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IMPACT OF BOLT POSITIONING ON THE STIFFNESS OF ANGULAR SUPPORT BRACKETS

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Abstract. Bolts and screws are usually preferred over other joining techniques when assembly and disassembly operations are required. However, they add extra weight to the system, so it is essential to reduce their size and weight by optimizing bolt parameters. Additionally, the stiffness of bolted members is very crucial; those with low stiffness may affect the correct functioning of the other connected components. This study focuses on the impact produced by bolt positions, specifically their center of gravity and spacing among them, on the stiffness of angular L-shaped brackets using Finite Element Analysis. Bending and torsional loads were applied to the free end of the member and deformations were recorded under these loads. The results revealed that a triangular bolt pattern is recommended for three bolts, whereas for four or more bolts, the pattern should be uniform to avoid stress concentrations. Moreover, the center of gravity and bolt spacing have a significant impact on stiffness. By optimizing bolt spacing and the center of gravity, a combination of six bolts can be replaced with four bolts of the same size while maintaining the same stiffness.

Keywords: Stiffness, bolt positioning, angular brackets, optimization, numerical analysis.

1. Introduction

Bolts and screws are widely used in the automotive and aerospace industry due to their easy handling especially during multiple tightening and untightening operations. Sometimes, these joints are avoided to keep the system's weight low. Therefore, it is a necessary to avoid the use of extra bolts by optimizing different bolt parameters. Moreover, the stiffness of bolted connections plays a crucial role in the uniform distribution of forces. Most of the time, it is required to make the structures so stiff that they could not affect the functioning of other connected components. A recently published review article addresses the significant optimization factors i.e. bolt layouts, thread geometry, bolt size, and tightening sequences for bolted joints [1].

There are several ways to improve the stiffness of angular L-shaped brackets by varying bolt parameters. The most important bolt parameters for improving the stiffness are bolt layouts and spacing between bolts [2]. Kiamanesh et al. [3] studied the effect of rectangular and circular bolt patterns on extended end plate connections using non-linear 3D finite element analysis. The study revealed that the circular pattern improves the connection strength and enhances the energy dissipation capability. Similarly, Wang et al. [4] examined the impact of rectangular and staggered bolt patterns on t-stub connections and proposed that the staggered bolt patterns are the best to get the stiffer structures.

There are also few studies reported in the literature that used Artificial Intelligence (AI) techniques to optimize the bolt parameters. As, Shen [5] used genetic algorithms to optimize the bolt locations to reduce the accelerations in the electronic board circuit. With optimized bolt positions the acceleration in the circuit reduced 67 percent from $43.9\,\mathrm{m\,s^{-2}}$ to $14.4\,\mathrm{m\,s^{-2}}$. Similarly, Lu [6] used the gray wolf algorithm to optimize the peripheral stresses in the Nickel plates using different triangular bolt patterns. In optimized bolt patterns, the stresses reduced by 24 percent. Moreover, Sari [7] has developed a software to optimize the placement of bolts in bolted connections based on C language. This program takes few values as inputs and suggests the optimized bolt positions for objective function.

However, a limited literature is available on the optimization of stiffness for bolted joints by varying bolt parameters. The objective of the following study is to design a bolted connection with higher stiffness using simulation software, and comparing the results obtained with those theoretically. An L-angle piece subjected to variable loads that generate bending and twisting moment was examined. Subsequently, an attempt was made to optimize the joints by varying some parameters i.e. bolt layout, center of gravity and bolt spacing and trying to obtain a configuration that guarantees greater stiffness.

2. Materials and methods

In the study, SolidWorks has been used for drawings and three-dimensional parametric designs. The numerical analysis was performed using Ansys software due to its better solving capabilities, accuracy of strain, stiffness and stress results.

The angular L-shaped bracket is subjected to two forces acting on the midpoint of the free corner, one in a vertical downward direction, and other acting horizontally as shown in Figure 1. These forces generate bending and twisting moments respectively.

The material for the plates and angular bar is structural steel S275 (standard EN 10027-1:2016) [8] and the bolts of resistance class 8.8 [9] were chosen for the analysis. The analysis was carried out by verifying the deformation undergone by the angle piece as the load acting on it varies in order to determine its stiffness. Moreover, the load was applied from 0 to 30 kN in 16 steps to list the results.

In Ansys, the bolted joint is represented as an assembly of several solid bodies using the one-sided non-penetration constraint. To achieve this, the resistant section of the bolt is represented by a beam (in Ansys command Beam) with a circular section with a diameter corresponding to that of the bolt under examination. Additionally, the initial preload on the bolts was applied using the Bolt Preload tool available in Ansys.

Initially, the CAD geometry was imported into Ansys Workbench's Static Structural module, while for the materials reference was made to the database present in the software. Frictional and bonded contacts were used to model the contacts between the various components. In particular, the frictional contact was used to model the contact at the interface between the plates and in the contact surfaces between the underhead of the screw and plate. Bonded contacts were used to connect the different portions of the screw: shank not in socket and threaded portion in socket.

The discretization used is different on different components. In particular, a multi-zone approach was used for the bolt components in order to obtain a smooth and sufficiently dense mapped mesh. The elements used for these components are of type SOLID186 with a size of 1 mm. As far as the plates are concerned, a hex dominant approach has been chosen to carry out a mapped mesh discretization, the elements used are SOLID187 type 3 mm in size. In all simulations, the load was applied in two different steps. The first step applies the nominal preload to the bolt producing a shortening of the shank. The second step "locks" the preload value achieved through the specific lock function and applies the external loads.

The parameters that were analysed to design the bolted connection as the load varies are the following: nominal diameter, number of bolts, the influence of the center of gravity, bolt spacing, and bolt layout.

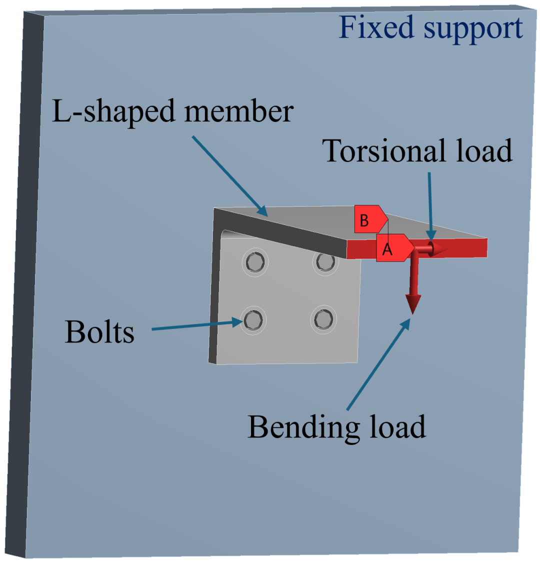

Figure 1. L-shaped angular bar subjected to bending and twisting loads.

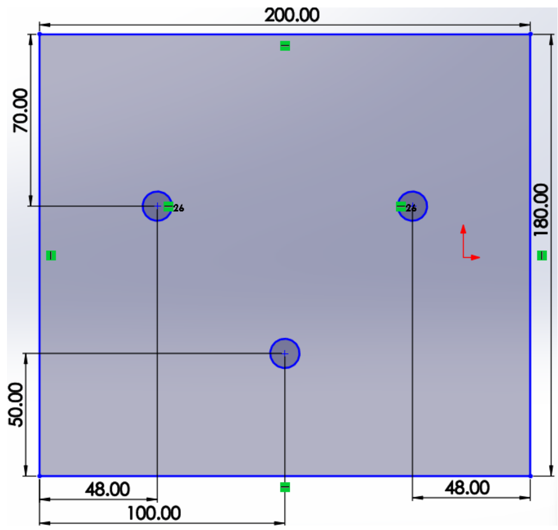

Figure 2. Triangular bolt pattern.

3. Results and discussion

3.1. Influence of bolt size on stiffness

Initially, 3 bolts of sizes M8, M12 and M16 were analysed using a triangular pattern as shown in Figure 2. The deformation of angle bar was recorded at the extreme free end in mm, and it varies according to the applied load. The maximum preloads were applied on each bolt following VDI-2230 standard [10] and friction coefficient of 0.2 was taken for the dry conditions. The maximum sliding force that the connection can support is equal to

$$R_t = z \cdot \mu \cdot F_i, \tag{1}$$

where z represents the number of surfaces in contact, μ the coefficient of friction and F_i is the applied preload. The same procedure is followed for the rest of the cases.

From analysis, it was noted that as the nominal diameter of the bolt increases, the structure shows a more rigid behaviour; however, the increase in stiffness obtained is negligible. Figure 3 shows the relationship between applied load and displacement under bending and twisting loads.

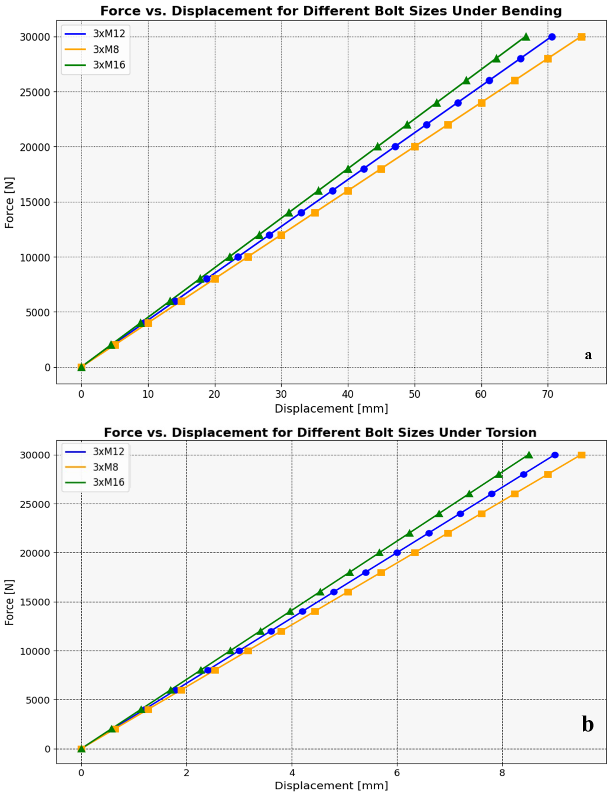

Figure 3. Force vs displacement diagrams (a) bending load (b) twisting load.

3.2. Influence of number of bolts on stiffness

In this case, three, four, and six bolts of the same size were analysed. The bolts were arranged in such a way that the center of gravity remained the same for all cases. From the results, it was deduced that the stiffness increases as the number of bolts increased as expected; however, this increase is not linear, as greater displacement difference was registered going from 3 to 4 bolts than from 4 to 6 bolts as shown in Figure 4.

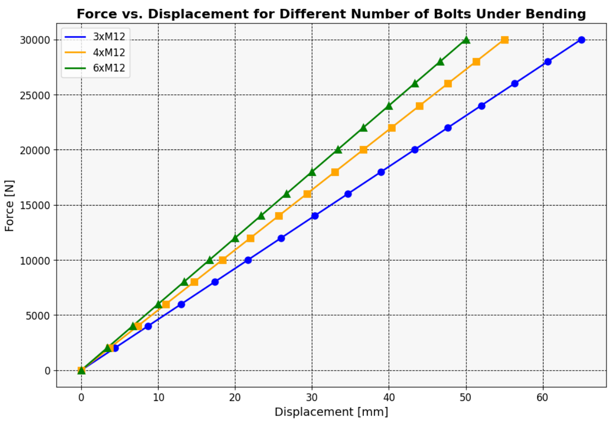

Figure 4. Force vs displacement for different number of bolts.

3.3. Influence of bolt center of gravity on stiffness

The center of gravity or centroid is the point where moments act, and it changes when the position of bolts changes. In this analysis, three cases with M12 bolts have been analysed to check the effect of the center of gravity on stiffness as shown in Figure 5. The center of gravity in the Y direction has been increased and decreased by 30 percent. A similar procedure was also followed for x-coordinates to shift the centroid left and right by 30 percent to check the impact of torsional load.

It is evident that the best configuration for bolted joints subjected to bending and twisting moments is achieved by shifting the y-coordinates of the bolts upwards and the x-coordinates towards the negative x-direction, as illustrated in Figure 6. Shifting the bolts upwards reduces the chance of the L-shaped member separating from the fixed plate. Similarly, positioning the x-coordinates of the bolts towards the side of the applied load increases resistance to deformation due to twisting torque.

3.4. Influence of bolt spacing on stiffness

It was examined from the center of gravity section that bolts should be placed upward and towards the negative x-direction for the given loads. Regarding bolt spacing, the previous best bolt locations were chosen with an increase and decrease in center distance by 35 percent. The results indicated that the best stiffness was achieved when the bolts were placed away from the centroid. This is due to the uniform distribution of forces and a reduced chance of the structure rotating. Figure 7 shows the effect of bolt spacing for twisting load only.

The results explained that the highest stiffness for both twisting and bending moments is given by the increase in the number of bolts i.e. six-M12 bolts; however, it is possible to obtain approximately the same stiffness by optimizing the center of gravity and by increasing the center distance for four-M12 bolts. In particular, it was noted that by increasing the y-coordinate of the center of gravity by 30 percent for four-M12 bolts, decreasing the x-coordinate of the center of gravity by 30 percent, and increasing the center distance of bolts by 35 percent, the stiffness obtained is similar to that obtained by six-M12 bolts.

3.5. Influence of bolt layout on stiffness

Finally, the effect of bolt layouts for four different configurations namely, inline, rectangular, trapezoid and T-shape were analysed as shown in Figure 8.

The configuration that enjoys greater stiffness was observed to be the rectangular one with an increase in center of gravity by 30 percent. The in-line arrangement is the worst of all, in fact for a load of 30 kN the

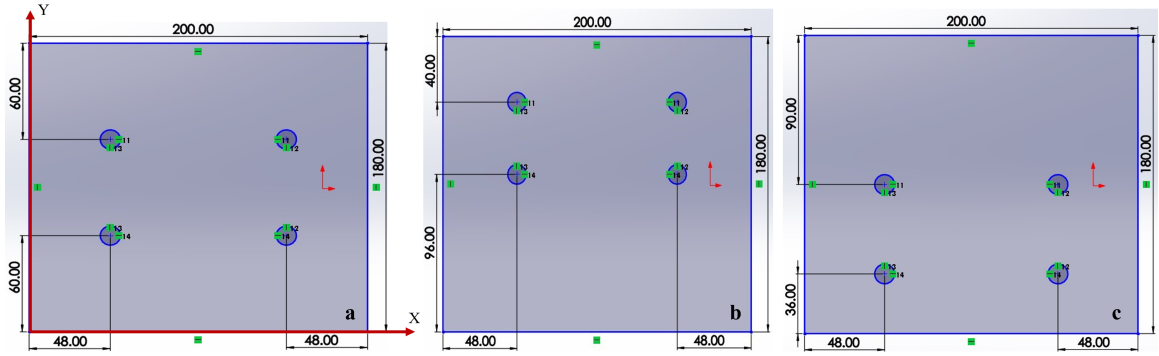

FIGURE 5. Center of gravity (a) $Xg = 100$, $Yg = 90$ (b) increased 30 percent in Y (c) decreased 30 percent in Y.

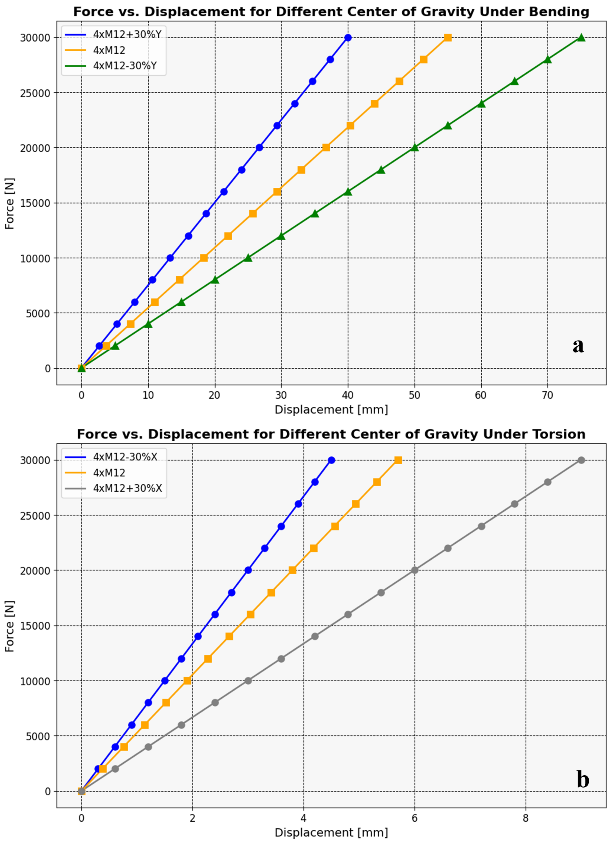

FIGURE 6. Force vs displacement diagrams (a) three cases under bending moment for Y (b) three cases under twisting moment for X.

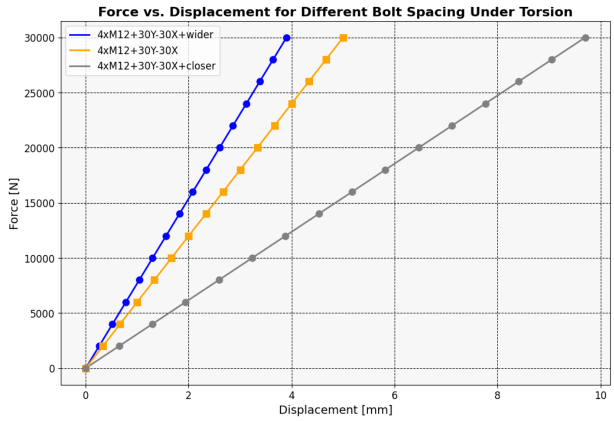

FIGURE 7. Force vs displacement diagram for different bolt spacing subjected to twisting load.

recorded deformation was 65 mm. Figure 9 illustrates the force and displacement for different layouts.

3.6. STRESS ANALYSIS

A brief stress analysis was performed on the optimal configuration, which includes four M12 bolts arranged in a rectangular pattern with Yg increased by 30 percent, Xg decreased by 30 percent, and the center distance increased by 35 percent. The maximum preload was applied to the bolts, along with the external applied loads. The maximum external load was determined from the maximum sliding force (R_t) for each individual bolt. Through static analysis, the safety coefficient for the most stressed bolt was calculated and found to be greater than 2, as shown in Figure 10. This clearly indicates that under these loading conditions, the joint is completely safe.

4. CONCLUSIONS

The study presented in this paper demonstrates the influence of bolt parameters on the stiffness of a simple bolted corner connection subjected to bending and twisting moments. In general, the arrangement of the screws plays a fundamental role in the stiffness of the connection. Specifically, the parameters that most significantly influence stiffness are the center of gravity and the center distance between bolts. Although the nominal diameter of the bolts contributes to increased stiffness, it has relatively little effect on the final stiffness. By appropriately modelling the configuration of the screws, it is possible to achieve considerable stiffness, comparable to using a greater number of screws. A notable example is the configuration with 4-M12 bolts, where the center of gravity is vertically increased and horizontally decreased, and the center distance is increased. In this setup, the displacement of the angle piece due to the load is almost equal to that obtained with 6-M12 bolts.

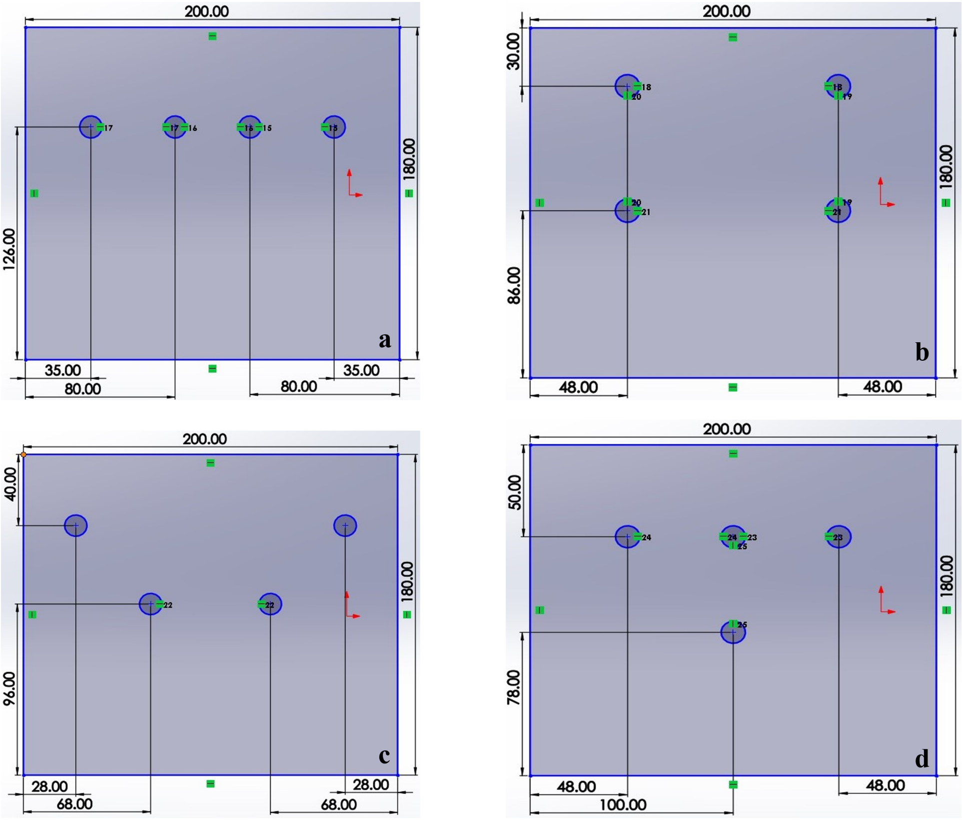

Figure 8. Bolt layouts (a) Inline (b) rectangular (c) trapezoid (d) T-shape.

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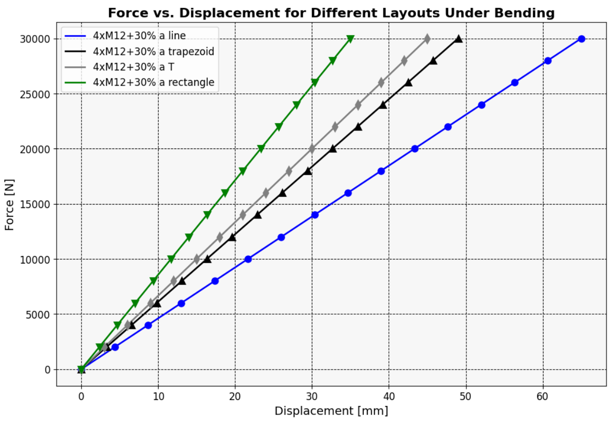

Figure 9. Force vs displacement for different layouts.

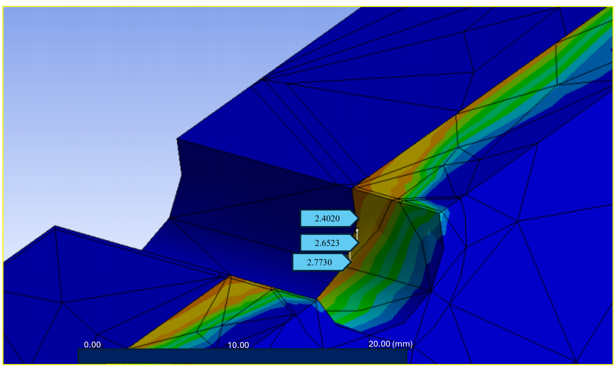

Figure 10. Minimum safety factor calculated through static analysis for the most stressed bolt.

5. Future recommendations

In the future, more configurations will be investigated using advanced AI optimization techniques, such as evolutionary algorithms, to find the optimal bolt parameters. Additionally, the effects of angle piece length, width, and material will be studied. It would also be interesting to include fatigue analysis and examine the effect of bolt preload on stiffness.

References

[1] D. Croccolo, M. De Agostinis, S. Fini, et al. Optimization of bolted joints: A literature review. *Metals* **13**(10):1708, 2023. `https://doi.org/10.1086/144770`

[2] N. R. Nelson, N. S. Prasad, A. Sekhar. Structural integrity and sealing behaviour of bolted flange joint: A state of art review. *International Journal of Pressure Vessels and Piping* **204**:104975, 2023. `https://doi.org/10.1016/j.ijpvp.2023.104975`

[3] R. Kiamanesh, A. Abolmaali, M. Razavi. Effect of circular bolt pattern on behavior of extended end-plate connection. *Journal of Structural Engineering* **139**(11):1833–1841, 2013. `https://doi.org/10.1061/(ASCE)ST.1943-541X.0000765`

[4] P. Wang, J. Xu, J. Li, L. Yu. Tensile behavior of cruciform stubs with four bolts per row. *The Structural Design of Tall and Special Buildings* **32**(1):e1988, 2023. `https://doi.org/10.1002/tal.1988`

[5] B. Shen, Z. Pan, H. Lin, W. Li. Bolt layout optimization design based on genetic algorithm. In *IOP Conference Series: Materials Science and Engineering,*

vol. 576, p. 012005. IOP Publishing, 2019. https://doi.org/10.1088/1757-899X/576/1/012005

[6] X. Lu, M. Zhu, Y. Liu, et al. Triangular position multi-bolt layout structure optimization. *Applied Sciences* **13**(15):8786, 2023. https://doi.org/10.3390/app13158786

[7] K. Sarı, H. Dilipak. A design software based on the placement of bolts for bolted joints. *Artvin Çoruh Üniversitesi Mühendislik ve Fen Bilimleri Dergisi* **1**(2):104–114, 2023.

[8] DIN. Designation systems for steels - Part 1: Steel names; German version EN 10027-1:2016. [2017-01-01]. https://www.dinmedia.de/en/standard/din-en-10027-1/262540217

[9] European Committee for Standardization. BS EN 1993-1-8:2005 Eurocode 3: Design of steel structures - Part 1-8: Design of joints, 2005. [2005-01-12]. https://www.phd.eng.br/wp-content/uploads/2015/12/en.1993.1.8.2005-1.pdf

[10] VDI. Systematic calculation of highly stressed bolted joints - joints with one cylindrical bolt, VDI 2230 Part 1, 2014. [2015-11-01]. https://www.vdi.de/en