HYBRID TITANIUM COMPOSITE MATERIAL IMPROVING COMPOSITE STRUCTURE COUPLING

Axel Fink and Dr. Boris Kolesnikov

German Aerospace Center, Institute of Composite Structures and Adaptive Systems, 38104 Braunschweig, Germany

ABSTRACT

One method of increasing mechanical joint efficiency entails the reinforcement of the joining area with thin metal laminates. The suitability and efficiency of titanium as a reinforcing material was researched and proven at the Institute of Composite Structures and Adaptive Systems of the German Aerospace Center in Germany (DLR). Experimental results show a significant gain of bearing strength and bolted joint strength. An efficient design of the transition from composite to hybrid titanium composite material has been developed which enables the local use of metal reinforcement techniques in structure interconnections and force transmission points.

Key words: bolted joint; hybrid material; local reinforcement; composite structure; titanium.

1. INTRODUCTION

The increasing requirements for weight reduction demand more and more the use of composite material in aerospace applications. There has been a progressive increase in the number of metal parts and structures replaced by composite materials, not only in military but also in civil aircraft design. Thus, the A380 aircraft shows a composite content of 23%, and the future Boeing 787 is expected to contain 53% of composite material. The use of advanced composite material not only permits a useful reduction in structural weight, but also virtually eliminates fatigue and corrosion handicaps and offers flexible and cost-efficient manufacturing possibilities with high structural integrability .

The use of composite material for spacecraft applications is also steadily increasing. The efficiency of space launchers is limited by the systems structural weight. Thus, every design measure for structural weight reductions contributes to a payload increase and a cost reduction.

The replacement of the Ariane 5 steel booster by a composite wound structure represents a good example of this trend, which arises from the requirements of manufacturing cost reduction, higher structural integrability, weight savings and higher performance by higher operating pressures (Dudenhausen et al., 2002).

Although composite technology offers the advantage of reducing the need of structural coupling by means of integral design and special manufacturing techniques, huge composite structures like future composite boosters may show structural interconnections due to production limitations as well as handling and transportation requirements due to established logistics.

One of the main methods currently used for joining components is still mechanical fastening, which has the advantage of no special surface preparations, easy disassembly and inspection and represents a reliable well-established and well-known method from its origin in the design of metallic structures. Nevertheless, to attain a satisfactory structural coupling efficiency with mechanical fastening is much more challenging with composite materials than it is for metals due to a high notch sensitivity, a lower shear and bearing strength and a dependance on laminate configuration. These properties represent a limiting factor on structural performance of composite structures and require special reinforcement techniques.

The load capacity of composite bolted joints is typically increased by means of a local laminate buildup at the structure coupling area. Thus, root joints, which are characterized by a high structural load transfer, tend to have a considerable laminate thickness. This can result in additional stresses due to eccentricities, particularly in the case of a one-sided padup, and can lead to complex geometries of adjacent structures as well as weight penalties due to

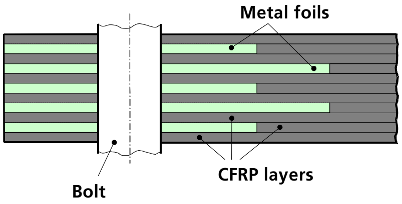

Figure 1. Local reinforcement at bolted joints

larger bolts and metal fittings.

2. CFRP/TITANIUM HYBRID MATERIAL

One design approach to increase the joint efficiency of highly loaded joints entails the local reinforcement of the joining area with thin metal foils, which are embedded into the composite laminate by replacing corresponding composite plies. This approach eliminates any laminate thickening, keeps membrane loads undeflected thus eliminating secondary stresses and reduces the geometrical complexity of the structures (Figure 1). Composite plies contributing most to total load carrying remain uninterrupted and pass from the composite region to the titanium reinforced region. The use of thin titanium foils enables a smooth load transfer from the composite plies being interrupted at the transition region to the titanium hybrid material and reduces stress concentrations due to load deflection and cross-section diminution. The minimum usable titanium foil thickness is limited by the laminate stacking and composite single ply thickness on the one hand and the foil raw material costs and foil production limitations on the other. The foil thickness determines the manufacturing efforts and costs of the reinforcement technique; though manufacturing costs can be reduced, using thicker metal foils compromises the coupling efficiency of the transition region.

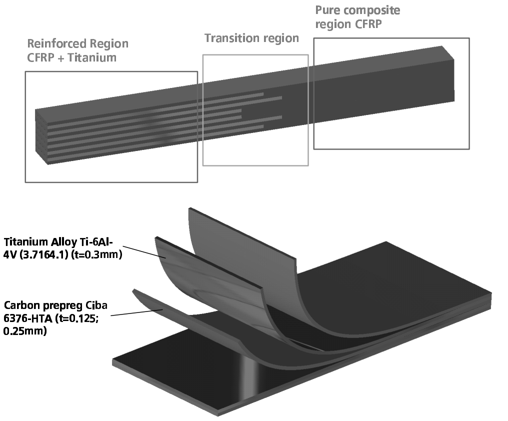

Figure 2. Hybrid Material Configuration

With its high specific mechanical properties, its corrosion resistance and electrochemical compatibility to carbon material, titanium is deemed to be the best material choice in combination with carbon composite material. The relatively low coefficient of thermal expansion in comparison to carbon laminate leads to low residual thermal stresses excited during curing at high temperatures (180° for conventional prepreg systems) and cooling down to room temperature. Thus, both stress concentrations at free edges and holes, and the diminution of the elastic behavior of the hybrid material can be kept low. However, due to its higher absolute strength and low raw and foil material cost, stainless steel is also considered and researched as reinforcement material. Its higher thermal expansion coefficient and density and its electrochemical sensitivity to carbon are some disadvantages.

2.1. Manufacturing

Prepreg technology is deemed to be the most appropriate manufacturing technology since it is widely used for highly loaded structures in a great variety of applications. Furthermore, prepreg technology offers a high flexibility considering the design of the multilayered hybrid material. Ply substitutions can be optimally arranged within the transition region with regard to the laminate configuration. Nevertheless, the suitability of resin infusion techniques considering the local use of hybrid material has also been successfully demonstrated. However, the use of tailored non crimped fabrics does not offer the high design flexibility of prepreg material and complicates to a certain degree the realization of an optimal ply substitution technique. A reasonable infusion strategy ensures the complete impregnation of the reinforced area without voids.

The lay-up process consists of stacking alternate layers of 0.3mm thick titanium alloy foils (Ti6Al4V) and 0.125 and 0.25 thick prepreg plies (Ciba 6376C-HTA/HTS), without adding any adhesive film (Figure 2). The selected titanium surface pretreatment consisted of a surface cleaning and a chemical pickling pretreatment which provided an optimal adhesion quality between the metal and the prepreg resin. Higher adhesion performance and delamination growth attenuation was achieved generating a metal surface macroroughness by means of surface grit blasting.

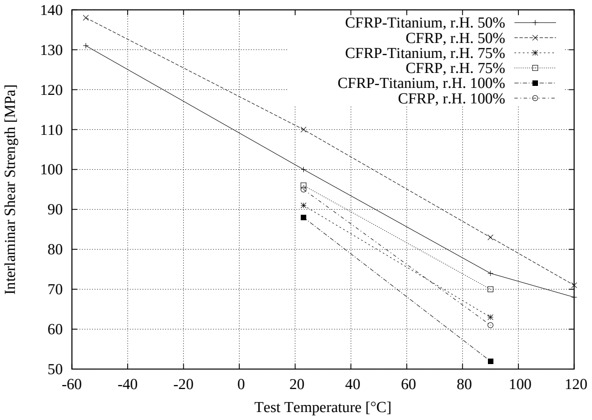

Figure 3. Interlaminar shear strength in dependance of temperature and moisture

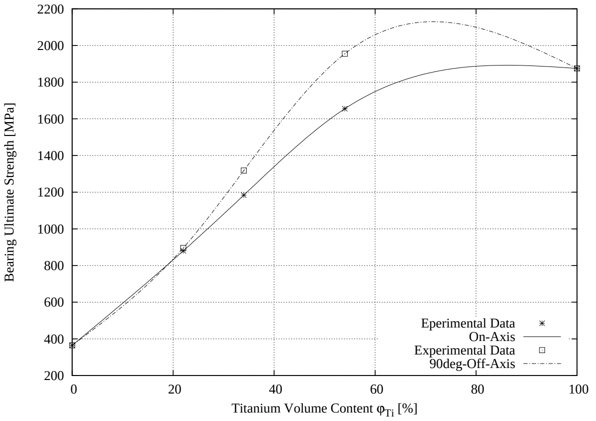

Figure 4. Bearing strength of Hybrid material in dependance of the titanium content

3. MECHANICAL PROPERTIES

Based on the prepreg technology, the mechanical behaviour of CFRP/Titanium as a reinforcement hybrid material has been analyzed by means of a variety of experimental tests. The investigation of the mechanical potential has been mainly focused on the strength increase of bolted joints.

3.1. Interlaminar Shear

The fracture resistance of the adhesion interface between the pre-treated titanium surfaces and the resin was evaluated by means of mode II in-plane shear tests. Short beam tests were run under the combined effect of temperature and moisture exposure. Cohesive failure has been observed. The reason for lower interlaminar shear values measured for the hybrid material is found in the superposed effect of thermal residual stresses (Figure 3).

3.2. Bearing Ultimate Strength

Bearing tests have been conducted with specimens showing different titanium contents. All prepreg plies were oriented in one direction. In addition, carbon specimens with different laminate configurations were tested for comparison (Figure 4). A bolt diameter of 6mm was used and installed with a clearance fit and a clamping torque of 0-0.6mm. The tested specimens featured an edge distance to diameter ratio of 3 and a width to diameter ratio of 4 and 5. The static tests were conducted up to failure in on-axis and 90°-off-axis loading direction.

Test results demonstrate the advantage of titanium reinforced composite material which offers a strength increase of about 80% under on-axis loading and 180% under 90°-off-axis loading compared to the bearing properties of a [50/40/10] carbon laminate (Figure 5). Higher strength increase rates result when comparing with laminates with a higher degree of anisotropy. Hybrid material containing 54% titanium offers similar bearing strength to titanium alloy.

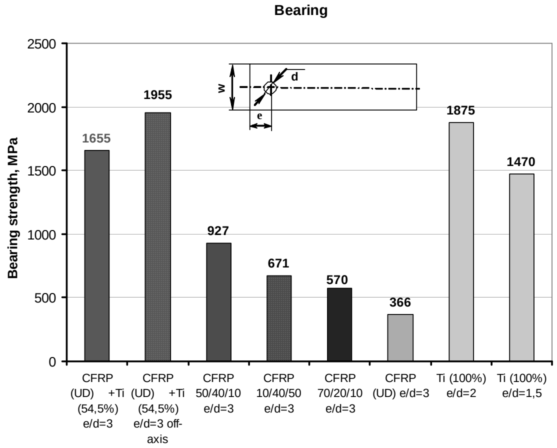

Figure 5. Bearing strength of different material configurations

The maximum specific on-axis bearing strength of the hybrid material, found at a titanium content of about 55% (Figure 6) is slightly lower in comparison to that of [50/40/10] carbon laminate, whereas the 90°-off-axis bearing strength is about 40% higher (Figure 7). However, the laminate specific strength does not reflect the absolute weight efficiency of the joint, since the laminate represents only a fraction of the whole local joint design of the structure. The realization of high absolute joint strengths contributes to reduced complexity and weight of secondary joint components such as bolts, fittings and connecting parts to a high extent, thus reducing the overall joint weight. The crucial effect of indirect weight savings

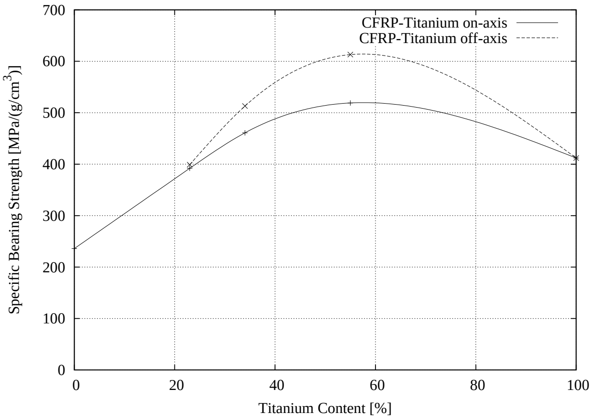

Figure 6. Specific bearing strength of hybrid material in dependance of the titanium content

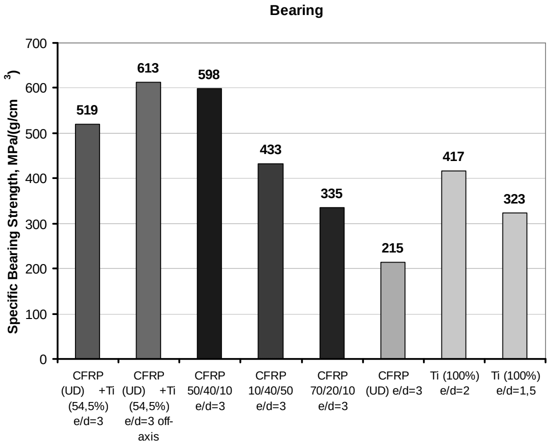

Figure 7. Specific bearing strength of different material configurations

can be demonstrated in the composite booster application. Analytical estimations predict an absolute weight saving of about a quarter tonne for each intersegmental joint in comparison to a composite monolithic design, due to a one-row instead of a two-bolt-row design, smaller steel connecting rings and less amount of bolts.

3.3. Bolted Joint Strength

3.3.1. Static Ultimate Strength

Double-lap three row bolted joints on hybrid laminates containing unidirectional carbon plies and various titanium contents (13, 23, 34 and 54.5%) were subjected to both on-axis and off-axis static tensile tests (Figure 8). For comparison, unreinforced 50/40/10 carbon laminates were also tested. Hi-Lok bolts (HL20-8) with a diameter of 6.35 mm and steel collars HL94-8 were used and installed with a clearance fit of H8/f7 and a clamping torque moment of 7-9 Nm. Absolute joint strength behavior is characterized by a steady increase, with rising titanium content, attaining its maximum value at about 25 volumetric content (Figure 9). The comparison to the bearing results demonstrates the dependence of the optimal titanium content on the number of rows.

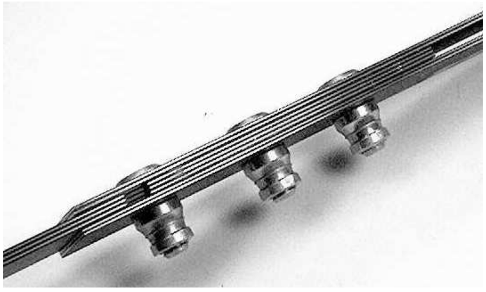

Figure 8. Three-row bolted joint

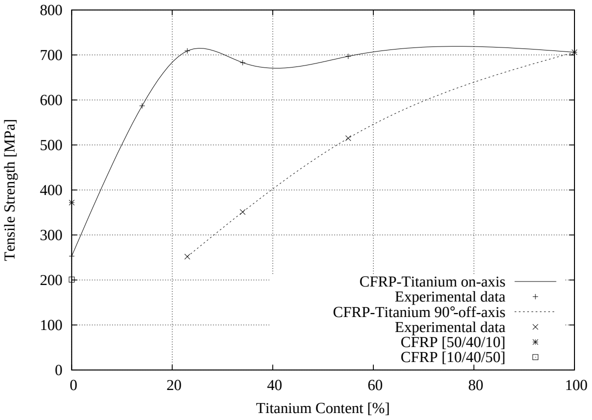

Figure 9. Bolted joint strength of hybrid material in dependance of the titanium content

In comparison to unreinforced bolted joints, the test results show not only a tensile strength improvement of up to 91% but also a maximum gain of specific tensile strength of 32% for a titanium content of approx. 20% (Figure 10). The failure mode of all tested specimens was characterized by net tension and delaminations located at the outer bolt row.

The effect of through-the-thickness clamping forces on torqued bolts was roughly analyzed on specimens containing 23% and 34% titanium. In comparison to torqued joints, the tensile strength of untorqued joints show a reduction of only 4%. Since unclamped bolted joints on 70/20/10 prepreg laminates feature a 21.8% lower tensile strength in comparison to clamped bolted joints, CFRP/Titanium is deemed to show a relatively low sensitivity regarding through-the-thickness clamping.

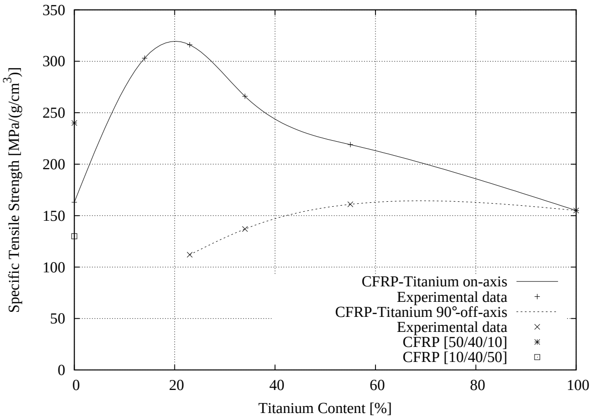

Figure 10. Specific bolted joint strength of hybrid material in dependance of the titanium content

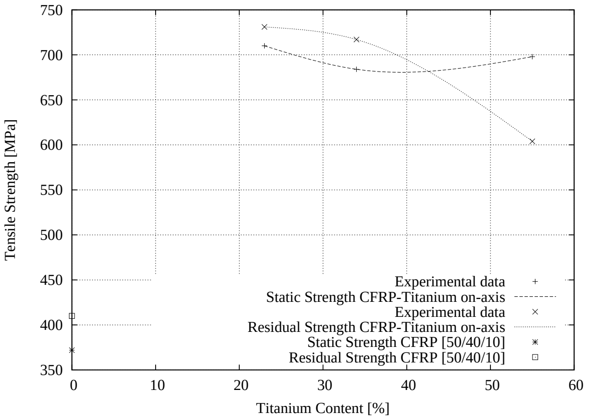

Figure 11. Ultimate residual strength after dynamic test

3.3.2. Dynamic Strength

The fatigue strength of bolted joints was experimentally evaluated with specimens being subjected to the standardized MINITWIST load sequence, which is commonly applied for the analysis of the dynamic behavior of wings. The maximum overload amounted to 66% of the static tensile strength. All specimens withstood 180000 flights without failure, which represent 5 times the A-320 aircraft life. The residual strength after dynamic loading was even higher than the static tensile strength (Figure 11).

4. TRANSITION REGION

In order to exploit the mechanical advantages of a local metal reinforcement by means of ply substitutions without laminate thickening, the transition region between the titanium reinforced material and the composite laminate has to be carefully designed to achieve a joint efficiency at least as high as that of the bolted joint (Figure 12). Due to their lowest load carrying, first the 90°-layers and then the ±45° layers are replaced by titanium foils. Finally, some of the highly loaded 0°-layers may be replaced. Thus, a smooth transition from carbon laminate to the reinforced composite is achieved without laminate thickening and eccentricities, reaching joint efficiencies of 80% which enable the local use of the reinforcement approach. Since the use of fabrics for resin infusion techniques usually do not permit the separation of single plies with one orientation, the design of the transition region and the suitability of the reinforcement philosophy has to be carefully analyzed.

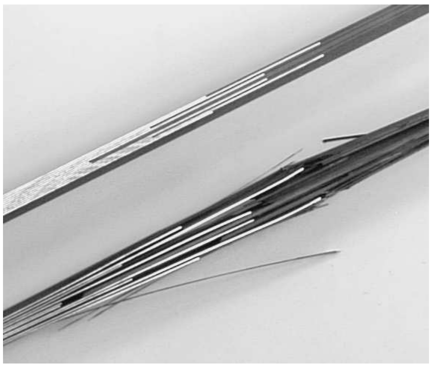

Figure 12. Transition region before and after testing

5. APPLICATION

The advantages of a hybrid material as a locally applied reinforcement technique could be demonstrated with reference to the advanced CFRP Ariane 5 booster case (MAN, 2004). The reference CFRP monolithic joint design was characterized by a two-row bolted joint with a considerable local laminate thickening of 122%. An alternative hybrid joint design results in a weight reduction of about 36% (Fink et al., 2005). Since no laminate thickening is needed to improve the laminate bearing properties, no secondary stresses are excited by local eccentricities. An eccentricity of the magnitude of half the laminate thickness leads to 4 times higher stresses (Kolesnikov, 1999). Elimination of laminate thickening also leads to lower bolt bending and consequently to lower through-the-thickness stress gradients. Shrinkage stresses due to through-the-thickness gradients of the cooling rate, mainely associated with thicker laminates, are eliminated, since the laminate thickness is kept low and the inserted metal foils contribute to a homogeneous heating and cooling process. The lower number of fasteners not only reduces weight but also assembly work. The use of a one-row design results in smaller and lighter steel connecting rings (Figure 13). Of course, the application of a local reinforcement technique may result in additional manufacturing efforts and costs which

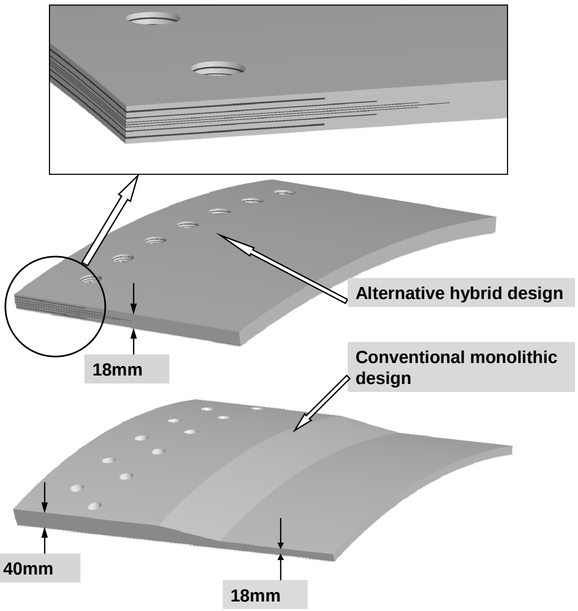

Figure 13. Hybrid material application on root joint design

have to be evaluated in relation to the assembly and weight advantages.

In addition, closed cylindrical configurations have specific design and manufacturing requirements. In view of the laminate thickness and configuration, the suitability of resin infusion or resin injection manufacturing techniques has successfully been demonstrated experimentally.

6. CONCLUSIONS

CFRP/Titanium hybrid material reinforcement is expected to be a technology which enables a considerable increase in the coupling efficiency of bolted joints of highly loaded composite structures. It offers the following advantages:

- High bearing strength, shear strength and compression strength
- High joint efficiencies of bolted joints
- Low influence of temperature and moisture
- Avoidance of local build-up
- Avoidance of local eccentricities and secondary stresses
- Reduction of overlap lengths
- Reduced number of bolts, and smaller bolt lengths
- Smaller and lighter connecting parts
- Simplification of structure geometry
- Reduction of through-the-thickness stresses excited by shrinkage gradients in thick laminates

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