JOINTS OF THICK 3-D WOVEN E-GLASS COMPOSITES: FABRICATION AND MECHANICAL CHARACTERIZATION

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Abstract

A comprehensive experimental study focusing on strength efficiency factors determined for several characteristic bonded and co-cured joints of 3-D woven E-glass fiber/vinyl ester resin composites is presented. Various double-lap and single-lap joints were fabricated and tested under uniaxial in-plane tension. The composite adherents were made via Vacuum Assisted Resin Transfer Molding method. Single-lap and double-lap joints were made using both co-curing (primary bonding before consolidation of adherends) and traditional bonding of already consolidated composite adherends. Special 'tapered' 3-D woven preforms were manufactured for the studied composite joints. Joint strength efficiency of co-cured single-lap joint was found at 38.5%, of co-cured double-lap joint at 61.3%, and of the classical type double-doubler bonded joint at 67.3%. Tapering was found the most efficient method of increasing joint efficiency; the highest joint strength efficiency of 88.8% was obtained for the balanced double-doubler with 7.5° taper angle.

1 Introduction

Many advantages offered by advanced 3-D woven fabric reinforcements for composites [1] are now well understood and appreciated, and the scope of their industrial and military applications is fast growing, see for example references [2-5]. Among major performance advantages are full suppression of delamination, substantially improved damage tolerance, through-thickness stiffness and strength, along with much higher resistance to impact, ballistic and blast threats.

However, some serious obstacles to a broader and faster penetration of 3-D woven fabric composites into different markets have been revealed in the course of interaction with various industrial customers. One of them is uneasiness of joining relatively thick, unitary fabrics (as the ones shown in Fig. 1 and Fig. 2) and composite components made thereof (as in Fig. 3) within a complex structure. In spite of a large volume of theoretical and experimental studies performed in the past two decades on specific bonded, bolted and other types of joints of composite materials and structures, the industry still lacks a practical, reliable and commercially attractive joining technology that would be applicable to thick 3-D reinforced composites. Obviously, if simply overlapping two solid pieces of materials of the kinds shown in Figs. 1-3, one would get their added thicknesses in the overlap zone, which would likely be not acceptable from the structural and/or aesthetical considerations.

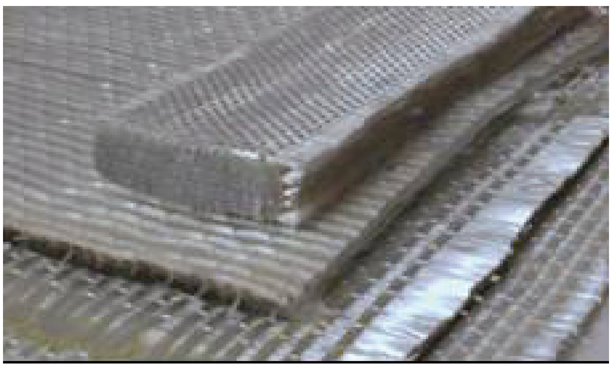

Fig. 1. Examples of 3WEAVE™ E-glass preforms

Fig. 2. Examples of 3WEAVE™ carbon preforms

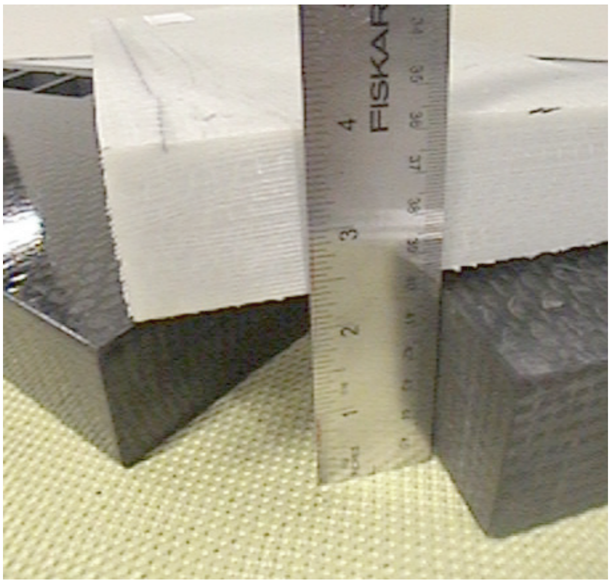

Fig. 3. Examples of composites made with single layer 3WEAVE™ glass and carbon preforms

Indeed, smoothness of the airplane, boat or automobile body would be lost, and high transverse normal and shear stress concentrations at the ends of the overlap would result in premature failure. One possible solution is applying conventional 'tapered' or 'scarf' lap joint approaches to the finished composite components. This is possible in principle, due to 3-D woven fabric composites can be cut and machined as easily as metals, see [1]. However, this approach has not been yet elaborated and applied in large-volume industrial production. Also, the problem of significant thickness increase in the overlap area would be not completely resolved. Besides, strength of such joint, as strength of any bonded joint, would be highly dependent on the strength of adhesive material.

A more appealing alternative approach is to make special shape (tapered, scarf, or which else is appropriate) at the stage of preform fabrication. Then the preforms would be overlapped, co-infused by resin and co-cured. Additionally, stitching, stapling or other strength-enhancing method can be applied to the overlapped preforms before resin infusion. The anticipated advantages of this approach are in (a) resolving (at least partly) the overlap thickness increase problem and (b) having more control over the stress concentration reduction in the critical zones of the joint. The disadvantages may appear in the complications of irregular shape preform manufacturing and difficulties of molding large preform assemblies that would also have rather complex shapes.

The authors are not aware of any previous attempts to experimentally study either of the two joining approaches suggested above. Specifically, there are no published information validating the manufacturing aspects, and no published data on the strength efficiency evaluation of specific practical joint configurations and materials. An extensive experimental study, part of which is summarized in this paper, has been performed with two aims: (i) to validate the aforementioned bonding and co-infusion approaches on several practical thick 3WEAVE™ fabrics and composites and (ii) to evaluate the joint strength efficiency factors under uniaxial tensile loading. The preform design and manufacturing aspects, composite joint fabrication, their testing methodology and essential experimental results are presented and discussed in this paper.

2 Materials

In all studies reported here, the authors used two kinds of E-glass roving (PPG produced Hybon® 2022) 3-D orthogonal woven fabrics made by 3TEX under product codes P3W-GE004 and P3W-GE002. The former fabric has 5.03 kg/m^2 areal density. It contains approximately 1.5% of fiber in through-thickness direction, with the remaining fiber content balanced between warp and fill directions. The fabric is constructed from 4 warp layers (218 yield/lb roving in all of them; 7 ends/inch insertion), 5 fill layers (675 yield/lb roving in layers #1 and #5; 450 yield/lb roving in layers #2, #3 and #4; 6.5 picks/inch insertion), and 1800 yield/lb roving in Z (through-thickness) direction with 7 ends/inch insertion using 2 harnesses. The P3W-GE002 fabric is constructed similarly to the above described P3W-GE004, with the difference that the fabric contains 2 warp and 3 fill layers. Accordingly, this fabric is about twice thinner and its areal density is 2.58 kg/m^2.

The resin used was Dow Derakane 8084, which is a non-thixotropic, non-promoted, epoxy-modified vinyl ester resin. The resin was mixed with 0.3% by weight of 6% solution cobalt napthanate promotor and catalyzed with 1.5% by weight Akzo Nobel Trigonox® 239A cumene hydroperoxide (CHP) initiator. This recipe gives an initial viscosity of 300-400 cP at ambient temperature, and a pot life of 1-1.5 hours, both depending on lab temperature. According to DOW internet homepage, the resin tensile strength is 72.4 MPa and tensile modulus 3.2 GPa.

The main adhesive used in this study is a 3M Scotch-Weld^{TM} DP-420 Epoxy Structural Adhesive. According to the manufacturer's internet data, its pot life is 20 minutes, viscosity 45000 cps, elongation at break 5%, and shear/flexural strength 31 MPa.

3 Joint Designs

Depending on the preferred joining technology, the authors used two approaches for producing the composite joints: (i) flat consolidated composite panels based on 3-D woven textile reinforcement were fabricated and then adhesively bonded (secondary bonding) and (ii) co-cured joints were manufactured by infusing resin into the joint of 3-D woven preforms via VARTM method and then co-curing the whole joint (primary bonding). The composite joints were then cut into specimens of standard length and width resulting in total of 155 specimens covering 26 different joint configurations. Some of them were stitched or stapled prior to resin infusion; results for those samples are not included in this paper. Schematic configurations of the others, which are in the focus of this paper, are illustrated in Fig. 4, with principal dimensions indicated there.

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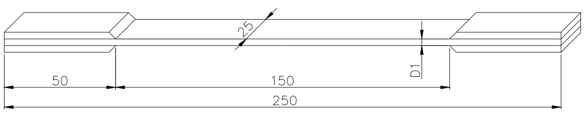

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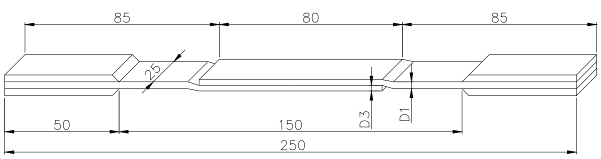

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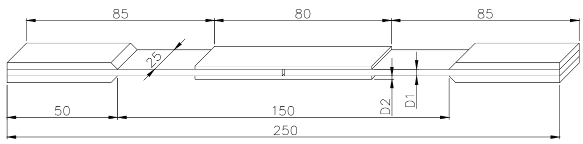

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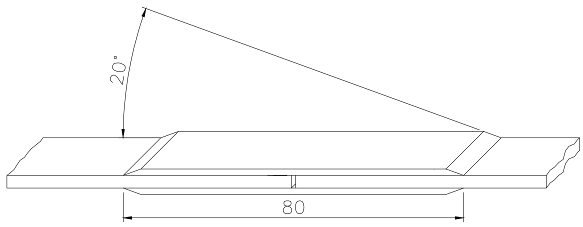

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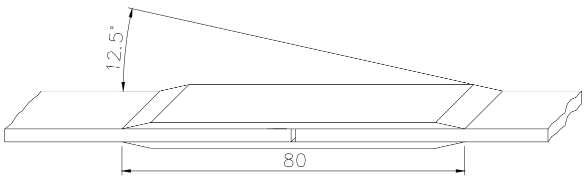

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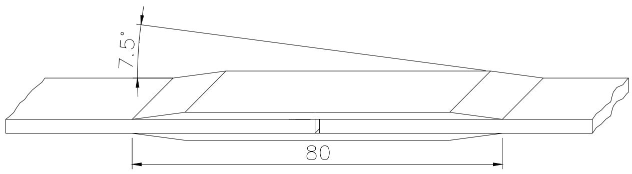

Fig. 4. Schematics of the designed and fabricated baseline flat composites (a), single-lap (using drop-off fabric) co-cured and bonded joints (b), double-lap (a.k.a. 'double-doubler') co-cured and bonded joints (c), and bonded tapered joints with angle 20º (d), 12.5º (e) and 7.5º (f)

The baseline flat composite samples (see Fig. 4a) were made with 3WEAVE™ preforms P3W-GE004 and P3W-GE002 described in Section 2. The single-lap joints (Fig. 4b) were made with P3W-GE004 preforms having 'step-down' section. Owed to this, thickness of composite specimen outside the overlap was ~3.7 mm, while within the overlap it was ~5.2 mm (it would be ~7.4 mm in the case of simply overlapping two layers of P3W-GE004 fabric). All double-lap joints were made using P3W-GE004 preform for inner adherends and P3W-GE002 preform for outer adherends. Overlap length was 80 mm for all single-lap and double-lap joints.

4 Joint Sample Fabrication

Single-lap and double-lap joints were made using both co-curing (primary bonding before consolidation of adherends) and traditional bonding of already consolidated composite adherends. Panels containing each of the joints examined were produced by VARTM method. Cut preforms were placed on an unheated flat, stiff, smooth table, then covered by a polypropylene or polyethylene sheet. In all joint samples, their longitudinal axis was parallel to the fill direction. Fig. 5 shows schematics of co-cured joint fabrication.

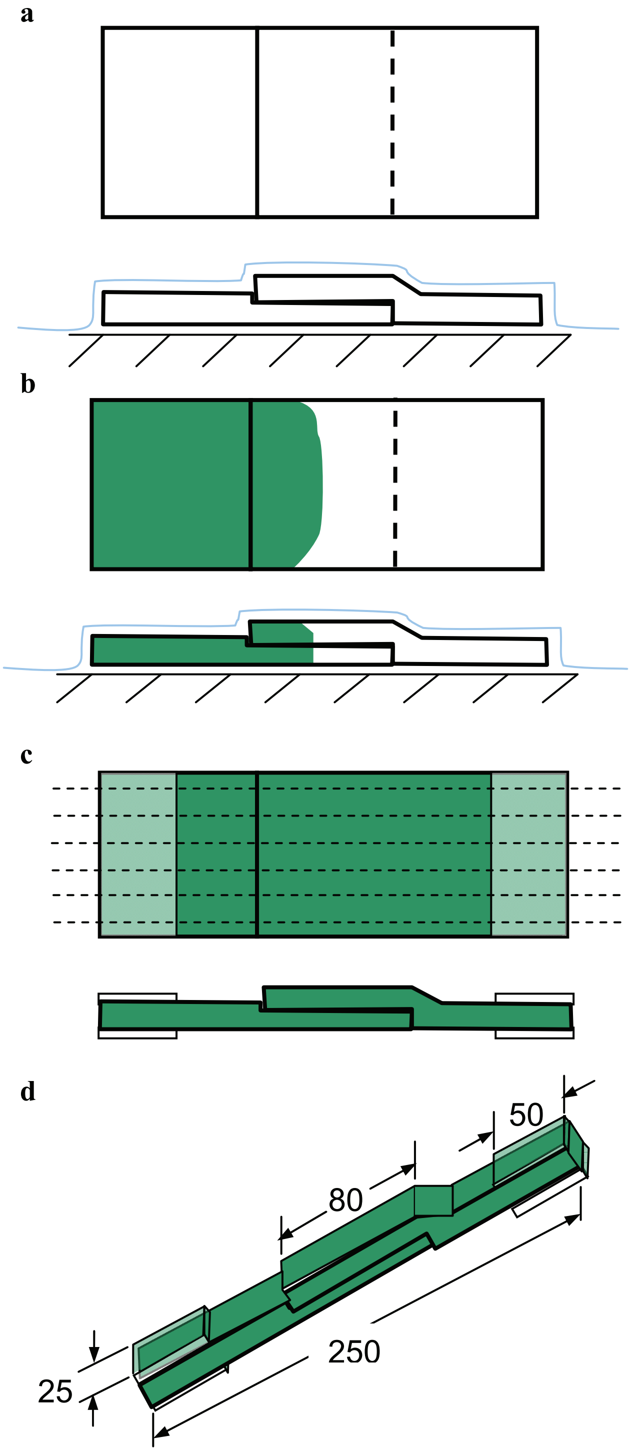

Fig. 5. Schematic of a step-by-step joint fabrication

The preform assemblage was first covered with a vacuum bag, sealed, and evacuated (see Fig. 5a). Then, it was mounted on shims, to load path eccentricity between the adherends. Other joints were laid on a flat table. After that resin was injected through the preform assemblage (see Fig. 5b). Typical vacuum pressure differential was 29 in-Hg (98 kPa). The mixed resin was degassed for five minutes at the above pressure differential after mixing, then infused across the length of the panel. Typical panel dimensions were 350 mm x 300 mm. Specimens were made at lab temperatures between 20°C and 24°C (68°F and 75°F). The actual VARTM production set up is shown in Fig. 6.

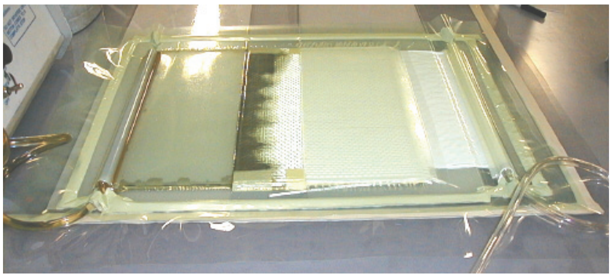

Fig. 6. Joint preform in the process of resin infusion

Fully infused and cured composite panels were debagged, bonded to tabs and cut into test specimens along dashed lines indicated in Fig. 5c. One composite panel was produced for each type of joint. An example of the actual fabricated composite joint panel is shown in Fig. 7.

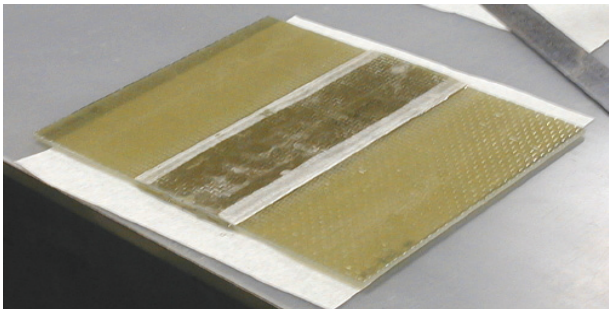

Fig. 7. Example of VARTM fabricated composite joint panel

Composite panel thickness, measured away from the overlap area, was used in conjunction with the fabric areal weight to determine fiber volume fraction in composite adherends (ASTM D3171 standard, Method 2); it was found ~52.6% for P3W-GE002 fabric composite and ~54.9% for P3W-GE004 fabric composite.

Schematic of the final test specimen is shown in Fig. 5d. The fact that the thickness drop-off at the edges of the P3W-GE004 fabric was about 40% means that resulting single lap joints were asymmetric, as clearly seen in Figs. 5c and 5d.

Adherends and doublers of secondary bonded joints were made separately, using the same VARTM technique as described above. All secondary bonded specimen surfaces were first lightly abraded by hand with 80-grit sandpaper, then wiped clean with acetone. The quality of surface decontamination was checked qualitatively with the so-called 'water break' test: sanded and cleaned surfaces were immersed in distilled water and extracted. Surfaces were considered suitably clean and decontaminated if the water remained a film, rather than beading. Wet surfaces were then wiped clean and bonded within one hour using adequate pressure.

Tabs were bonded to the test panels using 3M DP 420 epoxy and a commercial laminate of woven E-glass/polyester laminate, ~3 mm thick, untapered, cut at 45º to the tabbing laminate fiber directions. These tabs were clamped by the test frame during subsequent specimen tests.

5 Mechanical Testing

Between five and seven specimens were cut from each fabricated composite panel. Specimens were sawn from the panel using a diamond-impregnated wet saw. Specimens' cut edges were not machined prior to testing. One specimen of a double-lap tapered joint is shown in Fig. 8.

Fig. 8. Double-lap tapered joint specimen

Due to the joints created inhomogeneities in the strain field within each specimen's gage section, the strain field of each specimen was a function of joint construction and the gage position along the specimen length. Since it was believed that strain readings did not have a consistent meaning among different types of fabricated joints, no strain gages or extensometers were used in this part of experimental program.

Specimens were tested in uniaxial, monotonic tension, using a displacement-controlled, screw-driven Instron® test frame at North Carolina State University, Department of Mechanical and Aerospace Engineering facility. The tests used a 10,000 kg-force load cell (maximum breaking strength was ~4000 kg-force). Specimens were secured by hand in sliding block-type clamps. Five specimens of each joint type were tested.

Due to no appropriate standard for tensile testing of joints of fiber reinforced composites could be found, the testing was performed in accordance with German standard DIN EN 61 "Tensile Testing of GFRP" [6]. Dimensions of the test specimens, selected following this standard, are shown in Fig. 4. One important non-standard feature of the performed tests has to be pointed out: the joint specimens contained significant thickness variation along their length. Also worth noting that the specimens were only tested in fill fiber direction, which is at the same time the longitudinal specimen direction. As mentioned above, the only output of the tests was maximum load carried by the specimen; such load value was taken as the joint breaking load.

6 Experimental Results and Discussion

After testing the described variety of specimens, their Joint Strength Efficiency (JSE) were determined as the joint breaking load normalized over the breaking load of the unjoined baseline composite made of P3W-GE004 (5.03 kg/m^2, BC).

Fig. 9 shows the JSE for the single-lap co-cured (SLC) and single-lap bonded (SLB) joints using drop-off fabric. Both joint configurations show strength efficiency of approximately 38%.

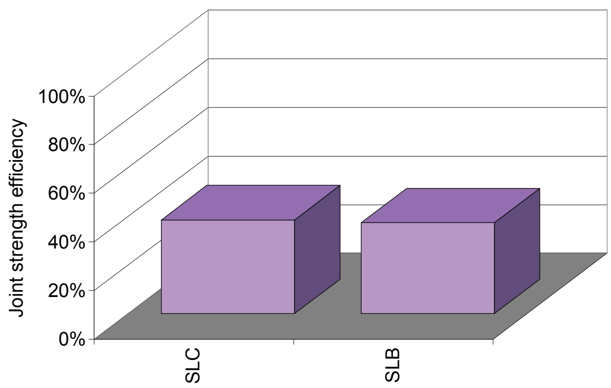

Fig. 9. JSE for co-cured (SLC) and bonded (SLB) single-lap joints

According to the literature data, a common single-lap joint usually achieves strength efficiency of about 30%. The higher JSE obtained for the tested single-lap joints can be attributed to the reduced eccentricity owed to the use of drop-off fabric.

Crack initiation was observed at the ends of the joint zone. The cracks were gradually propagating towards the center of the joint zone under increasing load, until the final failure occurred. The progressive failure mechanism observations allowed the authors to identify transverse normal ('peel') stress as the main cause of failure. The still existing eccentricity in the loading path along with unbalanced shear stresses at the ends of the overlap have significantly contributed to the high values of the peel stress. Fig. 10 shows a breaking pattern of a SLC joint.

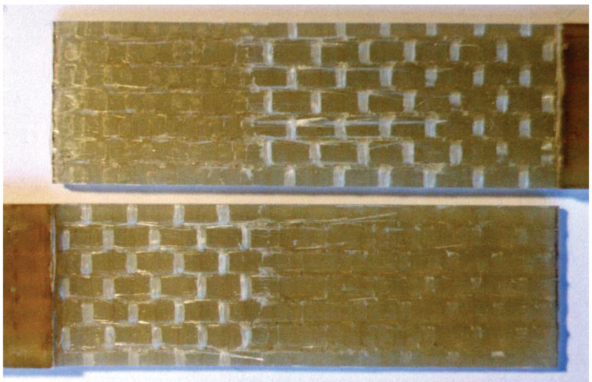

Fig. 10. Breaking pattern of the SLC joint

The adherends remained nearly undamaged after testing. The joint was separated between the resin layer and the fibers on the surface of the adherends; this indicates the fiber-matrix debond type failure. White spots seen in Fig. 10 are the loops of uncovered Z-yarns.

The effect of different outer joint adherends is illustrated in Fig. 11. The four different configurations are the double-lap co-cured (DLC) and double-lap bonded (DLB) joints with outer adherends reinforced with P3W-GE004 (5.03 kg/m^2, DLB-thick), P3W-GE003 (3.23 kg/m^2, DLB-mid) and P3W-GE002 (2.58 kg/m^2, DLB-thin) preforms.

The adherends remained nearly undamaged and no delamination was seen after total failure of the joint. Crack initiation was observed at the ends of the outer adherends. Crack propagation was continuous, and the breaking pattern indicated failure of the resin layer adjacent to the surface fibers of the adherends, similar to what was seen in the SLC joint. These observations led to the conclusion that the peel-type failure of the resin layer between the adherends is the dominating failure mode of this joint.

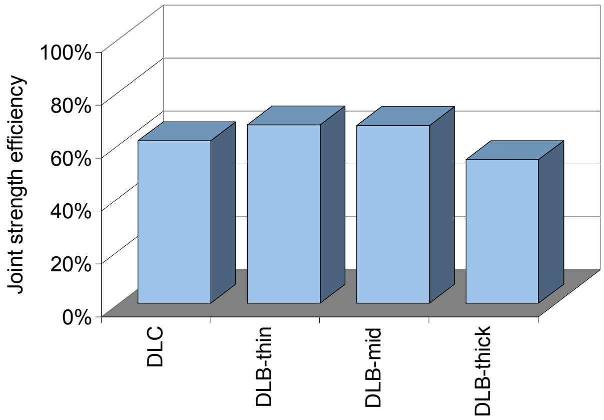

Fig. 11. JSE for the double-lap co-cured (DLC) and double-lap bonded (DLB) joints made with different outer adherend materials

It can be seen in Fig. 11 that on average the JSE is about 60% for the tested double-lap joints. The best JSE, 67.3%, was obtained for the DLB-thin joint. A comparison between DLC and DLB-thin shows that the secondary bonded joint has a 10% higher efficiency than the co-cured joint. Both double-lap joints are geometrically equal, and the only difference is that one of them was made via bonding while the other one via co-curing. The fact that resin at the surface of adherends was removed by grinding prior to bonding allowed to directly bond the fibers, and this made its positive effect on the joint strength.

Results in Fig. 11 also reveal that joints of increasingly thicker outer adherends have decreasing JSE. This result is primarily related to increasing peel stress concentration with increasing thickness of adherends. It emphasizes again that the problem of joining composites made with unitary fabric preforms, stated in the beginning of this paper, gets more and more serious with increasing preform thickness. Further improvements of the joining techniques, primarily aimed at reducing peel stress concentration at the ends of the overlap, are on demand. One possible method, which is well known in traditional joining technology, namely tapering end zones of the outer adherends, is applied here in a modified fashion (with the use of special tapered preforms). Schematic of the respective joint specimens is shown in Figs. 4d, 4e and 4f.

The effect of tapering DLB joint on JSE is illustrated in Fig. 12. An impressive increase of JSE, up to 44% compared to the DLC joint, has been achieved with tapered outer adherends. The highest increase was observed for the smallest taper angle of 7.5° (DLB-7.5).

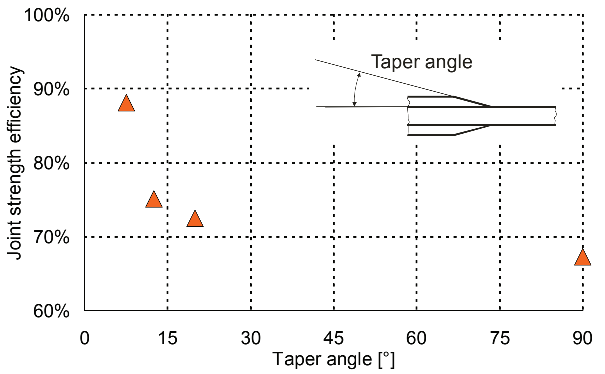

Fig. 12. Effect of taper angle on JSE of DLB joints

Obviously, the reason why tapering makes so strong positive effect on JSE of DLB joints, is in reduced peel stress concentration at the ends of the overlap. The alleviating peel stress by tapering makes a shear-type failure of the joint more likely. Fig. 13 illustrates this effect on the broken joint DLB-7.5 specimen.

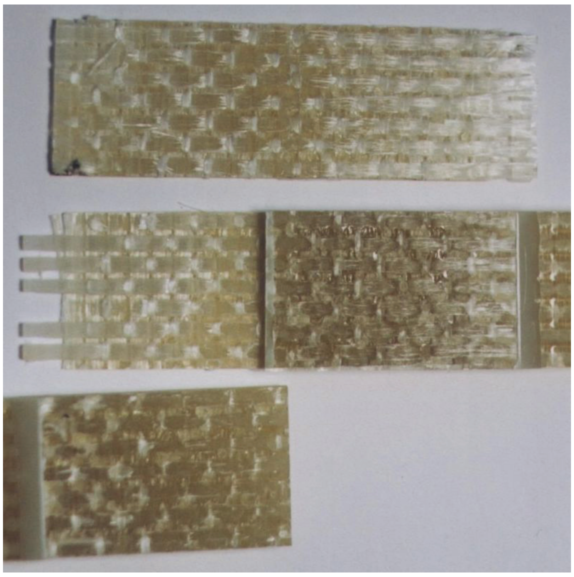

Fig. 13. Shear-type failure pattern of the DLB-7.5 joint

It is seen in Fig. 13 that in this failure pattern matrix material was totally removed from the ends of the tapered outer adherends. The defects of the matrix at the surface of the adherends were much deeper and more pronounced than in the case of the DLC joint.

Fig. 14 compares the JSE values obtained for the DLC, DLB-thin and DLB-7.5 joints. It is obvious that secondary bonding of the joint can achieve an increase of the strength efficiency. Obviously, 'smoothing' geometrical transition from the outer adherend to the inner one reduces stress concentrations at the ends of the overlap, and this explains in turn why tapering of the outer adherends makes the most pronounced positive effect on the JSE.

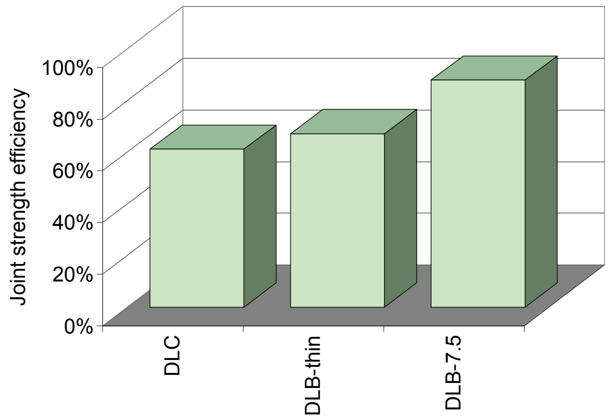

Fig. 14. Comparison of JSE values for co-cured (DLC), bonded (DLB-thin) and tapered bonded (DLB-7.5) double-lap joints

It should be also noted that no classical delamination within composite adherends was observed even at 88% level of the joint failure load. This emphasizes again the known fact that when using unitary 3WEAVE™ preforms for composites, delamination as the failure mode is totally excluded due to the presence of Z-fiber [1]. The dominating failure modes of such composites under in-plane tensile loading typically include matrix cracking and fiber-matrix disbond at the initial stage, followed by fiber fracture in the loading direction that leads to ultimate failure.

As can be concluded from Figs. 13 and 14, the goal of reaching 100% JSE has not yet been achieved even with the lowest taper angle, due to the specimen disintegrates by shear-type failure prior to adherend failure. This directs further design and manufacturing efforts towards improving shear strength of the joints within overlap region.

7 Conclusions

As one could anticipate, in contrast to the case of 2-D reinforced laminated composite adherents, the failure of 3-D woven composite joints does not occur due to delamination within adherents. This was confirmed in the performed tests – 3Weave™ reinforced adherents were never the "weakest link" of the joint. This means that 3-D woven composites can be effectively joined by conventional joint designs, with joint strength efficiency typical of thinner, 2-D woven reinforcements. The experimental observations made in this paper can be summarized as follows:

- No adherent failure due to delamination was observed even for joint strength efficiency at 88%.
- Joint strength efficiency of co-cured single-lap joint was found at only 38.5%, while that of co-cured double-lap joint was 61.3% (joints made with tapered preform, the overlap length 80 mm).
- Joint strength efficiency of the classical type double-doubler bonded joint was found at 67.3% (the overlap length 80 mm).
- A balanced joint design (with equal stiffness of the outer adherents) is always preferable; also, thinner outer adherents show higher strength efficiency.
- Tapering is shown to be the most efficient method of increasing joint efficiency; as small taper angle as possible should be used. The highest joint strength efficiency of 88.8% was obtained for the balanced double-doubler with 7.5° taper angle.
- Further work will address the effects of 3WEAVE™ preform stitching and other similar techniques used to further increase strength within overlap region.

8 Acknowledgements

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