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Investigation of the Structural-Mechanical Properties of the Different Lug Joints

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Abstract. Lug Joint is a typical connecting structure in the engineering field, which is often used to connect different components. Analyzing lug stresses is crucial for structural integrity and failure understanding. This study focuses on investigating the stress concentration factor and displacements of different types of lug joints under axial loading. Lug modelling in SolidWorks, results via Finite Unit Analysis plug-in. The ESDU files will be used as validation and compared with the obtained results to ensure the reliability of the experiments. This study compared the structural performance of a waisted lug and a waisted lug with additional flat (or called: flat-sided lug) under different geometric ratio conditions (a/w and t/d). The flat-sided lug consistently exhibited lower stress concentration factors (SCF) and smaller displacements, which indicate greater bearing capacity and less deformation, although it the volume and weight larger than the waisted lug. The different lugs exhibited similar behaviour with respect to t/d, showing a continuous improvement until reaching the medium thickness range, after which performance began to deteriorate at higher thicknesses due to bending effects. Overall, the flat-sided lug shows superior mechanical performance. However, the final design must strike a balance between these advantages and physical and economic considerations.

Keywords: Waisted lugs, Waisted lug with additional flat, Stress Concentration Factor, FEA

1. Introduction

The lug joint is a ubiquitous connection method in various mechanical fields. The structure of the lug joint is simple, it can be regarded as a bolted joint consisting of a pin, male, and female lugs. It is also considered a bolt joint. The world's first unthreaded bolt was invented during Roman times where it was primarily used for door locks. As the screw technology developed, it found more diverse applications. The first machine to make bolts and screws was designed in 1568 by Besson in France, which significantly improved production efficiency [1]. In the present day, modern alloy bolts include nickel-based grades for high-temperature use (e.g., turbochargers, engines) and lightweight options like aluminium, magnesium, and titanium for aerospace applications [2].

Bolted joints offer several advantages, one of which is high tensile strength. Furthermore, the tensile strength of a bolted joint can often be increased by changing the fasteners or adjusting the clamp load. However, with the increase in application range of bolts, several drawbacks have come to light. For instance, if the operating force exceeds the bolted joint's clamp load, it may cause the

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joint to fail prematurely. Additionally, bolted joints can also fail from corrosion. If the nut or bolt begins to corrode, it may loosen to the point where it can no longer support the operating force. In addition, vibrations can induce bolt loosening. Therefore, there is an urgent need to study bolt characteristics and improve bolt design [3].

McCarthy experiments showed that increasing bolt clearance reduces connection stiffness and delays load bearing, but significantly increases failure displacement [4]. Tight-fit joints fracture early (approximately 2.25–3 mm), while a 240-micron gap allows displacement exceeding 5 mm with almost no fracture. The plastic initiation load decreases from 18 kN to approximately 15 kN with increasing clearance, reflecting the significant impact of different clearances on elastic deformation and overall stiffness.

Pratik reported that in waisted lugs, increasing the width-to-bolt-diameter ratio (w/d) reduces the stress concentration factor (SCF) because the nominal stress rises faster than the peak stress, although the peak stress at the hole edge always increases with larger hole diameters or narrower lug widths [5]. Winklberger compared waisted and round-ended lugs, finding that waisted lugs exhibit consistently higher stress intensity factors (SIF) with similar trends [6]. As the hole-to-edge ratio (a/b) increases, the SIF first decreases and then increases, reaching its minimum at a/b = 0.5, and different materials lead to different crack initiation positions. Markus applied electromechanical impedance (EMI) methods with piezoelectric sensors to detect, locate, and quantify fatigue cracks in waisted lugs, identifying two typical crack sites: inside the bolt hole at θ_i = 9° and outside the transition region between the shaft and the lug's maximum diameter [7].

Based on the above research, bolt performance is affected by a variety of factors, such as the gap between the bolt hole and the bolt, and the tightening torque. Therefore, engineers must conduct thorough design based on the application scenario and predict its mechanical properties to ensure that the bolts and lugs do not undergo severe deformation or damage under structural loads. This project numerically investigates lug joint structures, focusing on waisted lugs and those with an additional side flat. Among these, SolidWorks FEM for modelling and ESDU for validation. The study aims to:

1. Modeling different lugs in SolidWorks and assembled them together. Creat density of meshing of the model and add axial loads and boundary conditions to the model to simulate the mechanical properties of the lug connection.

2. The effect of bolt diameter (d) on displacement, maximum pressure and SCF will be investigated for five different types of lugs under the same load and boundary conditions. The simulation results will then be compared with the theoretical results.

3. Waited lugs and waisted lugs with additional side flat will be selected to focus on the effect of varying their thickness (t) and the distance of the bolt hole centre to the lug's edge (a) on SCF and displacement. Finally, the obtained values will be compared with ESDU.

4. To investigate the effect of forces in different directions on the SCF and displacement of the lug joint.

2. Methodologies

2.1. Analytical method

In project number 81006, ESDU engineers devised a series of theoretical formulae for lug joints (ESDU 1981). They classified commercially available lug joints into five different types based on geometry and function: square-ended lug, round-ended lug, waisted lug, waisted lug with an

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additional side flat and waisted lug with a slot. Different calculation methods were then provided to calculate and validate the theoretical values of the stress concentration factors for each lug type.

Taking the square-ended lug mentioned in the document as an example (as illustrated in Figure 1), it transforms the ratio of the bolt aperture (d) to the lug width (w), and the ratio of the distance from the aperture centre to the lug end (a) to the lug width. The concentration stress coefficients are thus calculated for almost all commercially available square lug joints with different geometries. By doing so, the stress analysis and mechanical behaviour of lug joint structures will be validated using the calculation methods provided in this document.

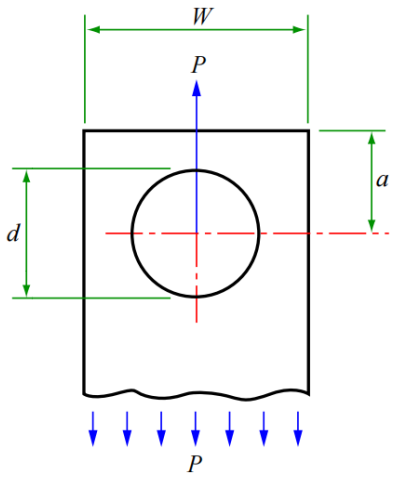

Figure 1. The geometry of the square-ended lug

2.2. Numerical methodology

The Finite Elements Method (FEM) is a general numerical technique used to solve differential equations arising in engineering and mathematical modelling. In stress analysis, the finite elements analysis divides a monolithic object into smaller, simpler parts by spatially discretising the object's mesh, which are called finite elements. These simple finite elements undergo data analysis. Then the system of simple equations modelling these finite elements are synthesised into a more extensive equation to model the whole problem. In engineering, FEM usually consists of three main steps: pre-processing, analysis and post-processing. Due to the complexity of the lug joint geometry, the model cannot be reduced to two dimensions for simulation. Given this issue, SolidWorks software emerges as a good choice for CAD and simulation.

In this study, all analytical results are obtained through numerical methods. The three-dimensional geometry of the lug joints is first created in SolidWorks, and the individual components are then assembled using the mate tool. After defining the appropriate material properties, the interaction between the assembled parts is established. The load is a tensile force of 5,000 N applied to the cross-section at the end of the lug. The fixed constraints are located on the surfaces of each side of bolt. Finally, the FEM is performed using the built-in simulation plug-in, and the results are interpreted during the post-processing stage. This six-step workflow—geometry modeling, assembly, material definition, interaction setup, load/boundary application, and post-processing—ensures a systematic and reliable structural evaluation of the lug joints.

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3. Results and discussion

3.1. Validation of different parameter

For the a/w parameter, in waisted lugs and flat-sided lug, the clearance in a/w for waited lugs ranged from 5% to 15%, while the clearance for flat-sided lug remained about 7%. Furthermore, the comparison revealed that when t/d < 0.5 for the waisted lugs, the values about 12%, while when t/d > 1, the bending moment effect of lug bolt may cause the clearance between FEA result and ESDU (reaching the maximum at t/d = 2.25 (about 18%). As the ESDU is based on 2D assumption, it may cause the main clearance. The flat-sided lug presented a similar trend to the previous result. Overall, this indicates that the finite element method has high reliability within a medium geometric scale range.

3.2. Trends in SCF and displacement under different a/w

Figure 2 compares the SCF values of the waisted lug and the waisted lug with additional side flats at different a/w (d =40mm, w=80mm and t=10mm) ratios from 0.5 to 0.9, with the former generally higher than the latter. Figure 3 illustrates the effect of different a/w on the displacement of two different lugs: the waisted lug and the waisted lug with an additional side flat. Overall, the displacements of both lugs decreases as a/w increases. In addition, the fluctuation of waisted lugs are more significant, whereas the waisted lug with additional side flat had a more stable rate of decline.

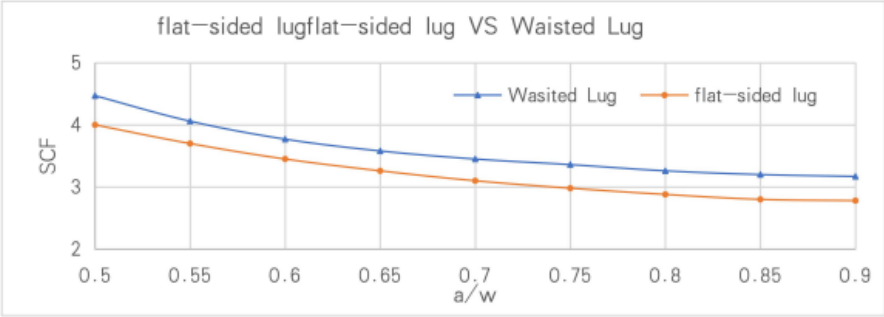

Figure 2. Effect of the ratio a/w of different waisted lugs on SCF

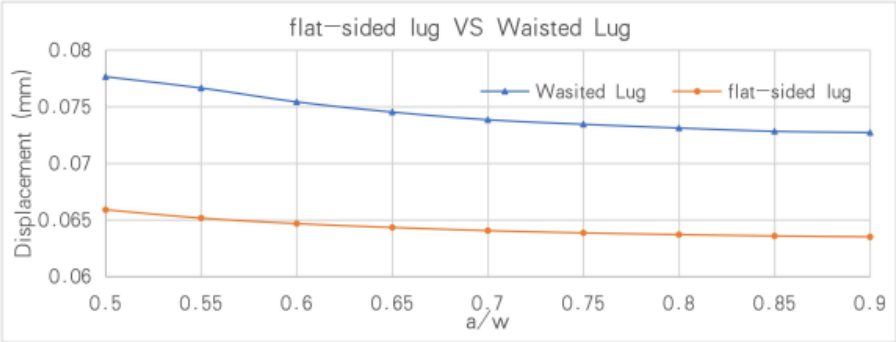

Figure 3. Effect of the ratio a/w of different waisted lugs on displacement

Combining Figures 2 and 3, a waisted lug with additional side flat produces less deformation and has a lower maximum stress than a waisted lug for different a/w when they are under the same force.

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Therefore, the waisted lug with additional side flat can withstand higher ultimate tensile force than the waisted lug. However, a waisted lug with additional side flat usually takes up more volume and weight than the waisted lug.

3.3. Trends of SCF under different t/d

Figure 4 compares the SCF values of the waisted lug and waisted lug with an additional side flat at different t/d (a=40mm, d=40mm, w=80mm) ratios. Overall, the SCF of the waited lug is higher than that of the waited lug with an additional side flat at any time. Furthermore, their trend is roughly the same.

The waisted lug and waisted lug with an additional side flat was at their lowest points when t/d was 0.125. When t/d is between 0.25 and 1, they both remain stationary. However, when t/d is greater than 1, they rise again, and the rising rate of the waisted lug with an additional side flat was greater than that of the waisted lug, thereby narrowing the gap between them. This point also reflected their highest values.

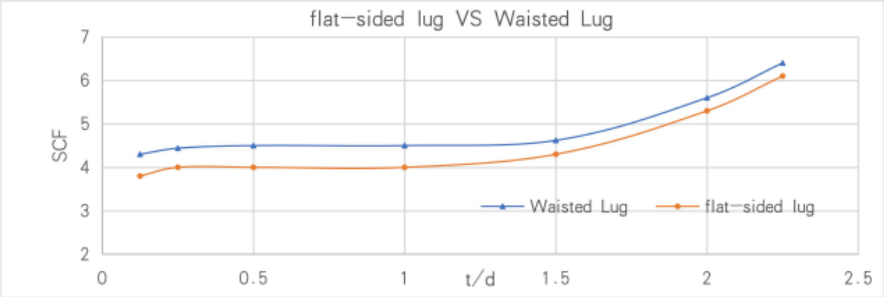

Figure 4. Effect of the ratio t/d of different waisted lugs on SCF

3.4. Trends of maximum pressure and displacement at alter t/d

Figure 5 compares the maximum pressure of the waisted lug and waisted lug with an additional side flat as the t/d ratio from 0.125 to 1.25. It is important to note that since the input force at the end of the lug does not change when SolidWorks is set, the average pressure on the end of the lug will become smaller as the thickness increases; this leads to entirely different trends of their SCF and maximum pressure as t/d changes.

Overall, the waisted lug always exhibits higher maximum stress than the waisted lug with additional side flat. In addition, that as the lug width increases, the contact area between the bolt and the lug bolt hole becomes larger, so the force is distributed to different lug positions. Conseuently, this leads to a considerable decrease in maximum stress. However, when t/d is greater than 1, the bolt starts to generate a bending moment. The force is not evenly distributed to the lug hole surface but will be concentrated on the outside of the lug bolt hole. This leads to a gradual reduction, and eventual stabalisation, of maximum stress when t/d surpasses 1. The trends of SCF and displacement of waisted lug and waisted lug with an additional side flat are almost the same. Hence, under a constant force magnitude, with the increase of t/d, the ability of the lug to withstand force is better. However, in the real-world industrial field, lugs with a particularly large thickness are not used. Excessively thick widths will increase the size, weight, manufacturing difficulty and cost of the lugs.

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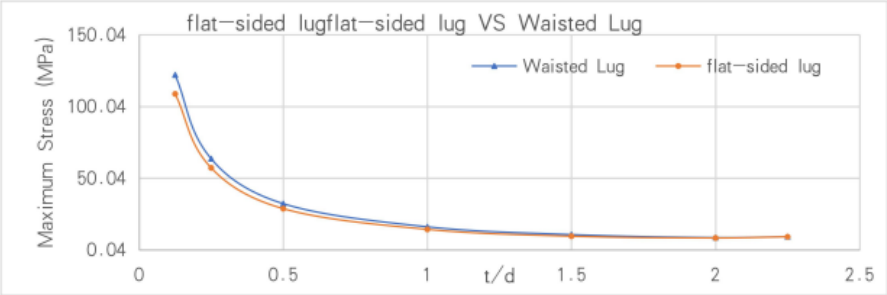

Figure 5. Effect of the ratio t/d of different waisted lugs on maximum stress

The waisted lug consistently shows slightly higher displacement than the flat-sided lug. In addition, when t/d is < 0.5, the trends of both lugs decrease sharply. The increase in displacement when t/d is greater than 1.5 can be attributed to the clearance between the bolt and lug bolt holes being set to 0.27, meaning there is a small gap between them. Consequently, when the bolt length is too long, it will still cause a small bending moment, which increases the displacement slightly.

4. Conclusion and future perspectives

This paper uses SolidWorks finite element analysis to analyse the mechanical behaviour of the waisted lug and the waisted lug with an additional side flat when subjected to axial loads under a series of different diameters, lug thicknesses, and distances from the centre of the bolt to the edge of the lug. Additionally, axial loads at different angles are also investigated. The critical research parameters include displacement, maximum stress and stress concentration. Furthermore, the simulation results in this paper agree with the theoretical results of ESDU. Based on the results and discussion presented in this study, the following conclusions can be drawn:

(1) The bolt diameter affects the SCF of the waisted lug and waisted lug with additional side flat. As the bolt diameter gradually increases, the SCF of the waisted lug with additional side flat will drop sharply at first and then remain roughly at the same level. At the same time, the waisted lug has decreased slowly. In addition, the displacement of the two waisted lugs decreases initially and then increases sharply with the increase in bolt diameter. When the ratio of d/w is 0.25, their displacements are the smallest. The displacement of the waisted lug is always greater than that of the waisted lug with additional side flat. The simulated results are slightly larger than the theoretical ones at smaller bolt diameters.

(2) The distance between the bolt centre and the lug edge will also affect the SCF and displacement of the above two waisted lugs. As the distance increases, the SCF and displacement curves of the two lugs are roughly similar, slowly decreasing and then tending to stabilise. The SCF and displacement of the waisted lugs are greater than those of the waisted lugs with additional side flat. In addition, the simulated data are very similar to theoretical data, albeit having a slightly higher value.

(3) The thickness of the lug has a significant influence on its mechanical properties. When the ratio of lug thickness to bolt diameter (t/d) between 0.25 to 1, the SCF of waisted lug with additional side flat remains constant. When t/d is greater than 1.5, SCF gradually increases, and the rising point of waisted lug will be earlier. Furthermore, SCF of the waisted lug is higher than that of the waisted lug with additional side flat at any time. Besides that, when t/d is relatively small, the displacement of both lugs will decrease sharply with an increase in lug thickness. Conversely when t/d is

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relatively large, the bolt will generate bending moments and make the lug displacement increase. Additionally, when t/d is 1.5, the displacements of the two lugs are minimized.

(4) The direction of the force acting on the lug has varying effects on the stress concentration factor (SCF) of the bolted connection. The SCF of the waisted lug against tension and compression is approximately the same, with both yielding minimum values. When under pressure, the waisted lug with additional side flat has a lower SCF than under tension. The SCF of both lug types is the largest when subjected to a force at 90°, and the SCF of the waisted lug is higher. Besides this, the two different lugs' displacement and SCF curves are about the same.

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