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Electro-mechanical performance of double-flushed riveted joints

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Abstract. This paper revisits double-flush riveting to compare the static and fatigue performance of the resulting joints with those fabricated by conventional bolting. Experimental measurements of electrical resistance, combined with finite element analysis of electric current flow, serve a dual structural and electrical purpose of validating the number of cycles after which the loss of contact between the overlapping sheets becomes significant, and evaluating the relative performance of both types of joints in electric energy distribution systems built upon aluminum strips. The first of these purposes is a novelty in fatigue testing while the second paves the way for improving the efficiency of electric power grids.

1 Introduction

Mechanical joining provides various solutions for connecting overlapping metal sheets, with joining by forming and fastening serving as key technologies. A notable advantage of mechanical joining over welding is its operation at ambient temperature, which avoids the distortion and residual stresses induced by heating-cooling cycles and prevents weldability problems encountered when the sheets to be joined are made from dissimilar materials with different thermomechanical properties.

Although adhesive bonding offers a solution to the challenges associated with welding, its application in mass production is constrained by various requirements concerning surface preparation, temperature control, durability, and crashworthiness, and by environmental compliance resulting from the utilization of epoxy or solvent-based agents. Furthermore, the necessity of using clamps, jigs, and fixtures to ensure uniform pressure application on the adhesives during the curing process further reinforces the preference for joining by forming or fastening technologies whenever possible.

Joining by forming encompasses a diverse range of processes that utilize form-closed, force-closed, and/or material-closed mechanisms to create permanent connections between overlapping sheets, with or without auxiliary elements [1]. These processes involve significant local plastic deformation of the sheets to be joined and are conducted at ambient temperature, thus avoiding thermal-induced issues experienced with welding. They also eliminate the need for hazardous substances present in adhesive bonds.

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However, the use of joining by forming processes as an alternative to welding and adhesive bonding is often limited by material formability issues, which can lead to failure due to cracking or instability, and by end-of-life recycling concerns arising from the creation of permanent connections. The need for specialized tools to produce mechanical joints in overlapping sheets further restricts the applicability of these processes.

The aforementioned problems of welding, adhesive bonding, and joining by forming justify the reason why fastening is often the preferred technology for connecting overlapping sheets in a wide variety of applications. Bolting is the most widespread fastening process due to its ease of assembling and disassembling lap joints during installation, maintenance, and removal at the end of life. However, its application is constrained by the protrusions of bolt heads and nuts above the overlapped sheet surfaces, as well as issues related to non-uniform contact pressures and unintended self-loosening during service [2].

Riveting is another widespread fastening process that offers advantages over bolting in applications where permanent or semi-permanent connections are appropriate, as it provides enhanced resistance to vibration-induced loosening and the ability to secure multiple sheets with minimal clamp length. However, its application is also limited by the protrusions of the rivet head and of the deformed rivet end above the overlapped sheet surfaces.

To eliminate protrusions and fabricate lap joints with flat surfaces on both sides, authors have recently proposed a new double-flush riveting (DFR) process [3]. The process is built upon a punching-compression sequence and makes use of simple cylindrical rivets made from materials with lower mechanical resistance than the sheet materials to ensure that mechanical joining is mainly accomplished by plastic deformation of the rivets instead of the sheets.

This paper revisits the newly proposed DFR process to evaluate the performance of double-flush riveted lap joints compared to bolted lap joints under static and cyclic (fatigue) loadings. Electro-mechanical characterization of the two types of joints is conducted with a dual purpose. Firstly, to validate the number of cycles after which the loss of contact between the overlapping sheets becomes significant, as the flow of electric current through the joint is greatly influenced by the contact conditions along the overlapped sheets. Secondly, to showcase the application of this new joint type in fabricating aluminum busbar joints for electrical distribution systems. This second objective aligns with the increasing trend of using aluminum instead of copper due to the rising price and scarcity of the latter in the ongoing green energy transition.

2 Materials and methods

2.1 Fabrication of unit cells

In the first stage of the DFR process, two AA6082-T6 aluminum sheets with a thickness of 5 mm are punched to obtain 10 mm diameter holes. A punch-to-die clearance of 0.8 mm is used to create a tapered cut surface (Fig. 1a) for a cylindrical C11000 copper rivet with 10 mm diameter to be subsequently forged into during the second stage (Fig. 1b) to obtain a predominant form-closed joint (Fig. 1c). In general terms, DFR uses the fracture depth and the angle of the tapered cut surface resulting from punching, often seen as defects, as functional surfaces with countersunk holes. The process is conducted in unit cells that are representative of lap joints under laboratory conditions but can be easily implemented in industrial progressive tools.

Bolted joints are created by drilling an 8.4 mm hole in the aluminum sheets. Unlike the double-flush riveted lapped joints, these sheets are then cleaned with acetone, and contaminant and oxide films are broken into small particles by grinding with emery paper of

80 grit size. An M8 bolt (of class 8.8) is then used to connect the sheets together with a tightening torque of 20 Nm, identified as the minimum torque necessary for optimal electric performance [4] and below the recommended maximum tightening torque for these bolts.

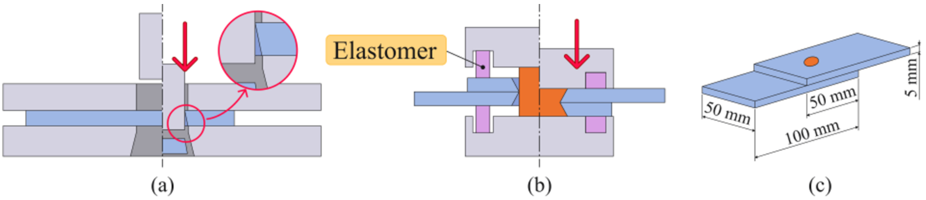


Fig. 1. Schematic representation of (a) the punching and (b) compression stages of DFR and of (c) the resulting double-flush riveted lap joint.

2.2 Mechanical and electrical characterization of the materials

The mechanical characterization of the AA6082-T6 sheets and C11000 copper rods (from which the rivets were machined) was conducted through tensile tests following the ASTM E8 standard and compression tests following the ASTM E9 standard, respectively [4]. The resulting flow curves are depicted in Fig. 2a.

Additionally, the electrical resistivity at ambient temperature of aluminum, copper, and steel utilized in both double-flush riveted and fastened joints is presented in Fig. 2b, with data also retrieved from a previous work of the authors [4].

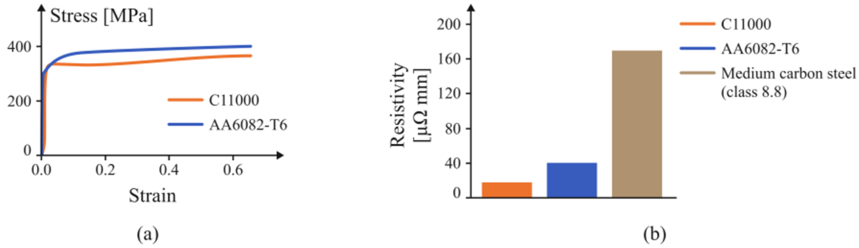


Fig. 2. (a) Flow curves of the aluminum AA6082-T6 and copper C11000 and (b) electric resistivity at ambient temperature for the different materials utilized in the investigation.

2.3 Assessment of mechanical and electrical performances

The mechanical reliability of the double-flush riveted and bolted joints was evaluated through static and cyclic (fatigue) destructive shear tests (Fig. 3a). Static tests were conducted using an INSTRON 4507 universal testing machine, while fatigue tests were carried out with an INSTRON 8874 biaxial servohydraulic fatigue testing machine.

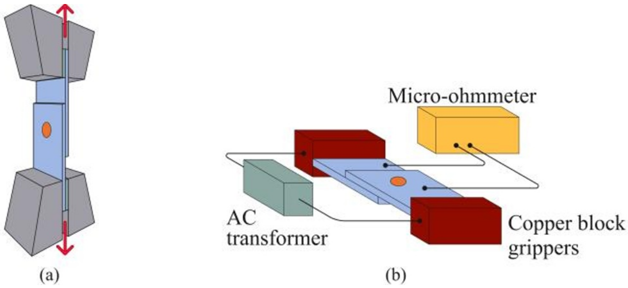


Fig. 3. Schematic representation of the (a) destructive shear tests and (b) electrical testing apparatus.

The fatigue tests employed an applied force ratio $R_f = 0.1$, calculated as the ratio of the minimum force $F_{\min}$ to the maximum force $F_{\max}$, with $F_{\max}$ values set at 4 kN, 9 kN, and 11 kN. Testing continued until a displacement variation was observed after undergoing steady-state conditions.

After application of the cyclic loading to the unit cells, their electrical resistance was measured at ambient temperature (Fig. 3b) to assess the post-loading electrical performance and to validate the loss of contact between the overlapping sheets and rivets.

The electrical resistance of the joints was measured before (for reference purposes) and after cyclic loading using an experimental setup developed by the authors [4]. The measurement was performed with a four-point probe technique [5] using a KoCos PROMET R600 micro-ohmmeter. The micro-ohmmeter supplied a 600 A current for approximately 2 seconds, while two probes separated by 100 mm measured the drop in voltage that was needed to determine the electrical resistance of the lap joints.

2.4 Numerical modelling

Numerical modelling was conducted in the in-house finite-element software i-form. The unit cells of the two different types of joints were discretized by approximately 60,000 hexahedral elements, while the copper block grippers that are used to fix the unit cells and apply the electric current of 600 A were discretized by means of spatial triangular surface elements (Fig. 4). An interface layer, with a thickness of 0.05 mm and discretized with hexahedral elements, accounted for the electric resistivity due to roughness and oxide films along the contact interface between the overlapping sheets.

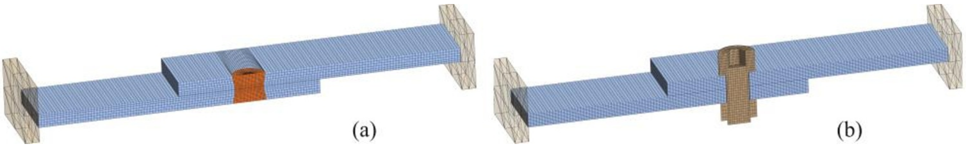


Fig. 4. Three-dimensional finite element models of the (a) double-flush riveted and (b) bolted joints.

3 Results and Discussion

3.1 Destructive testing

Fig. 5a shows the evolution of static shear destructive force with displacement for both the double-flush riveted and bolted joints.

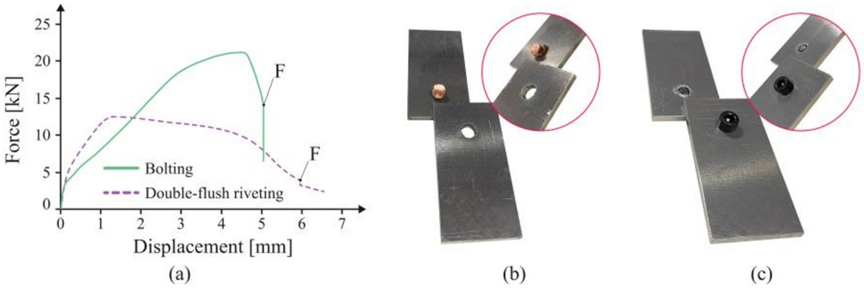
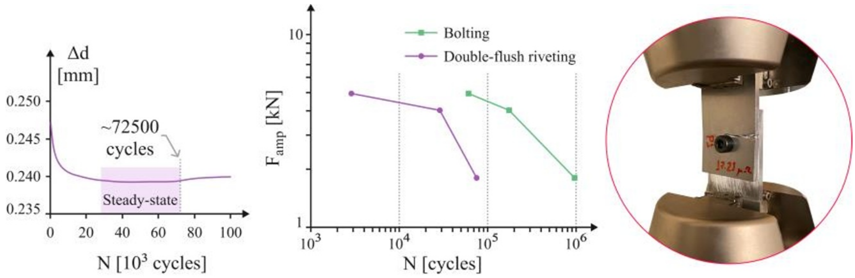


Fig. 5. (a) Experimental force-displacement evolution during the static shear destructive tests of the two types of joints with photographs of the (b) double-flush riveted and (c) bolted joints after testing.

As seen, the bolted joint (Fig. 5c) withstands higher forces than the double-flush riveted joint (Fig. 5b), but this comes at the cost of having smaller displacements until complete failure, as indicated by the 'F' labels in Fig. 5a. This difference is attributed to the higher strength of the bolt and to the greater ductility of the copper rivet.

Fig. 6 shows the results of the cyclic (fatigue) shear destructive tests. The tests were carried out using a force ratio of $R_f = 0.1$ until the displacement variation ($\Delta d = d_{F\max} - d_{F\min}$) begins to increase after achieving steady-state conditions (Fig. 6a).



(a) (b) (c)

Fig. 6. (a) Displacement variation vs. the number of cycles for a double-flush riveted joint subjected to cyclic loading with $R_f = 0.1$ and $F_{\max} = 4$ kN, (b) F–N curves obtained for the double-flush riveted and bolted joints, and (c) photograph of a bolted joint after fracture ($R_f = 0.1$ and $F_{\max} = 11$ kN).

Fig. 6b presents the F–N curves obtained for the double-flush riveted and bolted joints, where the vertical axis represents the force amplitude ($F_{\text{amp}} = (F_{\max} - F_{\min})/2$) and the horizontal axis represents the number of cycles (N) until the displacement variation Δd begins to increase. Results show that the bolted joints exhibit higher mechanical resistance than the double-flush riveted joints under the same applied cyclic loads, in close agreement with the findings from the static tests shown in Fig. 5a. Notably, in the case of the bolted joint tested under cyclic loading with $F_{\max} = 11$ kN, fracture occurred in one of the aluminum sheets (Fig. 6c). This outcome is different from that observed in static tests, where fracture primarily occurred in the bolt rather than the sheets.

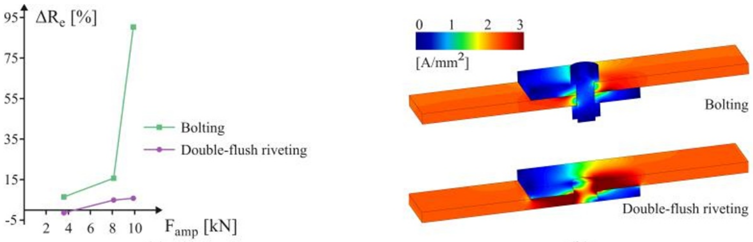
3.2 Electrical analysis

Fig. 7a, discloses the variation of the electrical resistance $\Delta R_e = \left(R_e^{amp} - R_e\right)/R_e$, with the force amplitude F_{amp} of the cyclic loading, for the two types of joints, where R_e is the electrical resistance of the joints before testing and R_e^{amp} is their electrical resistance after cyclic loading with a specific force amplitude F_{amp}.

The analysis of these results from a structural perspective confirms that the increase in force amplitude F_{amp} leads to progressive loss of contact between the overlapped sheets that can be indirectly validated by the increase in the variation of the electrical resistance ΔR_e. For instance, in the case of the double-flush riveted joints, the largest value $\Delta R_e = 5.7\%$ is achieved for cyclic tests performed with the highest force amplitude ($F_{\text{amp}} = 9.9$ kN). It is worth notice that the very large increase in $\Delta R_e = 90.2\%$ observed for the bolted joint cannot be used for comparative purposes, as it is mainly caused by the aforementioned fracture of the sheet (Fig. 6c).

However, from an electric distribution system perspective, the results also demonstrate that not only is the electric resistance of the double-flush riveted joint ($R_e = 17.1$ μΩ·mm) smaller than that of the bolted joint ($R_e = 18.4$ μΩ·mm) before cyclic testing, but this trend is even more favorable to the former, as ΔR_e is consistently smaller for the double-flush riveted joint (Fig. 7a).

This last conclusion can be justified by the finite element predicted current flow in the two types of joints. In fact, as shown in Fig. 7b, electric current barely flows through the bolt, making this joint highly dependent on sheet-to-sheet contact while in the case of the double-flush riveted joint, as the rivet is made of a material with higher electric conductivity than that of the sheets, the current flows through it. Consequently, any eventual sheet separation observed during cyclic loading due to loosening will disrupt the electric current flow in the bolted joint, but not as significantly in the riveted one, as electric current will continue to flow freely through the rivet.



(a) (b)

Fig. 7. (a) Variation in electric resistance vs. force amplitude of cyclic loading and (b) finite element predicted distributions of electric current density for the two types of joints.

4 Conclusions

Bolted joints demonstrate superior mechanical performance compared to double-flush riveted joints obtained through punching and compression, rendering them a preferable choice for structural applications. However, when applications are in the field of electric distribution systems, double-flush riveted joints emerge as the best option, as electric characterization before and after cyclic loading yields better results than bolted joints. This is attributed to the rivets being made of a more conductive material than the bolts and to a better contact between rivets and sheets compared to bolts and sheets.

Finally, the results also demonstrate the effectiveness of using measurements of electrical resistance as an indicator of sheet separation in cyclic destructive shear tests.

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