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Design of adhesively bonded lap joints with laminated CFRP adherends: Review, challenges and new opportunities for aerospace structures

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ABSTRACT

Adhesive bonding is one of the most suitable joining technologies in terms of weight and mechanical performance for current carbon fiber reinforced polymer aircraft fuselage structures. However, traditional joint topologies such as single overlap joints induce high peel stresses, resulting in sudden failure and low joint strength when compared to metal adherends. This drawback in using carbon fiber reinforced polymer is hindering their performance and efficiency in full-scale structures where joints are essential.

The goal of this paper is to review how the joint design can help to improve the lap shear strength of composite bonded joints, to recognize the challenges that still need to be understood and to give insight into new opportunities. The focus is thereby on means to increase the matrix-dominated out-of-plane strength of the adherend in order to postpone delamination failure, as it is known to be the most prone type of failure of composite bonded joints. The paper is divided in two main parts: firstly, a review of topology-related and material-related design parameters is given and secondly, future opportunities to improve out-of-plane strength of CFRP bonded joints yet to be explored are discussed.

1. Introduction

With the increasing pressure to meet unprecedented levels of eco-efficiency, the aircraft industry aims for super lightweight structures. Towards this aim, polymer composites are replacing the conventional Aluminium as the number one material used in aircraft. With the launch of the *BOEING 787 Dreamliner* in October 2011 and the *AIRBUS A350-XWB* in January 2015, airplane fuselage structures made out of Carbon Fibre Reinforced Plastic (CFRP) were introduced in civil aviation.

However, the joining design of those fuselage structures is not following this transition. Currently, composites are being joined using bolts and rivets, a joint design mainly developed for metals. This leads to an increase in structural weight, since the areas where holes cut through the fibres and disturb the load path have thicker laminates. The mismatch between the use of new materials and traditional “metal-joining” techniques results in inefficient composite structures and gives ample room for improvement. A suitable joining method is therefore the missing puzzle piece to efficiently use composites in full-scale aircraft structures. One of the most promising joining methods in terms of weight and performance is adhesive bonding [1]. A well-designed bonded joint has the potential to be nearly as strong in terms of tensile loading as the base laminate itself.

Yet the lack of acceptance of adhesive bonding by the aviation authorities is currently limiting its application in primary aircraft structures. So far, fasteners are always included along with the bonded systems (so-called *chicken-rivets*), as a back-up in case the bond fails. There are two main reasons for this lack of acceptance. Firstly, current non-destructive testing technology is unable to detect weak bonds (i.e. interfacial contamination or weak adhesion) [2]. Secondly, in a joint topology that induces high peel stresses in the thickness direction, using CFRP adherends may result in lower ultimate joint strength than using metal adherends, since the inter- and intra-laminar strength of composites is often lower than a cohesive peel strength of an adhesive [2–5].

Nonetheless, by changing the laminate design, composite properties can be tailored to the external loading and research in this field of composites shows that certain stacking sequences can retard delamination [6–8]. Therefore, making use of the composite’s anisotropy could potentially counteract their poor out-of-plane strength, which can have a positive impact on the performance of composite adhesively bonded joints subjected to peel stresses. Nevertheless, CFRP lay-ups being used in state-of-the-art aerospace structures are still

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designed as quasi-isotropic [9]. This choice is mainly tied to the easiness of manufacturing and to composite design rules used by the industry (e.g. 10%-rule) [10], while it may not be the optimum design for a laminated adherend in the vicinity of a multi-axial load hot spot, like in a bonded joint. Furthermore, the geometry of such joint plays an important role for the predominant stress state. A Single Overlap Joint (SLJ) design, as illustrated in Fig. 1, is still being used as the most common topology for primary aircraft structures, aiming for low manufacturing complexity and costs.

The latest developments in manufacturing techniques allow for a wider choice of CFRP-layups. As an example, the fuselage and the wings of the *AIRBUS A350 XWB* are being built by Automated Fibre Placement (AFP) techniques. Furthermore, recent studies have demonstrated how a reduction of ply thickness in composite laminates enables great freedom with respect to layup design and leads to a delay in damage onset as well as enhanced ultimate load [11–13]. Those two developments mark a significant step in terms of manufacturing quality, allowing for more complex stacking sequences and joint topologies. Suddenly, a simple but structurally inefficient SLJ-design with quasi-isotropic layup can be replaced by a more advanced joint topology, such as a stepped, scarfed or slotted joint, with a non-conventional layer orientation. Tailoring the laminate design parameters can play a key role in the reduction of detrimental peel stresses in load carrying joints and can contribute to the goal of further promoting adhesive bonding for primary aircraft structures.

The goal of this paper is to review how the joint design can help to improve the lap shear strength of composite bonded joints, to recognize the challenges that still need to be understood and to give insight into new opportunities.

2. Topology

Generally, one can cluster the topology design parameters for CFRP overlap bonded joints in two categories: global and local topology. The global includes different overall joint topology, such as SLJ, Double Overlap Joints (DLJ) or scarf joints, and other general geometric features like overlap length and bond line thickness. The local joint topology includes parameters related with fillet geometry and tapering the tip of the overlap. Both points will be review and discussed hereafter.

2.1. Global topology

Various topologies for overlap-bonded joints have been studied. Fig. 2 shows a general overview of some of the topologies found in literature [3,5]. Global joint topologies can thereby be classified into two categories of either disturbed or undisturbed shapes. Disturbed, as in Fig. 2 a)-e), is thereby defined, in the context of this paper, as a joint topology with one or more offsets between the adherends, while undisturbed, as in Fig. 2 f)-i), is defined such that the adherends are aligned (no offset).

The most commonly used joint in practice is probably the SLJ, in Fig. 2 a), and the reason for this is the easiness of design and manufacturing [5]. When the SLJ is under tensile loading, the bonding area suffers shear stress. In addition, the offset between the adherends creates a secondary bending moment, which results in peel stresses at the edge of the bond line. In order to reduce the peel stress at the bond line edge, it seems necessary to avoid the offset [14,15]. In a symmetric double lap joint, Fig. 2 b), the centre adherend experiences no bending moment, but the outer adherends do, thus giving rise to tensile stresses in the adhesive layer at the unloaded overlap end, and compressive stresses at the loaded overlap end [16]. A similar concept is the use of an additional butt strap, aligning both adherends, as can be seen in Fig. 2 c). This result in a reduction of peel stresses at the end of the bond line. Adding a second butt strap on the bottom side provides full symmetry. However, the use of butt straps adds weight to the structure and interrupts the aerodynamic efficiency, both important drawbacks in aerospace structures. In the following sub-sections, a review is given on the believed to be the most relevant and promising global topologies for aerospace structures, both disturbed and undisturbed types.

2.1.1. Wavy lap joint

Researchers have constantly been working on new alternative joint designs, looking for better performances. One of these new designs is the bonded wavy lap joint presented by Zeng and Sun [17], as can be seen in Fig. 3. With this new topology, they were able to transfer the shear stress more evenly over the length of the joint than in a SLJ of the same adherend layup and thickness. For the two adherend layups studied, $[0/90/0/90]_{2s}$ and $[90/0/90/0]_{2s}$, the average lap shear strength of the wavy joint was significantly higher than that of conventional SLJs, reaching at least 100% higher average lap shear strength, σ_{LSS}, for layup $[90/0/90/0]_{2s}$ and at least 50% higher σ_{LSS} for layup $[0/90/0/90]_{2s}$ [17]. Avila and Bueno [18,19] performed experimental and numerical studies on wavy lap joints with 25 mm overlap length, 16-layer plain weave E-glass/epoxy adherends and epoxy paste adhesive. It was found an increase in maximum load of 41%, compared to a reference SLJ-design, which is believed to result from the out-of-plane compressive stresses developed near the tip of the overlaps. Generally, the wavy lap joint appears as an interesting structural optimization concept, turning out-of-plane tensile (peel) into compressive stresses. However, the quite disturbed shape of the overlap region would be a drawback for some aerospace applications such as circumferential joints of aircraft fuselage panels, where aerodynamic aspects play a crucial role. Aside from the embracing shape of the overlap, studies showed that the joint strength also depends on the chosen layup of the adherends [18].

2.1.2. Scarf and stepped joints

Scarf joints or stepped lap joints are often studied in the context of repair of composite laminates [20]. Undisturbed shapes, as in Fig. 2f) to i), avoid offset, while at the same time no extra weight is added. This comes with the cost of a reduced cross-section at the joint area and a geometrically more complex design. A stepped joint is basically a single overlap where the adherends loose half of their initial thickness for the length of the overlap joint. It can result in a decrease of peel stress [21]. For a smoother stress distribution, it makes sense to implement several steps. The ultimate level of this idea leads to the scarf joint, where a straight overlap occurs under an angle. Through this optimization, the strength of the joints can be increased by 90% to 150% compared to a reference SLJ-design [21]. Wu et al [22] compared the damage tolerance of scarf and stepped-lap joints under quasi-static loading, using FEA. Thereby the damage was represented

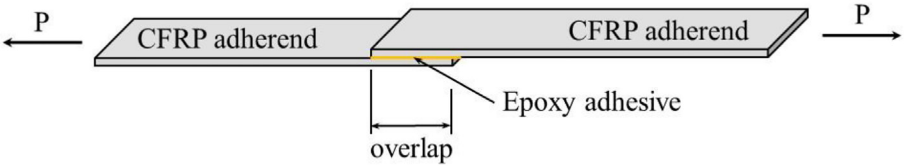

Fig. 1. Schematic illustration of a SLJ under tensile loading.

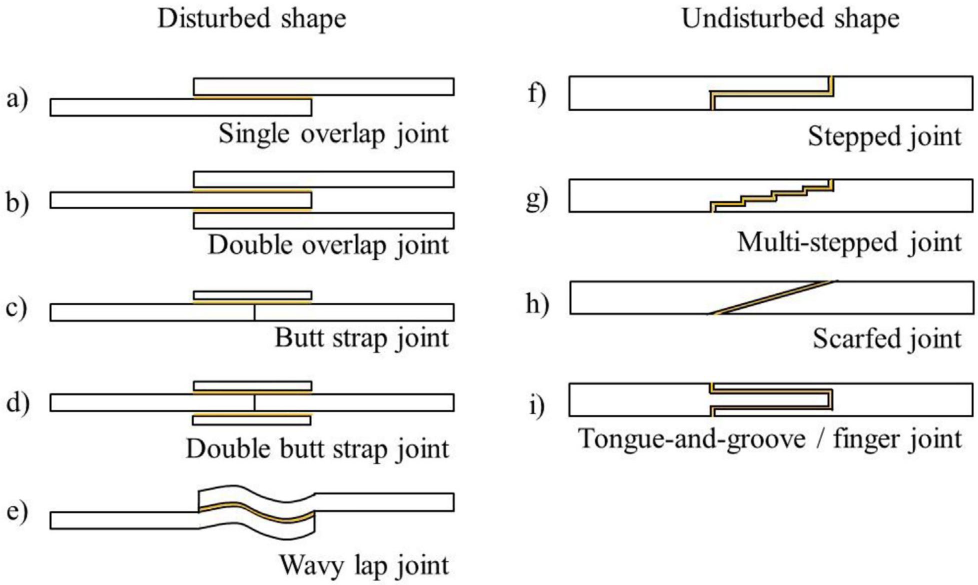

Fig. 2. Global joint topologies.

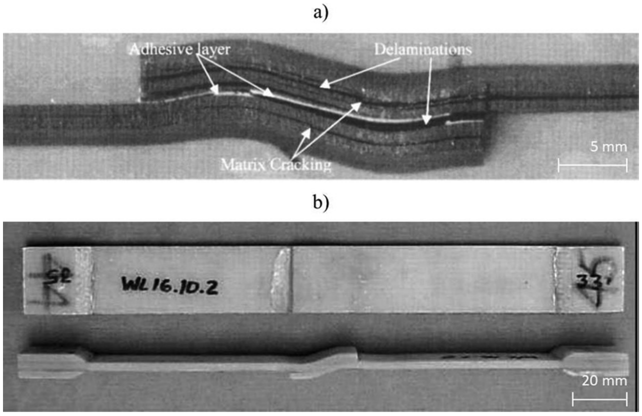

Fig. 3. Wavy lap joint, a) cross-section of overlap area of Zeng and Sun [17], b) wavy lap joint design of Avila and Bueno [18] in top and side view.

by an artificial interface discontinuity embedded in the bond line between composite adherents. The results showed that the stepped lap joint exhibited better damage tolerance than the scarf joint, assuming the chosen adhesive holds a linear elastic material response. The scarf joint topology can overall provide a smoother stress distribution, but remains challenging to manufacture with CFRP-adherends. Therefore, the stepped joint would be a better candidate for CFRP-bonded joints, especially since multiple steps can be created throughout the lamination process.

2.1.3. Finger joints

Compared to the traditional SLJ-design, finger joints (FJ) are a promising alternative to increase joint strength due to a more gradual load transfer to the composite adherends as they lead to lower peel stresses [3,23]. FJs, also referred as tongue-and-groove (TG) joints, are commonly used in the wood industry, where slots are created by profiling the bonding surface with a rotational milling tool. In CFRP-adherends, FJ-topologies were mostly studied for laminates with an adherend thickness above 5 mm [24], such as glass fibre reinforced polymer (GFRP) and composite sandwich structures, to connect, for example, components of wind turbine blades. Sayer et al. [24] investigated the effect of FJ-topologies on the fatigue life in bonded wind turbine blades. The connection of the shear web to the spar caps of a wind turbine blade was tested experimentally and a specific FJ-topology (Henkel UpWind Beam) was chosen to increase fatigue life over a SLJ design. The use of particular cover laminates at the bond line between spar cap and web resulted in up to 50 times higher joint strength under fatigue loading, compared to a reference beam design without cover laminates. Another method to create a FJ-topology is the so-called ply interleaving technique of single plies. This means two adherends with overlapping fingers are laminated together, letting the plies of left and right adherend interleave each other in the joint area. This method is mainly used to join adherends with different materials, such as CFRP/GFRP or CFRP/Titanium, in one co-curing step [25]. Ahamed et al. [26] developed a ply-interleaving technique for joining quasi-isotropic CFRP/GFRP adherends. The strength of both interleaved-scarf and finger joints were 75% of the un-notched GFRP laminate strength, provided the distance between 0 and 0 ply terminations exceed a certain threshold value, approximately 6 mm. It was concluded that joint failure is caused by delamination at the location where plies terminate, as well as by transverse matrix cracking within off-axis plies. Dvorak et al. [27,28] investigated adhesive FJs for woven E-glass/vinyl-ester composite laminated plates to steel or other composite plates, with applications in ship structures. The study was focused on the stress distributions inside the FJs. As in other joint configurations, they found peel stress concentrations at the tips of the bonded area that depend on the local topology of the adherends. They also found a significant advantage of FJ- over SLJ topologies: Peel stresses inside the joint region remained independent from the adherend thickness. Canyurt et al. [29] used a genetic algorithm tensile strength estimation model (GATSEM) to estimate the strength of adhesively bonded FJs, considering overlap length (OL), bond line thickness (BLT), pre-stress near the free edges of the bond line and material type of joining parts. With this model, they were able to optimize the overlap length and bond line thickness for maximum fatigue life. Compared to an initial FJ-configuration with reference overlap length and bond line thickness, the fatigue life could be increased by 219% for CFRP/CFRP, by 182% for steel/CFRP and by 195% for Al/CFRP FJ-configurations.

Generally, the finger joint, as a type of a multi-stepped lap joint, seems a promising candidate for overall joint strength enhancement. Nevertheless, Ahamed et al. [26] could demonstrate the technical fea-

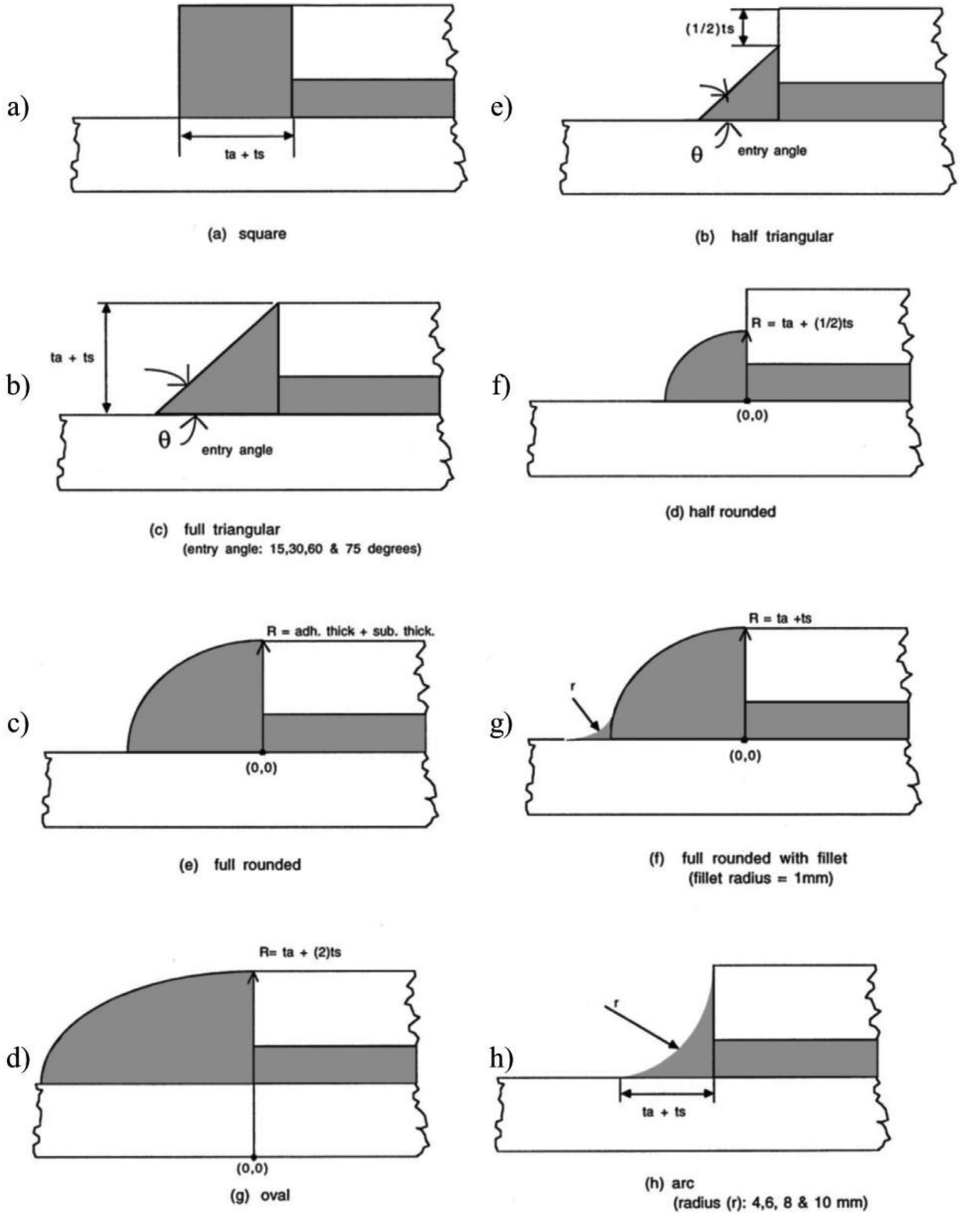

Fig. 4. Spew fillet designs to reduce stress concentrations at the overlap edge, after Lang and Mallick [36]

sibility of very narrow finger slots with their ply interleaving method, at least in a co-curing step. Kupski et al. [30] recently conducted a comparison study between single overlap and overlap stacking. It was found that, a topology with 2 fingers and layup $[90/0]_{4s}$, which fails entirely inside the adherend, provides the lowest peak shear and peel stress and the highest load at damage initiation. It is however outperformed in maximum load by a single lap joint topology with layup $[0/90]_{4s}$, with mostly cohesive failure. Different trends at damage initiation and at maximum load under quasi-static tensile loading are believed to result from how the damage propagates inside the joint. Unlike in SLJs, the most dominant stress component for damage in FJs, is the in-plane tensile stress at the butt joint region, rather than the peak peel or shear stress level at the overlap region. Manufacturing imperfections due to resin flow-out, layup undulations and ply drops inside the adherend laminates were identified in the FJ-topologies, when compared to the SLJ-topologies. Based on the discrepancy between the trends at damage initiation and at maximum load, it is believed that damage evolution may be affected by those manufacturing imperfections.

2.2. Local topology

Local joint topology parameters have shown to have a significant influence on the overall joint strength, such as in the areas of stress concentration. Tapering the adherend edges and/or adding a spew fillet at the edges of the adhesive cam significantly reduce the stress singularities [31]. Shaping locally the adherend and/or adhesive edges can provide a smoother transition in the joint geometry, reducing the stress concentration. Work performed in metal-to-composite DLJs show that the combination of inside taper and spew fillet could reduce the stresses by up to 50% in comparison with the basic design, resulting in an increase in strength of up to 50% [31–35]. However, if thermal loads become significant, such as at low temperatures, inside taper and spew fillet decrease the overall strength. For composite SLJ, shaping the adhesive fillet and chamfering the composite adherend also reduces the stress concentrations at the substrate, which can result in an increase up to 30% in strength [36–40]. Fig. 4 presents an overview of spew fillet designs after Lang and Mallick [36].

Nevertheless, it is also agreed in literature that the strength increase based on local topology changes, highly depends on the materials properties (adhesive and adherend) and load conditions (if thermal loads are significant), so there is no generalized rule [40]. Schollerer et al. [41] investigated different state-of-the-art concepts to reduce the peel stress at the bond line tip of SLJs, by chamfering the adherends, by using different adhesive spew fillet geometries, by using a mixed adhesive joint, among others - see Fig. 5.

These designs were compared to a novel local adherend surface toughening concept, using a thermoplastic Polyvinylidenfluorid (PVDF) layer, illustrated in the following Fig. 6. It was found that the local surface toughening concept was more efficient in increasing overall joint strength than any of the studied the state-of-the-art concepts. The joint strength for the surface toughening specimens could be increased by 84% compared to the reference SLJ design, outperforming all other concepts in Fig. 5. However, this result is not exactly in line with other studies on local topology optimization, and it is, once again, highly depended of the adhesive bond line length, the adhesive thickness, and on the length of the surface toughening patch. Generally, local topology optimization through taper and spew fillet shaping appears to be an effective way to reduce particularly the high peak peel stresses at the bond line tips, but at the same time, it has to be in line with a well-designed global joint topology.

3. Material

The materials present at the joint have an influence on its overall strength. They can be divided into adhesive materials and adherend materials. A substantial amount of work was published in both fields. Section 3.1 gives an overview of the adhesive parameters that can be tailored to improve the strength of the joint, while Section 3.2 focusses on the adherend parameters. In the later, CFRP-adherends themselves consist of laminated plies, which can be tailored, for example in terms of fiber orientation, ply thickness or stacking sequence. These laminate specific design parameters are not extensively studied in literature so far. It is believed to be a good opportunity, and is thus discussed in more detail.

3.1. Adhesive material

It is important to distinguish between adhesive strength and joint strength. The joint strength may not increase if a stronger adhesive is used. A strong and stiff adhesive will withstand higher stresses but its high stiffness will rapidly increase stress concentrations at the edges. A flexible adhesive will distribute more evenly the stresses along the bonded area, but it is generally less strong and will withstand lower stresses before failure [42]. To overcome this bottleneck, a large amount of work has been published on varying the material properties of the adhesive along the overlap, either by placing different adhesive at the edges and at the center of the overlap (mixed or dual adhesive) or by grading the adhesive properties along the overlap.

3.1.1. Mixed adhesives

Da Silva et al. [43,44] performed experimental lap shear tests with the same brittle adhesive for the center part but three different ductile adhesives for the tip region of the overlap. The mixed-adhesive technique was found to give up to 221% increase in joint strength compared to a ductile adhesive alone, and up to 212% increase in joint strength compared to a brittle adhesive alone. It was concluded that, for a mixed adhesive joint to be stronger than the brittle and the duc-

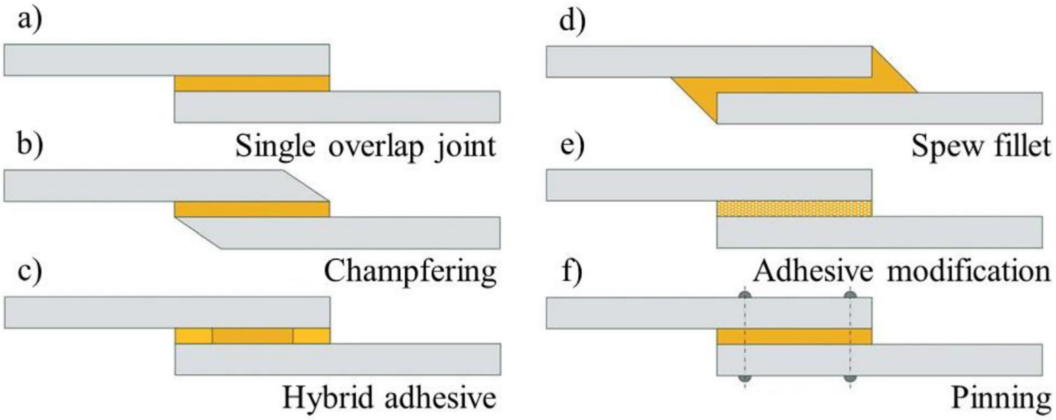

Fig. 5. State-of-the-art joint designs [41].

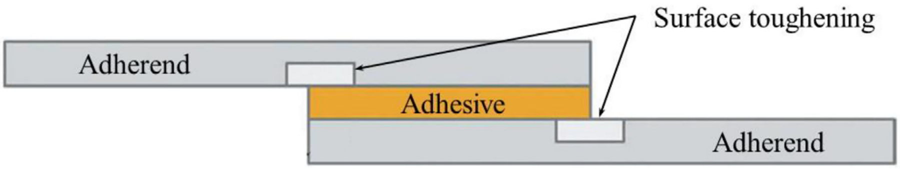

Fig. 6. Surface toughening method after Schollerer et al [41]

tile adhesive used individually, the load carried by the brittle adhesive must be higher than that carried by the ductile adhesive [44]. In the work on surface toughening, mentioned in the previous section, Schollerer et al. [41], also studied the concept of a mixed adhesive in order to decrease stress peaks on the tip of the bond line, see Fig. 5c). A reduction of 30% in shear stress and 60% in peel stress was numerically demonstrated at the bond line tip, compared to a SLJ reference design with one continuous adhesive. However, this promising stress analysis could not be further validated through experimental data. Loebel et al. [45] presented a hybrid bond line concept for CFRP bonded joints, implementing a rather ductile thermoplastic adhesive towards both tips and a brittle epoxy adhesive in the center of the bond line of a SLJ, so that a physical barrier for growing disbonds was obtained, providing a fail-safe design, see Fig. 7. For this design, it was needed to combine the two different joining techniques of adhesive bonding and thermoplastic welding. The study demonstrates that manufacturing complexity, in the form of two different joining methods can be overcome.

Da Silva and Adams [46] proposed a numerical FEA on strength predictions for DLJs, used over a wide temperature range by the combination of two adhesives, one for strength at high-temperatures and one for strength at low-temperatures. Following the mixed modulus concept described by Hart-Smith [47], a brittle adhesive with high modulus in the middle of the joint retains the strength and transfers the entire load at high-temperatures, while a ductile adhesive at the ends of the joint is the load-bearing adhesive at low-temperatures. Fig. 8 summarizes the results of the study. The legend entries Supreme 10HT, Redux 326 and MAJ3 refer to the names of different adhesive systems, with Redux 326 being the stiff and brittle high-temperature adhesive and Supreme 10HT being the ductile low-temperature adhesive. A mixed adhesive joint (MAJ3) is the third of several functionally graded combinations of both systems, that were studied. As can been seen from Fig. 8, for a joint with dissimilar adherends, the combination of two adhesives, as MAJ3, was found to give a higher load capacity over the full temperature range than the use of a high-temperature adhesive alone.

Neves et al. [48] extended the previous work with analytical models. Over the entire overlap length, adhesive shear and peel stress distributions of the analytical model were in very close agreement with the previous FEA developed by da Silva and Adams [46].

3.1.2. Functionally graded adhesives

Adhesives with functionally graded material properties are being considered for use in adhesively bonded joints to reduce the peel stress concentrations located near adherend discontinuities [49]. Durodola [50] reviewed a wide range of theoretical and experimental work on the use of functionally graded adhesive bonding from the 1960s to date. Studies generally agree on the conclusions that, strength of bonded joints can be significantly increased with functionally graded adhesive, compared to a constant modulus adhesive. In particular along the bond line at mid-thickness, peel stress is more sensitive than shear stress to changes in adhesive tensile modulus grading. Variable modulus adhesives were studied by Fitton and Broughton [51] as an approach to optimize joint strength. In agreement with previous literature [43–48], it was concluded that bond lines with variable modulus in the adhesive could reduce stress concentrations and consequently increase joint strength. The variable modulus of the adhesive also changed the failure mode, from interlaminar failure inside the adherend in the case of high modulus adhesive to cohesive failure for a variable modulus bond line. Stein et al. [52] proposed a closed form analytical solution for stress distribution of functionally graded adhesive lap joints with laminated adherends of any joint configuration. It was identified an effect of locally incorrect stress results at the very ends of the overlap, occurring within their employed framework. Interestingly, it was concluded that, for design studies or widely used nonlocal failure criteria, this drawback was shown to be of minor importance.

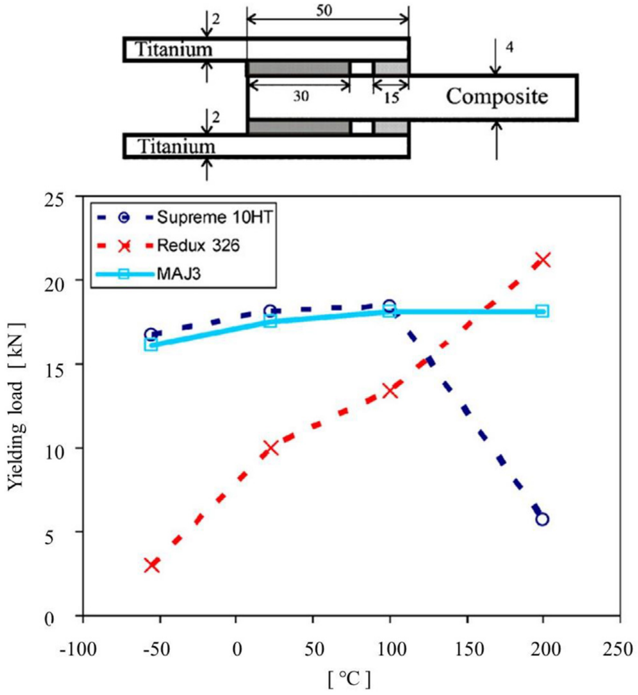

Fig. 8. Yielding load of functionally graded CFRP-Titanium DLJs over a wide range of temperature [46].

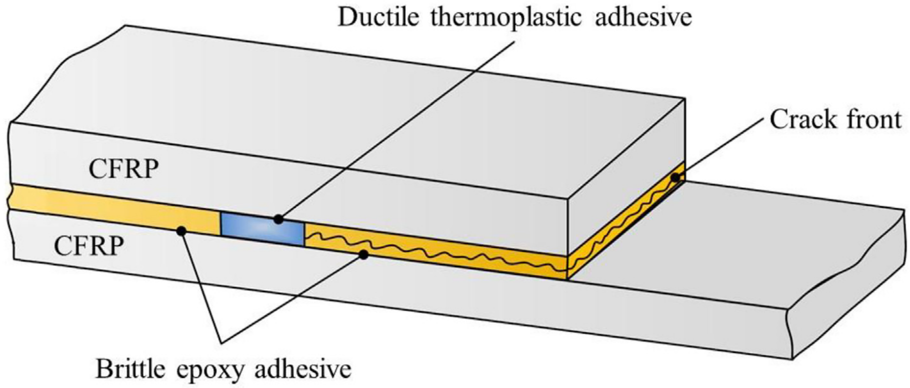

Fig. 7. Hybrid thermoplastic-thermoset bond line concept for CFRP-SLJs [45].

Overall, the concept of mixed and functionally graded adhesives appears to be ideal to disseminate local peel stress concentrations around the tip of the overlap, or if joints are exposed over a wide range of temperature or for joints with dissimilar adherend materials or bending stiffnesses. A dual adhesive, same as the tapered spew fillet, could therefore be combined with other global topology concepts, like a finger joint, in order to achieve higher joint strength than with each of these concepts individually.

3.2. Adherend material

3.2.1. Adherend bending stiffness

Ganesh and Choo [53] have varied the braiding angle of composite materials to vary the adherend elastic modulus along the overlap length. Numerical simulations show a decrease of 20% in the peak shear stress at mid-thickness of the adhesive layer, when using a variation of braiding angle from 10° to 35° in comparison with the reference joint with constant braiding angle of 10°. Boss et al. [54] found that the combination of this technique with local topology changes, such as tapering the adherends, can further decrease the peak shear stress by another 20%. Finally, it was pointed out that, modulus grading of adherends is simpler to implement in terms of manufacturing than geometrical grading through tapering.

3.2.2. Stacking sequence and layup variation

Another way to modify the adherend stiffness or overlap properties in composite adherends is to tailor the laminate stacking sequence. Research in the field of composites shows that certain stacking sequences can retard delamination. Therefore, making use of the composite's anisotropy could potentially counteract their poor out-of-plane strength, which can have a positive impact on the performance of composite adhesively bonded joints subject to peel stresses. However, the few publications found on this topic give contradictory results: The stress analysis of Renton and Vinson [55] and Aydin [56], showed that 0° plies close to the bond line give smother stress distribution both at the adherends and at the adhesives. Nevertheless, tests performed by Purimpat [57] showed that larger angles close to the bond line result in a more complex crack path and increase the final joint strength up to 30%. Similar trends were found under fatigue loading, in which a 45° angle close to the bond line increased significantly the crack propagation resistance [58,59]. Finally, Ozel [60] showed that by only varying the composite layup, the lap shear strength can vary up to 120%. Thus, there is a clear potential to improve strength of the SLJ by tailoring the composite adherend properties.

Kupski et al. [61] recently studied the composite layup effect on the failure mechanism of single lap bonded joints. In this study, a clear distinction is given between the influence of adherend layup on the first failure and final failure of the bonded joint. It was shown that, increasing the adherend bending stiffness postpones damage initiation but not final failure. Instead, the ultimate load is influenced by how the damage progresses inside the joint. It was shown that, the failure mode is highly influenced by the orientation of the interface lamina in contact with the adhesive, such that, a 0° interface ply causes failure within the bond line, while a 90° interface ply causes failure inside the composite adherend. The study concluded that, the adherend layup should be optimized for bending stiffness until first ply failure. Beyond damage initiation, the stacking sequence influences tensile strength up to final failure, if it provides complex crack paths inside the composite adherend. Finally, it could be concluded that a quasi-isotropic layup with main industrial manufacturing may not be the best choice in terms of tensile joint strength.

3.2.3. Ply thickness

Thin plies are currently among the most promising approaches to improve the performance of CFRPs due to their ability to enhance the off-axis performance of composites and postpone delamination. With the development of the fiber tow spreading technology, it is nowadays possible to produce laminates with a very thin single ply thickness, meaning from conventional size (>100 μm) down to about 20 μm [13]. Significant research was carried out to evaluate the mechanical performance of thin plies in comparison with conventional composites. Camanho at al. [11] experimentally demonstrated that a decrease in ply thickness would lead to a delay of matrix cracking and delamination growth and would therefore enhance the mechanical performance of the composite laminate in their off-axis and out-of-plane directions. Sihn et al. [12] published the first experimental study of composite thin ply laminates in 2007. Uniaxial tensile tests under static and fatigue loading were carried out on unnotched and open-hole (OHT) specimens. Tests on impact and compression strength after impact (CAI) were also conducted. By analysing stress–strain curves, and by applying several measurement techniques, such as Acoustic Emission (AE), X-ray photography and ultrasonic C-scanning, they observed that micro-cracking, delamination and splitting damage were suppressed in thin ply laminates under static, fatigue and impact loadings. Yokozeki et al. [62] performed similar experimental studies to prove that the decrease of ply thickness would have an effect on strength and damage resistance of the laminates. The results showed superior characteristics of thin ply laminates on static tension, tension–tension in fatigue, on no hole compression strength (NHC), open hole compression strength (OHC) and CAI tests. About 10% increase in OHC and CAI strength was measured with decreasing the ply thickness from 145 g/m^2 to 75 g/m^2. In addition, a decrease in damage accumulation was found for thin plies in uniaxial tensile tests using AE measurement techniques. Arteiro et al. [63] developed a micro-mechanical finite element (FE) model of a composite sub-laminate, in order to accurately represent the micro-mechanical response of composite laminates with thin plies. The model consisted of a representative volume element of a 90° ply in between two homogenised $\pm\theta°$ plies. The theory of in-situ strength, presented earlier by Camanho et al. [11], was applied to demonstrate that a decrease in ply thickness can be correlated to an in-situ effect, characterised by a reduction in the applied stress that was needed to extend a transverse crack along the thickness of the ply when the ply thickness increases. Furthermore, the in-situ effect was identified to play an important role on the delay of other matrix-dominated failure mechanisms [63]. Amacher et al. [13] followed the work of Yokozeki et al. [62] using the same approach of experimental characterization and modelling of size effects. The results agreed very well with previous research of Sihn et al. [12], showing that thin ply composites exhibit a significant delay in damage initiation in comparison with conventional laminates. By using different ply thicknesses, ranging from 30 g/m^2 to 300 g/m^2 in quasi-isotropic (QI) tensile tests, quasi-brittle failure was identified in the thin plies instead of extensive delamination and transverse cracking patterns in thick plies. Arteiro et al. [63] recently published a comprehensive review on thin ply polymer composite materials. It was concluded that thin plies improve the in-plane matrix related allowable, but can also enhance residual strength and damage tolerance. Moreover, the increased design flexibility allows for multifunctional optimisation with great potential regarding weight and cost reduction [64]. Therefore, the thin plies concept is a promising candidate to help increasing joint strength in the challenge of this thesis.

After repeatedly demonstrating their effect in composite laminates, thin plies were introduced to CFRP bonded joints by Kupski et al. [65]. Single lap bonded joints with three different ply thicknesses of 200 μm, 100 μm and 50 μm were tested. Experimental results showed an increase of 16% in the lap shear strength and an increase of 21% in the strain energy when using the 50 μm instead of 200 μm ply thicknesses. Acoustic Emission measurements showed that the damage initiation is postponed up to a 47% higher load when using 50 μm instead of 200 μm ply thicknesses. Moreover, the total amount of acoustic energy released from initiation up to final failure was significantly less with thin plies. A failure analysis of the numerical results up to damage initiation indicated that with decreasing ply thickness, the damage onset inside the composite is postponed to higher loads and moves away from the adhesive interface towards the mid-thickness of the adherend.

Despite the overall impromevent by reducing the ply thickness, one cannot help but notice that the increase in the damage onset (47%) is much more promising than in the final strength (16%). Which means that using thin plies postpones damage onset but decreases the overall damage tolerance of the joint, i.e., the damage propagation life is somehow shorter. Recent studies reported in Cugnoni et al. [66] tackled exactly this limitation of thin plies. They evaluated eight different formulations of thin ply composites ranging from low modulus to high modulus carbon fibres through compression strength after impact (CAI) and open hole tensile (OHT) tests. They showed that, by adding a thermoplastic interlayer toughening component, an increase in damage resistance in the thin plies could be achieved.

3.2.4. Adherend interface

Bisagni et al. [67] carried out experimental studies to investigate the behaviour of bonded CFRP joints with through-thickness local reinforcement. Spiked thin metal sheets, were inserted as local interlaminar reinforcement, see Fig. 9, which enable a significant delay in damage progression under cyclic loading, when compared to pristine joints.

Shang et al. [68] worked on improving the resistance to delamination of composite adhesive joints by using a novel CFRP laminate with a reinforced high toughness resin on the bond line surface. Results showed an increase of 22% in average lap shear strength, compared SLJs with non-toughened resin on the surface. They observed how the failure mode changed from delamination inside the adherends in case of the non-toughened to cohesive failure in the adhesive in case of the surface-toughened adherends.

4. Hierarchical structures in bonded joints as new opportunity

Tailoring fiber direction, decreasing ply thickness or interleaving plies, as proposed in previous literature, are effective ways to improve the out-of-plane strength of a CFRP-laminate. A step further is the idea of hierarchical structured laminates. Hereafter, a few of those are presented which are believed to be the most promising new opportunities to improve joint strength. Pascoe et al. [69] inserted interlocked thin ply reinforcement units between laminae and found that mode-I fracture toughness was increased by 78%, while mode II fracture toughness was not affected, as illustrated in Fig. 10.

Minakuchi [70,71] introduced continuous fibers in the adhesive layer, so called “x-type arrester”, providing a fiber bridging effect and suppressing the crack propagation. This concept is illustrated in Fig. 11.

Ramirez et al. [72] interleaved nonwoven thermoplastic-veils within CFRP-laminates. Results show that in modes I and II the interlaminar fracture toughness (IFT) increases with the areal density of the veil up to a plateau and at a given areal density. The mode-I IFT is greater for thin fibres than for thicker fibres. Haese et al. [73,74] mimicked the crossed-lamellar microstructure of a sea-shell, to reproduce the biological toughening mechanisms, tunnel cracking, crack deflection and debonding, within a CFRP-laminate, as shown in Fig. 12. Results demonstrate that this bio-inspired hierarchical structure can be loaded up to record large curvatures (in comparison with other CFRPs and hybrid CFRPs) while retaining its structural integrity and dissipating energy under stable conditions [73]. A bonded joint would greatly benefit from this design. The compliance introduced by large curvatures could decrease the peel stresses at the tips of the overlaps.

Other interesting design concepts for bonded joints are hierarchical structures inside the bonding interface. Budzik et al. [75,76] created distinct bond line discontinuities that reduce the interfacial crack growth at the bonding interface. Carducci et al. [77] developed a film-casting technique to deposit 13 μm thin layers of polylactic acid (PLA) on the interface between carbon/epoxy prepreg plies. By doing so, they achieved to increase by 80% in mode-I and by 12% in mode-II fracture toughness in the interface.

One of the latest trends in 3D composite design is the use of aligned carbon nanotubes, graphene layers or non-woven nano-veils in the interface between laminated plies. Kalfon-Cohen et al. [78,79] realized a hierarchical architecture termed ‘nanostitching’ by aligning carbon nanotubes and using them as interlaminar reinforcement of thin ply unidirectional CFRP-prepregs. They found an increase in interlaminar fracture toughness and in-plane strengths. FE-predictions of damage progression highlighted the complementary nature of positive thin ply and nanostitching effects that are consistent with a 15% improvement in modes I and II interlaminar fracture toughness due to the aligned carbon nanotubes at the thin ply interfaces. More work was conducted on the development of nanofibrous interlayer toughening to increase mode-I fracture toughness, and therefore delamination resistance [80–90]. These studies are good opportunities for composite bonded joints yet to be explored, because an increase in interlaminar fracture toughness would result in increased damage resistance of the joint, subjected to high peel and shear stresses.

5. Combined design approach

Shang et al. [91] recently reviewed various techniques to reduce peel stresses inside laminated adherends. They concluded that global design parameters, such as overlap length, bond line thickness or fillet design may have the most significant effect on the lap shear strength. Therefore, it is expected that a change in global joint topology, such as an FJ-design with interleaved plies, would lead to higher increase in lap shear strength than a local change in fiber orientation and ply thickness.

When comparing the three methods in previous work of the authors which tackle global joint topology [30], composite layup effect [61], and ply thickness [65], the question can be raised, how much the load at damage initiation increases due to a change in each of the

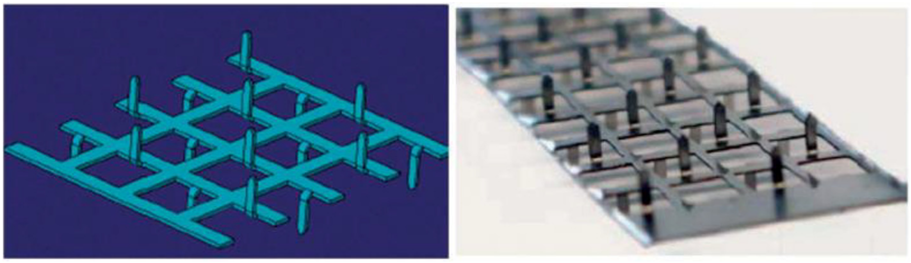

Fig. 9. A sketch and a photograph of the spiked thin metal sheets inserts [67]

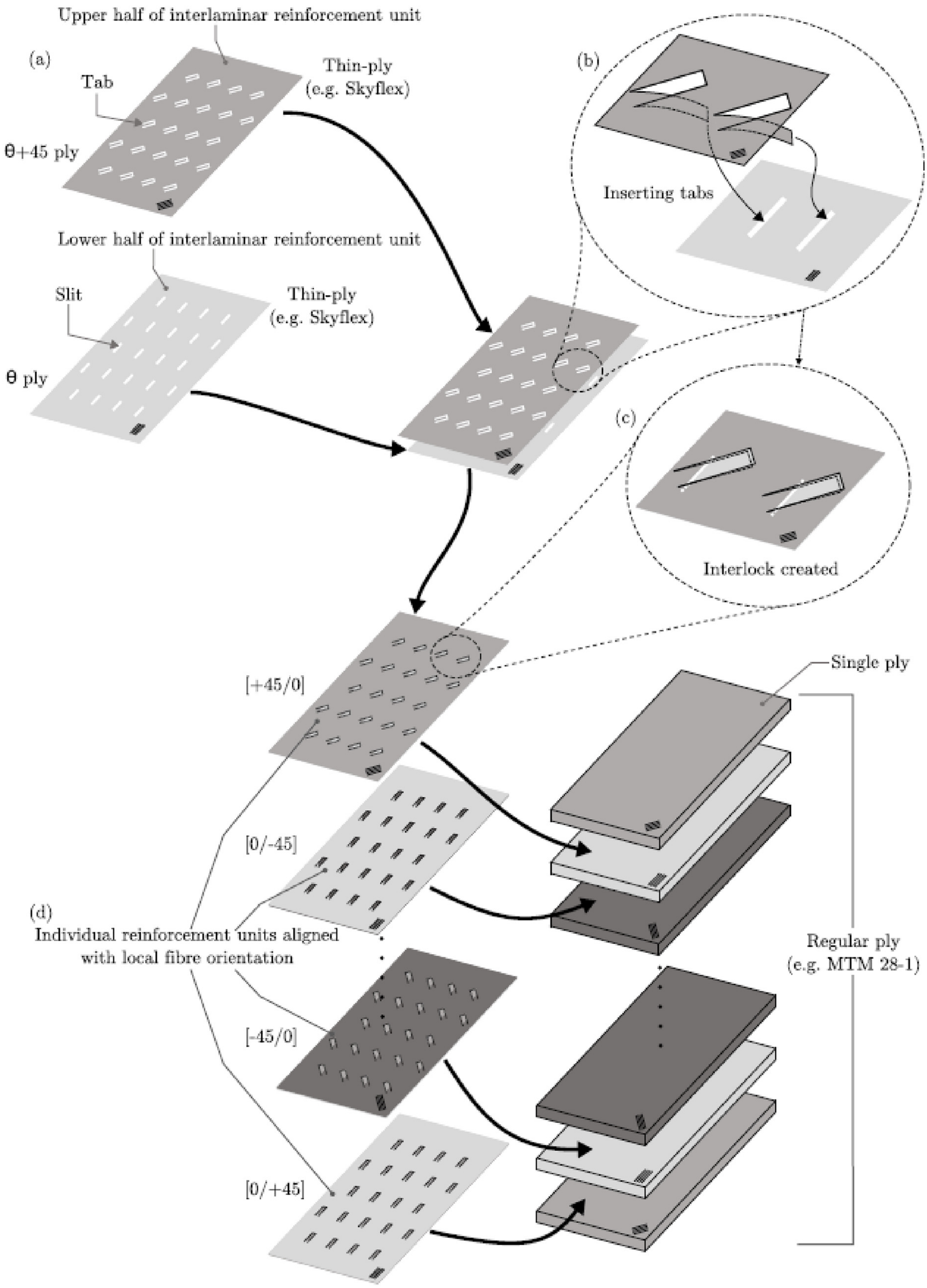

Fig. 10. Schematic illustration of the reinforcement concept, showing: (a) the two halves of a reinforcement unit, (b) insertion of the tabs, (c) an interlocked reinforcement unit, and (d) insertion of reinforcement units in a composite laminate [69]

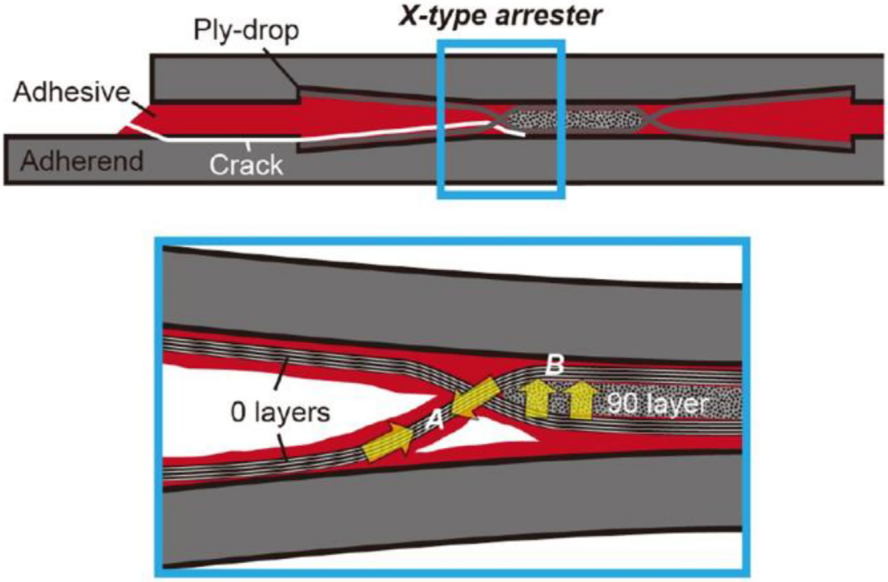

Fig. 11. X-type arrester after Minakuchi et al. [70,71]

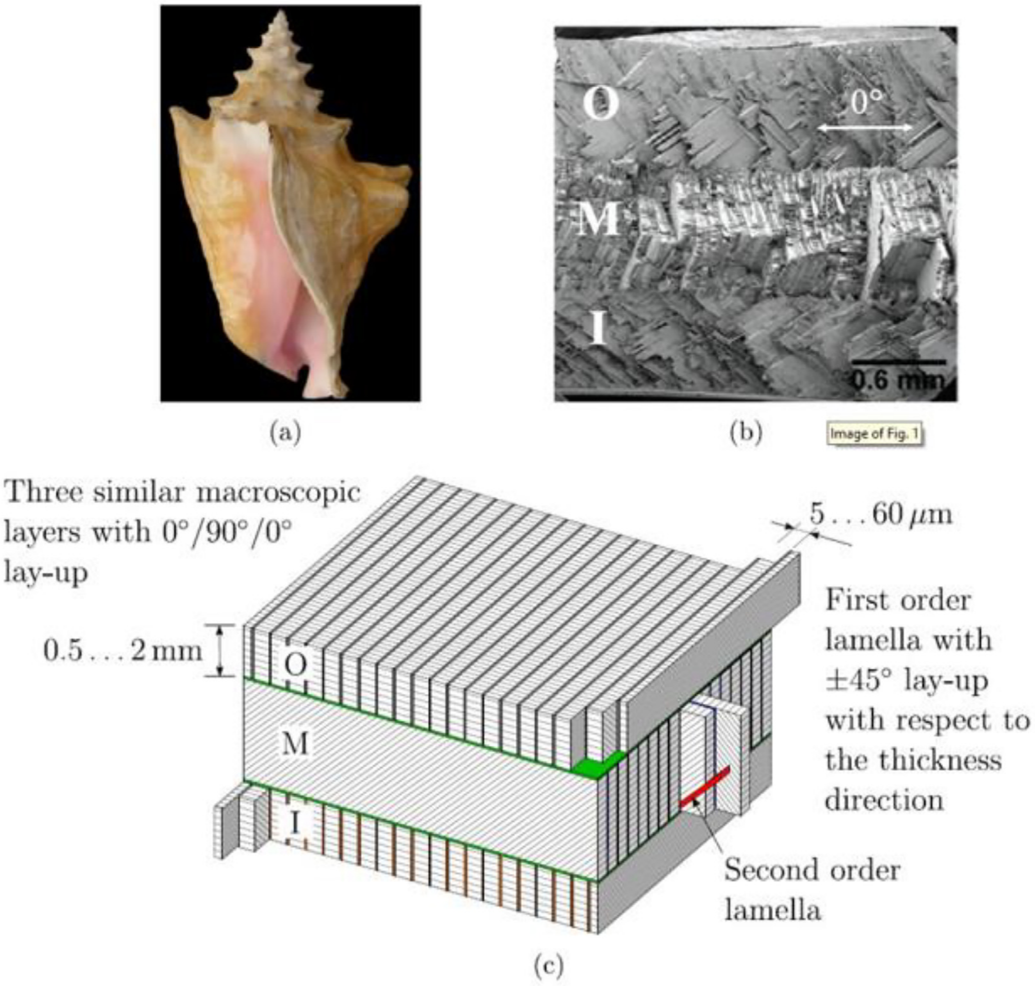

Fig. 12. (a) Strombus gigas shell (Zell); (b) fracture surface of the shell showing a crossed-lamellar microstructure (adapted with permission from Su et al., 2004. Copyright 2004 American Chemical Society.); (c) schematic illustration of the microstructure (not to scale) [73]

parameters. From experimental AE-results, a change in layup increases the load at damage initiation by 35% from 2.5 kN in case of $[45/90/-45/0]_{2s}$ to 3.4 kN in case of $[0/45/90/-45]_{2s}$ [61]. In comparison, a reduction of ply thickness provides up to 49% increase of load at damage initiation, from 11.0 kN in case of 200 μm to 16.4 kN in case of 50 μm ply thickness [65]. Finally, a FJ-topology with 2 fingers and layup $[90/0]_{4s}$ indicates 58% higher load at damage initiation (4.78 kN), compared to a SLJ-topology with the same bonding area and layup (3.03 kN) [30]. The change in topology, as a global parameter, is apparently more effective than a change of laminate specific parameters, stacking sequence and ply thickness. This result would be in agreement with the work of Shang et al. [91], who compared different techniques to enhance joint efficiency by considering the increase on average lap shear strength and the manufacturing difficulty associated with each technique. However, those numbers are in a close range and it is important to keep in mind that different studies use different prepregs and adhesives, which makes them difficult to compare. A fair comparison would therefore require a study on the effect of different laminate parameters, with at least a fixed material set, if available.

The comparison of different techniques to improve joint strength imposes the idea of a combined approach: For instance, a 2-finger joint from interlayer-toughened prepreg material, with optimized fiber orientation and ply thickness in the bond line region, providing multiple techniques to enhance joint strength either towards damage initiation, or damage resistance, or maybe to both. As Boss et al. [54] stated, a combination of increasing bending stiffness through higher in-plane longitudinal modulus and geometrical grading by use of taper, for example, would provide an overall better joint strength. The idea of combining different design features in one joint stands however in contradiction to the need for simple and robust solutions that industry entails. Furthermore, one could conclude that different out-of-plane reinforcement techniques could impair each other. Such studies are currently lacking in literature and could bring important knowledge for implementation in optimized aerospace structures.

6. Concluding remarks

This paper reflects on the topics investigated in literature to improve the joint strength of a composite bonded joint for aerospace applications.

While some parameters, such as, overlap length and adhesive thickness, are studied for several decades, others like functionally graded adhesives were more recently discovered. Particularly those concepts of increasing out-of-plane properties, which are related to the laminate specific parameters, such as fiber orientation, ply thickness and ply interleaving, are not yet well understood and represent a great potential. On this topic, the following can be concluded from the literature:

- On the fiber orientation, there were different studies conducted with non-conclusive results. The failure mode is highly influenced by the orientation of the interface lamina in contact with the adhesive, such that, a 0° interface ply causes failure within the bond line, while a 90° interface ply causes failure inside the composite adherend. Increasing the adherend bending stiffness postpones damage initiation but not final failure. Instead, the ultimate load is influenced by how the damage progresses inside the joint. Therefore, the adherend layup should be optimized for bending stiffness until first-ply failure. Beyond damage initiation, the stacking sequence influences tensile strength up to final failure, if it provides complex crack paths inside the composite adherend and it can be concluded that a quasi-isotropic layup may not be the best choice in terms of tensile joint strength.
- The beneficial effect of thin plies was so far mostly demonstrated on CFRPs alone. The one study performed on bonded joints shows that, decreasing the ply thickness of a laminated adherend increases the maximum load and delays damage initiation of the joint, however the damage progression until final failure is more sudden.

Other recent techniques, such as mixed and functionally graded adhesive or interlayer toughening demand various specific materials and high manufacturing tolerances. The following challenges have been identified from the literature:

- Global topology change inspired by the ply interleaving technique, such as in Finger Joints, has a great potential to reduce peak peel and shear stresses but could so far mostly be achieved in co-cured repair patches. The challenging part is to perform a sufficient surface pre-treatment prior to the bonding process and to assure accurate geometrical tolerances in the assembly.
- Moreover, manufacturing imperfections play an important role for the resulting joint strength for these finger joint topologies.

The extensive amount of recent work on micro- and nano-scaled hierarchical structures on laminated plies and on the bond line interface indicates the untouched potential that still lies in CFRP bonded joints. The rising complexity of advanced composite design stands thereby in contradiction to the need for simple and robust solutions. In any case, there are new joint designs yet to explore and the future holds stunning possibilities to pave the way for structural adhesive bonding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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