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Villegas, Irene Fernandez; Rans, Calvin

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The dangers of single-lap shear testing in understanding polymer composite welded joints

Irene Fernandez Villegas and Calvin Rans
Delft University of Technology, Faculty of Aerospace Engineering
Kluyverweg 1, 2629 HS Delft, The Netherlands

Abstract

Single-lap shear joints are straightforward to manufacture. This makes them especially attractive for testing polymer composite welded joints. Owing to local heating, which is characteristic of composite welding processes, the production of more geometrically intricate joints (such as double lap or scarfed joints) or bigger joints (such as end-notched flexure or double cantilever beam) typically entails a significant complexity in the design of the welding process. Testing of single lap shear joints is also uncomplicated and, even though, owing to mixed-mode loading and uneven stress distribution, it does not provide design values, it is widely acknowledged as a valuable tool for comparison. Even so, comparing different aspects of composite welded joints through their corresponding single lap shear strength values alone can be deceptive. This paper shows that comparison of different welding processes, adherend materials, process parameters or different types of joining techniques through single lap-shear testing is only meaningful when strength values are combined with knowledge on other aspects of the joints such as joint mesostructure, failure modes and joint mechanics.

Keywords: mechanical testing, thermoplastic composites, resistance welding, induction welding, ultrasonic welding, mechanical fastening

Introduction

The *scientific method* is the empirical backbone that supports the development of new knowledge and understanding through research. The premise of the scientific method is simple – new ideas and concepts are formulated as hypotheses that can be scrutinized through careful observation. That observation, however, should be subjected to a healthy dose of rigorous scepticism to avoid the tendency for humans to be biased about their own ideas and expectations. In essence, we should not seek to prove our hypotheses, but gain confidence in them through repeated failed efforts to disprove them. It is important to keep this philosophical view in mind as the pace of research and development sometimes results in approaches that can dangerously circumvent the intent behind the scientific method. One such approach may be the blind application of testing standards which were developed for a specific application and state of the art to new technologies or in new ways without once again applying a healthy dose of rigorous scepticism. Consider for example the classic single-lap shear (SLS) test which was developed as a means to assess the manufacturing quality of adhesively bonded joints. Is it appropriate to apply such a test to a relatively new joining process such as polymer composite welding?

Polymer composite welding refers to a group of techniques in which two or more polymer composite parts are joined together upon local application of heat and pressure. Welding processes are typically classified into different families based on the nature of the source of heat. Thus, there are *electro-magnetic* welding techniques, such as induction, resistance or microwave welding; *friction* welding techniques, such as ultrasonic or vibration welding; and *thermal* welding techniques such as hot tool or laser welding [1]. Common to all welding processes, the joining mechanism is molecular inter-diffusion of polymer chains between to welding partners, which erases the initial welding interface(s). Polymer composite welding is mostly used for thermoplastic composites owing to the fact that thermoplastic polymers can be softened and/or melted upon the application of sufficient heat. However, recent research work has shown that thermoset composites can be also welded if, for instance, they are provided with a thermoplastic-rich outer surface [2]. Welding processes are in general faster and more composite-friendly that adhesive bonding and mechanical fastening, respectively. As a consequence, welding is one of the main contributors to the cost-effective manufacturing of thermoplastic composite structures, and as such a key driver for a broader future use of thermoplastic composites in, for instance, the aerospace industry [3].

In the scientific literature on polymer composite welding, SLS testing is the most prevalent mechanical testing approach for the characterization of the strength of the welded joints. It is however interesting to note that, as suggested before, there is no specific standard for SLS testing of polymer composite *welded* joints. Alternatively, researchers make use of standards for adhesively bonded joints in either metals (e.g., ASTM D1002 [4]) or polymer composites (e.g., ASTM D5686 [5]). Other types of mechanical tests also used for research on polymer composite welded joints are double-lap shear [6,7], interlaminar shear strength [8], cross tensile [9], pull through [6], three-point bending [10], double cantilever beam and end-notched flexure [11]. Arguably, the main reason for SLS testing being so commonly used for composite welded joints is the simple geometry of the test coupons. This simplicity is of special importance given the moderate to high level of complexity of existing welding processes. In particular, the complexity resulting from the high sensitivity of welding processes to their boundary conditions and from the limitations to the size of the welds in most lab-scale welding setups.

By sensitivity to boundary conditions, we refer to the interdependence between the temperature evolution at the welding interface and external factors such as the thermal properties of the adherends [12] or of the tooling material [13]. Such interdependence stems from the local nature of heat generation during welding, which translates into a *transient* heat transfer problem. Consequently, when producing, for instance, double-lap shear coupons in a sequential manner (i.e., obtaining a SLS coupon and subsequently welding a third adherend to it) one needs to consider that for the two welded overlaps to have the same level of quality the process parameters (e.g., heating time) for the first and second weld more likely need to be different. Regarding the weld size, off-the-shelf equipment for a number of welding processes (e.g., induction and ultrasonic welding) can be used in a relative straightforward manner to obtain welded joints of limited size. However, in order to obtain the longer welds in principle necessary for e.g. double cantilever beam test coupons, relatively complex experimental setups need to be built in which an end effector with heating and pressure application capabilities is automatically translated along the area to be welded [14,15,16]. Furthermore, the addition of this extra degree of freedom requires, on some occasions, a substantial redefinition of the basic aspects of the welding process itself [17,18].

According to the most common SLS test standards [4,5], which as mentioned above focus on adhesively bonded joints, the test provides *apparent* shear strength values which may be used with the purpose of comparing and selecting adhesives or bonding processes. They are however not suitable for determining design-allowable stresses. Indeed, the SLS test is known to generate not only shear but also peel stresses in the bondline (translated into *weldline* in polymer composite welds) as a consequence of the secondary bending undergone by the adherends during the test [19]. Furthermore, the stress state in the bondline is non-uniform featuring stress peaks at the edges of the overlap [20]. The magnitude of the stress peaks is sensitive to a number of factors including bondline and adherend thickness, stiffness ratio between bondline and adherends and taper ratio in the adherends [20,21].

Given the similarities between adhesive bonding and welding (also known as fusion *bonding*), one may assume that SLS testing can be used for comparison, selection and optimization of the welding process. Based on the experience presented in literature, this seems to be a valid assumption. What happens, however, when we add a dose of rigorous scepticism to this assumption?

Anatomy of a Single-Lap Shear Specimen

When looking at the applicability of the SLS test typically used for assessing bondline strength to assessing weldline strength, one must consider the relevant "anatomy" of the specimen that can influence this strength. A bonded specimen comprises a bondline (adhesive), adherends and the interfaces between them. For a bonded specimen, strength data from a SLS test is considered relevant when the specimen exhibits cohesive failure of the bondline (metals and polymer composites) or, marginally, first-ply intralaminar failure in the adherends (polymer composites). Finally, interfacial failure is an indicative sign of poor bonding and hence not considered as a reliable measure of strength.

At a first glance, the anatomy of a welded specimen is similar to that of a bonded specimen. However, there are some subtle differences that need to be accounted for. First, unlike the neat adhesive layer and pristine adherends in a bonded joint, welded joints can feature diverse mesostructures, both at weldline and adherend level, depending on the welding process. This can have a profound effect on the failure of the joints. Second, welding implies the lack of distinct interfaces, suggesting the adherend itself may play a larger role in failure mechanisms. Thirdly, the welded joints could feature non-uniformities following the transient nature of welding processes which may interrelate with the uneven stress distribution in the SLS joints affecting the results of the test. And finally, some welding applications may result in welds more alike to metallic spot welds or mechanically fastened joints, which might entice researchers to use SLS testing well beyond its boundaries. Each one of these factors will be scrutinized based on the authors' experience over the last decades in studying such welded joints.

Variations in weldline mesostructure

The main difficulty in using SLS testing for the comparative assessment of different welding processes is that they may impact the mesostructure of the welded joints in different ways. Changes in the mesostructure might then affect the stress state during the tests. Consequently, the maximum loads obtained from SLS test campaigns attempting to comparatively evaluate different welding processes are likely to provide not only a measure of the strength of the welds but also a measure of the effect of each specific welding process on the mesostructure of the welded joints.

Figure 1 shows cross section micrographs of ultrasonic, resistance and induction welded joints in carbon fibre-reinforced polyphenylene sulfide (CF/PPS) adherends [22]. They illustrate two ways in which a welding process can impact the mesostructure of the welded joints, (a) by dictating the composition of the weldline and (b) by affecting the adherends. Firstly, regarding the *composition of the weldline*, it can either be a neat polymer weldline (ultrasonic and induction welds in Figure 1a and Figure 1c) or a *hybrid* weldline (resistance weld in Figure 1b). Resistance welding holds the particularity that it requires the use of a resistive element for heat generation, typically a metal mesh, which remains embedded in the weldline upon completion of the welding process [23]. The thickness and, arguably, the stiffness of such a hybrid weldline are hence influenced by the nature and geometry of the resistive element, which in turn can affect the stresses during the SLS tests [20, 21]. Indeed, our subsequent study on resistance welding of glass fibre-reinforced PPS (GF/PPS) adherends [24] indicated that the size of the mesh resistive element dictates the thickness of the weldline. This in turn was found to be linearly related to the SLS strength of the welded joints (Figure

2a). Different degrees of secondary bending during the SLS test for different size meshes, as suggested by the experimental data in Figure 2b, was believed to result in different peel stresses at the weldline and consequently to cause the strength evolution observed in Figure 2a.

Secondly, the welding process may *affect the adherends* resulting in. e.g., deformed adherends (induction weld in Figure 1c) versus non-deformed adherends (ultrasonic and resistance welds in Figure 1a and Figure 1b). In fact, there are welding processes such as susceptorless induction welding of carbon fibre-reinforced composites in which the adherends experience through-the-thickness heating in the overlap region [25]. Application of the welding pressure may hence result in matrix squeeze out and consequently in tapered adherends (Figure 1c). This local change in the geometry of the adherends may as well affect the stresses during SLS testing [20] and therefore the results of the test. Additionally, matrix squeeze flow can cause porosity (as also seen in Figure 1c) which can divert failure away from the weldline and adjacent composite plies and hence affect the maximum load attained during the test.

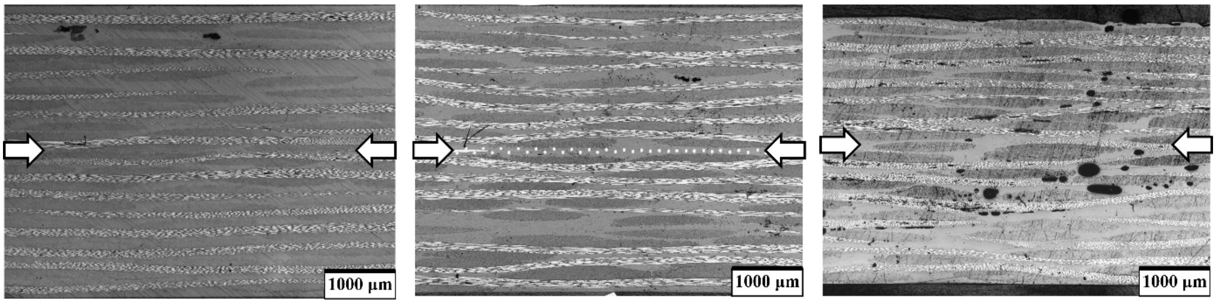

Figure 1: Cross section optical micrographs of (a) ultrasonic (left), (b) resistance (middle) and (c) induction (right) welded joints on CF/PPS adherends (twill fabric, Bond Laminates, Germany) [22].

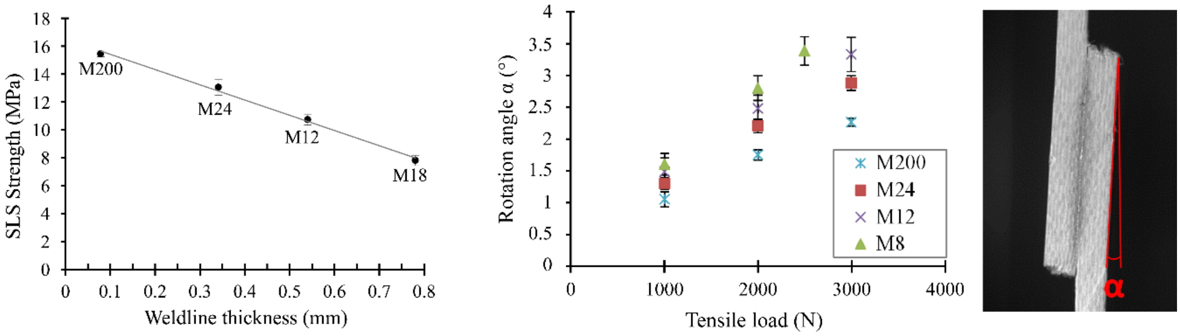

Figure 2: (a) SLS strength versus weld line thickness (left) and (b) rotation angles during SLS testing (right) of GF/PPS (8 harness satin fabric, Toray, The Netherlands) resistance welded joints with different size mesh resistive elements (AISI 304 stainless steel, woven). Different mesh size defined by wire diameter: 0.04 mm (M200), 0.2 mm (M24), 0.5 mm (M12) and 0.7 mm (M8). Weldline thickness measured on cross-section optical micrographs. Rotation angle measured on photographs taken during mechanical tests [24].

Variation in adherend properties

Contrarily to adhesively bonded joints in metals and in composites, SLS testing of polymer composite welded joints majorly results in first-ply failure, i.e., intralaminar failure in the layers adjacent to the weldline in the adherends. Consequently, SLS strength values in these joints are highly dependent on properties of the material the adherends rather than on the cohesive strength of the weldline. One of the factors that may influence the SLS strength of welded joints is the sizing of the reinforcement fibres, through its effect on the fibre-matrix interfacial strength, as shown in [26]. In that study, we investigated the effect of two different fibre sizings on the SLS strength of GF/polyetherimide (GF/PEI) resistance welded joints. Other than the treatment of the fibres, there were no differences in the adherends or the conditions in which the welds were obtained. The results of the mechanical tests (Figure 3a) showed indeed a significant effect of the fibre sizing on the SLS strength of the welded joints. The reasons underlying such effect were proposed upon analysis of the fracture surfaces of the welded joints. Fibre-matrix debonding was found to be the main failure mode in both types of joints (Figure 3b), thereby explaining the lower resistance to failure of the welded joints with the supposedly lowest fibre-matrix interfacial strength. It is interesting to note the evident difference between the state of the fibres, i.e. partially covered with resin versus naked, on both types of fracture surfaces (Figure 3b).

The abovementioned effect was further confirmed by the results obtained in our subsequent studies on the effect of test temperature on the SLS strength of resistance welded GF/PPS joints [27] and ultrasonically welded CF/PPS joints [28]. In those studies, the SLS strength of both types of welded joints was found to decrease with increasing test temperature resulting, at least partially, from the decreasing fibre-matrix interfacial strength ensuing the faster thermal expansion of the matrix as compared to the fibres. Also consistent with findings in [26], fracture surfaces showed predominant fibre-matrix debonding as well as fibres with an increasingly naked appearance as the testing temperature increased.

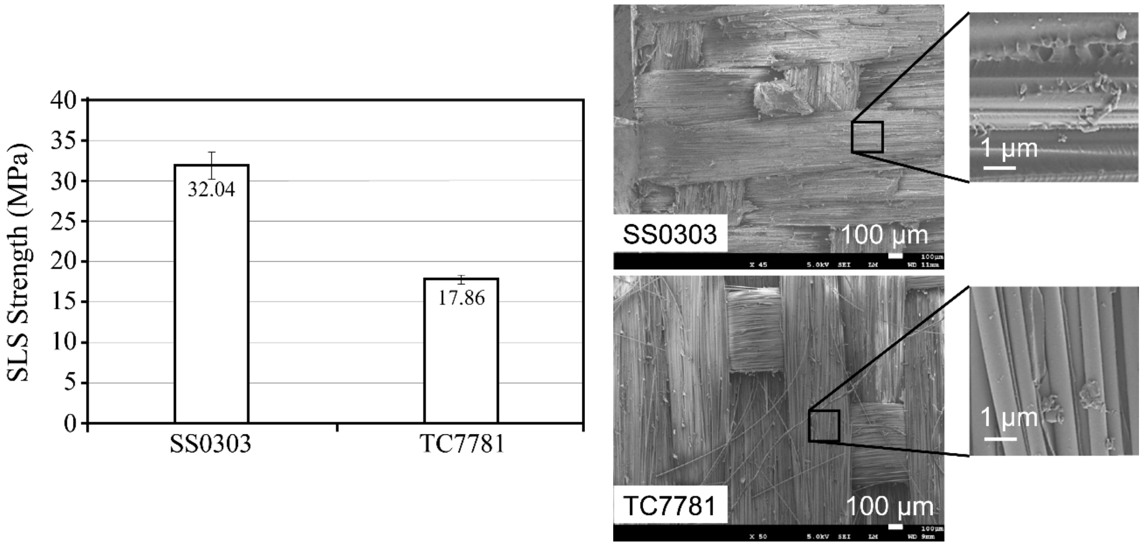

Figure 3: (a) SLS strength (left) and (b) corresponding fracture surfaces (right) of GF/PEI (8-harness sating fabric, Toray, The Netherlands) resistance welded joints. SS0303: chromium methacrylate sizing; TC7781: aminosilane sizing. Reprinted with adaptations from [26] with permission from Elsevier.

Variation in welding process parameters

One of the most frequent uses of the SLS test in the polymer composite welding community is the study of the effect of process parameters on the welded joints, generally linked to the optimization of the welding process. Figure 4 shows some of the results of such a study in which the SLS strength of CF/PPS ultrasonically welded joints was plotted versus the vibration (i.e. heating) time in the welding process [18]. It should be noted that these results correspond to a static welding process in which each test coupon was individually welded following a one-shot welding process. The graph in Figure 4 shows that between 260 ms and 440 ms vibration time the SLS strength of the welded joints plateaued at its maximum value. Based on this evidence only, one might infer that the optimum vibration time for this particular process, i.e. the shortest time at which maximum weld quality is obtained, was 260 ms. Note that maximum weld quality is usually defined by fully welded areas (i.e. absence of un-welded patches within the intended welding area), first-ply failure in the adherends upon mechanical testing and no signs of overheating (porosity and or fibre distortion). However, analysis of the fracture surfaces after the SLS tests indicated otherwise. Figure 5 shows that, in accordance with observations from different researchers [29,30], heating and hence welding of the adherends start at the edges of the overlap and progress towards its centre as the vibration time increases. This evolution is consistent with the increasing SLS strength observed at vibration times below 260 ms in Figure 4. However, Figure 6 shows that entering the plateau in Figure 4 did not necessarily mean that a fully welded overlap was achieved. Indeed, at 260 ms vibration time un-welded patches amounting to approximately 10% of the total overlap area could still be observed (Figure 6a). The SLS strength of these joints was however similar to joints obtained at 310 ms vibration time, which did show fully welded overlaps (Figure 6b).

These results indicate that owing to a potential effect of the welding process parameters on the uniformity of the weld quality, the SLS strength might lead to erroneous conclusions when attempting to optimize the process. In fact, the non-uniform stress distribution at the weldline during the SLS test makes its results insensitive to the presence of un-welded patches of a certain size in the centre of the overlap as shown above. Consequently, one needs to consider that the quality of the weld at the edges of the overlap has a higher weight on the results of the test and thus the SLS strength might not provide an accurate picture of the overall weld quality. Finally, it is interesting to note that the SLS strength was not sensitive to the occurrence of fibre distortion in the adherends either (Figure 6c). This is probably due to the counteracting effect of decreased weldline thickness with increased vibration time [31]. Further fibre distortion at increasing vibration times has however been shown to eventually cause the strength to drop [31].

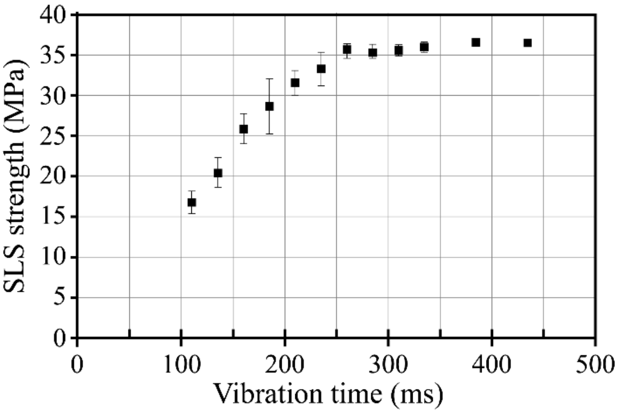

Figure 4: SLS strength of CF/PPS (5 harness satin, Toray, The Netherlands) ultrasonically welded joints at different vibration times (i.e. heating times) [18].

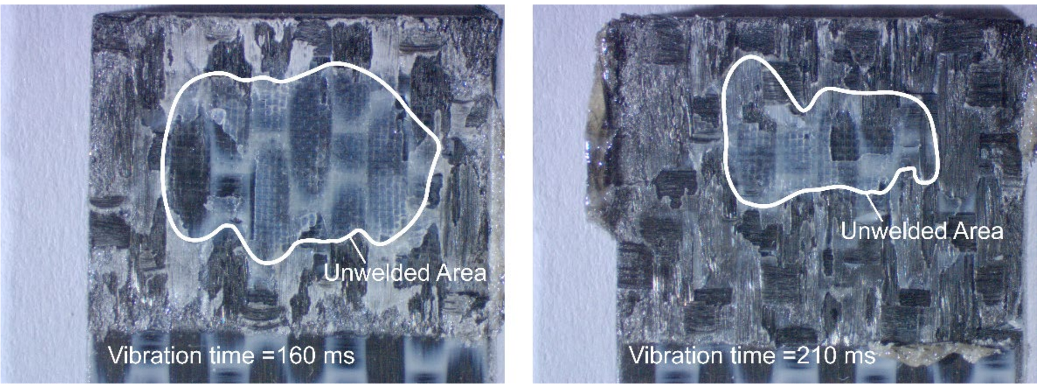

Figure 5: Representative fracture surfaces of joints obtained at (a) 160 ms (left) and (b) 210 ms (right) vibration times in Figure 4 [18].

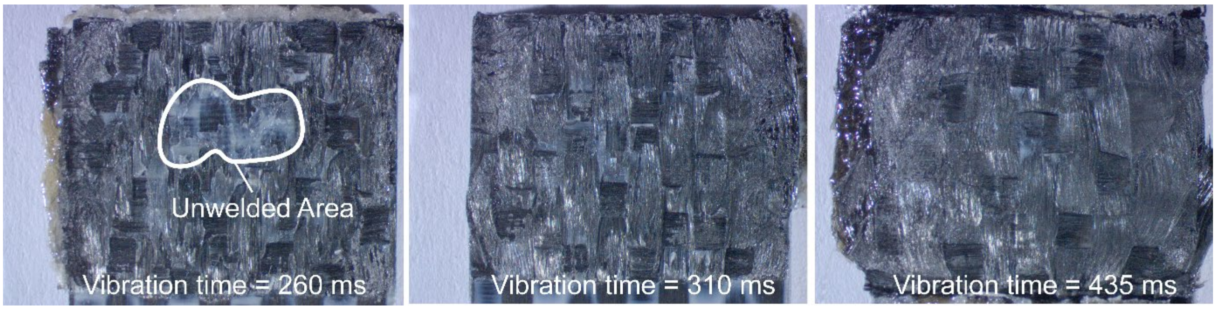

Figure 6: Representative fracture surfaces of joints obtained at (a) 260 ms (left), (b) 310 ms (middle) and (c) 435 ms (right) vibration times in Figure 4 [18].

Variation in weld application

Apart from fully welded overlaps, as seen so far, some welding processes, such as ultrasonic welding, are inherently well-suited for the production of spot-welded joints. Spot-welded joints are those in which the welded area intentionally covers only *a part* of the overlap. Spot-welded joints in polymer composites have higher affinity with mechanically fastened joints (and spot-welded joints in metals) than with adhesively bonded joints. Consequently, caution should be exercised when using SLS testing for these types of joints since it notoriously surpasses the boundaries established by the test standards.

An example of this is a number of studies in which we used a variety of testing techniques, including SLS testing, in order to compare the mechanical performance of *spot*-welded joints with that of mechanically fastened joints. Firstly, we compared the pure shear and pure peel behaviour of spot-welded and mechanically fastened joints in CF/poly-ether-etherketone (CF/PEEK) composites [6]. Secondly, we investigated the SLS behaviour of spot-welded and mechanically fastened joints in CF/PPS composites [32]. The spot-welded joints featured an approximately 10 mm-diameter round welded area and were obtained using ultrasonic welding. The mechanically fastened joints featured a titanium Hi-Lok fastener with 4.8 mm pin diameter. Spot and fastener dimensions were selected based on manufacturability and usual engineering constraints, respectively.

The pure shear and peel behaviours of welded and fastened joints were assessed through double-lap shear and pull-through tests, respectively [6]. In both types of tests, the welded joints featured a brittle behaviour as opposed to the yielding behaviour of the fastened joints (see Figure 7). Consistent with these differences, the spot-welded joints showed limited damage contrarily to the extensive damage observed in the fastened joints upon failure [6]. The maximum shear load in the welded joints was similar to the load at which onset of failure occurred in the fastened joints while the stiffness of the former roughly doubled the stiffness of the latter (Figure 7a). On the other hand, the maximum peel load in the welded joints was five to six times lower than the onset failure load in the fastened joints, stiffness values were however similar (Figure 7b).

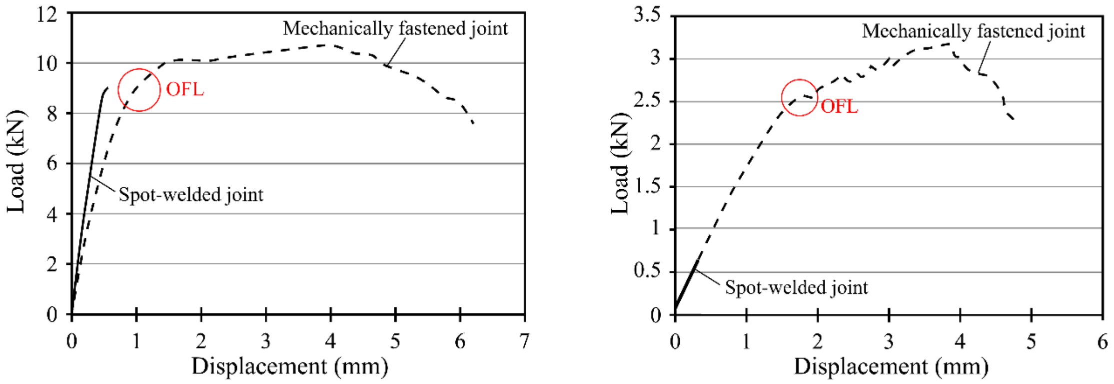

Figure 7: Representative load-displacement curves of spot-welded and mechanically fastened joints in CF/PEEK composites (5 harness satin, Toray, The Netherlands) when tested under (a) pure shear (left) and (b) pure peel (right) loading conditions. OFL: Onset of Failure Load. Reprinted with adaptations from [6] with permission from Elsevier.

Based on the results summarized in the previous paragraph and on the combination of shear and peel stresses developed in SLS tests, we expected the maximum SLS loads in spot welded joints to be markedly lower than in mechanically fastened joints. On the contrary, the results of the SLS tests showed the maximum and onset failure loads for welded and fastened joints to be comparable, 3527±239 N and 3919±78 N, respectively [32]. Figure 8 shows representative load-displacement curves of the two types of joints, featuring similar behaviours as the double-lap joints (Figure 7a). The unanticipated results from the SLS tests could be linked to the higher stiffness of the welded joints (Figure 7a and Figure 8) causing lower secondary bending and hence lower peel stresses during SLS testing [32]. Hence, using the SLS test beyond its boundaries in this particular example highlighted the sensitivity of the test results to joint stiffness thereby hindering its ability to comparatively assess joint strength.

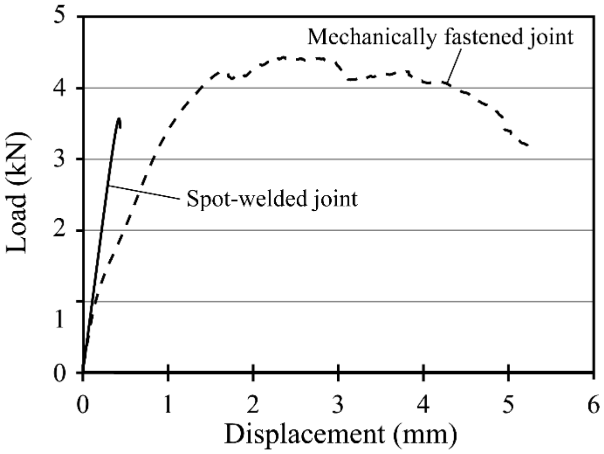

Figure 8: Representative load-displacement curves of spot-welded and mechanically fastened joints in CF/PPS composites (5 harness satin, Toray, The Netherlands) during SLS testing. Reprinted with adaptations from [32] with permission from Elsevier.

Conclusions

This paper makes use of the authors' experience on studying polymer composite welded joints to assess whether it is appropriate to apply the single-lap shear test, developed for adhesively bonded joints, to a relatively new joining process such as polymer composite welding. As main conclusion of this assessment, our answer to the question is that single-lap shear testing can be a valuable and relatively flexible tool in understanding polymer composite welded joints *provided that* the specific anatomy of the welded joints is accounted for. Hence the maximum load or apparent strength values coming out of the test are of no particular value if not accompanied by an understanding of how the mesostructure of the welded joints, the material of the adherends, any existing non-uniformities in the welded joints and the mechanics of the joints interact with the tests and their results.

References

1. Yousefpour A, Hojjati M, Immarigeon JP. Fusion bonding/welding of thermoplastic composites. J Thermoplastic Compos Mater 2004 July;17:303-41. DOI: 10.1177 /0892705704045187
2. Lionetto F., Nicolas Morillas M., Pappada S., Buccoliero G., Villegas I.F., Maffezzolli A. Hybrid welding of carbon-fiber reinforced epoxy based composites. Compos A Appl Sci Manuf 2018; 104: 32-40. DOI: 10.1016/j.compositesa.2017.10.021
3. Gardiner G. Welding thermoplastic composites. Composites World [Internet] 2018 [cited 2020 Nov20]. Available from: https://www.compositesworld.com/articles/welding-thermoplastic-composites.
4. ASTM D1002-10. Standard test method for apparent shear strength on single-lap-joint adhesively bonded metal specimens by tension loading (metal-to-metal). 2019
5. ASTM D5868. Standard test method for lap shear adhesion for fiber reinforced plastic (FRP) bonding. 2001
6. Zhao T, Palardy G, Villegas I F, Rans C, Martinez M, Benedictus R. Mechanical behaviour of thermoplastic composite spot-welded and mechanically fastened joints. Compos Part B Eng 2016; 112, 224–234. DOI: 10.1016/j.compositesb.2016.12.028
7. Dubé M, Chazerain A, Hubert P, Yousefpour A, Bersee HEN. Characterization of resistance-welded thermoplastic composite double-lap joints under static and fatigue loading. J Thermoplastic Compos Mater 2015; 28(6):762-76. DOI: 10.1177/0892705713490714
8. Reis JF, Abrahao ABM, Costa ML, Botelho EC. Assessment of the interlaminar strength of resistance-welded PEI/CF composite. Weld Int 2018;32(2):149-160. DOI: 10.1080/09507116.2017.1347329
9. Goto K, Imai K, Arai M, Ishikawa T. Shear and tensile joint strengths of carbon fibre-reinforced thermoplastics using ultrasonic welding. Compos A Appl Sci Manuf 2019 Jan; 116:126-37. DOI: https://doi.org/10.1016/j.compositesa.2018.10.032
10. Dubé M, Hubert P, Yousefpour A, Denault J. Int J Fatigue 2019; 31:719-25. DOI:10.1016/j.ijfatigue.2008.03.012
11. Harras B, Cole KC, Vu-Khanh T. Optimization of the ultrasonic welding of PEEK-carbon composites. J Reinf Plast Compos 1996 Feb;15:174-82.
12. Köhler F, Villegas IF, Dransfeld C, Herrmann A. Static ultrasonic welding of carbon fibre unidirectional thermoplastic materials and the influence of heat generation and heat transfer. J Compos Mater 2020; *in press*.
13. Holmes ST, Gillespie JW. Thermal analysis for resistance welding of large-scale thermoplastic composite joints. J Reinf Plast Compos 1993 June;12:723-36.
14. Pappada S, Salomi A, Montanaro J, Passaro A, Caruso A, Maffezzoli A. Fabrication of a thermoplastic matrix composite stiffened panel by induction welding. Aerosp Sci Technol 2015;43:314-320.
15. Senders F, van Beurden M, Palardy G, Villegas IF. Zero flow: a novel approach to continuous ultrasonic welding of CF/PPS thermoplastic composite plates. Adv Manuf: Polym Compos Sci 2016;2(3-4):83-92. DOI:10.1080/20550340.2016.1253968
16. Shi H, Villegas IF, Octeau MA, Bersee HEN, Yousefpour A. Continuous resistance welding of thermoplastic composites. Compos A Appl Sci Manuf 2015;70:16-26. DOI: 10.1016/j.compositesa.2014.12.007

17. Jongbloed B, Teuwen JJE, Palardy G., Villegas IF, Benedictus R. Continuous ultrasonic welding of thermoplastic composites: enhancing the weld uniformity by changing the energy director. J Compos Mater 2020;54(15):2023-35. DOI: 10.1177/0021998319890405
18. Jongbloed B, Teuwen JJE, Benedictus R, Villegas IF. On differences and similarities between static and continuous ultrasonic welding of thermoplastic composites. Compos B Eng 2020;203:108466. DOI: 10.1016/j.compositesb.2020.108466
19. Schijve J, Campoli G, Monaco A. Fatigue of structures and secondary bending in structural elements. Int J Fatigue 2009;31(7):1111–23. DOI: 10.1016/j.ijfatigue.2009.01.009
20. Guess TR, Allred RE, Gerstle FP. Comparison of lap shear test specimens. J Test Eval 1977; 5(3):84-93.
21. Gleich DM, van Tooren MJL, Beukers A. Analysis and evaluation of bondline thickness effects on failure load in adhesively bonded structures. J. Adhesion Sci. Technol. 2001;15(9):1091-101.
22. Villegas IF, Moser L, Yousefpour A, Mitschang P, Bersee HEN. Process and performance evaluation of ultrasonic, induction and resistance welding of advanced thermoplastic composites. J Thermoplastic Compos Mater 2012; 26(8): 1007-1024. DOI: 10.1177/0892705712456031
23. Stavrov D, Bersee HEN. Resistance welding of thermoplastic composites-an overview. Compos A Appl Sci Manuf 2005;36:39-54. DOI:10.1016/j.compositesa.2004.06.030
24. Shi H. Resistance welding of thermoplastic composites-process and performance. Delft. Delft University of Technology; 2014. DOI: 10.4233/uuid:58f16f99-afc1-4713-842e-562412583340
25. Moser L. Experimental analysis and modelling of susceptorless induction welding of high performance thermoplastic polymer composites. Kaiserslautern. Institut für Verbundwerkstoffe GmbH; 2012.
26. Shi H, Villegas IF, Bersee HEN. Strength and failure modes in thermoplastic composite resistance welded joints: effect of fibre-matrix adhesion and fibre orientation. Compos A Appl Sci Manuf 2013;55:1-10. DOI: 10.1016/j.compositesa.2013.08.008
27. Koutras N, Villegas IF, Benedictus R. Influence of temperature on strength of thermoplastic composite resistance welded joints. Compos A Appl Sci Manuf 2018;107:57-67. DOI: 10.1016/j.compositesa.2017.11.003.
28. Koutras N, Benedictus R, Villegas IF. Thermal effects on thermoplastic composites welded joints. Delft. Delft University of Technology; 2020. DOI: 10.4233/uuid:8bdf06e6-8e42-463a-af45-20a56e0e2022
29. Villegas IF. In situ monitoring of ultrasonic welding of thermoplastic composites through power and displacement data. J Thermoplastic Compos Mater 2015; 28(1): 66-85. DOI: 10.1177/0892705712475015
30. Levy A, Le Corre S, Villegas IF. Modelling of the heating phenomena in ultrasonic welding of thermoplastic composites with flat energy directors. J Mater Process Technol 2014; 214: 1361-1371. DOI:10.1016/j.jmatprotec.2014.02.009
31. Villegas IF. Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters. Compos A Appl Sci Manuf 2014;65:27-37. DOI: 10.1016/j.compositesa.2014.05.019
32. Zhao T, Rans C, Villegas IF, Benedictus R. On sequential ultrasonic spot welding as an alternative to mechanical fastening in thermoplastic composite assemblies: a study on single-column multi-row single-lap shear joints. Compos A Appl Sci Manuf 2019;120:1-11. DOI: 10.1016/j.compositesa.2019.02.013