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Numerical Analysis and Experimental Study of Shear Stress in Riveted Joints with Variation of Joint Type and Geometric Configuration

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Abstract: Riveted joints are still widely used in steel structures because of their good resistance to mechanical loading, and their performance is governed by the joint type and the rivet geometric configuration. This study investigates the effects of joint type (lap joint and butt joint) and rivet configuration (chain pattern and zig-zag pattern) on the mechanical behavior of AISI 1020 steel riveted joints through experimental and numerical approaches. Tensile tests were carried out using a Universal Testing Machine (UTM), while stress and deformation were simulated using ANSYS Workbench based on the Finite Element Method (FEM). The zig-zag pattern produced a higher ultimate tensile strength (UTS) than the chain pattern for both joint types: 192.02 MPa versus 186.32 MPa for the lap joint (about 3.06% higher maximum load) and 196.50 MPa versus 188.80 MPa for the butt joint. The butt joint carried about 1.33% (chain pattern) and 2.33% (zig-zag pattern) more maximum load than the lap joint. The simulations showed the same ranking, with the highest equivalent stress of 560.03 MPa obtained for the zig-zag pattern butt joint. Post-test observation showed that all joint variations failed by rivet shear initiated by stress concentration around the rivet holes. Overall, the zig-zag pattern and the butt joint gave a higher tensile capacity than the chain pattern and the lap joint, accompanied by a higher maximum local stress.

Keywords: ANSYS Workbench, butt joint, chain pattern, finite element method, lap joint, riveted joint, stress concentration factor, shear stress, zig-zag pattern.

I. INTRODUCTION

Mechanical joints are critical elements that determine the structural integrity of components in the construction, transportation and manufacturing sectors. Although welding and bolted connections have developed rapidly, riveted joints are still used in applications that require high resistance to vibration, load cycles and severe service conditions [1], [2]. Riveting does not create a heat-affected zone as welding does, and it offers a more uniform stress distribution than ordinary bolts, so riveted joints remain in use in steel bridges, aircraft structures, railway frames and several automotive components. A well-designed joint must transfer tensile, compressive and shear forces safely, yet it can still fail by rivet shearing, plate tearing around the holes, or local stress concentration [3].

In a riveted joint the shear strength of the rivets is one of the main parameters that governs the load transferred between structural elements. Previous studies reported that the shear capacity of mechanical joints depends not only on the fastener material but also on the contact condition and on the joint geometry [4], [5]. The arrangement of the fasteners therefore strongly influences the load distribution [6]. In a chain pattern the rivets are placed in aligned rows and columns, so that the force flows along a single path [7], whereas in a zig-zag pattern the rivets are staggered and the load path becomes more distributed and more complex. The joint type is also influential. A lap joint, in which the plates overlap, usually has a high shear capacity but is exposed to secondary bending caused by load eccentricity [8]. A butt joint uses a cover plate (strap) to obtain a more symmetric stress flow, although it may produce higher stress concentration at the plate transition near the rivet holes [3], [9]. Studies on rivet geometry [10] and on finite element modeling of riveted joints [11] exist, but the combined influence of joint type and rivet pattern on the shear behavior of the same specimens, evaluated by both testing and simulation, is still limited.

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This study therefore investigates AISI 1020 steel riveted joints with two joint types (lap and butt joints) and two rivet configurations (chain and zig-zag patterns). The objectives are (i) to analyze the effect of joint type and rivet configuration on the tensile and shear behavior, (ii) to compare numerical results from ANSYS Workbench with experimental results from a Universal Testing Machine, and (iii) to identify the failure mechanism of the joints.

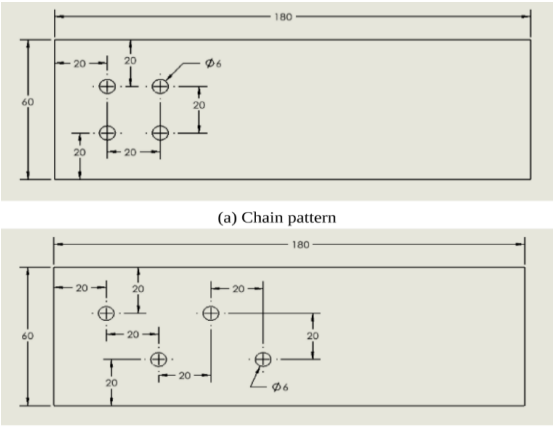
II. MATERIALS AND METHODS

2.1 Specimens and Materials

The main plates, the cover plates and the rivets were made of AISI 1020 carbon steel. The rivets had a diameter of 6 mm and each specimen contained four rivets. The plates were 60 mm wide and 180 mm long, and the 6 mm holes were positioned 20 mm apart as shown in Fig. 1. Four variations were prepared with reference to ISO 12996:2013: chain pattern lap joint, zig-zag pattern lap joint, chain pattern butt joint and zig-zag pattern butt joint. The material properties used in the experiment and in the simulation are given in Table 1.

Table 1: Material properties of AISI 1020 steel

Property	Value
Elastic modulus, E	200 GPa
Poisson's ratio, μ	0.29
Yield strength, σ_y	295 MPa
Tensile strength, σ_u	395 MPa
Shear modulus, G	80 GPa
Density, ρ	7850 kg/m³



(a) Chain pattern

(b) Zig-zag pattern

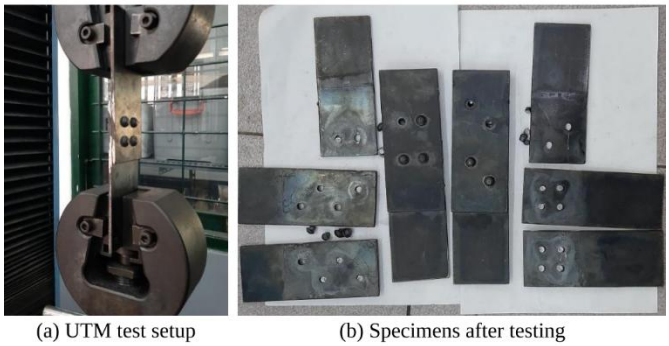
Figure 1: Specimen geometry (dimensions in mm): (a) chain pattern and (b) zig-zag pattern

2.2 Specimen Preparation and Riveting

The plates were cut to the planned dimensions and the edges were ground to remove burrs and surface irregularities that could cause unwanted stress concentration outside the joint. The holes were drilled according to each configuration. Hot riveting was then applied: the rivets were heated with a gas torch to about 700–800 °C, monitored with an infrared thermometer, and the closing heads were formed one by one with a hydraulic press and a rivet mold. The press force read on the machine was 1500 kgf (14.71 kN) per rivet, or 6000 kgf (58.84 kN) for the four rivets of one specimen. Shrinkage of the rivets during cooling generates a clamping force that holds the plates together [2]. After riveting, the heads were inspected visually for incomplete forming, asymmetric heads, misalignment and poor mold contact, because these factors may affect the failure of the joint [12].

2.3 Tensile Testing

Tensile tests were conducted on a Universal Testing Machine (UTM) [13]. The specimen dimensions were measured, the specimen ends were clamped vertically to minimize bending, and shims were used where necessary so that the load axis passed through the joint center. The load and elongation were set to zero and the specimen was loaded at constant speed until failure. The maximum load, ultimate tensile strength (UTS, the maximum load divided by the plate cross-sectional area) and total elongation were recorded, and the failure mode was documented after the test (Fig. 2).



(a) UTM test setup (b) Specimens after testing

Figure 2: Tensile testing: (a) UTM test setup and (b) specimens after testing

2.4 Numerical Modeling

The three-dimensional model of the plates and rivets was built in SolidWorks with dimensions equal to the test specimens and exported as a STEP file. The analysis was performed in ANSYS Workbench 2023 R2 (Static Structural) [11]. The

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material data of Table 1 were assigned to all components, and the contact between plates and rivets was defined. One end of the joint was given a fixed support, and a remote displacement was applied to the other end to represent the tensile loading of the UTM. The equivalent (von Mises) stress and the total deformation were extracted from the solution and compared with the experimental data.

2.5 Stress Concentration Factor

The stress concentration factor expresses the increase of local stress at the geometric discontinuity of a rivet hole. The nominal stress is calculated from the maximum test load, and the maximum stress follows from the stress concentration factor:

$$\sigma_{nominal} = F / A_{ef} \quad (1)$$

$$\sigma_{max} = K_t \cdot \sigma_{nominal} = K_t F / A_{ef} \quad (2)$$

where F is the maximum load from the tensile test (N), A_{ef} is the effective net cross-sectional area (144 mm²) and K_t is the stress concentration factor. For a plate width w = 60 mm and a hole diameter d = 6 mm, d/w = 0.1 and $K_t \approx 2.7$ is read from the standard chart for a plate with a transverse hole in tension [14].

III. RESULTS AND DISCUSSIONS

3.1 Grid Independence Test

The mesh was refined from 2.3 mm to 1.9 mm and the maximum equivalent stress was compared (Table 2 and Fig. 3). The change in stress is below 0.2% for all mesh sizes of 2.1 mm and smaller, so the result is considered mesh independent. A mesh size of 2.0 mm (35,254 elements) was selected for all simulations because it gives a stable stress with an efficient computation time.

Table 2: Grid independence test results

Mesh size (mm)	Elements	Stress (MPa)	Error (%)
2.3	32,228	347.29	–
2.2	34,088	348.80	0.433
2.1	35,298	348.86	0.017
2.0	35,254	348.27	0.169
1.9	35,826	348.28	0.003

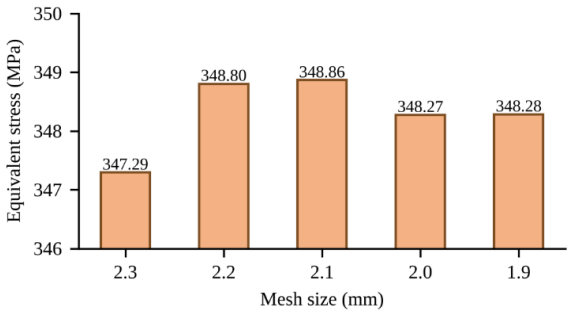


Figure 3: Maximum equivalent stress for different mesh sizes

3.2 Experimental Tensile Results

Table 3 summarizes the tensile test results. The zig-zag pattern carried a higher maximum load than the chain pattern in both joint types, i.e. 40,324.94 N versus 39,128.53 N for the lap joint and 41,266.38 N versus 39,648.28 N for the butt joint. The corresponding UTS values are 192.02 MPa versus 186.32 MPa and 196.50 MPa versus 188.80 MPa. The total elongation of the butt joints (13.72 mm and 12.36 mm) is about 1.8 times that of the lap joints (7.44 mm and 6.68 mm), while within each joint type the zig-zag pattern reached a higher load with about 10% smaller elongation, which indicates a stiffer response.

Table 3: Tensile test results

Variation	Max. load (N)	UTS (MPa)	Elong. (mm)
Chain pattern lap joint	39,128.53	186.32	7.44
Zig-zag pattern lap joint	40,324.94	192.02	6.68
Chain pattern butt joint	39,648.28	188.80	13.72
Zig-zag pattern butt joint	41,266.38	196.50	12.36

3.3 Numerical Results

The simulated maximum equivalent stress and total deformation are listed in Table 4, and the stress contours of the lowest and the highest cases are shown in Fig. 4. The stress is concentrated around the rivet holes and at the contact between the rivets and the plates, where the geometry is discontinuous. The maximum equivalent stress was 444.79 MPa for the chain pattern lap joint, 543.40 MPa for the zig-zag pattern lap joint, 467.63 MPa for the chain pattern butt joint and 560.03 MPa for the zig-zag pattern butt joint. The maximum total deformation was almost equal for the lap joint (10.06 mm and 10.14 mm) and the chain pattern butt joint (10.05 mm), but it reached 14.05 mm

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for the zig-zag pattern butt joint, which is 4.00 mm larger than for the chain pattern.

Table 4: Numerical results and theoretical maximum stress

Variation	Eq. stress (MPa)	Def. (mm)	σ_{max} (MPa)
Chain pattern lap joint	444.79	10.06	733.6
Zig-zag pattern lap joint	543.40	10.14	756.1
Chain pattern butt joint	467.63	10.05	743.4
Zig-zag pattern butt joint	560.03	14.05	773.7

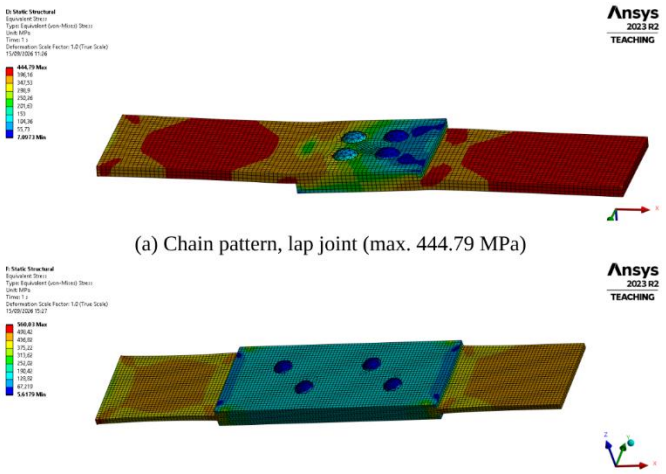


Figure 4: Equivalent (von Mises) stress contours: (a) chain pattern lap joint and (b) zig-zag pattern butt joint

3.4 Effect of Rivet Configuration

Fig. 5 compares the four variations. In the experiments, the zig-zag pattern increased the UTS by 5.70 MPa (3.06%) for the lap joint and by 7.70 MPa (4.08%) for the butt joint. The simulation shows the same trend: the equivalent stress of the zig-zag pattern is higher by 98.61 MPa (22.2%) in the lap joint and by 92.40 MPa (19.8%) in the butt joint. The staggered arrangement distributes the load transfer over a wider region of the plate, while the aligned rivets of the chain pattern force the load through a single line and concentrate the shear force on the rivet shanks [6]. The zig-zag pattern, however, also produces a larger local stress peak. The load-carrying capacity is therefore not inversely related to the local stress, and the geometry should be judged from both quantities together.

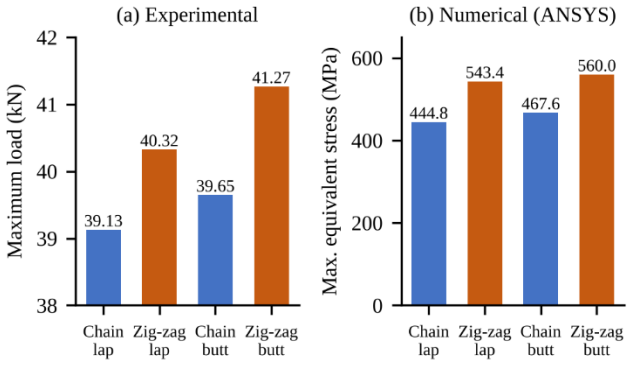


Figure 5: Comparison of the four joint variations: (a) experimental maximum load and (b) numerical maximum equivalent stress

3.5 Effect of Joint Type

For the same rivet configuration, the butt joint resisted a slightly higher load than the lap joint: 519.75 N (1.33%) higher for the chain pattern and 941.44 N (2.33%) higher for the zig-zag pattern, with UTS values of 188.80 MPa versus 186.32 MPa and 196.50 MPa versus 192.02 MPa. The numerical equivalent stress of the butt joint is also higher by 22.84 MPa (chain pattern) and 16.63 MPa (zig-zag pattern). The cover plate of the butt joint gives a more symmetric force flow and avoids the eccentricity of the lap joint, but it creates a stress concentration at the plate transition around the rivet holes [3], [9]. The differences between the joint types are small, about 1–2% in load, so replicate tests are needed to confirm them statistically.

3.6 Theoretical Stress and Comparison of Methods

Using Eq. (2) with K_t = 2.7, the theoretical maximum stress is 733.6 MPa and 756.1 MPa for the chain and zig-zag lap joints, and 743.4 MPa and 773.7 MPa for the chain and zig-zag butt joints (Table 4). These values exceed the tensile strength of the material (395 MPa), which means that local yielding is expected around the holes before the final failure. Experiment, simulation and theory all give the same ranking of the four variations: chain lap < chain butt < zig-zag lap < zig-zag butt. The maximum load and the simulated equivalent stress are strongly correlated (Pearson $r \approx 0.95$).

Fig. 6 compares the stress–strain response of the chain pattern lap joint. The simulated curve rises to a peak of 444.79 MPa and then decreases, whereas the experimental curve reaches 186.32 MPa and drops sharply at failure. The peak values differ because the simulation reports a local equivalent stress, while the experiment reports the nominal engineering stress, and because

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the model simplifies the material behavior and the contact conditions and neglects the clamping force and the plastic deformation caused by the riveting process. The numerical model therefore reproduces the trends and the locations of high stress, but it does not yet predict the absolute strength; an elastoplastic material model with a more realistic contact definition is recommended for further work.

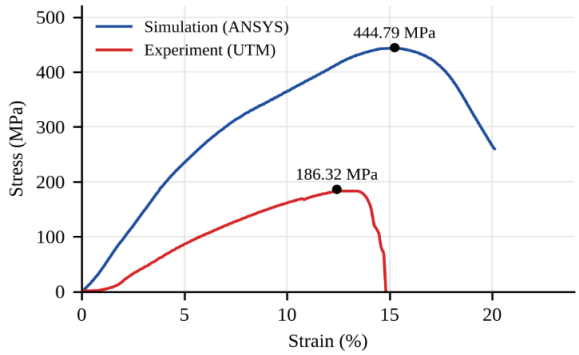


Figure 6: Stress–strain comparison between experiment and simulation for the chain pattern lap joint

3.7 Failure Mechanism

In all variations the specimens separated because the rivets were cut by shear force (rivet shear failure), and the rivet remnants stayed in the plates while the plates themselves showed no significant damage (Fig. 7). In the lap joint the tensile load is transferred from one plate to the other through the rivets, and in the butt joint through the cover plate to the rivets. When the shear stress in the rivet shank exceeded the shear capacity of the material, the rivets failed. The ANSYS results show a stress concentration around the holes and at the rivet–plate contact, which agrees with the location of the damage. The simulated von Mises stress alone, however, cannot prove the shear failure, and the identification here is based on visual inspection; examination of the fracture surfaces of the rivets is recommended to confirm it.

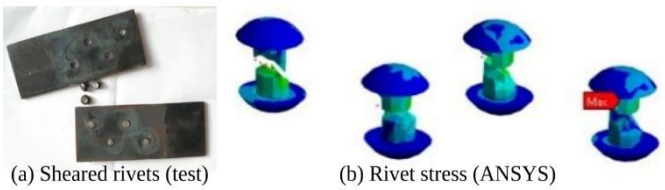


Figure 7: Rivet shear failure: (a) specimen after testing and (b) rivet stress in the simulation

IV. CONCLUSION

The effect of joint type and rivet configuration on AISI 1020 riveted joints was investigated by tensile tests and ANSYS simulations. The zig-zag pattern consistently gave a higher UTS than the chain pattern: 192.02 MPa versus 186.32 MPa for the lap joint and 196.50 MPa versus 188.80 MPa for the butt joint. The butt joint gave a slightly higher UTS and maximum load than the lap joint (1.33% for the chain pattern and 2.33% for the zig-zag pattern). The simulation showed the same ranking, with the highest equivalent stress of 560.03 MPa in the zig-zag pattern butt joint, so a higher capacity is accompanied by a higher local stress. All joints failed by rivet shear initiated by stress concentration around the rivet holes. Future work should use an elastoplastic material model, include the clamping force and plastic forming of the rivet heads, and extend the analysis to fatigue loading.

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