

# On the hybridization of double-flush riveting with adhesive bonding

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**Abstract.** This paper investigates the feasibility of combining the principles of a novel joining-by-forming process, known as double-flush riveting, with those of adhesive bonding to produce hybrid joints with enhanced characteristics. The study focuses on unit cells consisting of lap joints between 2 mm steel sheets, fabricated using: (i) commercial high-performance adhesives, (ii) solid rivets, or (iii) a combination of both. The experimental workplan begins with identifying the optimal conditions for surface preparation and curing to achieve sound adhesive-bonded unit cells. A similar approach is applied to double-flush riveted unit cells, focusing on the geometric variables of the process. Hybrid unit cells are constructed following a sequence that starts with adhesive bonding and concludes with double-flush riveting. Results are supported by finite element analysis using an in-house computer program and focus on the construction of the unit cells as well as destructive testing through lap-shear tests. The findings confirm that, although hybrid joints are more complex to produce due to the integration of two distinct joining processes, they ultimately provide greater joint strength making them promising solution for demanding applications where durability and reliability are paramount.

**Keywords:** Joining by forming; Double-flush riveting; Adhesive bonding; High strength steel.

## 1 Introduction

According to DIN 8593-7, joining by forming is the collective designation for processes in which the joining partners are locally or entirely shaped into a sound connection, secured by a tight fit that prevents unintentional loosening. This is a broad subfield resulting from the combination of forming and joining mechanisms, applicable to materials of various geometries and sizes. In certain conditions, it offers significant advantages over traditional processes based on welding, adhesive bonding or mechanical joining [1].

A good example to the above can be found in the automotive industry, where welding processes such as resistance spot welding and, more recently, laser welding are commonly used in body-in-white assembly [2]. Although welding is considered a favorable solution for fulfilling the typically high production rates of this sector, the resulting joints are often affected by distortions due to the expansion and contraction of the weld beads and adjacent material, limited mechanical performance caused by irregular microstructures, and are typically difficult to apply for joining dissimilar materials [3].

Joining by forming processes, like self-pierce riveting, clinching, or hemming [4], are examples of well-established solutions to the aforementioned problems. They eliminate the thermal effects of welding

and can be used to produce joints made from different materials, with or without auxiliary joining materials, depending on the process. However, joints secured only by joining by forming processes are not without issues. In fact, they are sensitive to stress concentration factors along local connections and, in most cases, are not hermetic under loading due to the open nature of the joints [5].

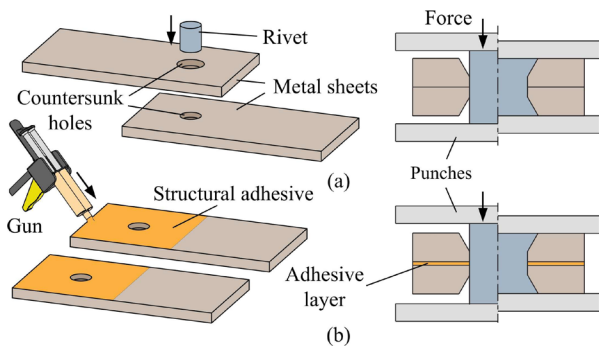
For these reasons, significant efforts are being made to improve the reliability and safety of joining by forming processes, particularly in applications requiring high-performance, lightweight, and durable joints. One of the most prominent trends is the combination of joining by forming with adhesive bonding to leverage the synergistic benefits of both technologies.

In the past, combining adhesive bonding with other processes, such as resistance spot welding [6] or mechanical joining [7], has proven effective in distributing loads more evenly (i.e., along the overlap area of the joints), reducing damping, and acting as a barrier against moisture and contaminants. More recently, several attempts have been made to integrate adhesive bonding with joining by forming processes, like clinching [8] and self-pierce riveting [9], to achieve similar benefits. For this purpose, structural adhesives - epoxy, polyurethane, acrylic/cyanoacrylate, anaerobic, and high-temperature adhesives [10]- are applied along the overlap areas, while the joining by forming stage can

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take place either before or after the adhesive is fully cured [11]. The obtained joints generally show increased strength, stiffness, and energy absorption compared to those obtained via adhesive bonding or joining by forming when performed individually.

In light of the above, this paper aims to extend the hybrid field resulting from the integration of joining by forming with adhesive bonding. The work focuses on the double-flush riveting process, recently developed by the authors [12] (Fig. 1a), for obtaining form-closed permanent joints, with emphasis on its adaptability to incorporate structural adhesives along the overlap region (Fig. 1b). The work includes experimental and numerical modelling on the fabrication of unit cells representative of lap joints made in high strength steel. Lastly, the new hybrid joints are subjected to tensile lap-shear testing and compared with purely riveted and bonded joints to validate the applicability of the proposed hybrid process.



**Fig. 1.** Schematic representation of the (a) double-flush riveting and (b) hybrid double-flush riveting processes.

## 2 Methods and procedures

### 2.1 Materials

The experimental work was based on unit cells made from S500MC high strength steel sheets with 2 mm thickness. The cylindrical rivets were made from S235JR structural steel rods with 6 mm diameter. The latter were machined from rods previously annealed at 700°C for one hour. In the case of hybrid joints, the structural epoxy resin adhesive Powerbond (Würth) incorporating glass beads was employed along the overlap region of the joints. This adhesive meets standard requirements for automotive manufacturers, namely for bodywork repairs [13].

The flow stresses of the sheets and rivet materials were obtained at room temperature via tensile and compression tests following the ASTM E8 and E9 standards. The material flow curves were modelled by the following Hollomon strain hardening equations,

$$\sigma = 970\varepsilon^{0.14} \text{ (S500MC)} \quad (1)$$

$$\sigma = 720\varepsilon^{0.27} \text{ (Annealed S235JR)} \quad (2)$$

### 2.2 Experimental workplan

The unit cells representative of lap joints were fabricated by means of three different processes: adhesive bonding,

double-flush riveting and hybrid double-flush riveting. All three types of unit cells made use of S500MC high-strength steel sheets cut into a length and width of 75 mm and 25 mm, intended to provide a square overlap area of 25×25 mm<sup>2</sup>. Table 1 provides a summary of the main processing parameters used in the work plan.

For adhesive bonded unit cells, the steel sheets were cleaned with acetone and surface treated along the overlap area using sandpaper with different grain sizes (P80, P1500 or none). Afterward, 100 mg of structural adhesive is applied to the overlap areas of each sheet, which are then assembled to create an adhesive layer approximately 0.3 mm thick. Finally, the adhesive region is clamped for the duration of the cold curing process, which occurs at room temperature for 4 hours.

For double-flush riveted unit cells, the sheets are first machined with a conical drill bit to create the countersunk holes with different inclination angles. The cylindrical rivets are machined to the height that matches the volume of the countersunk holes by material incompressibility. After assembly, the rivet is compressed on a punch pair to join both sheets under a form-closed mechanism (right-hand side of Fig. 1a).

Hybrid unit cells were double-flush riveted before and after the curing process of the adhesive. The remaining processing parameters resulted from the combination of the optimal conditions of both previous types of unit cells. To this end, destructive tensile lap-shear tests were conducted at room temperature on the universal testing machine Instron 4507 to evaluate the maximum forces that the unit cells can safely withstand. The same tests were performed on the hybrid joints to assess their effectiveness in enhancing the mechanical performance of adhesive bonding and double-flush riveting processes.

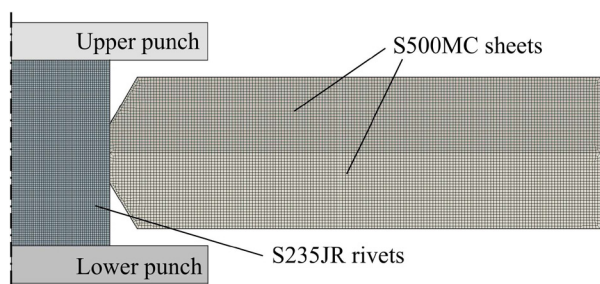
**Table 1.** Main processing parameters used in the experimental work plan according to each type of unit cell.

| Unit cells                   |  |
|------------------------------|--|
|                              |  |
| Adhesive bonding             |  |
|                              |  |
| Double-flush riveting        |  |
|                              |  |
| Hybrid double-flush riveting |  |
|                              |  |
| Tensile lap-shear tests      |  |
|                              |  |

### 2.3 Numerical modelling

Numerical modelling was focused on the double-flush riveting joining by forming process. The simulations were carried out in room temperature using the in-house computer program i-form built upon the finite element flow formulation [14].

The used models assumed rotational symmetry for the deformable objects (sheets and rivet) [12], as exemplified in Fig. 2. Their cross sections were discretized using 4000 quadrilateral elements and followed the Levy-Mises constitutive equations with the flow stresses previously presented in Section 2.1. The upper and lower punches used for deforming the cylindrical rivets into the countersunk holes of the sheets were modelled as rigid objects that were discretized using linear contact elements under constant friction with  $m = 0.1$ .



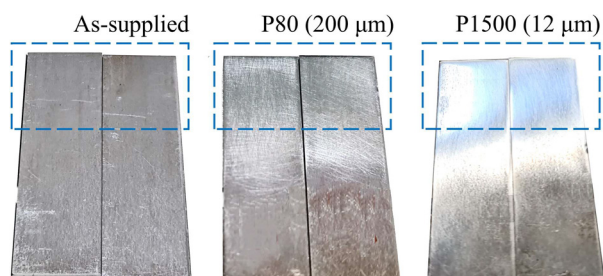
**Fig. 2.** Finite element model for simulating the double-flush riveting process.

## 3 Results and discussion

### 3.1 Adhesive bonding

The first results to be presented are focused on adhesive bonded unit cells and are aimed at finding out the optimal processing conditions that ensure proper bonding along the overlap regions of the joints.

The former was accomplished through the fabrication of the unit cells with different surface conditions (Fig. 3) that were subsequently subjected to tensile lap-shear testing until failure. A minimum of six tests for each condition were carried out to ensure repeatability.

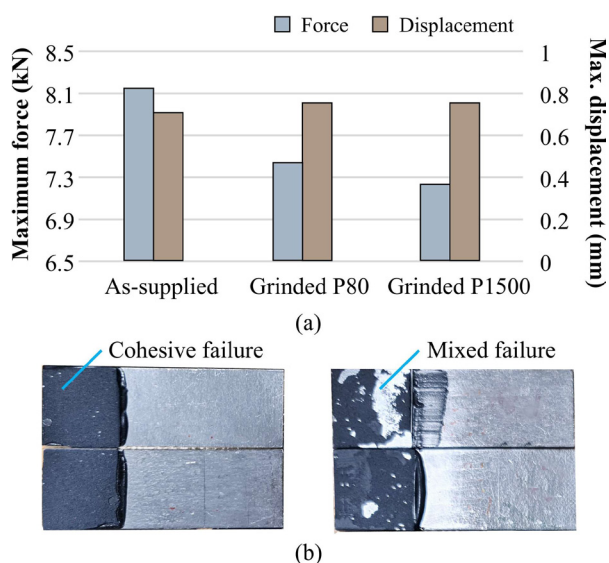


**Fig. 3.** Photographs of the different surface conditions considered for the adhesive bonded unit cells.

Fig. 4a shows the average maximum force values and average maximum displacements that the adhesive bonded unit cells exhibited during tensile lap-shear testing. The results are categorized according to the surface conditions previously shown in Fig. 3, which

allow identifying the as-supplied condition as the one that withstands higher shear forces until failure. In terms of displacement, the results are unaffected by the corresponding surface condition.

Fig. 4b shows the two predominant failure modes observed in the tests: cohesive failure, observed mostly on as-supplied unit cells, and mixed failure resulting from a combination of cohesive and interfacial failure that was most evident on unit cells grinded with P1500 sandpaper. Both modes are coherent with the corresponding maximum force values and allow concluding that the adhesive has limited wettability along grinded surfaces, which tends to occur if the adhesive possesses a high viscosity before curing. This justifies the utilization of the as-supplied surface condition for building the hybrid unit cells that will be presented in Section 3.3.



**Fig. 4.** (a) Average maximum force and displacement for each surface condition and (b) observed failure modes from tensile lap-shear testing on adhesive bonded unit cells in the as-supplied (left) and grinded P1500 (right) conditions.

### 3.2 Double-flush riveting

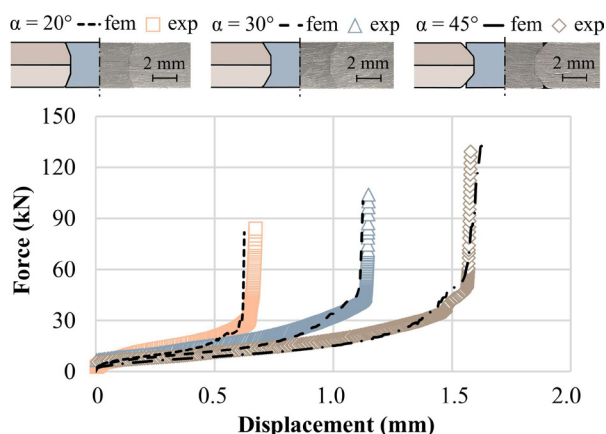
The second type of unit cells was fabricated using the double-flush riveting process, employing machined countersunk holes and cylindrical rivets. The primary focus was on analyzing the influence of the inclination angle  $\alpha$  of the countersunk holes on interlock quality and joining forces.

Fig. 5 shows the force-displacement evolutions during double-flush riveting under three different inclination angles  $\alpha = 20^\circ, 30^\circ, 45^\circ$ . The evolutions are represented by the experimental values retrieved from the hydraulic press and by numerical predictions from the finite element computer program i-form for each inclination angle under analysis. As observed, the agreement between finite element predictions and experimental data is very good, not only for the force evolutions, but also for the final cross-section of the joints (refer to the upper images of Fig.5).

Regarding the differences observed among the three inclination angles, it can be concluded that increasing the angle inevitably leads to higher joining forces in

order to fully compress the rivet into the countersunk holes without any protrusions above or below the sheet surfaces. For an inclination angle  $\alpha = 45^\circ$ , this was not fully achieved, as some of the volume regions of the countersunk holes remained with rivet material shortages, as shown in the respective experimental and finite element predicted cross-sections. This compromises the mechanical performance of the joints due to limited interlock quality, which, together with the high joining forces that could potentially lead to adhesive squeeze-out, allow concluding that an inclination angle  $\alpha = 45^\circ$  was not suitable for the fabrication of hybrid unit cells.

For the remaining two cases  $\alpha = 20^\circ; 30^\circ$ , protrusions and material shortages were avoided. This demonstrates the successfulness of matching the volume of the machined cylindrical rivets with that of the countersunk holes, thereby assuring material incompressibility. Under these circumstances, double-flush riveting under an inclination angle  $\alpha = 30^\circ$  was selected for building the hybrid unit cells that will be presented in the following Section due to its higher interlock quality imposed by an also higher inclination angle of the countersunk holes



**Fig. 5.** Experimental and finite element predicted cross-sections and force evolutions for double-flush riveting with different inclination angles.

### 3.3 Hybrid double-flush riveting

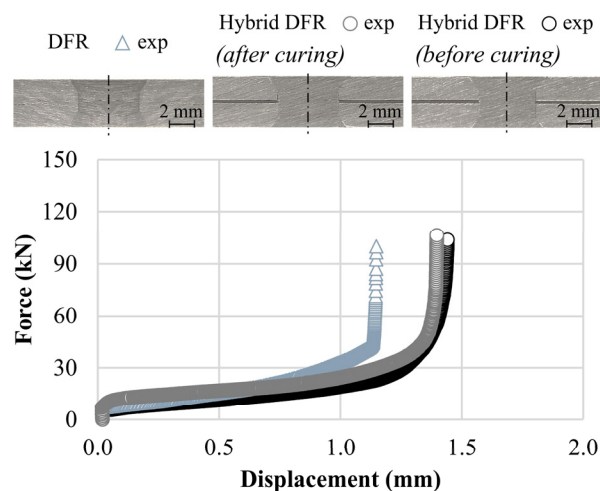
The final type of unit cells was fabricated under the optimal processing parameters for both adhesive bonding and double-flush riveting processes. Therefore, they were built using as-supplied sheets (i.e. with no surface finishing) that were machined for creating a countersunk hole with an inclination angle  $\alpha = 30^\circ$ . Afterwards, both sheets were assembled with the adhesive previously added to the corresponding overlap regions, followed by the double-flush riveting process. This last operation was carried out either right after assembling (without curing) or 4 hours after assembling, when the curing process for the adhesive is completed.

Fig. 6 shows the force-displacement evolutions for the fabrication of the hybrid unit cells according to both conditions mentioned above, added with photographs for the cross-sections of the final joints. Identical results for a double-flush riveted joint with the same inclination angle  $\alpha = 30^\circ$ , shown priorly in Section 3.2 (refer to

Fig. 5), are also presented in Fig. 6 for reference purposes.

As seen, the force evolutions for the hybrid unit cells are mainly distinguished by the slightly higher displacement needed to fully compress the cylindrical rivets into the countersunk holes. This is because the rivets had to be designed with a slightly higher height in order to accommodate the thickness of the adhesive layer with a value of approximately 0.3 mm. As seen by the photographs included in Fig. 6, the resulting hybrid joints, riveted either before or after curing, are also free of protrusions or material shortages.

For both hybrid unit cells, those riveted after the adhesive is fully cured require a slightly higher force than for those built before curing. This points out the role of the cured adhesive in supporting a portion of the forces made during riveting. In the case of hybrid unit cells built before curing, the thickness of the adhesive layer appears to be smaller but more uniform and without signs of excessive squeeze-out. This is due to the presence of glass beads within the structural adhesive used in this work, which is crucial for allowing the adhesive, while in its uncured state, to withstand the normal pressures created in between both sheets during riveting.



**Fig. 6.** Experimental force evolutions for hybrid double-flush riveting performed after and before curing. The force evolution for double-flush riveting (DFR) without adhesive is also included.

Fig. 7 presents the force-displacement evolutions for tensile lap-shear testing of the different unit cell types under analysis.

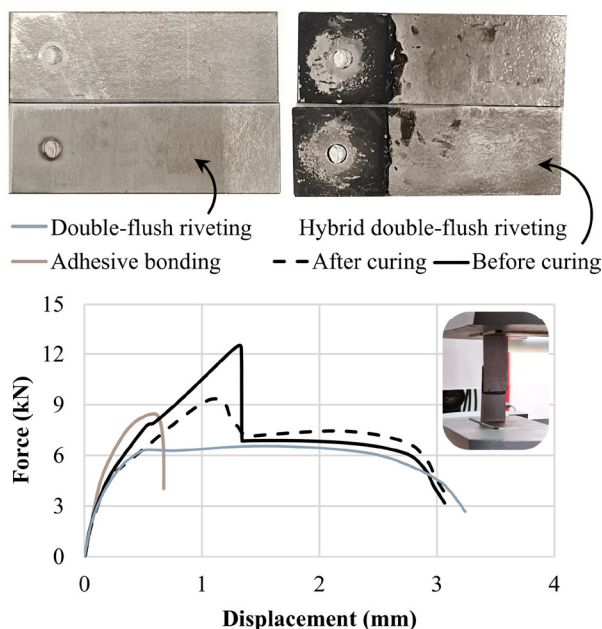
For the individually applied joining processes (i.e. adhesive bonding and double-flush riveting), the force evolutions correspond to the optimal processing conditions identified in the previous Sections 3.1 and 3.2. By comparing both, it is seen that adhesive bonded unit cells withstand higher forces but under lower deformations than double-flush riveted unit cells. Moreover, the failure mode for the latter corresponds to complete rivet shear [15] along the overlap region of the joints, as exemplified in the left-side photograph at the top of Fig. 7.

For unit cells created using the proposed hybridization of double-flush riveting and adhesive bonding, improvements are observed in both joining

processes compared to their individual applications. This is shown for hybrid cells built either before or after the completion of the curing process, as both exhibit force evolutions reaching maximum values higher than those of adhesive-bonded unit cells. However, hybrid unit cells that are riveted before the curing process completely remain the strongest, despite exhibiting a mixed failure mode, as shown in the right-side photograph at the top of Fig. 7.

This enhanced strength is attributed to the double-flush riveting operation combined with the high adhesive stiffness promoted by its glass bead composition, which creates a clamping mechanism supported by the normal pressures generated during joining by forming. As a result, the interfacial bonding of the adhesive is strengthened, leading to unit cells with superior mechanical performance, reaching their peak with the cohesive failure of the adhesive.

These findings clearly demonstrate the synergistic benefits of hybridizing double-flush riveting with adhesive bonding for producing mechanically robust joints.



**Fig. 7.** Force evolutions and failure modes from tensile-lap shear testing on adhesive bonded, double-flush rivet and hybrid unit cells.

## 4 Conclusions

The main conclusions drawn from this work on the hybridization of double-flush riveting with adhesive bonding are as follows:

- The proposed hybridization can be effectively applied to produce lap joints between high-strength steel sheets,
- Determining the optimal conditions for achieving stronger connections requires preliminary tests focused on the individual joining processes, considering the sheet and adhesive materials,
- The force levels required for the double-flush riveting stage in the production of hybrid joints are very similar to those needed for purely riveted joints,

- Cross-sectional analysis of the hybrid unit cells shows that, like purely riveted unit cells, they are also free of protrusions or material shortage. For this purpose, it is important to ensure that sheet materials are stronger than the rivet material and that the rivet volume matches the countersunk holes of both sheets and of the adhesive layer thickness,
- Tensile lap-shear tests on all unit cell types investigated show that hybrid joints riveted before curing achieve maximum force values 49% and 92% higher than those of adhesive-bonded and double-flush riveted joints, respectively, when applied individually,
- Hybrid unit cells riveted before curing circumvent the use of complex clamping systems during curing, as the necessary clamping stage is established by the normal pressures created by the rivet against both sheets of the joints.

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