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Local reinforcement of aerospace structures using co-curing RTM of metal foil hybrid composites

J. Studer[1] · A. Keller[1] · F. Leone[1] · D. Stefaniak[2] · C. Dransfeld[1] · K. Masania[1,3]

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Abstract
The increasing use of carbon fibre reinforced polymer (CFRP) composites in aviation and automotive industries has led to the adoption of automated production methods such as pultrusion or resin transfer moulding (RTM) for cost reduction in the production lightweight structures. These processes however, offer limited freedom to locally reinforce structures. This paper describes an approach to utilise a basic geometry for several similar parts and add local reinforcement patches only in regions of load introduction or high local stress. The approach offers the benefit of being able to combine automated production methods with unprecedented design freedom. The specific bearing performance for three different local reinforcement using (1) add-on CFRP patches, (2) surface mounted steel foils and (3) steel foil interleaving in replacement of 90° plies with foils of the same thickness as the CFRP plies (0.125 mm) is compared by double lap bearing tests. The bearing strength improves with the addition of patches, for surface mounted steel foils, more so as CFRP co-cured patches, and most as an interleaved configuration. Quasi ductile failure of the bearing joints was maintained due to additional plasticity of the steel foils, producing a joint that fails safely while enhancing the bearing strength. When examining the hybrid laminates, all samples buckled and failed in bearing compression/shear. Brooming was evident on the compressive side of the hole where the bolt indented the laminate. Indentation led to shear kink bands along the washer supported region and appear as large compression/shear damage above the washer confined region of the laminate. When normalised by weight, the three approaches show similar bearing performance. However, each approach has specific advantages with regards to processing, electrolytic potential, or absolute bearing strength, depending on the design of the load introduction.

Keywords Compression RTM · Co-curing · Hybrid laminates · Metal foil · Bearing strength

1 Introduction

The aviation industry is employing evermore carbon fibre reinforced thermosetting polymer (CFRP) structures in order to minimise weight, and hence emissions during flight. However, much of the efficiency that can be gained by using such materials is lost due to inefficient joining procedures and strict certification standards that prevent adhesive joining of primary structures in civil aviation [1]. At the same time, automated production methods such as pultrusion or resin transfer moulding (RTM) are developing as manufacturing techniques for aircraft structures due to their relative cost effectiveness. Since these structures usually have few material orientations, they need to be optimised for their relative load case, leading to inefficient joining strategies. Possible solutions include locally thickening structures via ramping up or a secondary procedure such as co-curing [2] to increase the bearing carrying load capacity with the compromise of larger section in the joining region of the structure. Co-cured joints can provide higher fracture toughness [3] and joint strength [4] than co-bonded joints due to mechanical intermingling and covalent bonding of the resins at the interface [5] By producing the structure and local reinforcements separately, this approach avoids the need for a bonding procedure while opening up valuable freedom to enhance properties locally, e.g. in the amount of toughener

✉ K. Masania
kunal.masania@mat.ethz.ch

[1] Institute of Polymer Engineering, FHNW University of Applied Sciences and Arts Northwestern Switzerland, Klosterzelgstrasse 2, 5210 Windisch, Switzerland

[2] German Aerospace Centre DLR, Ottenbecker Damm 12, 21684 Stade, Germany

[3] Complex Materials Group, Department of Materials, ETH Zürich, 8093 Zurich, Switzerland

[6, 7] that may be introduced, or indeed the reinforcing area or ply thickness that is chosen [8].

Hybridising the structure locally to enhance properties in only the regions that demand higher load carrying capacity is one possibility to overcome the change in section while still enhancing the composite properties [9]. Such a hybridisation technique was first studied with composite plies being substituted by thin titanium foils in the joint area, bypassing the need for local thickening [10]. Steel alloys are especially suitable as reinforcement and favoured over titanium due to their lower cost and their high stiffness, strength and elongation at break. For example, reinforcing a neat composite with titanium or steel, enhances bearing strength by a factor of 2 and 2.6, respectively. For the same resulting bearing strength, the composite steel-laminate requires about half the metal volume needed for a titanium hybrid laminate, hence leading to manufacturing and cost benefits.

This work compares the specific double lap bearing performance for local reinforcement using (1) add-on CFRP patches, (2) surface mounted steel foils during the impregnation and curing of the CFRP composite structure and (3) steel foil interleaving in replacement of 90° plies with foils of the same thickness as the CFRP plies (0.125 mm). Our results demonstrate that the local properties of a joint can be tailored to be application specific.

2 Materials and methods

Three local reinforcement methods to increase the specific bearing performance are compared to a reference RTM plate: using add-on CFRP patches, surface mounted steel foils during the impregnation and curing of the CFRP composite structure with steel foil interleaves as shown schematically in Fig. 1 and explained in Table 1. The B-stage CFRP patch and steel foil patch approaches allow for net shape hole preparation which significantly simplifies hole preparation in composites and were therefore utilised in preparation of the samples as would be the case in industrial applications.

The resin used was "HexFlow RTM6", Hexcel, UK, a monocomponent resin system consisting of a tetrafunctional epoxy component, tetraglycidyl 4–4′ diaminodiphenylmethane (TGDDM, Araldite MY 721), and two amine hardeners: 4,4′-Methylene-bis(2,6-diethylanaline) (MDEA, Lonzacure) with 4,4′-Methylene-bis(2,6-diisopropylaniline) (MMIPA, Lonzacure). The resin is a hot curing system with a high T_g developed for infusion and RTM processes.

CFRP parts were manufactured by a RTM process from a biaxial stitched non-crimp fabric, "ECS6090- Series

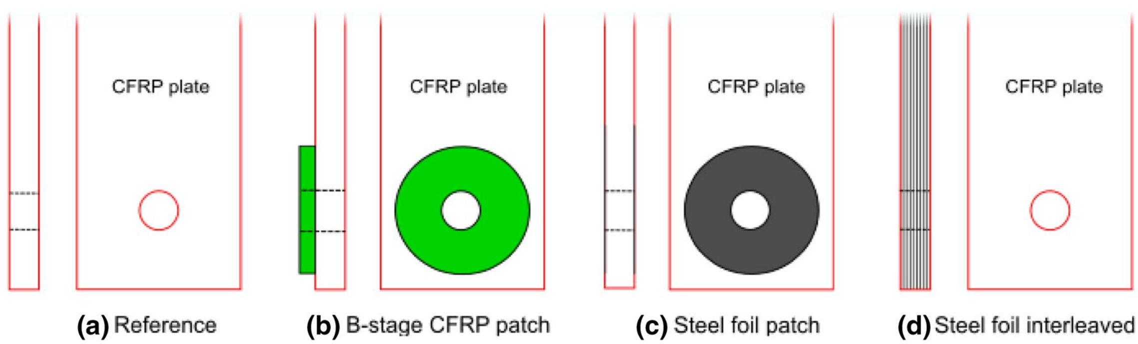

Fig. 1 Shows the investigated local reinforcement concepts of the bearing area. **a** Reference RTM plate. **b** B-stage co-cured CFRP patch. **c** Steel foil patch around the hole. **d** Steel foil integrated in the laminate (not entire figure is shown)

Table 1 Sample geometries with their manufacturing process, repsective hole preparation, resulting fibre volume contents and densities

Sample	Manufacturing method	Hole preparation	CFRP Fibre volume content	Structure density (g/cm^3)
Reference	RTM	Plate drilled after curing	0.63	1.38
B-stage CFRP patch	RTM plate, CRTM patch, Co-curing	B-stage hole in plate, net shape hole after co-curing	0.65	1.44
Steel foil patch	RTM	Plate fibres guided around pin, net shape patch	0.67	1.93
Steel foil interleaved	RTM	Plate drilled after curing	0.63	3.10

HTS 40”, Saertex GmbH & Co., Germany, with an area weight of 256 g/m^2. Quasi-isotropic parts were made from 16 plies: $2[0/90, +45/-45, 90/0, -45/+45]_s$ to produce 150 × 90 × 3.8 mm plates. The plates were completely cured at 0.4 MPa (4 Bar) and 180 °C for 90 min in the RTM tool as a reference, or to a partial degree of cure, α, of approximately 70% for the co-curing samples, in accordance to [11]. The tool was heated and cooled using a “LaboPress P200T”, Vogt, Germany. From each plate two samples for bearing tests were cut.

The reinforcing CFRP patches were manufactured from a thin ply material, 20 mm tape, 80 g/m^2 high tensile strength carbon fibre “TeXtreme Spread Tow”, Oxeon AB, Sweden which were cured to an incomplete conversion much the same as a prepreg, termed B-stage. The B-stage cured CFRP parts were cured at 0.4 MPa (4 Bar), 160 °C in the RTM tool and then cooled rapidly to stop the curing reaction at a desired value of α before drilling to produce a 6 mm hole. Kinetic [11] and rheological [12] models were implemented in order to monitor the rheokinetic behaviour of the resin during the cure cycle. Quasi-isotropic, 2 mm thick, 30 mm diameter, Ø 6 mm hole patches were made from 24 layers of the spread tow with the layup $3[45, 90, -45, 0]_s$. The CFRP patches were partially cured at near net shape using compression RTM at 2 MPa (20 Bar) for varying times at 160 °C depending on the desired value of α. To ensure good adhesion, a nylon peel ply (Econostitch, Aero Consultants AG, Nänikon, Switzerland) was used to provide a contamination free surface for co-curing. The B-stage plate was then attached to the B-stage patch applied via a local compression jig. A co-cured structural reinforcement was possible with an applied pressure of 2 MPa (20 Bar) as shown in Fig. 2 [11]. During co-curing, the fibre volume content of the part remains constant at 63 ± 3% due to the higher degree of conversion in the part. Conversely, the patch volume fraction was measured as 50 ± 6% before B-stage, increasing to 65 ± 5% as circa 1.5 ml is lost from the patch during the consolidation process.

To study the role of hybridisation with metal, 1.4310 CrNi-steel foils with a thickness of 0.125 mm were used as reinforcement, which present a stiffer and more economical alternative to metal hybridisation with titanium or aluminium, for example. To improve the adhesion between the steel foil and the epoxy resin, the Boeing sol–gel surface treatment was adopted [13]. The surface was first subjected to mechanical treatment (sand blasting [14]) followed by sol–gel processing. In order to avoid further oxidation, the surface was coated with an epoxy primer after the surface treatment process. For the manufacturing of surface mounted patches, steel foils were directly integrated on the top and on the bottom of the dry preform layup. Accurate positioning of the steel foils in the RTM tool was ensured by integrated pins at the location of the hole to provide both positional and dimensional tolerance, resulting in a net shape finished hole. To avoid fibre damage and misalignment of the dry preform, fibre tows were guided around the locating pin during layup. The same RTM process as for the reference samples was used for the cure cycle.

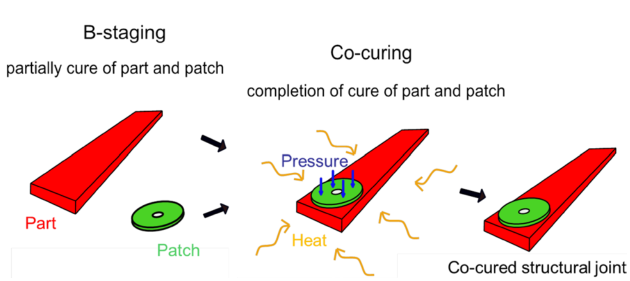

Fig. 2 Shows the concept of local patch reinforcement of a structural part via co-curing of B-stage cured components

The interleaved composite was prepared by beginning with the $2[0/90, +45/-45, 90/0, -45/+45]_s$ quasi-isotropic CFRP, and removing all of the 90° layers in favour of 0.125 mm steel foils. This allowed the replacement of the weaker 90° plies in favour of isotropic steel. Then the same RTM process as for the reference sample was used, and samples were cut and prepared for bearing tests by drilling a 6 mm H6 tolerance hole after the composite was cured.

Double lap bearing shear tests were conducted in accordance to ASTM D5961M-08 employing 6 mm bearing fasteners (f9/H6 fit, 12.9 steel) for all tests due to the superior bearing strength of the hybrid laminates with washers fitted and the joint tightened to provide 20 MPa (200 Bar) compression stress on the joint. The testing speed of 1 mm/min was used and the bearing strain was recorded using an LVDT placed 23.5 mm apart on either side of the bearing joint as shown in Fig. 3. The samples were loaded to either ultimate bearing stress or plasticity with no further load drop beyond approximately 20% bearing strain.

Optical microscopy samples of the co-cured joint were prepared by polishing epoxy resin-embedded samples with a “TegraPol-21”, Struers GmbH, Switzerland, using progressively finer grades of emery paper from 240 to 2400 grit. Polishing was performed up to 0.25 µm diamond polishing solution. A “VKX-200”, Keyence, Germany, 3D laser scanning microscope was used to obtain the optical cross-sectional images of the tested bearing samples.

3 Results

The double lap bearing stress was measured as a function of bearing strain for the different patch configurations is shown in Fig. 4. The first ply failure (FPF), 0.5, 1 and 2% and ultimate bearing strain for each configuration was considered, as shown in Table 2 and Fig. 5. The

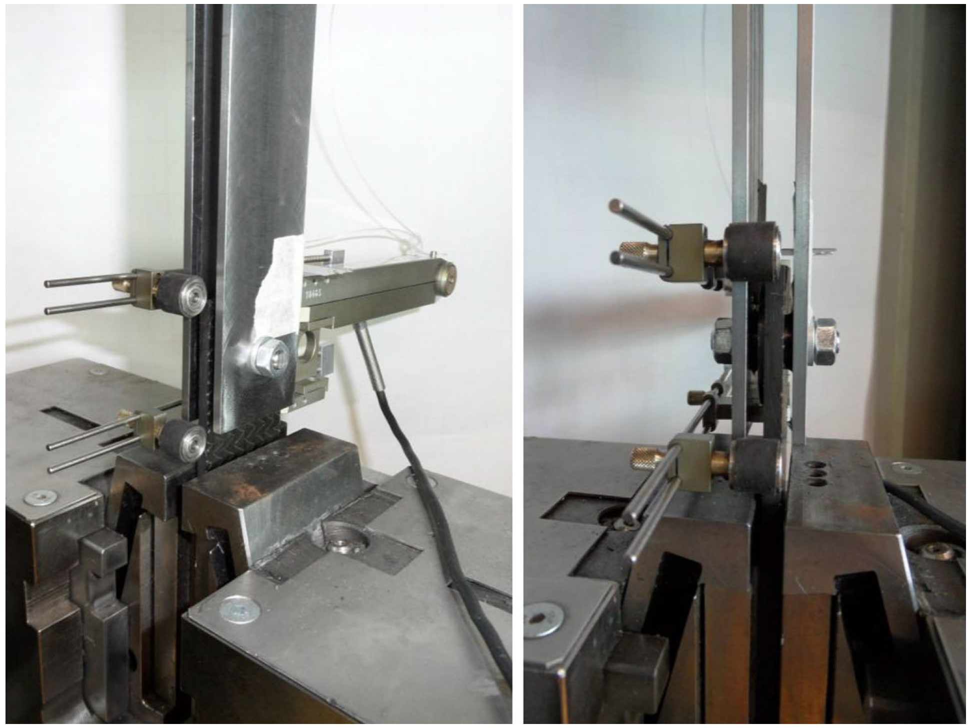

Fig. 3 Shows the test set up that was used for conducting the double lap bearing tests

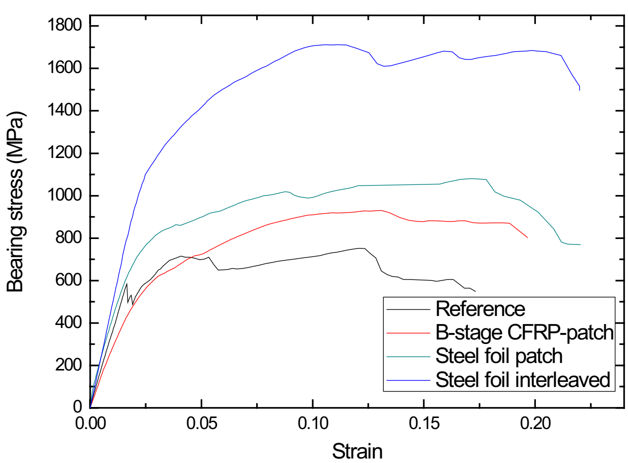

Fig. 4 Bearing stress versus bearing strain of the locally reinforced composites in double lap bearing

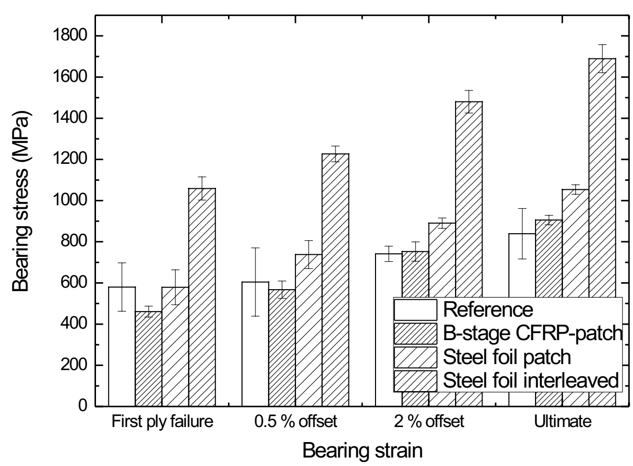

Fig. 5 Compares the bearing stress of the reference composite, B-staged CFRP patch, steel foil patch and steel foil patch reinforcement methods at progressively increasing bearing strain offsets

bearing strength improves with the addition of steel foil patches, even more with CFRP co-cured patches, and most in an interleaved configuration. Optical cross sections of the reference and reinforced composites after double lap testing are shown in Fig. 6. The composites were loaded via a loading pin on the right side of the image towards the left side, indicating the compression direction of the bearing pin.

In the reference, damage accumulation in the right side of the image (close to the bolt) shows kink bands due to compression stresses, which start to pile up as soon as there is no more restriction from the washer. It is apparent that the damage has led to loss of structural integrity in the joint.

No noticeable difference in FPF was observed with the B-stage CFRP patch or steel foil patch composites. The steel foil interleaved composites improved the FPF bearing stress by approximately 80–100% compared to the reference composite.

The B-stage CFRP patch reinforced part increased strength up to 40–55% for further hole deformation (0.5–2% bearing strain). The B-stage CFRP patch

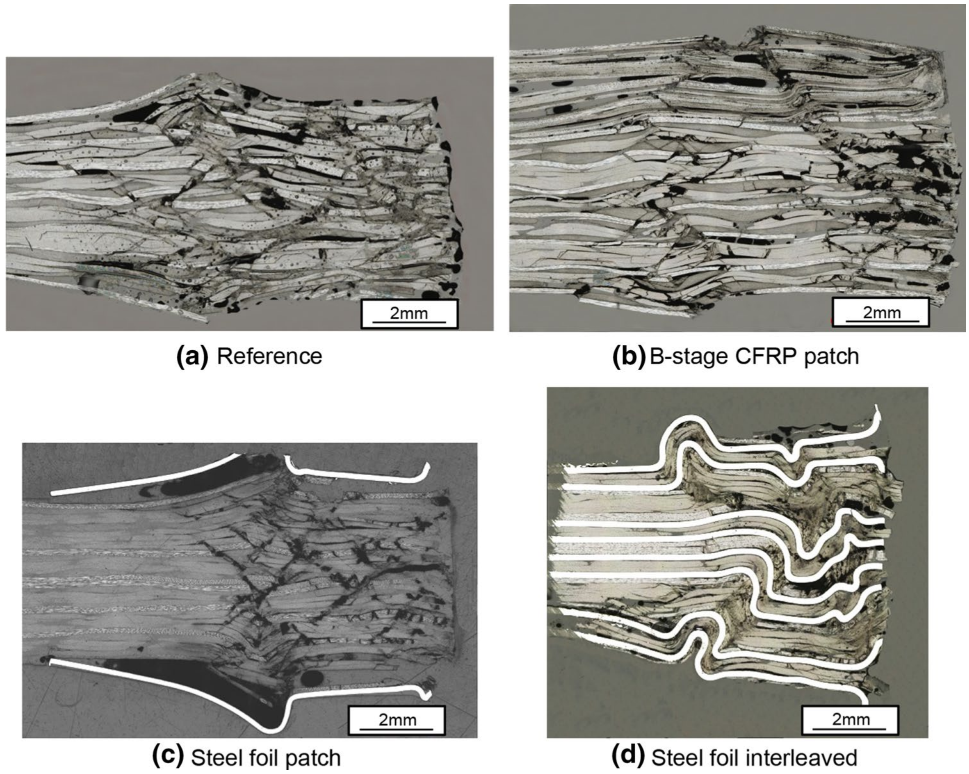

Fig. 6 Shows optical micrographs of the reinforced joints after a double lap bearing tests, shown represented damaged samples of the **a** reference composite, **b** B-staged CFRP patch, **c** steel foil patch and **d** steel foil patch

Table 2 Summary of bearing stress of the locally reinforced composites

Sample	Reference		B-staged CF-patch		Steel Foil patch		Steel foil interleaved	
Bearing stress (MPa)	Mean	±	Mean	±	Mean	±	Mean	±
First ply failure	580.0	117.5	460.9	26.4	579.1	85.0	1058.9	56.2
0.5% offset	604.6	166.0	567.4	42.0	737.9	67.8	1226.7	38.5
2% offset	741.6	37.1	752.7	47.2	890.4	25.2	1480.2	54.7
Ultimate	839.1	122.4	905.6	23.0	1053.9	23.2	1689.3	68.1

reinforced sample indicates that a void free bond was possible, with no evidence of porosity in the interface between the part and patch. Damage accumulation in the right side of the image also display evidence of kink bands due to compression stresses which transition into the thin ply laminate architecture patch; serving as further evidence of good interface.

For the steel foil patch reinforced composite, a roughly 20% improvement was measured in the bearing stress at 0.5–2% bearing strain. This was attributed to suppression of out of plane compression damage in the joint region of the composite. The sample with the steel foil patches shows that part of the outermost layer is still connected to the steel foil, which is evidence of good adhesion. The foil bends and disconnects from the CFRP plate where the washer ends and the kink bands pile up. In the washer area, kink bands are less expressed than in the reference and in the CF patch sample, which could be due to the locally higher fibre volume content in the patch area and the additional hindering of the piling up due to the steel foil patch.

Lastly, the steel foil integrated samples improved bearing stresses at progressive strains by approximately 80–100% for the range of strains that were studied. There was extensive plastic deformation in the steel foil interleaved joint, with evidence of good adhesion between the steel foils and thin CFRP plies due to damaged CFRP remaining attached to the steel foils. Plastic failure of the bearing joints was maintained due to deformation in the steel foils, producing a joint that failed safely while enhancing the bearing strength. When examining the hybrid laminates, each sample buckled and failed in compression/shear. Brooming was evident on the compressive side of the hole where the bolt indented the laminate. Shear kink bands reflected up the walls of the washer supported region and created large compress/shear damage area above the washer confined region of the laminate.

Table 3 Summary of specific bearing stress of the locally reinforced composites

Sample	Reference		B-staged CF-patch		Steel foil patch		Steel foil interleaved	
Bearing stress (MPa)	Mean	±	Mean	±	Mean	±	Mean	±
First ply failure	417.1	84.5	319.4	18.3	293.2	43	341.2	18.1
0.5% offset	434.7	119.4	393.2	29.1	383.2	35.2	395.2	12.4
2% offset	533.3	26.7	521.6	32.7	450.8	12.8	476.9	17.6
Ultimate	603.4	88	627.5	15.9	533.6	11.8	544.3	21.9

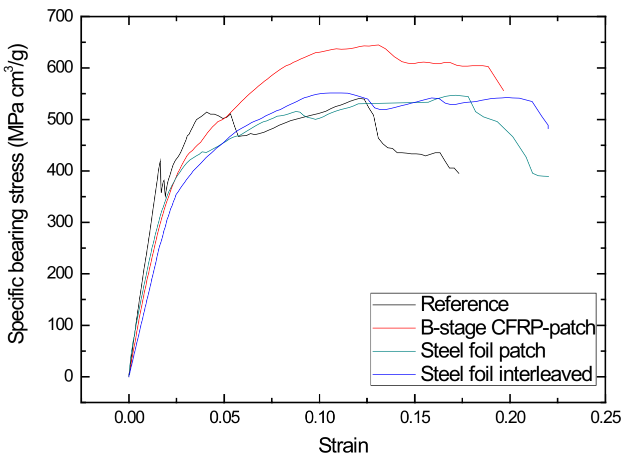

Fig. 7 Typical test results for the reference composite, B-staged CFRP patch, steel foil patch and steel foil patch reinforcement methods in double lap bearing normalised by density of the bearing region

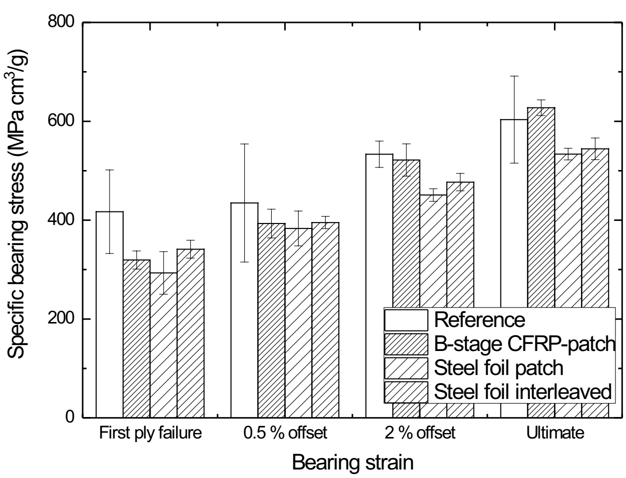

Fig. 8 Compares the specific bearing strength of the reference composite, B-staged CFRP patch, steel foil patch and steel foil patch reinforcement methods at progressively increasing bearing strain offsets

In Table 3 and Figs. 7 and 8 the specific bearing strength of the different reinforcement methods is shown. The fact that the data converges when normalised by weight of bearing area indicates that structures must be reinforced locally, but the best choice of reinforcement depends on the desired property optimisation.

4 Discussion

While all reinforcement techniques enhanced the bearing properties, each present independent advantages and challenges.

The B-stage CFRP patch reinforced joint has no electrical potential between constituents which eliminates corrosion challenges that fibre metal combinations face. However, this joint technique results in local thickening of the section. The possibility to net shape and co-cure saves cost preparing the hole after a drilling procedure. Since no adhesive is used, the B-stage CFRP patch avoids certification issues related to the use of adhesives in aircraft primary structures.

Steel foil patch reinforced samples result in constant net section, enhancing the bearing properties without adding too much weight, and can be straightforward to integrate into tooling. Since the dry preform fibres can be guided around locator pins, no specific hole preparation is needed, resulting in a low-cost reinforcement whilst also locally enhancing the fibre volume content in the high stress regions of a structure. Therefore, such reinforcement is well suited to RTM applications found in automotive, or sport applications.

The steel foil interleaved reinforcement demonstrates the highest bearing strength enhancement with up to double that of the reference composite material. However, the strategy is heavy and difficult to implement, therefore cost intensive using the approach that was studied. The RTM moulding processing route is viable despite the lack of through thickness permeability due to the steel foils. Post drilling of a hybrid metal joint presents challenges due the dissimilar materials in the hybrid composite with post drilling sealing of the hole required. Nevertheless, the sustaining of high bearing stress and plastic deformation of the joint without failure mean the technique is well suited for high end space or sport applications where bearing strength is vital without compromising section geometry possibly due to aerodynamic considerations or to reduce load offset effects.

5 Conclusions

B-stage CFRP locally reinforced patches can increase the bearing load of CFRP composites. Steel foil patches were also found to enhance the bearing strength, increasing bearing strain by delaying surface cracking while also locally enhancing the fibre volume content. In absolute values, the steel foil interleaves enhanced the composite bearing properties the most, up to double that of the reference composite material. However, when normalised by weight, the reinforcing efficiency converges, indicating that local reinforcement is important when lightweight is a primary consideration.

The described methods to locally reinforce CFRP composites was shown to be possible using manufacturing techniques that are readily scalable, and cost effective. The proposed co-curing approach is free of adhesives, thus may be applied to aerospace manufacturing without further additional certification. Addition of steel foils is shown to be most optimal when supreme bearing strength is needed locally within a structure without adapting the overall geometry of the structure. Depending on the desired property optimisation, there is now promising approaches for local reinforcement of an area without large weight penalties in the structure using the different approaches.

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References

1. Federal Aviation Administration (2009) Advisory circular 20–107B. Composite aircraft structure
2. Studer J et al (2014) Reinforcement of partially cured aerospace structures with B-stage patches. In: European conference on composite materials, vol 16, Seville, Spain
3. Seferis JC et al (2001) Scaled analysis of composite adhesive interphase properties. J Macromol Sci Phys B40(5):923–934
4. Kim K-S et al (2006) Failure mode and strength of uni-directional composite single lap bonded joints with different bonding methods. Compos Struct 72(4):477–485
5. Moosburger-Will J et al (2015) Joining of carbon fiber reinforced polymer laminates by a novel partial cross-linking process. J Appl Polym Sci 132:27
6. Giannakopoulos I et al (2011) Toughening of epoxy using core-shell particles. J Mater Sci 46(2):327–338
7. Kinloch AJ et al (2009) The fracture of nanosilica and rubber toughened epoxy fibre composites. In: International conference on composite materials, vol 17, Edinburgh, UK
8. Amacher R et al (2014) Thin ply composites: experimental characterization and modeling of size-effects. Compos Sci Technol 101:121–132
9. Masania K et al (2014) Steel foil reinforced composites: experimental and numerical study of strength, plasticity and ply size effects. In: European conference on composite materials, vol 16, Seville, Spain
10. Fink A et al (2010) Hybrid CFRP/titanium bolted joints: performance assessment and application to a spacecraft payload adaptor. Compos Sci Technol 70(2):305–317
11. Studer J et al (2016) An analytical model for B-stage joining and co-curing of carbon fibre epoxy composites. Compos Part A Appl Sci Manufac 87(Supplement C):282–289
12. Geissberger R et al (2017) Rheological modelling of thermoset composite processing. Compos Part B Eng 124(Supplement C):182–189
13. Blohowiak K et al (2008) Development of new thin adhesive systems and test methods for TiGr laminates. In: SAMPE conference, Long Beach, USA
14. Stefaniak D et al (2012) Improving the mechanical performance of unidirectional CFRP by metal-hybridization. In: 15th European conference on composite materials, Venice, Italy