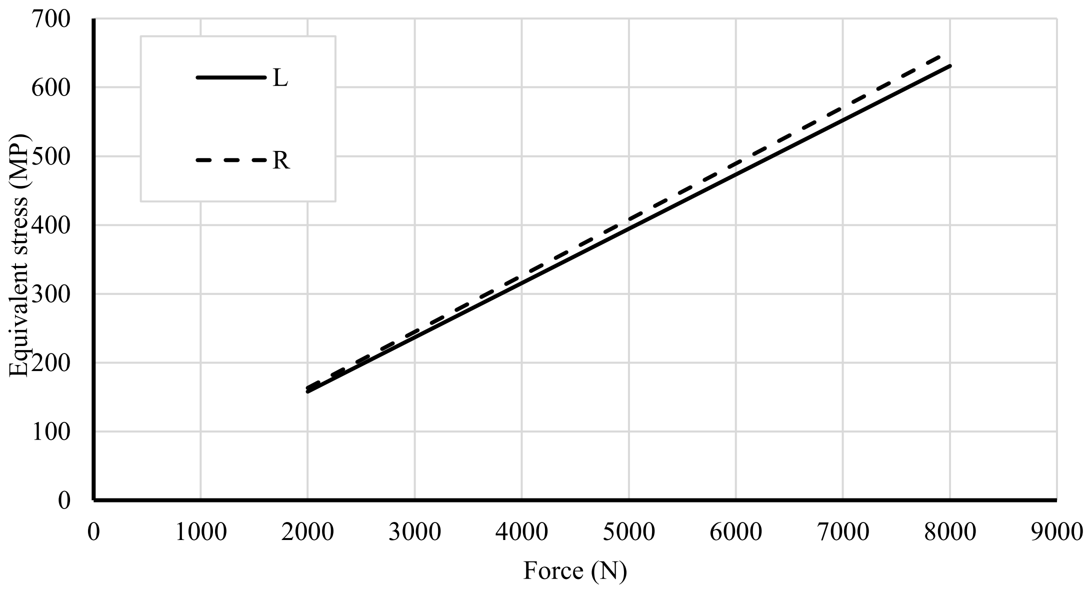


Figure 18. Equivalent stress for each rivet for rivet diameter of 0.2 cm under different forces (2-vertical configuration)

return benefit of increasing the rivet diameter starts to diminish. These Figures also show that for a rivet diameter of 0.2 cm to 0.4 cm, the stresses caused by the force of 4000 N to 8000 N exceeded the yield strength of the material and for a diameter of 0.8 cm, the rivets were able to handle 4000 N without plastic deforming.

As for the distribution of these stresses across the rivets, Figure 20 shows the equivalent stress distribution for (a) the left rivet (L) and (b) the right rivet (R) at 0.2 cm diameter and 2000 N force.

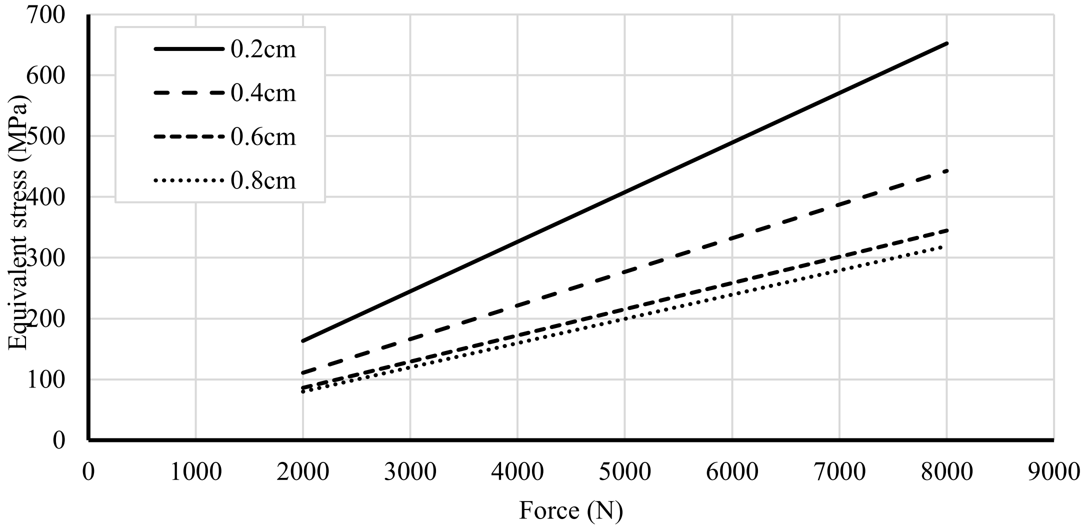


Figure 19. Equivalent stress for each rivet diameter for rivet R under different force (2-vertical configuration)

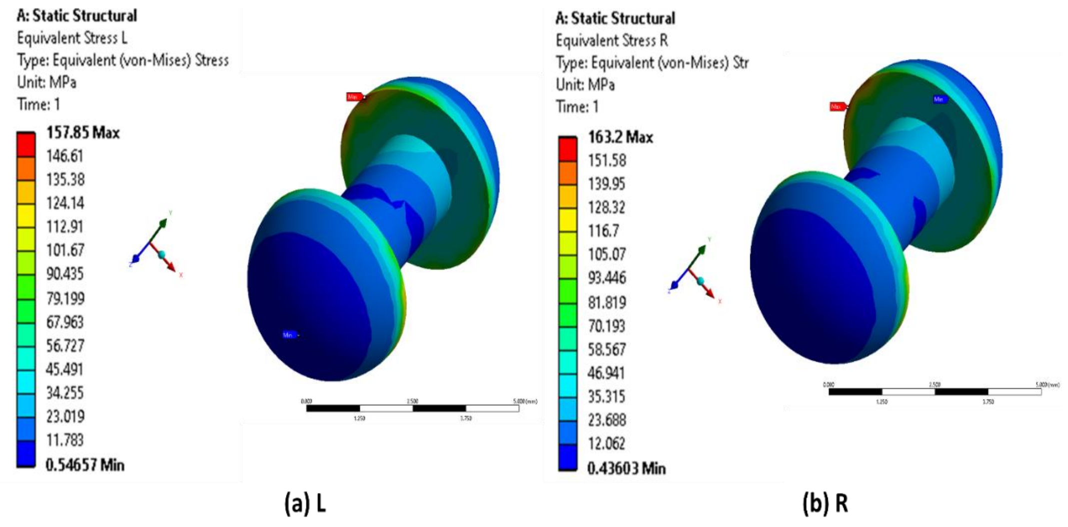


Figure 19. Equivalent stress distribution for (a) left rivet (L) and (b) right rivet (R) at 0.2 cm diameter and 2000 N force (2-vertical configuration)

5.5 2-horizontal rivet results

Figure 21 shows the equivalent stress for both front (F) and back (B) rivets at a diameter of 0.2 cm under different forces. These results show that the equivalent stress increased linearly with the increase in force. Figure 21 also shows that both the front and back rivets had extremely similar stresses at a rivet diameter of 0.2 cm. To show the effect of increasing the rivet diameter, Figure 22 illustrates the equivalent stress for the back rivet at each rivet diameter nder different forces. The figures clearly show that increasing the rivet diameter leads to a decrease in the equivalent stress; however, the rate of decrease also decreases with each increase in diameter, although this drop in the rate of decrease is very insignificant. Results also show that none of the rivet diameters could endure forces of 4000 N to 8000 N without the stresses exceeding the yield strength of the material, and only the rivet diameter of 0.2 cm couldn't endure 2000 N. As for the rivet diameter of 0.2 cm, it can only endure 2000 N of force.

As for the distribution of these stresses across the rivets, Figure 23 show the equivalent stress distribution for (a) the front rivet (F) and (b) the back rivet (B) at 0.2 cm diameter and 2000 N force.

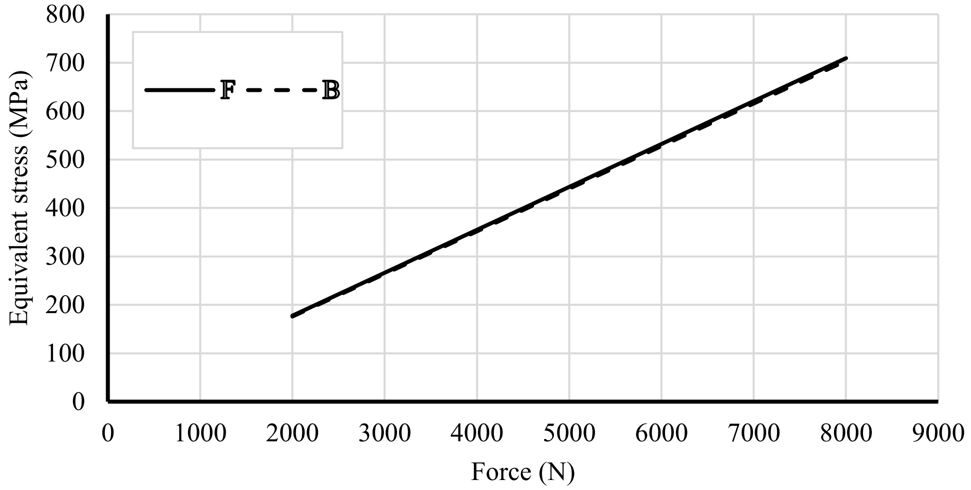


Figure 20. Equivalent stress for each rivet for rivet diameter of 0.2 cm under different forces (2-horizontal configuration)

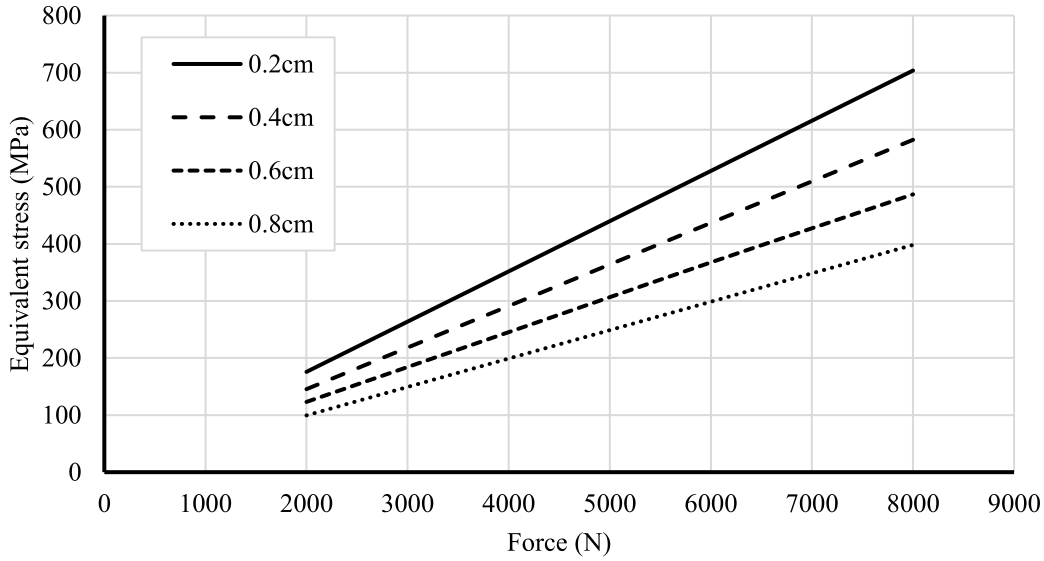
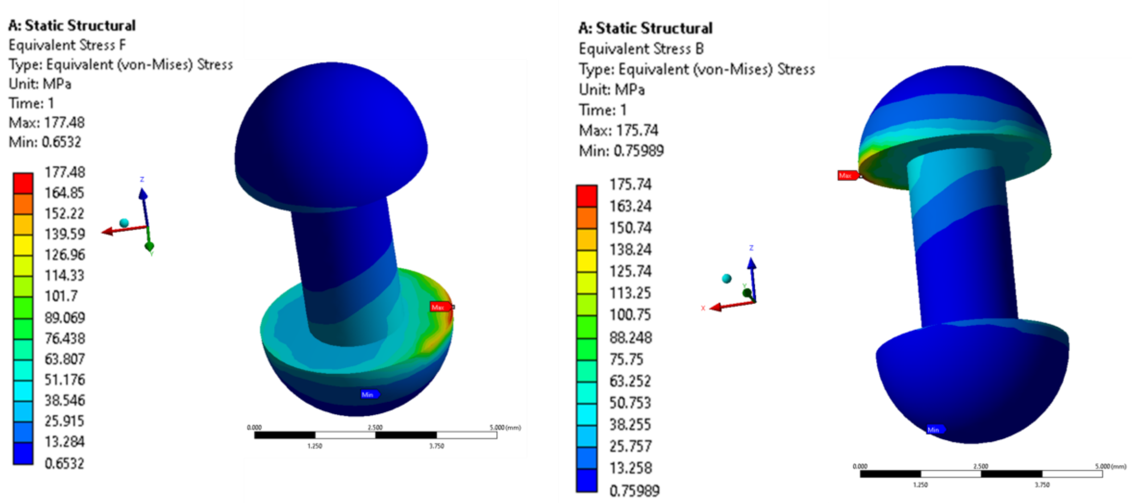


Figure 21. Maximum equivalent stress for each rivet diameter for rivet R at each force (2-horizontal configuration)

5.6 Comparison

In this section, each rivet configuration will be compared to another in terms of the equivalent stress of the rivets and plates. To perform this comparison for the rivets, the rivet with the highest stress will be chosen from each configuration and compared. The rivet chosen from each rivet configuration is shown in Table 3. As for the plate, the top plate had the highest stresses for all four configurations and was therefore chosen.

Figure 24 shows the highest equivalent stress of each rivet configuration at a rivet diameter of 0.4 cm under different forces. The results show that the 4-staggered and 2-horizontal configurations had the highest stress and were very close to each other. On the other hand, the 4-inline and 2-vertical configurations had significantly lower stresses than the previous two configurations, with the 4-inline configuration being slightly lower, which also means it is the best of the four configurations. This is due to the 4-inline and 2-vertial configurations having 2 rivets in the direction of the force, which helps decapitate the force over a larger area, while the 4-staggered and 2-vertical configurations have rivets that are alone in the direction of the force, which means less area to dissipate the force. The results also show that for forces of 2000 N, any one of the configurations will work, but for a force of 4000 N, only the 4-inline and 2-vertical configurations can be used at a diameter of 0.4 cm. As for the forces of 6000 N to 8000 N, none of the configurations with a diameter of 0.4 cm will work and a larger diameter would be needed.



(a) F **(a) B**

Figure 22. Equivalent stress distribution for (a) front rivet (F) and (b back rivet (B) at 0.2 cm diameter and 2000 N force (2-horizontal configuration)

Table 3. The rivet with the highest stresses chosen from each rivet configuration

Rivet configuration	4-inline	4-staggered	2-vertical	2-horizontal
Chosen rivet	BL	B_S	R	B

5.7 Stress on Plate comparison

Figure 25 shows the equivalent stress of the top plate for each rivet configuration at a rivet diameter of 0.4 cm under different forces. The results show that configuration 2-horizontal had the highest stresses, followed by 4-staggered and the 4-inline configuration had the lowest stresses followed by 2-

vertical. This is very similar to the results for the rivet, with the exception that, unlike with the rivet results, there is a very clear difference between the 4-staggered configuration and the 2-horizontal configuration as opposed to being nearly identical for the rivets. This is probably due to the fact that while the plate would still need to dissipate the force over the same area for the front and back rivets, the 4-staggered configuration has two more rivets (L_S and R_S rivets) that can help in dissipating the forces even if they are further away, and the 2-vertical configuration does not have this advantage. Based on these results, it is clear that the 4-inline configuration is the best configuration for the plates, followed by the 2-horizonrtal and 4-staggered configurations and finally, the 2-vertical configuration has the worst performance among all four configurations. For all four configurations, none of them could endure forces of 6000 N and higher, and only the 4-inline and 2-horizontal configurations could handle a force of 4000 N without entering plastic deformations.

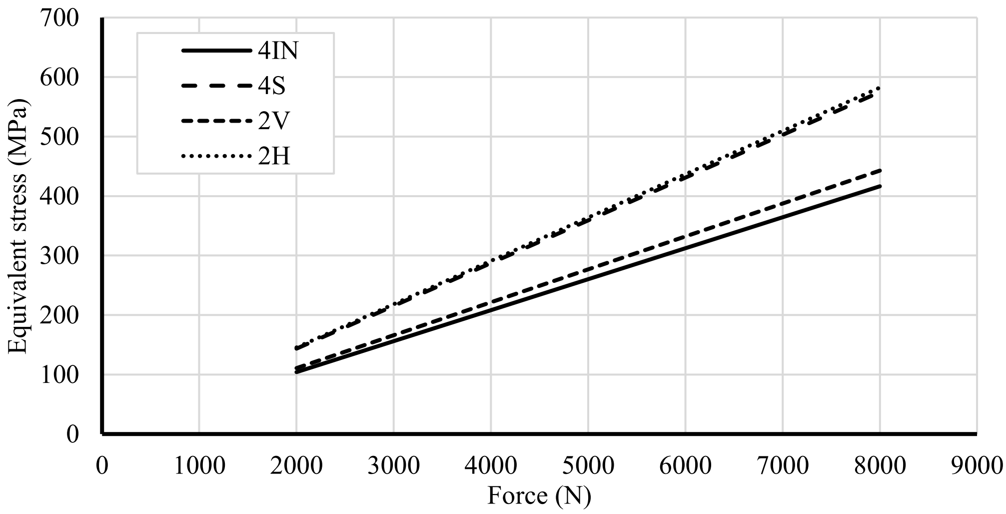


Figure 23. The highest equivalent stress of each rivet configuration at a rivet diameter of 0.4cm under different forces

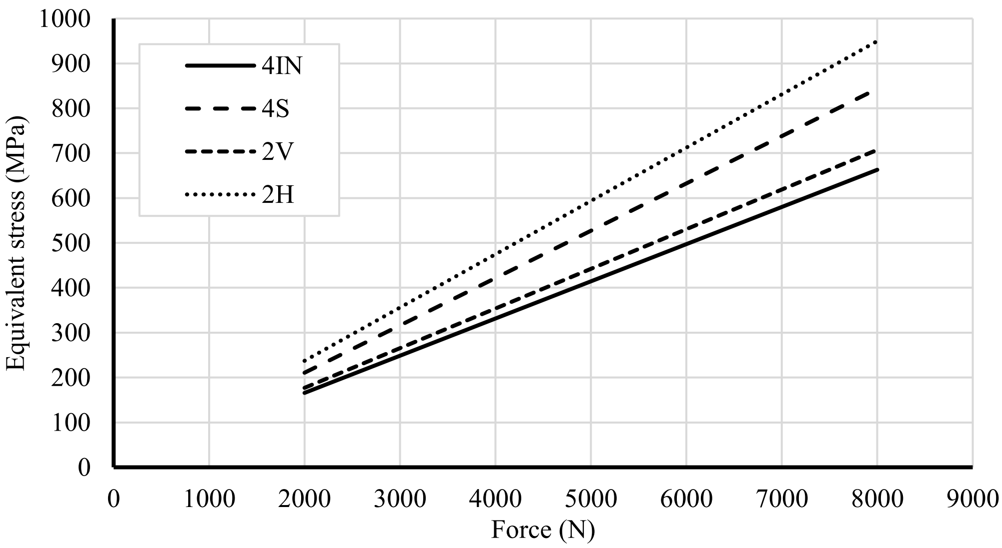


Figure 24. Equivalent stress of the top plate for each rivet configuration at a rivet diameter of 0.4 cm under different forces

6. Conclusions

In this study, four different rivet configurations were studied and analyzed using the ANSYS static structure. The results were compared and the effect of increasing the rivet diameter was also analyzed. Based on the results, it mis clear that the 4-inline configuration was the best due to it having lower stresses than the other configuration, followed by the 2-vertical configuration. The 2-horizontal and 4-staggered configurations had the worst performance and had similar performances. Results also show that increasing the rivet diameter lowers the stresses; however, the rate of decrease from increasing the diameter decreases every time. The stresses produced by the forces had a linear relationship with the magnitude of the force. Finally, the best rivet design was the 4-inline configuration with a diameter of 0.4 cm, since increasing the diameter beyond that had a much lower benefit.

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