Optimization study of hybrid spot-welded/bonded single-lap joints
R.D.S.G. Campilho, A.M.G. Pinto, M.D. Banea, L.F.M. da Silva

ABSTRACT

Joining of components with structural adhesives is currently one of the most widespread techniques for advanced structures (e.g., aerospace or aeronautical). Adhesive bonding does not involve drilling operations and it distributes the load over a larger area than mechanical joints. However, peak stresses tend to develop near the overlap edges because of differential straining of the adherends and load asymmetry. As a result, premature failures can be expected, especially for brittle adhesives. Moreover, bonded joints are very sensitive to the surface treatment of the material, service temperature, humidity and ageing. To surpass these limitations, the combination of adhesive bonding with spot-welding is a choice to be considered, adding a few advantages like superior static strength and stiffness, higher peeling and fatigue strength and easier fabrication, as fixtures during the adhesive curing are not needed. The experimental and numerical study presented here evaluates hybrid spot-welded/bonded single-lap joints in comparison with the purely spot-welded and bonded equivalents. A parametric study on the overlap length (Ld) allowed achieving different strength advantages, up to 58% compared to spot-welded joints and 24% over bonded joints. The Finite Element Method (FEM) and Cohesive Zone Models (CZM) for damage growth were also tested in Abaqus® to evaluate this technique for strength prediction, showing accurate estimations for all kinds of joints.

Keywords: Epoxy/epoxies, Steels, Finite element stress analysis, Joint design, Cohesive zone models

1. Introduction

Joining of components is usually accomplished by mechanical fastening, welding or adhesive bonding. Joining with structural adhesives is nowadays one of the most widespread techniques for advanced structures (e.g., aerospace, aeronautical, automotive or sports equipment) because it offers more uniform distribution of stresses, since drilling operations are not needed, and it distributes the load over a larger area than mechanical joints, it increases fatigue life and weight saving, and it prevents corrosion between dissimilar materials. However, peak stresses tend to develop near the overlap edges because of differential straining between the adherends at the overlap and load asymmetry [1,2]. As a result, premature failures can be expected, especially for brittle adhesives. Additionally, bonded joints are very sensitive to the surface treatment, service temperature, humidity and ageing [3–5]. Hybrid joints combine adhesive bonding with another joining technique (e.g., weld-bonded, rivet-bonded or fasten-bonded unions), and have previously been considered to improve damage tolerance (either static or fatigue) or repair of structures, combined with ease of fabrication because of adhesive curing without fixtures requirement [6,7]. Besides, the joint geometry and materials can be adjusted for a specific application, depending on design goals and service conditions [8]. Regarding fasten-bonded joints, few works were published in the recent years [9,10], although these are already common in automotive applications [8]. Lee et al. [11] studied fasten-bonded joints and the influence of some parameters on the joints strength, with emphasis on Failure Area Index theoretical prediction technique, which resulted in a maximum deviation of 23% to the experiments. The analytical work of Hart-Smith [12] is one of the first ones regarding bolt-bonded joints, by the consideration of stepped joints with composite adherends, using nonlinear continuum mechanics theories to achieve a fair reproduction of the test results. Kelly [13] analyzed bolt-bonded single-lap joints with composite adherends using a three-dimensional FEM technique that included the effects of the bolt–hole contact and the nonlinear material behavior. Results showed that this technology benefits the joint strength, especially for flexible joints. Rivet-bonded joining has equally been studied (e.g. fatigue strength optimization of riveted unions with adhesive reinforcement [14]). The combination of adhesive bonding with resistance spot-welding (weld-bonded joints) is also feasible, and a large number of works are currently published regarding this technology,
either for static [15,16] or fatigue studies [17,18]. In conventional spot-welding, the faying surfaces are joined by melting of the adherends through the flow of electric current, which in turn increases the temperature at the interface due to electrical insulation. Heating is performed by a short-time pulse of low voltage and high amperage current to form a fused nugget of welded metal [19,20]. The weld nugget forms locally at the interface between faying surfaces and it does not extend up to the outer surfaces of the joint [7], while its size and shape mainly rely on the geometry of the welding electrodes. The synergy between adhesive bonding and spot-welding provides competitive advantages to the traditional adhesive bonds [11,21,22] like superior strength and stiffness, higher resistance to peeling and easier fabrication, as fixtures during the adhesive curing are not needed [7]. Compared to spot-welding, weld-bonded joints excel in improved fatigue characteristics, because of the reduction of stress concentrations at the weld-nugget periphery. Evaluated against bonded joints, weld-bonded unions result in a more uniform stress distribution than bonded joints, justifying for both situations the improved characteristics of these hybrid joints [22,23]. Thus, by combination of spot-welding and bonding, their individual disadvantages are eliminated. Currently, many load bearing components in aircrafts, helicopters, the shell of missiles, spaceship sounders and vehicle structures are produced by weld-bonded techniques [24–27]. Weld-bonded joints were initially developed for aircraft applications [24], and the flow-in method was employed at initial development stages of this technology, in which the components were firstly spot-welded, and a low-viscosity adhesive subsequently filled the bonding regions by capillarity, followed by heating for curing. The weld-through quickly became a viable alternative to permit higher viscosity adhesives to be used. By this technique, the components are primarily bonded, and the bonded region is then spot-welded before curing of the adhesive, i.e., within the working time (WT) of the adhesive [7,28]. This process was not fully understood until recently due to lack of systematic theoretical and experimental investigations, e.g., the experimental work of Charbonnet et al. [29] and the experimental/metallurgical and numerical studies of Darwish and Ghanya [7] and Darwish [25]. Charbonnet et al. [29] tested weld-bonded unions with three grades of mild steel for the adherends and two kinds of adhesives (epoxy and rubber sealer). A higher overall performance was found when compared to conventional spot-welded joints. The work has also proved that conventional spot-welders can be used for weld-bonding. Regarding the strength of weld-bonded joints, different studies showed, either by testing or FEM stress analyses, the benefits of single-lap weld-bonded joints compared to spot-welded joints under static or fatigue loadings [28,30–32]. Melander et al. [18] also testified the higher efficiency of weld-bonding compared to spot-welding on a peel test geometry. Santos et al. [28] published a numerical/experimental investigation of weld-bonded single-lap joints between steel adherends, for optimization of material and fabrication parameters. Three adhesives were tested (epoxy and methacrylate-based), considering varying time intervals between the bonding and welding operations. The numerical analysis allowed the optimization of welding parameters, while for the experiments the weld-through fabrication method was selected. Three conditions were tested: welding immediately after bonding and assembly (0% of the WT), at 50% of the WT and at 100% of the WT. Testing revealed a premature adhesive layer debonding, whilst the maximum load was governed by the spot weld. However, welding at 100% of the WT further anticipates the premature failure of the adhesive layer. In the work of Moroni et al. [8] weld-bonded, rivet-bonded and clinch-bonded joints were compared to adhesive, spot-welded, riveted or clinched joints. The Design of Experiments was used to test the influence of parameters such as materials, geometry (adherend thickness and weld/rivet/clinch pitch) and environment on the joints strength, stiffness and energy absorption. The main advantage of weld-bonding was related to the substantial increase in energy absorption, although a non-negligible increase of stiffness and strength was also found. The adherend thickness was found to highly influence welded and weld-bonded joints, as the weld nugget diameter increased with the adherend thickness, while it had a small influence for bonded joints, in this case related to the reduction of peel effects [1]. A significant improvement under ageing and high temperature was also found with weld-bonded joints compared to bonded joints. Despite the reported studies, failure load predictions for hybrid joints are scarce in the literature ([11] for fasten-bonded joints). Additionally, the failure process of weld-bonded joints is still not fully understood, and established failure criteria do not exist [22], mainly because of the co-existence of the weld nugget and adhesive layer, which makes the stress and strain analyses more complex [22]. As the available numerical techniques for bonded joints by the FEM combined with CZM analyses for fracture prediction are quite accurate, effective and economic [33,34], it is essential to test this technique for weld-bonded joints. Actually, provided that the predictions are accurate by a faithful representation of the phenomena involved, hybrid joint design will become highly facilitated, allowing an easier optimization and reduction of design costs.

In this work, an experimental and numerical study was carried out on hybrid weld-bonded single-lap unions, in comparison with the spot-welded and adhesively bonded equivalents, considering a ductile adhesive. A parametric study on $L_0$ allowed proper characterization of the strength advantages of this hybrid technique under different conditions. The FEM work was performed in *Abaqus*®, comprising a stress analysis that provided a background for discussion of the presented results. CZM were used for damage simulation, allowing the evaluation of this technique for the strength prediction and design of weld-bonded joints.

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**Fig. 1.** S–ε curves of the low carbon steel used and respective approximation for the FEM analysis (a) and S–ε curves of adhesive Araldite® 2015 (b).
A. acetone, abrasion welded and weld was selected as the maximum allowable for welding, thus engineering and performance of the bonded joints were considered to achieve a high quality bond. The WT of the adhesive was also equated, to prevent premature adhesive curing and increased electrical insulation, resulting in excessive heat generation and metal expulsion, and subsequent damage to the adhesive, or obstruction to the welding operation by canceling of the current flow [28]. The adhesive Araldite\textsuperscript{a} 2015, holding a WT of 35 min, was selected and characterized for the FEM analysis. The adhesive bulk specimens for mode I loading were fabricated according to the NF T 76-142 French standard. The Thick Adherend Shear Tests (TAST) for mode II loading followed the guidelines of the standard ISO 11003-2:1999. Fig. 1(b) shows, as an example, s-e curves in mode I loading. More details on the fabrication procedure and characterization of the adherends and adhesive can be found in Refs. [35–37]. The fracture toughness in tension (\(G_{\text{t}}\)) and in shear (\(G_{\text{s}}\)) were derived in previous works by Double-Cantilever Beam and End-Notched Flexure tests, respectively [33,34], whilst the fracture toughness in the tearing mode of loading (\(G_{\text{t}}\)) was equaled to \(G_{\text{t}}\) [2,38]. Table 1 summarizes the collected data [37].

2.2. Joint geometries

Fig. 2 depicts the geometry of the joints, applicable to the welded, bonded and weld-bonded joints. The characteristic dimensions were defined as (in mm) \(L_0\) 15, 30, 45 and 60, width \(b\) 25, total length between grips \(L_1\) 150, adherend thickness \(t_b\) 2 and adhesive thickness \(t_h\) 0.4 for the welded joints and \(t_b\) 0.2 for the bonded and weld-bonded joints. The value of \(t_b\) was selected as the maximum allowable for welding, thus minimizing stress concentrations at the weld-nugget periphery [16]. For the welded joints, only \(L_0\) 15 mm was considered. For the welded and weld-bonded joints, the spot is located at the mid-length of \(L_0\). The joint faying surfaces were prepared by manual abrasion with 220 mesh sandpaper, followed by wiping with acetone, and the joints were fabricated using a bonding apparatus that allowed the proper adherend alignment. The weld-bonded joints were fabricated by the weld-through technique, with the welding operation taking place at a maximum of 10 min after bonding. During welding, the adhesive usually degrades and carbonizes at around 1–2 mm outside the nugget periphery [22], not contributing to the load-bearing capability of the joints [39]. For the bonded and weld-bonded joints, \(t_b\) was achieved by placement of \(0.2 \text{ mm}\) nylon wires around the overlap region, jointly with the application of pressure with grips. A CE\textsuperscript{a} NKL-28 spot-welder was used to fabricate the spot-welded and weld-bonded joints, equipped with truncated cone shape electrodes (06 mm at the contacting edges) in accordance with the ISO 5182 standard. The electrode clamping load is adjustable (up to 2.2 kN) and applied by a foot pedal. The spot-welder holds a maximum short-circuit current of 14 kA and a nominal welding power of 25 kVA. The input parameters are squeeze time, representing the time \((\text{in 50 Hz cycles of applied current})\) between the plates squeezing and the beginning of welding, set to 3 cycles, the upstroke, representing the time needed to proportionally reach the defined welding current, set to 5 cycles, the welding time, defining the duration of the current flow, considered at 35 cycles, and the welding current, providing the percentile of the maximum current supplied by the spot welder, set at 45% \((6.3 \text{ kA})\).

Despite the reported welding parameters used throughout this work, an initial study was carried out on the influence of these parameters on the joints behavior. Before testing, tabs were glued at the specimens edges for a correct alignment. The joints were tested 1 week after fabrication for complete curing of the adhesive (bonded and weld-bonded joints). The tests were carried out in a Shimadzu AG-X 100 testing machine with a 100 kN load cell, at room temperature and under displacement control (1 mm/ min). The testing machine grips displacement was used to build the P-d curves. Five specimens were tested for each joint configuration, with at least four valid results.

3. Numerical analysis

3.1. Analysis conditions

The FEM analysis was performed in Abaqus\textsuperscript{a}, aiming to check the suitability of its CZM embedded formulation to predict the strength of the bonded, welded and weld-bonded joints, and it accounted for geometrical non-linear effects [40]. The weld nugget and adhesive were fully modeled by the triangular CZM laws presented in Section 3.2. In the welded and weld-bonded models, a few simplifications were employed, such as the non-consideration of the steel properties variations near the nugget due to the applied thermal cycle [41,42], or the minor electrode indentation at the welding loci. The adhesive properties also relate to room temperature curing, despite the thermal cycle applied during welding [28], which is prone to degrade the adhesive [43], and adhesive degradation at the spot periphery.

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Table 1

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus, (E) [GPa]</td>
<td>1.8570.21</td>
</tr>
<tr>
<td>Poisson's ratio (\nu)</td>
<td>0.33</td>
</tr>
<tr>
<td>Tensile yield strength (\sigma_y) [MPa]</td>
<td>12.6370.61</td>
</tr>
<tr>
<td>Tensile failure strength (\sigma_f) [MPa]</td>
<td>21.6371.61</td>
</tr>
<tr>
<td>Tensile failure strain (e_f) [%]</td>
<td>4.7770.15</td>
</tr>
<tr>
<td>Tensile toughness (G_t) [N/mm]</td>
<td>0.4370.02</td>
</tr>
<tr>
<td>Shear modulus (G) [GPa]</td>
<td>0.5670.21</td>
</tr>
<tr>
<td>Shear yield strength (\tau_y) [MPa]</td>
<td>14.671.3</td>
</tr>
<tr>
<td>Shear failure strength (\tau_f) [MPa]</td>
<td>17.971.8</td>
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<tr>
<td>Shear failure strain (\gamma_f) [%]</td>
<td>43.973.4</td>
</tr>
<tr>
<td>Shear toughness (G_s) [N/mm]</td>
<td>4.7070.34</td>
</tr>
</tbody>
</table>

\(^a\) Manufacturer's data.
was also neglected [22]. The three-dimensional models were built with longitudinal symmetry conditions (Fig. 2). Fig. 3 shows the meshes for the Lₜ=15 mm bonded (a) and weld-bonded (b) joints at the overlap, emphasizing on the smaller elements at the spot-weld outer boundary and also towards the contacting region between adherends, because of the respective concentrations of stresses [22,28,44]. The models used 8-node hexahedral solid elements (C3D8R from Abaqus®) and COH3D8 8-node cohesive elements. The joints were clamped at one of the edges, while the other edge was subjected to a tensile displacement concurrently with transverse restraining, to simulate real testing conditions [45,46]. The thin adhesive layer was modeled by a single row of cohesive elements [36] incorporating a mixed-mode traction-separation law between the element faces, including the stiffness of the adhesive layer, as defined further in this work. The weld-nugget was modeled in a similar fashion, considering a 0.2 mm thickness zone collinear with the adhesive layer to account for failure of the weld-nugget, whilst the surrounding steel portion was modeled using the previously defined bulk steel properties. This choice was made despite the large and continuous gradient of steel properties between the weld-nugget and the bulk steel for simplification purposes [22]. The proposed modeling technique is currently implemented within Abaqus® CAE suite and will be briefly described in the following section.

3.2. Cohesive zone modeling

CZM are based on a relationship between stresses and relative displacements (in tension, shear or tearing) connecting paired nodes of the cohesive elements [Fig. 4], to simulate the elastic behavior up to the cohesive strength (c_t in tension, c_s in shear or c_d in tearing) and subsequent softening, to model the degradation of material properties up to failure [47]. The shape of the softening region can also be adjusted to conform to the behavior of different materials or interfaces [40]. The areas under the traction-separation laws in tension, shear or tearing (G_t, G_s, or G_d, respectively) are equal to G_t, G_s, or G_d in the respective order. Under pure loading, damage grows at a specific integration point when stresses are released according to the respective damage law. Under a combined loading, stress and energetic criteria are often used to combine tension, shear and tearing [36]. The triangular law (Fig. 4) assumes an initial linear elastic behavior followed by linear degradation. Elasticity is defined by a constitutive matrix (K), containing the stiffness parameters and relating stresses and strains across the interface [48]:

\[
\begin{bmatrix}
 t_{1} \\
 t_{2} \\
 t_{3}
\end{bmatrix} =
\begin{bmatrix}
 K_{11} & K_{12} & K_{13} \\
 K_{21} & K_{22} & K_{23} \\
 K_{31} & K_{32} & K_{33}
\end{bmatrix}
\begin{bmatrix}
 s_{1} \\
 s_{2} \\
 s_{3}
\end{bmatrix} = K_{E}.
\]

A suitable approximation for thin adhesive layers [49] and weld-nugget debonding is provided with \( K_{E}=E, K_{11}=1/4K_{22}, K_{12}=1/4G, K_{21}=1/4K_{22}, K_{23}=1/4K_{33}, K_{31}=1/4K_{33}, K_{32}=1/4K_{33} \) (G is the shear modulus). Damage initiation can be specified by different criteria. In this work, the quadratic nominal stress criterion was considered for the initiation of damage, already shown to give accurate results [40] and expressed as [48]

\[
\left( \frac{t_{1}}{t_{2}} \right)^{2} + \left( \frac{t_{1}}{t_{3}} \right)^{2} + \left( \frac{t_{2}}{t_{3}} \right)^{2} = 1.
\]

\(<a\) are the Macaulay brackets, emphasizing that a purely compressive stress state does not initiate damage [50]. After the mixed-mode cohesive strength is attained (\( t \) in Fig. 4) by the fulfillment of Eq. (2), the material stiffness is degraded. Complete separation is predicted by a linear power law form of the required energies for failure in the pure modes [48]:

\[
\frac{G_{t}}{G_{s}} + \frac{G_{s}}{G_{d}} + \frac{G_{t}}{G_{d}} = 1.
\]

4. Results and discussion

4.1. Parametric study on the welding parameters

The nugget strength in welded and weld-bonded joints is known to significantly vary with the welding parameters [22]. To fully understand these effects, the failure mechanisms and the perceived influence on the adhesive curing, three sets of welding parameters were tested (in the following order—squeezing time, upslope, welding time and welding current): 1-3/5/30/40, 2-3/5/35/45 and 3-3/5/43/53 (proposed by the manufacturer for t₁=2 mm carbon steel plates). Fig. 5(a) shows representative P-d curves for each one of these three conditions. Table 2 provides the collected data for 5 specimens of each set. The effect of the welding parameters is notorious, with a brittle shear fracture of the weld-nugget for set 1, a weld-nugget fracture after plasticization of the adherends initiating at d E 0.65 mm for set 2 and an adherend failure near the weld-nugget for set 3. Regarding the visible effect of each parameter set on the weld-bonded joints, sets 1 and 2 cause only a minor heating of the adherends at the overlap and do not significantly change the adhesive curing cycle,
while set 3 immediately solidifies the adhesive during welding (with visible burning at the overlap periphery), anticipating its degradation. As a result of these tests, set 2 of welding parameters was selected, as it provides an acceptable ductility of the joints without affecting the adhesive layer properties.

### 4.2. Definition of cohesive parameters

Table 3 shows the parameters introduced in Abaqus® for the simulation of damage growth in the adhesive layer and weld-nugget [36,40]. The adhesive parameters were estimated from the data of Table 1, considering the average values of failure strength from the characterization tests to define and , and the experimentally determined values of and (equally with ). The weld-nugget parameters are known to substantially differ from the bulk steel properties due to the thermal strengthening induced by the welding cycle. Actually, in the work of Chang and Shi [22], a large variation of yield strength was found between the base metal and the weld-nugget, the latter having a yield strength of nearly 400% of the base metal. As a result of these property gradients, the weld-nugget parameters were estimated by fitting between the experimental and FEM P-d curves of the welded joints considering set 2 of welding properties, using a trial and error analysis, such that an empirical law can be established to accurately model the weld-nugget failure, equally allowing extrapolation for the simulation of the weld-bonded joints. Fig. 5(b) shows the final result of the parameter determination method by comparison between the experiments and FEM simulation.

#### 4.3. Stress analysis

The present stress analysis, aiming to provide a basis for discussion of the results that follow, includes stress field plots at the overlap region for the welded joint immediately before failure, for an assessment of the typical adherend/weld-nugget stress distributions, followed by elastic plots of the through-thickness normal [s] and shear [t] stresses of the bonded and weld-bonded joints at the adhesive mid-thickness and at the symmetry plane A-A (Fig. 2), for the values considered in the analysis. The stress distributions are normalized by , the average shear stress along the overlap for the respective joint configuration [51].

#### 4.3.1. Welded joints

Fig. 6 shows von Mises equivalent stresses at the spot-welded joints in the overlap region, emphasizing the large joint rotation due to the bending asymmetry [70] and peak stresses at the weld-nugget periphery, as this is the primary region of plastic straining due to the sharp geometry change [23]; stresses (Fig. 7a) are relevant only at the weld-nugget, and are caused by the asymmetric transmission of loads. The existence of peel [s] values at weld-nugget periphery and compressive ones in the inner regions is due to the joint curvature induced by the adherends rotation [31]. However, the weld-nugget transmits the loads between adherends mainly by shear (Fig. 7b), with peak stresses equally emerging at the nugget periphery by the effect of the sharp change of geometry [31,52]; stresses are similar at the nearby regions of the nugget within the adherends, being nil away from this zone.
allow plasticization at the spots of stress concentrations due to the diverging longitudinal distributions (Fig. 7). The observed profiles of stresses in the spot-welded joints in the overlap region (view of the symmetry plane) are highly peaked at the weld nugget and decreasing along the overlap region (Fig. 8). The normal profiles of stresses in the weld-bonded joints at the adhesive mid-thickness as a function of $x/L_0$ are shown in Fig. 9.

4.3.2. Bonded joints

$S_y$ stress distributions (Fig. 8a) exhibit singularities caused by the sharp overlap edges [53,54]. The observed profiles of $S_y$ stresses suggest that higher longitudinal deformation gradients at the overlap edges; $S_y$ stresses at the inner region of the overlap are nearly nil; $S_y$ stress variations are negligible for $L_0 \leq 15$ mm, gradually increasing with $L_0$ because of higher longitudinal deformation gradients at the overlap [58]. This variation usually gives a non-linear increase of the failure load with $L_0$, especially for brittle adhesives that do not allow plasticization at the spots of stress concentrations [35,36]. Ductile adhesives such as Araldite\textsuperscript{®} 2015 are not as prone to these effects as brittle ones because of the allowable redistribution of stresses in the highly loaded regions when the yield strength is achieved [59].

4.3.3. Weld-bonded joints

The sole visible inconsistency on $S_y$ stresses between the weld-bonded (Fig. 9a) and bonded joints (Fig. 8a) is found for $L_0 \geq 15$ mm, as the weld-nugget in weld-bonded joints supports all the peel $S_y$ stresses, while $S_y$ stresses in the surrounding bonded regions of the overlap are compressive, which benefits the adhesive layer, typically vulnerable to premature failures due to peel [1,36]. For bigger $L_0$ values, the majority of $S_y$ stresses are transmitted by the adhesive layer [16]. Thus, on account of $S_y$ stresses, the weld-bonded configuration is expected to give an advantage only for small $L_0$ values. On the other hand, $T_{xy}$ stresses...
However, this occurrence was always contained within 1–2 mm of the weld-nugget outer perimeter. The maximum load at first failure ($P_{fr}$) is introduced in the discussion for the evaluation of the joints strength, corresponding to the first drop of $P$, either nugget failure or debonding. Fig. 11 compares the experimental and FEM $P$–$d$ curves for the bonded joints with $L_0$\textsubscript{145} mm (a) and $L_0$\textsubscript{160} mm (b), showing a close agreement. The $L_0$\textsubscript{145} mm curves behave linearly up to failure (Fig. 11a), similar to the $L_0$\textsubscript{145} mm bonded joints. Due to the large steel ductility (Fig. 1), the $L_0$\textsubscript{145} mm and 60 mm (Fig. 11b) bonded joints the adherends endure large plasticization (beginning at $\varepsilon$ 10 kN in the $P$–$d$ plots) before cohesive failure of the adhesive. Fig. 12 relates to the experimental and FEM $P$–$d$ curves of the weld-bonded joints, for $L_0$\textsubscript{130} mm (a) and $L_0$\textsubscript{145} mm (b). For the $L_0$\textsubscript{145} and 30 mm (Fig. 12a) weld-bonded joints, no adherend plasticization was found at $P_a$ (accompanied by a sudden drop of $P$), which was related to premature debonding. The weld-nugget continued to withstand loads before separation of the adherends at a similar load to the welded joints [22,28]. Equally to the collected data in this study, the results of Santos et al. [28] showed a slightly higher stiffness after $P_a$ for weld–bonded joints, compared to bonded joints, due to residual areas of adhesive bonding. Opposed to this behavior, the $L_0$\textsubscript{345} (Fig. 12b) and 60 mm weld-bonded joints failed after adherend plasticization (shortly after plasticization onset for $L_0$\textsubscript{145} mm and largely after for $L_0$\textsubscript{160} mm). In general, although this is not directly comparable in the $P$–$d$ plots of Figs. 11 and 12, the weld-bonded joints in this study exhibited a bigger global stiffness than bonded or spot-welded joints because of stiffening effects in the overlap region [28].

3.4. Fracture modes and strength of the joints

Fig. 10 depicts representative fracture surfaces for the $L_0$\textsubscript{145} mm spot-welded joint (a), the $L_0$\textsubscript{130} mm bonded joint (b), the $L_0$\textsubscript{145} mm weld-bonded joint (c) and the $L_0$\textsubscript{145} mm weld-bonded joint (d). All bonded and weld-bonded joints fractures were cohesive in the bonded regions. Nonetheless, Fig. 10(c) and (d) clearly shows a burnt adhesive ring around the weld-nugget, corresponding to carbonization caused by the elevated temperatures during welding, and invariably leading to a reduction of the load-bearing capability of the joints [22,28]. However, this occurrence was always contained within 1–2 mm
exactly the average of the experiments, because it was obtained by the previously mentioned fitting procedure. The bonded joints experienced an increase of $P_n$ at a decreasing rate with $L_o$, which is due to the adherends yielding from $L_o^{1/4} 45$ mm to $L_o^{1/4} 60$ mm (Fig. 11b). Otherwise, a nearly linear $P_n$-$L_o$ relationship would be expected, because of the high strength of the adherends and large ductility of the adhesive that help global yielding conditions at failure, due to the allowance of generalized yielding and redistribution of adhesive stresses [58,60-62]. Regarding the effectiveness of the traditional joining methods, the bonded joint surpasses the spot-welded joint for $L_o^{1/4} 30$ mm, which is closely related to the increase of bonded area with $L_o$. The weld-bonded joints show a non-negligible strength improvement over the bonded conditions for $L_o^{1/4} 15$ and $30$ mm, which is consistent with the stress analysis of Section 4.3.3 (Fig. 9 vs. Fig. 8). Since the weld-nugget provides a higher transfer of loads between the adherends at the time of cohesive failure of the adhesive. However, for bigger values of $L_o$, the values of $P_n$ are on the same order of magnitude of the bonded joints because of the elimination of the peel advantage (Fig. 9a vs. Fig. 8a), and also the reduction of the relative influence of the weld-nugget on $t_w$ stresses averaged over the entire overlap (Fig. 9b). The adherend plasticization for the bigger $L_o$ values also helped this tendency, since any increase of the load bearing characteristics of the adhesive bond is also rendered less significant on $P_n$. Summarizing the strength advantage of weld-bonding compared to welded or bonded joints, for $L_o^{1/4} 15$ mm a 24% improvement was found to the bonded joint (obtained from the experimental data; valid throughout this section), although no improvement occurred in relation to the welded joint because of premature failure of the adhesive induced by the adherends separation [63]. For $L_o^{1/4} 30$ mm, the weld-bonded joint provides a 6.4% improvement to the bonded joint and a 22% increase of $P_n$ to the welded joint, the latter occurring by failure of the adhesive at a higher $P_n$ value than the spot-welded joint equivalent. Opposed to this behavior, for bigger values of $L_o$, the strength advantage of the weld-bonded joint to the bonded one is smaller (3.3% for $L_o^{1/4} 45$ mm and 1.8% for $L_o^{1/4} 60$ mm), while the improvement of the technique to the spot-welded joints is 46% ($L_o^{1/4} 45$ mm) and 58% ($L_o^{1/4} 60$ mm). The global results presented in this section showed the suitability of the FEM and CZM for the simulation of bonded, welded and weld-bonded joints (maximum deviation of 12% for the $L_o^{1/4} 45$ mm bonded joint), thus aiding quicker, more effective and cheaper design of bonded joints, but the quantitative results and relative advantages between all techniques should be considered valid only for the particular set of geometric and material conditions selected for this study. Actually, for stronger adherends, a substantial increase of $P_n$ is expected for the bigger values of $L_o$ as they would prevent adherend plasticization. As regards the adhesive layer, Darwish and Al-Samhan [16] showed the major influence of $E$ (of the adhesive) on $P_n$, as adhesives with smaller values of $E$ maximize the joints strength because they allow the weld-nugget to support the majority of the loads whilst the adhesive bond undergoes larger strains and, thus, allowing bigger joint loads before failing. The mentioned authors concluded as well that the increase of $t_i$ is also effective to reduce stress concentrations at the weld-nugget periphery and at the overlap edges, which reflects on higher values of $P_n$, while bigger values of $E$ for the adherends effectively reduce peel and shear peak stresses, increasing the strength of hybrid joints.

5. Conclusions

An experimental and an FEM study were carried out on hybrid spot-welded/bonded single-lap joints, by comparison with the spot-welded and adhesively bonded equivalents, for the evaluation of this technique and the capability of CZM for design purposes. The study began with an influence analysis of the welding parameters on the strength of spot-welded joints and on the visible adhesive degradation by welding-induced heating, which allowed selecting the most suitable conditions. After proper characterization of the CZM laws of the adhesive and weld-nugget, a FEM stress analysis provided a background for further discussion and showed, for the welded joints, $S_y$ and $t_w$ stress concentrations at the weld-nugget periphery and also a large rotation of the adherends and consequent separation at the overlap edges; $S_y$ and $t_y$ stresses for the bonded joints peaked at the overlap edges, while weld-bonded joints benefit from higher
transmission of \(L_0\) loads in the inner overlap region by the weld-nugget, because of the stiffness differential to the bonded region. The strength comparisons between the three joint techniques showed a marked advantage of weld-bonding over the traditional equivalents for \(L_0/4\). For \(L_0/4\), the improvement was found only in comparison with the bonded joint, because of premature failure of the adhesive bond. Higher values of \(L_0\) revealed a smaller influence on the strength improvement to the bonded joints due to the adherends plasticization for the achieved \(P_s\) values and stress distribution issues, even though they were recommended over spot-welding. Although the presented results cannot be directly extrapolated to other geometries and materials without a specific analysis, validation of the proposed FEM/CFZM technique for the design of bonded, welded and hybrid joints was successfully accomplished.

References


