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Comparison of the strength and energy absorption of adhesive-bonded with resistance spot-welded single-lap joints

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In lightweight body-in-white design, joints must not only provide strength but also allow for ductility and sufficient energy absorption. In this study, Single Lap Joints (SLJs) made with adhesive bonding are compared experimentally with those joined by Resistance Spot Welding (RSW) in low-carbon steel sheets. The influence of overlap length (15 and 25 mm) and weld number (one or two spots) is examined. Tensile force–displacement tests, conducted at room temperature with a crosshead speed of 1 mm/min, revealed that extending the overlap from 15 to 25 mm improved the peak load, final displacement, and fracture energy of the adhesive joints. Among the tested configurations, double spot welds (2RSW) provided the greatest capacity and toughness. However, adhesive joints with a 25 mm overlap (AB25) exhibited higher strength than single spot welds (1RSW), while their ductility was comparable. The observed failure modes varied across the joint types. In resistance spot welds, failure occurred mainly through button pull-out, whereas adhesive joints exhibited a mixed adhesive–cohesive failure mode. In contrast, the 2RSW specimens displayed pull-out and necking sequences, reflecting load sharing between the weld nuggets. Overall, the findings suggest straightforward design guidelines. When maximum strength and energy absorption are required, two Spot Welds (2RSW) are the best choice. On the other hand, AB25 joints, with a 25 mm overlap, provide higher strength than single Spot Welds (1RSW).

1. Introduction

Adhesive bonding is increasingly adopted in automotive manufacturing as an alternative to welding/clinching. By transferring load through a continuous bonded area rather than a spot-weld nugget, it enhances durability, strength, and fatigue life, and it enables joining dissimilar materials (e.g., aluminum–composites) to reduce vehicle weight—especially vital for EVs, where lower mass improves energy efficiency and extends battery range [1]. Accordingly, adhesive bonding is recognized as an enabling technology in the advancement of lightweight, safe, and energy-efficient vehicles. Single-lap joints (SLJs) are a common configuration for evaluating sheet-metal bonding [2]. Classical models (Volkersen; Goland–Reissner) established shear/peel stress concentrations at bond ends, later refined and validated [3, 4]. Subsequent refinements (e.g., accounting for adherend bending and shear deformation) have improved stress predictions, yet experimental characterization remains essential for practical metallic joints. Despite these advances, most analytical models still rely on idealized assumptions; therefore, for many practical metallic joints, experimental evidence remains indispensable, and ASTM D1002

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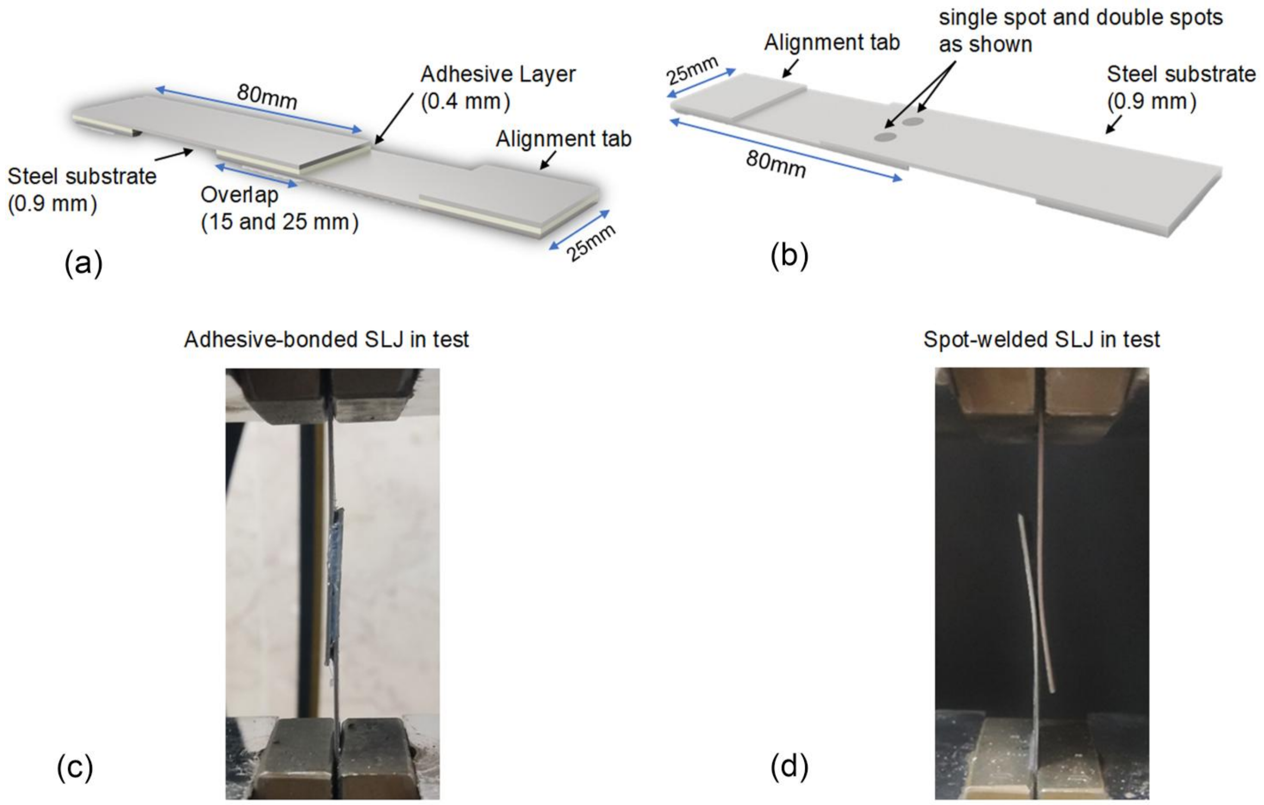

Figure 1: Single Lap Joint (SLJ) specimens and test setup.
(a) Schematic of adhesive-bonded SLJ with overlap lengths of 15 and 25 mm.
(b) Schematic of spot-welded SLJ showing both configurations: 1RSW (single spot) and 2RSW (double spots).
(c) Adhesive-bonded SLJ specimen under tensile shear test.
(d) Spot-welded SLJ specimen under tensile shear test.

continues to serve as a benchmark for metal–metal SLJ testing [5].

The geometry of a joint has a strong influence on its behavior. Overlap length, width, and the thickness of both adherends and adhesive control load capacity and stiffness [6]. Prior experiments confirm these trends—e.g., capacity increases with overlap until limited by adhesive strength, and thicker bondlines reduce strength [7,9].

Resistance spot welding (RSW) remains the dominant joining route for automotive steel sheets due to its high speed, suitability for automation, and the absence of filler material; weld quality is governed by current, weld time, electrode force, and tip geometry [8]. Under tensile–shear loading, spot welds typically fail either by interfacial fracture (IF) or by pull-out (PO); the PO mode is generally preferred because it indicates a stronger weld. Robust welds typically fail in button pull-out once the nugget diameter $\gtrsim 5\sqrt{t}$, as specified in standards [10, 11]. Hybrid weld–bonded concepts have been reported to enhance joint stiffness and energy absorption; however, direct baseline comparisons between purely adhesive SLJs and purely spot-welded joints under identical materials and geometries remain essential for design selection. This study compares adhesive SLJs with single- and double-spot RSW in terms of strength, energy absorption, stress distribution, and failure modes.

2. Materials and methods

Single-lap joints were prepared from low-carbon steel sheets (thickness 0.9 mm, size 25 × 80 mm). The mechanical properties of the ST12 steel sheets are summarized in Table 1. The overlap length was 25 mm, and the edge distance was 8–9 mm. One or two spot welds were used (pitch about 20 mm) (Fig. 1b). Welding was done with an AC 50 Hz machine using CuCrZr domed caps (tip face ≈ 5.8 mm, dome radius ≈ 45 mm) and water cooling (≥4 $L \cdot min^{-1}$). The welding schedule was 10 cycles squeeze, 10 cycles weld (~200 ms), and 10 cycles hold. Current was 7 kA and electrode force was 2.50 kN (2500 N), checked with a load cell before each series (force error ±0.05 kN). The nugget diameter (dn) was measured from peeled buttons and cross-sections. Measured dn: 1RSW = 5.2 ± 0.2 mm (n = 4);

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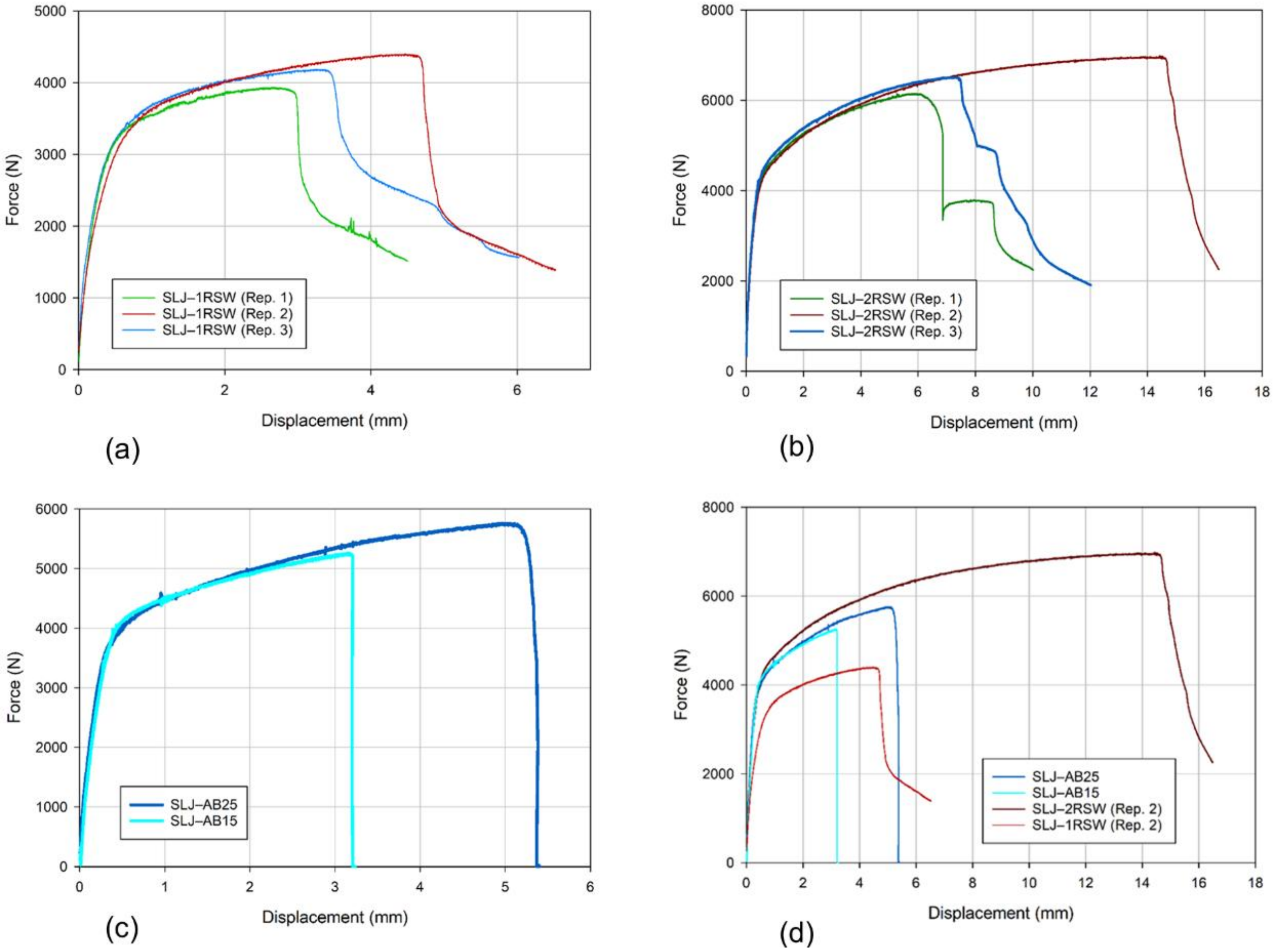

Figure 2: Force–displacement responses of single-lap joints (SLJs).
(a) 1RSW specimens (three repetitions).
(b) 2RSW specimens (three repetitions).
(c) Adhesive-bonded SLJs with overlap lengths of 15 mm (AB15) and 25 mm (AB25).
(d) Direct comparison of adhesive-bonded and spot-welded SLJs in terms of strength and ductility.

2RSW = 5.3 ± 0.2 mm (n = 4). These values follow the design rule dn ≈ (5–6)√t for sheet thickness t ≈ 0.9–1.0 mm.

Adhesive SLJs used 15 or 25 mm overlaps. Adherend surfaces were lightly abraded (P320 SiC) and degreased with acetone, then bonded with a rigid two-part epoxy adhesive (Hel, Iran; mix ratio 1:1 by volume; pot life ~10 min at 23 °C). The bondline thickness was 0.40 ± 0.03 mm, set with 0.40 mm stainless-steel spacer wires (Fig. 1a). Assemblies were clamped (~0.1 MPa) and cured 24 h at 23 ± 2 °C; specimens were conditioned 24 h before testing. Owing to the low between-replicate variance in adhesive SLJs, only the mean curve (n = 3) is shown for each overlap; the corresponding point metrics are reported as mean in Table 1. To reduce secondary bending, equal-thickness tabs were attached at the grips (Fig. 1c,d).

All specimens were tested in tensile–shear on a SANTAM universal testing machine at 23 ± 2 °C and 1 mm/min, with n = 3 per configuration to failure; force–displacement curves, fracture energy, and failure modes (PF/IF) were recorded.

Table 1: Mechanical properties of the adherend (St12 cold-rolled steel)

Material	σ_{UTS} [MPa]	σ_{YS} [MPa]	E [GPa]	ε_f [%]	ν [-]
St12 (Cold-rolled steel)	300	185	210	31	0.3

3. Results and discussion

3.1 Spot-weld joint tests

At 7 kA, single-point SLJs reached ~3.9–4.4 kN (Table 2) and failed by button pull-out (PF). The tight scatter reflects sensitivity to nugget size; combined shear/peel intensifies secondary bending. Larger nuggets resulted in higher peak loads and gentler post-peak softening, indicating

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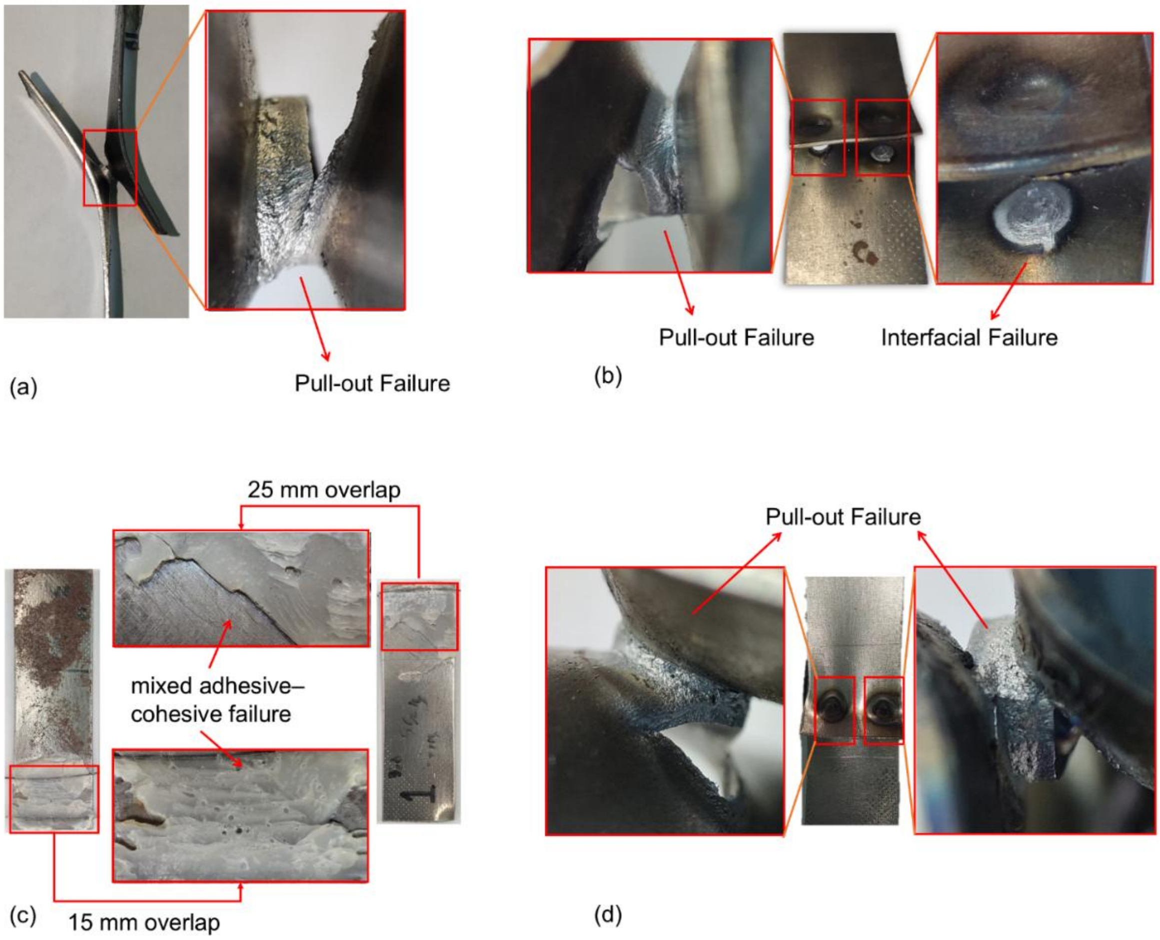

Figure 3: Common failure types seen in single-lap joint tensile-shear testing include:

(a) SLJ–1RSW (red curve in Fig. 2a): Macro/overall view shows the nugget remained intact while the surrounding sheet was torn out; failure occurred in a button pull-out (PF) mode.

(b) SLJ–2RSW (green curve in Fig. 2b): After failure, the right weld failed by IF and the left by PF; the stepwise load drops in the curve reflect this combination of IF and PF and the progressive load transfer.

(c) Adhesive joint: Fracture surfaces revealed a mixed cohesive–interfacial mechanism during testing.

(d) SLJ–2RSW (Dark red curve in Fig. 2b): PF in both welds with clear necking around the nuggets, consistent with the high peak load and large energy absorption.

more stable plastic flow around the nugget. In 2RSW, two responses appeared: in the first, interfacial failure (IF) initiates in the weaker member, load transfers to the second, and the force–displacement curve shows a two-step drop before final failure. Best 2RSW: 7.0 kN at 14.7 mm with ~98 J, with necking in both members—evidence of base-metal-controlled capacity and more uniform load sharing that increases energy absorption. Versus 1RSW at 7 kA, adding a second spot raised peak load by ~55%, ultimate displacement by ~3×, and failure energy by ~3.8×, but also increased scatter in ductility/energy (sensitivity to fragment coupling and IF to PF sequence).

3.2 Adhesively bonded joints

The expected positive effect of overlap length was observed: increasing from 15 mm (AB15) to 25 mm (AB25) raised peak load by ≈10%, roughly doubled fracture energy (≈14 to 27 J), and increased ultimate displacement (~3.2 to ~5.2 mm). Fractography showed mixed modes (interfacial debonding and cohesive failure within the adhesive); AB15 had a larger interfacial share, consistent with its lower capacity. These trends stem from more uniform stress distribution and reduced peak peel/shear in the end regions as the effective load-transfer length increases.

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Table 2: Summary of the mechanical performance of different single-lap joints (SLJs).

Joint type	Condition	F_{max} (N)	δ_f (mm)	U_f (J)	Failure mode
1RSW	7 kA – mean of 3	4197	3.65	17.84	Button pull-out
2RSW	7 kA – mean of 3	6519	9.41	67.77	Double pull-out + necking
Adhesive	AB15 – mean of 3	5343	3.01	14.40	Mixed Cohesive/Adhesive
Adhesive	AB25 – mean of 3	5745	4.96	26.62	Mixed Cohesive/Adhesive

3.3 Cross-configuration comparison

Representative curves (Fig. 2d) and consolidated metrics (Table 2) indicate a clear hierarchy: 2RSW is the strongest and most energy-absorbing configuration (peak ~7 kN, displacement ~14–15 mm, energy up to ~98 J). AB25 offers a favorable strength–ductility balance and surpasses 1RSW in both peak load and displacement, whereas AB15 fails earlier and absorbs less energy. Mechanistically, 2RSW benefits from parallel load paths and base-metal plasticity around nuggets; AB25 benefits from distributed shear transfer and mitigated end-peel. Both reduce

catastrophic interface-controlled failure and increase the area under the curve. Fracture energy (Uf) = ∫ F(δ) dδ up to complete separation (trapezoidal rule; sampling details in SI).

4. Conclusion

Adding a second spot weld (2RSW) significantly improved SLJ performance over 1RSW—Fmax from ≈4.4 to ~7.0 kN, δf from 4.4 to 14.6 mm, and Uf nearly ×3.8 (best 97.9 J)—although greater scatter was observed due to nugget size and failure sequence; these gains originate from stable load sharing between the welds and base-metal pull-out. For adhesive joints, increasing the overlap from 15 to 25 mm raised Fmax by about 10% and nearly doubled Uf (14.4→26.6 J), with mixed cohesive–interfacial fracture underscoring the need for proper surface preparation. In comparison to the best 1RSW (4400 N, 4.60 mm, 21.49 J), the adhesive joint with a 25 mm overlap (AB25) performed better (Fmax = 5745 N, δf = 4.96 mm, Uf = 26.62 J), corresponding to ~31%, ~8%, and ~24% increases, respectively. In conclusion, 2RSW is the best option when maximum capacity is paramount, whereas AB25 outperforms 1RSW when strength–ductility balance and energy absorption are prioritized.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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