Effect of Sheets’ Thickness and Rivet Geometry on Mechanical Properties of Orbital Riveted Aluminium Joints: Experimental and Numerical Analysis

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Abstract: Orbital riveting is an innovative joining technology used in various industrial fields. Despite its diffusion in recent years, it has not been accompanied by an equivalent interest from the scientific community, which has neglected the aspects of process optimization and joint performance. In this experimental/numerical study, six different configurations of orbital riveted joints were realised and tested to determine the effects of sheet thickness and rivet geometry on the mechanical properties of the joints and their failure modes. The results showed that the configuration of the joint significantly affects both its resistance and fracture mechanism. Moreover, it was possible to identify a transition between different failure modes by changing the rivet diameter. A non-optimal joint geometry favours a premature fracture at very low load (i.e., S9A21 batch with net tension fracture). The highest mechanical resistance was found in the S8A15 batch, which experienced unbuttoning failure. In order to better correlate the joint geometry with the mechanical behaviour and the relative stress distribution, a simplified numerical FEM was validated with the experimental results.

Keywords: joining; riveting; aluminium

1. Introduction

The correct identification of the appropriate joining technique in industrial applications is becoming an increasingly important step in the design phase of the engineering structures [1]. In addition, the need to build lightweight, high-performance structures at reasonable cost and without sacrificing safety has led to the use of aluminium alloys in various industrial fields. However, conventional welding techniques are severely limited in joining aluminium alloys due to their low melting point, surface oxide layer, high thermal conductivity, high hydrogen solubility, and high solidification shrinkage. This fact leads to significant limitations in the design of joints [2].

In this context, several innovative solutions for joining aluminium sheets have emerged in recent decades, i.e., friction stir welding [3,4], self-piercing riveting [5], clinching [6], and orbital/planetary riveting [7]. In particular, orbital riveting is a cold-forming process that gives good results at a lower cost [8]. The desired predetermined shape of the part is achieved by a forming tool mounted on a rotating spindle that, similar to impact and compression forming and unlike traditional riveting processes, rotates 3 to 6 degrees off-centre, and applies axial and radial forces to the work piece by maintaining a line of contact. This peculiarity leads to the need for several tool revolutions, which take 1.5 to 3 s, to complete the orbital forming process and consequently to plastically deform the part [9].

Solid rivets made with orbital riveting are characterised by a smooth surface, whether they have a crowned, conical, or flat head. As the same point of the tool is always in contact with the same point of the rivet, there is little friction and no tearing of the material. Consequently, there is no damaged or hammered surface.
As the deformation work is only on the contact line between the tool and the rivet, the axial loads are lower than the traditional riveting techniques (about 80% less) by inducing the following advantages:

- Less stress on the parts to be joined;
- Elimination of cracks caused by other technologies such as impact riveting;
- Cold-head forming by avoiding bending or swelling of the fastener shank;
- Use of smaller presses in terms of size, energy consumption, and cost;
- Less rigid fixturing and longer lasting tools;
- Virtually silent and vibration-free process;
- Consistency and uniformity of the joint.

In addition, the process is capable of handling a wide range of materials including steel, aluminium, brass, bronze, copper, lead, and zinc, as well as many polymers.

Recently, due to its high efficiency, energy saving, low cost, and low noise, orbital riveting is being increasingly used in various industries, such as the manufacture of wheel hub bearings for automobiles [10], the assembly of aircraft structures (fuselage and wings), railway cars, lorry bodies, and large turbine plants.

The final strength of orbital riveted joints is influenced by several factors, including the strength and thickness of the sheet materials, the rivet geometry, the geometry of the die and the configuration of the specimen [2].

Although this technique has numerous advantages, in the literature, few works investigated this process, the operating parameters, and their optimization, unlike other innovative technologies.

In as early as 2003, Stutz [11] described orbital riveting and the main process parameters, demonstrating that it is an efficient and precise technology for joining components, providing strength, attractive appearance and batch-to-batch uniformity. Sontakke et al. [12] designed and analysed a drilling cum riveting machine for the orbital riveting that reduces the operation as well as transportation time required for completing the job with the aid of a finite element tool. Similarly, Jagtap et al. [9] presented a brief overview of design and development of an orbital riveting machine, main orbital riveting characteristics, and comparison with conventional riveting machine. In a following work, Satbhai et al. [13] applied scientific principles, technical information, and imagination for development of multipurpose riveting machine to perform a specific function with maximum economy and efficiency. Mahmoudi et al. [14] studied the rotational radial frictional riveting, by evidencing that the function of this machine is hyperbolic, and this causes uniformity and minimum displacement in the molecular structure of the piece. Patil et al. [15] tried to determine optimal tool angle in tool head, and tool geometry and mechanism of table feed for accurate positioning. Di Bella et al. [16] focused their attention on the performances and, in fact, they investigated the mechanical resistance and the durability in salt spray fog of hybrid aluminium/steel joints, realised with an orbital forming process.

This limited state-of-art demonstrates the need to optimise the geometry parameters of the orbital riveting process in order to produce efficient and secure joints. A correct joint design allows an optimal stress distribution to minimize the risk of premature and unexpected fracture of the mechanical component.

In such a context, the main objective of this experimental work was to investigate how changes in sheet thickness and rivet size can affect the mechanical properties of an orbitally formed joint between aluminium sheets. A single lap shear test was used as an experimental approach to evaluate the mechanical stability of the joint. A finite element analysis was also performed to develop a numerical tool to simulate the behaviour of orbital riveted joints. This model was validated by the experimental results.

2. Materials and Methods
2.1. Materials

The joints were realised on aluminium alloy AA 6082-T6 sheets with aluminium alloy AA 2011 rivets. The aluminium alloy AA 6082 is characterised by a good compromise be-
tween mechanical strength and corrosion resistance, allowing its use in different structural application contexts, whereas the aluminium alloy AA 2011 is a high mechanical strength alloy that machines exceptionally well, being suited to be used in automatic lathes.

2.2. Geometry

The samples were prepared according to [16]. Figures 1 and 2 show the geometry of the sheets and the rivets, respectively. In particular, the sheets were drilled with a manual column drill, while the rivets were made with a turning centre Yamazaki Mazak—Quick Turn Nexus 200MY mk II. They are characterised by the following sizes: 100 (L) × 25 (w) × 12.5 (mm). The distance between the centre of the hole and the edge of the sample (e) is 12.5 mm.

![Figure 1. Geometry of the sheets (mm).](image1)

![Figure 2. Geometry of the rivet (mm).](image2)

Six different riveted joints with different rivet diameters and sheet thickness ratios were investigated. Five repetitions were performed for each configuration, thus a total of 30 samples were prepared.

In particular, two different configurations of the sheet thickness ratio were investigated according to Table 1 (keeping the total thickness of the sheets equal to 3 mm):

- Symmetrical joints, where the two sheets have the same thickness, i.e., 1.5 mm;
- Asymmetric joints, where the upper and lower sheets have different thicknesses, i.e., 2 mm and 1 mm, respectively.

| Type of Joint | Configuration | Rivet Diameter ϕr (mm) | Hole Diameter ϕ (mm) | Top Sheet (mm) | Bottom Sheet (mm) |
|---------------|---------------|------------------------|----------------------|----------------|------------------|
| Symmetric     | S6A15         | 6.0                    | 6.2                  | 1.5            | 1.5              |
|               | S8A15         | 8.0                    | 8.2                  | 1.5            | 1.5              |
|               | S9A15         | 9.0                    | 9.3                  | 1.5            | 1.5              |
| Asymmetric    | S6A21         | 6.0                    | 6.2                  | 2.0            | 1.0              |
|               | S8A21         | 8.0                    | 8.2                  | 2.0            | 1.0              |
|               | S9A21         | 9.0                    | 9.3                  | 2.0            | 1.0              |

Additionally, three different rivets were used for each configuration in order to optimise the joint studied. Each rivet has a different diameter, namely 6, 8, and 9 mm.
The samples were characterised by the following code: SxAy, where x represents the rivet diameter (i.e., 6; 8; or 9) and y the sheet thickness (i.e., 15 if the joint is symmetrical and 21 if it is asymmetrical). For reference, batch S9A21 is referenced to an asymmetric joint configuration (aluminium sheets 1 mm and 2 mm, respectively) with rivet diameter of 9 mm.

2.3. Joining Process

The joining process was carried out using a BK-TAUMEL “BK80” machine, shown in Figure 3, and its main features are summarised in Table 2.

![Figure 3. BK-TAUMEL “BK80” machine.](image)

**Table 2. Characteristics of the BK-TAUMEL “BK80” machine.**

| Stroke Min Max (mm) | Max Push Strength (kN) | Motor Output (kN) | Air Pressure (bar) | Air Consumption (Nlt) |
|--------------------|------------------------|-------------------|--------------------|----------------------|
| 0–40               | 13.5                   | 0.37              | 5.2                | 10.4                 |

In the orbital forming, a forming tool, mounted off-centre in a rotating spindle, is inclined at a slight angle to the spindle centre (5° was used here). The tool axis of the form at the working end of the tool intersects with the true centreline of the spindle. The machine spindle rotates, but the tool in the orbital head or chuck is free to rotate in its bearings [17].

The process can be divided into three stages: in the first stage, the drive spindle advances and brings the tool into contact with the work piece. Then, pressure is applied in the smoothing stage and the line contact between the non-spinning tool and the work piece never changes. At each revolution of the spindle, the same line of contact is maintained to smooth the material. As the same point of the tool is always in contact with the same point of the work piece, there is virtually no friction and no tearing of the material, regardless of the shape of the component. Finally, the riveting tool is lifted.

Different set-up parameters were used for each configuration of the joints studied (see Table 3).
Table 3. Set up parameters.

| Type of Joint | Configuration | Punch Force (kN) | Working Time (s) | Displacement of the Punch (mm) |
|---------------|---------------|-----------------|------------------|-------------------------------|
| Symmetric     | S6A15         | 5.0             | 4                | 0.8                           |
|               | S8A15         | 8.0             | 4                | 0.8                           |
|               | S9A15         | 9.0             | 3                | 0.8                           |
| Asymmetric    | S6A21         | 5.0             | 4                | 0.8                           |
|               | S8A21         | 8.0             | 4                | 0.8                           |
|               | S9A21         | 9.0             | 3                | 0.8                           |

2.4. Single-Lap Shear Test

The manufactured joints were characterized through a single lap shear test, according to ISO/CD 12,996 [18]. All tests were performed using a Zwick/Roell Z600 testing machine equipped with a 10 kN load cell. All specimens were loaded to joint failure at a cross-head speed of 1 mm/min.

3. Finite Element Analysis

A 3D numerical analysis was performed using a commercial finite element software (i.e., DEFORM®) to both further investigate the behaviour of the tested joints and set a predictive tool for the design of riveted joints. Two different numerical models were analysed for each joint configuration: the first simulates the orbital forming process with a rigid punch lowering speed of 4 mm/min and a rotation speed of 1500 rpm, and the second models the single-lap shear test (see Figure 4).

Figure 4. Numerical model set up: orbital forming process and single-lap shear process.

The output of the first simulation is the formed joint. This is the input in the latter model, in which the tensile test constraints are applied according to ISO/CD 12,996 [18]. In Table 4 are reported the characteristic parameters of the model.
Table 4. FEM parameters.

| Component | Size (mm) | Elements | Nodes |
|-----------|-----------|----------|-------|
| Rivet     | 6         | 29,400   | 6900  |
|           | 8         | 32,600   | 7400  |
|           | 9         | 38,000   | 8900  |
| Sheets    | 1.5 (top) | 21,000   | 5800  |
|           | 1.5 (bottom) | 22,600 | 6100  |
|           | 2         | 25,800   | 6500  |
|           | 1         | 12,000   | 3700  |

Fracture Criterion

The normalised fracture criterion of Cockcroft and Latham [19] (see Equation (1)) was used to model ductile fracture during tensile testing and to evaluate the nature of fastener fracture. Both standard upsetting of cylinders and tensile tests are the simplest and most widely used tools for testing workability and establishing threshold for failure criteria [20,21].

\[ D = \int_0^{\varepsilon_f} \frac{\sigma_1}{\sigma} d\varepsilon \]  

where \( D \) = damage variable; \( \sigma_1 \) = first stress principal component; \( \sigma \) = effective stress; and \( \varepsilon_f \) = fracture strain.

The damage variable \( D \) represents the internal plastic energy required to deform the material until the ultimate strain \( \varepsilon_f \) is reached. The fundamental role of tensile stress (represented by the first principal stress component) in crack formation underlies the expression. Given the limited range of situations in which the Cockcroft and Latham model provides a reliable fracture prediction, a normalized version was introduced to improve its capabilities when the stress state is not purely tensile.

The Cockcroft and Latham criterion states that fracture occurs when the cumulative energy due to the maximum tensile stress exceeds a certain value. This criterion has shown good agreement in predicting the location of a tensile failure based on a maximum damage value.

In this study, the threshold values of the criterion were evaluated by tensile tests.

In order to properly simulate the joining process, the mechanical properties of the studied material were determined. Tables 5 and 6 show the chemical-mechanical data and the critical values according to Cockroft and Latham Damage, respectively.

Table 5. Aluminium chemical composition.

| Aluminium Alloy | Cu   | Fe   | Si   | Mg   | Mn   | Zn   | Bi   | Pb   | Cr   | Ti   | Other | Al   |
|-----------------|------|------|------|------|------|------|------|------|------|------|-------|------|
| AA 2011         | 0.40 (Max) | 0.20 (Max) | 0.05 (Max) | 0.05 (Max) | 0.10 (Max) | 0.2 (Max) | 0.2 (Max) | 0.10 (Max) | 0.25 (Max) | 0.10 (Max) | Other | Al |
| AA6082 T6       | 0.10 (Max) | 0.50 (Max) | 0.7 (Max) | 0.6 (Max) | 0.4 (Max) | 0.20 (Max) | 0.25 (Max) | 0.10 (Max) | 0.10 (Max) | Other | Al |

Table 6. Cockroft and Latham Damage critical values.

| Aluminium Alloy | Flow Curve Parameters | Damage Critical Value |
|-----------------|-----------------------|-----------------------|
|                 | C(MPa) | \( \varepsilon \) | D |
| AA 2011         | 292.463 | 0.027 | 0.29 |
| AA6082 T6       | 572.425 | 0.211 | 0.2 |
4. Results from the Single-Lap Shear Tests

Figures 5 and 6 report typical load/displacement curves for symmetric and asymmetric joints, respectively, at varying rivet diameter.

In particular, in Figure 5, it is possible to observe three distinct regions, as described in [22]:

- In the initial region, at low displacement, two sub-steps can be seen. First, mechanical adjustments (i.e., backlash and axis deviation) occur. These have no effect on the mechanical behaviour of the joint and are not considered in the performance evaluation.
of the riveted joints. Then, in the second sub-step, a progressive and linear increase in load with increasing displacement is observed. The strength of the joint depends on the shear strength of the rivet. The slope, which is indirectly related to the stiffness of the joint, is similar for all specimens of this configuration.

- In the next region, a gradual loss of linearity of the load–displacement trend is observed followed by a decrease in the slope $\Delta P/\Delta L$ of the curve. The sample starts to twist, and the sheets move away from each other, causing some local deformation. Consequently, at this stage, the performance of the joint depends only on the rivet and the resistance is carried by the joining point. The curve increases until reaching the maximum value.

- Additionally, in the last region, two sub-steps can be seen. First, the load starts to decrease, but its specific trend depends on the type of failure mode, which can occur for rivet shear or unbuttoning. For a smaller rivet diameter (i.e., sample S6A15), the load decrease is slighter: the fracture occurs for rivet shear, i.e., the shear cracks propagate gradually in the rivet. For a higher rivet diameter (i.e., samples S8A15 and S9A15) the corresponding curves show a similar trend, and the load decrease is more drastic, with the slope also changing at the end: the fracture occurs for unbuttoning, while the load decreases gradually. Finally, all specimens break down and the load decreases drastically.

When evaluating Figure 6, which refers to asymmetric specimens, although the first two regions seem similar, a different mechanical behaviour can be observed. After the local adjustments, the load increases almost linearly with increasing displacement, as previously observed for symmetric joints. However, the slope of the curve is slightly lower for A21 batches than for the corresponding A15 batches. Subsequently, the load continues to increase non-linear with a progressive reduction in the slope until reaching a plateau: the damage does not affect the rivet or locally the area around the hole, but the sheets deform around the hole. In the last regions, each configuration shows a different trend due to the different failure mode that affects the thinner sheets of the joint:

- For a low rivet diameter, the load slightly decreases at first, and then the slope of the curve changes and the reduction is more sudden. The distance between the edge of the hole and the edge of the sheet is small, and the fracture occurs for shear out.
- For a high rivet diameter, the load decreases drastically. The area of the sample cross section is particularly small, and fracture occurs for net tension.
- For a medium rivet diameter, the trend shows a few steps with a final residual load. This trend seems to be a compromise between the previous ones: drastic decrease, slight, again drastic, and plateau. In fact, the fracture occurs for cleavage, which can be considered as a mixed failure modes between shear out and net tension [23].

Figure 7 summarises the behaviour for both configurations by showing the different stages and the failure modes.

In Figure 8, the maximum values are given and compared. In particular, the joints of the SxA15 series are characterised by a higher resistance than those of the SxA21 series. This fact is related to the different behaviour observed during the test. In the first series, the symmetry reduces the bending phenomena, the area around the hole is subjected to a bearing phenomenon and the breakage occurs mainly for unbuttoning. In particular, this consists of a compressive stress that occurs near the contact area at the edge of the hole. Consequently, the hole tends to expand by promoting the extraction of the rivet shank (i.e., unbuttoning) [23]. If the rivet has a diameter of 6 mm, the load is even lower. In fact, it is possible to observe a fracture of the rivet head for a shear action. Thus, there is a transition line between the two failure modes.

In the second series, the load is lower not only due to the asymmetry of the joint, but also due to the lower thickness of the upper aluminium sheet, which promotes deformation around the hole and the resulting progressive damage. In this case, fracture occurs in several different modes. There is a transition from shear out to net tension.
To better correlate the strength of the joint with the fracture mechanism that occurred, Figure 9 shows the photographs of the observed failure modes. For sample S6A15, the head of the rivet breaks drastically at its low resistance. At higher diameters, the unbuttoning occurs. In fact, in these joints, thanks to the resistance offered by the cross section of the sheets, shear out or net tension failure modes are avoided. At higher loads, the aluminium sheets lose contact within the overlapping surface. Then, the rivet is the only element that contributes to the resistance with its shear behaviour. The area around the rivet undergoes greater deformations until the rivet pull-out occurs [24].
The orbital forming process was modelled by assigning a rotational speed equal to 157 rad/s and an axial speed of 4 mm/s to the riveting head. The analysis of Table 7 shows the effectiveness of the FE model, i.e., the agreement between analytical and experimental results is confirmed in terms of punch force and geometry of the orbitally formed rivet (diameter and height).
In particular, it is found that, for the symmetrical joints, the difference in the punch force increases from 5.7% for sample S9A15 to 11.3% for sample S8A15. For the asymmetric joints, this difference changes from 2.3% for sample S8A21 to 15.4% for sample S6A21. In the numerical model, the punch force is slightly higher for the ideal properties of the aluminium. Experimentally, it is found that the presence of defects or intermetallic compounds in the alloy promotes deformation and consequently reduces the acting forces.

The difference in the geometry of the rivet is minimal. For the symmetrical joints, the final diameter of the riveted shank ranges between −0.4% for the sample S8A15 and 1.0% for sample S6A15. For the asymmetric joints, it ranges between −3.2% for sample S6A21 and 0.9% for sample S8A21. The final height of the rivets is between 1.9 and 3%.

Figure 10 reports the cross-section comparison between the sample realised with the orbital riveting and the sample obtained with the numerical model of the process for the configuration S8A21. There is a good correlation for this geometry, i.e., it is possible to observe comparable values for the thickness of the sheets, the height of the shank rivet and the orbital riveted part. The only difference is in the misalignment of the sheets that characterises the real process caused by the punch force. This is not observed on the numerical model, where the contact between the sheets is perfect. However, the misalignment does not significantly affect the experimental results more than the numerical ones as the rivet guarantees the interlocking. Similarly, the agreement between the experimental and numerical results is also observed for the remaining configurations.

![Figure 10. Numerical/experimental sample comparison for batch S8A15.](image)

After the process was completed, the forming tool was removed and the orbitally formed joints were tested by simulating the single lap shear test. The shear test was performed by assigning a constant velocity of 1 mm/s to two fasteners until failure occurred.

Table 8 summarizes the comparison of the joint failure load determined by the experimental shear test and the numerical model. The maximum loads are close to each other.
Table 8. Numerical/experimental comparison of the joint ultimate load.

| Type of Joint | Configuration | Maximum Load (kN) | Exp. | FEA | Δ   |
|---------------|---------------|-------------------|------|-----|-----|
| Symmetric     | S6A15         | 5.52              | 5.50 | -0.4% |
|               | S8A15         | 6.06              | 5.90 | -2.6% |
|               | S9A15         | 5.96              | 6.00 | 0.7%  |
| Asymmetric    | S6A21         | 4.72              | 4.50 | -4.7% |
|               | S8A21         | 4.69              | 4.50 | -4.1% |
|               | S9A21         | 4.38              | 4.30 | -1.8% |

Figures 5 and 6 also show the comparison between the numerical and experimental load/displacement curves. It is obvious that the numerical trend agrees well with the experimental one. The numerical curves are interrupted at the step where one of the two critical values of damage was overcome, except for S8A15 and S9A15, where unbuttoning led to a rapid decay of the load.

Figure 11 shows the damage maps for the six investigated joints.

| Joint | Damage | Failure mode |
|-------|--------|--------------|
| S6A15 |        | Rivet shear  |
|       |        |              |
| Symmetric |     |              |
| S8A15 |        | Unbuttoning  |
|       |        |              |
| S9A15 |        | Unbuttoning  |
|       |        |              |
| Asymmetric |   |              |
| S6A21 |        | Shear out/Cleavage |

Figure 11. Cont.
Figure 11. Damage maps.

The following considerations can be derived from the analysis of the damage maps (Figure 12).

- Symmetrical joint S6A15: the damage value at the rivet exceeds the threshold (0.29) at the neck of this last, while the values at the sheets are less than 0.2, proving the prediction of failure due to the shear of the rivet.
- Symmetrical joint S8A15: in this numerical simulation, the values of damage are very low, while the hole of the thinner sheet is subjected to a strong deformation. At high strain, the rivet head inside the hole lifts off. The type of failure of the joint can be considered as unbuttoning.
- Symmetrical joint S9A15: in this configuration, the results are similar to the previous ones, so the failure can be predicted as unbuttoning of the rivet.
- Asymmetrical joint S6A21: the damage is localised in the lower (thinner) sheet, around the hole and near the edge of the same sheet. It can be determined that the failure mode is shear out or cleavage.
- Asymmetrical joint S8A21: a very similar distribution to the previous one is observed, high damage values are localised between the hole and the edge of the sheet; this distribution leads simultaneously to shear out and net tension of aluminium, i.e., cleavage failure mode.
- Asymmetrical joint S9A21, the damage reaches the critical value in the thinner sheet along a line perpendicular to the axis of the joint; the failure mode is clearly due to the net tension.

Figure 12. Failure maps for fixed values of \( \omega \) and \( e \).
The model thus allows us to predict the failure mode characteristic of the orbital riveted joint with a good accuracy. Thus, in the design phase, the use of the numerical tool allows, firstly, the verification of the stress distribution around the hole and, secondly, the tracing of the possible failure mode. Finally, the product designer can redesign the joint to maximise its performance in terms of mechanical stability.

5. Failure Map

It was noted that geometric parameters can affect both joint resistance and failure modes. Specifically,

- For a thickness of 1 mm, the hole diameter affects the values of the ratios $e/d$ and $w/d$, which determine the observed transition between net tension and shear out, respectively;
- For a thickness of 1.5 mm, the hole diameter determines the observed transition between rivet shear and unbuttoning.

Theoretically, a particular fracture mode occurs under a particular geometric condition when the associated apparent strength is lower than that of other fracture modes. To define the theoretical curves that quantitatively describe the different fracture modes, the fracture loads must be equated by determining the geometric parameters that govern the fracture transition [23].

The stress correlated to the failure modes are the following:

- **Rivet shear stress**: $\sigma_{RS} = \frac{(16P_{RS})}{3\pi d^2}$ (2)
- **Unbuttoning**: $\sigma_{UN} = \frac{(2P_{UN})}{\pi dt}$ (3)
- **Net tension**: $\sigma_{NT} = \frac{P_{NT}}{[(w-d)t]}$ (4)
- **Shear out**: $\sigma_{SO} = \frac{P_{SO}}{2et}$ (5)

where $P_{RS}, P_{UN}, P_{NT},$ and $P_{SO}$ are, respectively, the fracture loads for rivet shear, unbuttoning, net tension, and shear out; $d$ is the rivet diameter; $t$ is the sheet thickness were the failure occurs; $w$ is the sheet width; and $e$ is the distance of the hole edge from the free edge.

From these, it is possible to draw out the equations that describe the fracture transitions:

- **Rivet shearUnbuttoning**: $t/d = \frac{(3\sigma_{RS})}{(8\sigma_{UN})}$ (6)
- **Net tensionShear out**: $e/d = \frac{\sigma_{NT}}{2\sigma_{SO}} \cdot (w/d - 1)$ (7)

By fixing $w$ and $e$ that are constant values, this last can be rewritten as a function of $d$:

- **Net tensionShear out**: $d = w - \left[\frac{(2e\sigma_{SO})}{\sigma_{NT}}\right]$ (8)

The values of stress were found based on the experimental results.

In order to depict the transition in a single graph, Figure 12 reports the trend of the ratio between the thickness of the sheet, where the failure occurs, and the rivet diameter (i.e., $t/d$) as a function of $d$. The points that represent the geometrical characteristics for each thickness, where the failure occurs, are on equilateral hyperbolas. On these curves, on the basis of Equations (5) and (7), it is possible to identify:

- A transition point between rivet shear and unbuttoning, on the hyperbola related to $t = 1$ mm;
- A transition point between shear out and net tension, on the hyperbola related to $t = 1.5$ mm.

In particular,

- For $t = 1$ mm: for high diameters, the failure occurs for net tension (NT), whereas for low diameters it occurs for shear out (SO). For a middle value, the point overlaps with the transition point and, consequently, a mixed fracture can be observed, i.e.,
cleavage (C). This is interesting as it is difficult to predict it with, for instance, a typical $e/d\omega/d$ graph;
- For $t = 1.5$ mm: by decreasing the hole diameter, it is possible to observe the transition between unbuttoning (UN) and rivet shear (RS).

This tool can be useful for predicting the failure of similar joints where the hole diameter changes by the values examined. A more detailed map identifying all transitions can be produced in a future work using the finite element model studied in the previous section.

6. Conclusions

The analysis of the results has led to the following considerations:
- In the symmetrical joints, the symmetry reduces the bending phenomena, the area around the hole is subjected to a bearing phenomenon, and the fracture occurs mainly for unbuttoning. If the rivet has a diameter of 6 mm, it is possible to observe a fracture of the rivet head for a shear action. Then, there is a transition between the two failure modes.
- In the case of asymmetrical joints, the resistance is lower not only due to the asymmetry of the joint, but also due to the lower thickness of the upper aluminium sheet, which favours deformation around the hole and the resulting progressive damage. In this case, a transition from shear out to net tension is evident as rivet diameter is increased: shear out < cleavage < net tension.

Finite element analysis makes it possible to create a model that simulates not only the orbital riveting process, but also the single lap shear test. The agreement between the experimental results and the numerical data is good, so the model can be used to design the joints based on the industrial application requirements.

Finally, a failure map predicting fracture for different hole diameters was constructed based on the experimental results.

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