INCREASE OF BOLTED JOINT PERFORMANCE BY MEANS OF LOCAL LAMINATE HYBRIDIZATION

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ABSTRACT

One effective method of increasing the mechanical joint efficiency of highly loaded composite joints entails the reinforcement of the joining area with thin high-strength metal foils. These foils are locally embedded into the composite laminate by means of ply substitution techniques, thus avoiding any local laminate thickening and providing for a local hybrid laminate with high bearing and shear capabilities and high robustness.

In the frame of an ESA-TRP project, the feasibility and suitability of this advanced reinforcement technique is being extensively studied in view of its application on highly loaded bolted joints of cylindrical and conical spacecraft structures and monolithic and sandwich laminates. The future Ariane 5 composite Booster, payload adaptors and distancing modules are some of the main applications being considered within the study.

The numerical and experimental studies are focused on the mechanical performance improvement in comparison to the reference conventional design.

Sensitivity studies are performed which analyze the impact of different parameters on the reinforcement efficiency and bearing capabilities. The delamination behavior of the transition region from the basis composite laminate to the hybrid region, which is characterized by a gradual replacement of certain composite plies, is analyzed by means of numerical simulations. The manufacturing integrability, the processability as well as the impact on the overall structural design and the dimensional stability are some further issues to be evaluated within the scope of the present project.

1. INTRODUCTION

One of the main methods currently used for joining composite components for aircraft and spacecraft applications is still mechanical fastening, which shows the advantage of reliability, detachability and inspectability and represents a well-established and well-known method from its origin in the design of metallic structures. However, attaining a satisfactory structural coupling efficiency with composite materials is much more challenging than it is for metals due to the low bearing and shear strengths, the higher notch sensitivity, the dependence on laminate configuration and the influence of environmental effects. These properties represent a limiting factor on the structural performance of composite structures – especially considering highly anisotropic laminates, since the coupling efficiency of bolted joints considerably decrease with increasingly directional material performance. This problem becomes much more critical for multi-row bolted joints due to the non-uniform load distribution characterized by overloaded outer rows.

The load capacity of composite bolted joints is typically increased by means of a local laminate build-up at the structure coupling area. The resulting laminate thickness increase, especially for highly loaded root-joints, leads to additional laminate stresses due to eccentricities, particularly in the case of a one-sided pad-up, to complex geometries of adjacent structures as well as to a significant weight increase due to larger grip lengths, larger bolt diameters and heavier metallic fittings.

The increasing requirements for weight reduction and cost efficiency for aerospace and spacecraft structures demand the development of alternative advanced coupling techniques. The coupling efficiency of highly loaded composite root joints has been proven, in the frame of extensive previous research activities at the German Aerospace Center DLR, to be considerably improved by the use of a local reinforcement of the joining area with thin high-strength metal foils using ply substitution techniques, thus providing the laminate at the coupling region with significantly higher bearing and shear strengths, a higher coupling stiffness and a lower sensitivity of the mechanical properties to the laminate configuration and environmental effects. Higher absolute mechanical properties lead to an avoidance of any local laminate thickening and eccentricities and allow possible reductions of the number of bolts and bolt rows – and the corresponding assembly work –, thus resulting in a mechanically and economically efficient design.

In the frame of the present ESA-TRP project “Increase of Bolted Joint Performance for CFRP” (scheduled end of project: February 2008) diverse European partners (DLR, HPS, EADS CASA Espacio, INEGI, MT Aerospace, Kayser-Threde, Contraves Space) are involved under the technical leadership of the DLR in the development and implementation of this advanced technique for highly loaded spacecraft applications, aiming at structural weight savings, assembly work reductions, robustness increase and overall structural design optimizations.

2. LOCAL REINFORCEMENT CONCEPT

The local reinforcement technique is characterized by the gradual substitution of specific composite plies by high-strength metal foils within the coupling region (Fig. 1; Fig. 2). The remaining composite plies are not interrupted and pass from the pure composite region through the transition region to the hybrid region, thus acting there as adhesion interlayers between each embedded metal foil. The continuous plies should preferably contribute most to the total load carrying of the laminate.

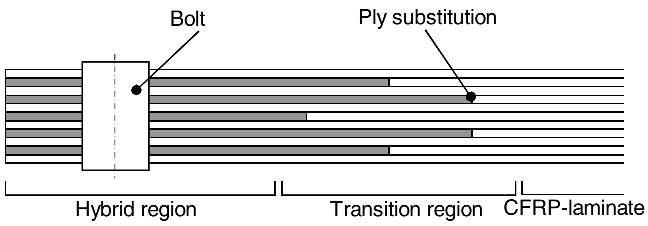

FIG 1. Local reinforcement concept

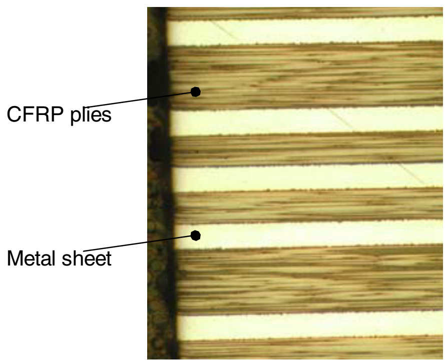

FIG 2. Hybrid laminate at bolt location

The local implementation of metal foils by composite ply replacement results in a hybrid material with high bearing capabilities, high tension, shear and compression strengths at the coupling region, which are indispensable to obtain high bolted joint efficiencies. This approach eliminates any laminate thickening thus avoiding eccentricities and secondary stresses and reduces the size and weight of fastening elements.

The ply substitution strategy, as well as the maximum possible titanium content is strongly dependant on the basis composite laminate configuration and stacking sequence. Provided the case of a main loading direction, weak plies contributing less to total load carrying should be replaced first. Highly loaded plies should be only replaced last within areas with high metal content.

Each ply substitution point represents a material discontinuity (Fig. 3), which is a source of stress concentrations due to ply load transfer mechanisms, in analogy to the effects known for conventional ply-drop-off and add-on techniques. Overstressing of composite plies adjacent to the ply substitution points on the one hand, and delamination onset and propagation on the other are two essential issues related to the ply substitution techniques that affect the load capability of the transition region.

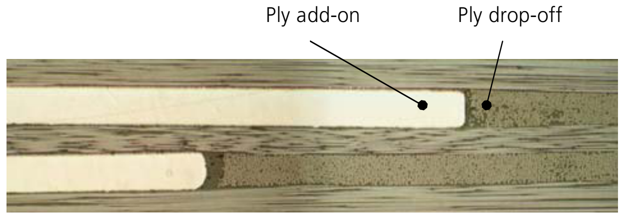

FIG 3. Ply substitution points

With its high specific mechanical properties, its corrosion resistance and electrochemical compatibility and the relatively low CTE mismatch, titanium is deemed to be the best choice in combination with carbon composite material. The low CTE mismatch leads to relatively low thermal residual stresses and structural deformations, as well as to a low diminution of the titanium elastic behaviour. However, due to its higher ultimate strength, higher stiffness and low raw material cost, stainless steel is also considered as a possible alternative reinforcement material, which shows, on the contrary, important penalties in terms of CTE mismatch and density.

Table 1 shows some mechanical properties of diverse reinforcement materials, which are being considered within the present study. However, the focus is set on the titanium alloy Ti15-3-3-3 due to its cold workability and hardenability, which enable the tailoring of high yield and ultimate strengths required to reach high bearing capabilities of the hybrid material.

Reinforcement Material	**Ti 6Al-4V**	**Ti 15Mo** [7]	**Ti 15-3-3-3**	**St 1.4310**
Ultimate Tensile Strength [Mpa]	925 [4]	1350 [6]	1370 [5]	2000 [2,8]
Bearing Strength [Mpa]	1875 [4]	2084 [1]	2085 [1]	3280 [1]
E-modulus [Gpa]	110 [2]	78 [2]	118	190 [2]
CTE [10-6/°C]	8.6 [2,3]	8.4	8.6 [2,3]	16.4 [2,3]

[1] Estimated value acc. to HSB 20110-01
[2] Manufacturer information
[3] At 20°C
[4] Acc. to HSB 12571-01
[5] Cold formed and age hardened
[6] Theoretically reachible value
[7] Under development ATI
[8] Cold formed

TAB 1. Properties of different reinforcement materials

In order to ensure a strong and durable adhesion between the metal sheets and the prepreg plies the metal surfaces are subjected to a pre-treatment process which principally consists of mechanical deoxidation, caustic etching, Sol-Gel application and Primer coating. No additional adhesive coating is used.

3. PROJECT OBJECTIVES

The objective of the current project is found in the analytical, numerical and empirical characterization of the mechanical performance of hybridized bolted joints which encloses the evaluation of the impact of local reinforcement techniques on the overall structural efficiency and dimensional stability, sensitivity and parametric studies and an extensive coupon test program. The different activities are accomplished based on previously selected applications.

The integrability for real structures and the compatibility of the hybrid technology with a nominal industrial process is intended to be demonstrated and evaluated by means of the design, the manufacturing and test of a full-scale breadboard.

Following work activities are being elaborated:

- Identification of highly loaded joints of spacecraft applications and elaboration of evaluation criteria
- Screening of alternative advanced techniques for bolted joint performance increase
- Preliminary analytical joint assessment and design, selection of relevant applications
- Numerical analysis, sensitivity and parametric studies, performance prediction
- Coupon test, failure analysis, correlation analysis
- Breadboard design, manufacturing, test.

4. SELECTED APPLICATIONS

A wide variety of real applications were defined and evaluated according to the specified criteria. With regard to the technological suitability and feasibility, three applications have been finally selected for detailed development:

- ACU VEGA Adaptor interface joints and discrete attachments
- Ariane 5 booster intersegment joint
- Interface ring attachment of ATV SDC

The selected joints cover very diverse applications in terms of manufacturing techniques, reference laminate configuration and reference design, thus setting different requirements on the reinforcement integrability.

4.1. ACU VEGA Adaptor

The ACU GEGA Adaptor is a conical monolithic shell, which is manufactured by automatic fibre placement at EADS CASA Espacio. The laminate shows a moderate thickness of 3mm which is built of 0.25mm composite plies. The main loading of the continuous interference ring, which shows a one-row bolted joint design, is in tension and compression along the cone generatrix. The reference design does not show any local thickening.

While the loads acting on the bolted joint are relatively low, this structure has been deemed to be an important candidate with regard to the verification of manufacturability, inspectability and compatibility with standard industrial processes. With regard to its moderate size, this structure has been selected for full-scale studies within the breadboard phase.

4.2. Ariane 5 booster intersegment joint

Contrary to the adaptor, the advanced composite design of Ariane 5 booster developed by MT-Aerospace (Fig. 4) is a highly loaded cylindrical pressurized vessel with a laminate thickness of 18mm and an inner diameter of about 3m. The reference structure is manufactured with resin infusion techniques and uses 0.5mm thick unidirectional fabrics. The reference design shows a local thickened laminate of 40mm and a two-bolt row design. The coupling between two intersegments is performed with heavy steel interface rings.

Resin infusion laminates are often characterized by the use of thick tailored fabric plies, which enables manufacturing cost and process time reductions. The use of thick plies, however, implies some disadvantages in terms of the design flexibility of a local reinforcement technique using ply substitution techniques. Since single plies are replaced by metal sheets, the substitution strategy becomes much more challenging for laminates with a large ply-to-laminate thickness ratio. The interruption of thick plies lead to higher stress concentrations and load deviations, thus exciting a higher risk of delamination occurrence and overstressing of adjacent plies.

Moreover, since a through-the-thickness laminate impregnation is not realizable at the hybridized region, a proper infusion strategy has to be accounted for during the infusion process to ensure proper impregnation free of voids and porosity of the reinforced area by an in-plane injection.

FIG 4. Ariane 5 booster composite case (MT)

4.3. ATV SDC Interface ring attachment

The ATV Separation and Distancing Module, developed by Contraves Space, is a sandwich cylindrical shell with an inner diameter of almost 4m which is manufactured with prepreg technologies (Fig. 5). The sandwich facesheets feature a small thickness of about 1 mm and are built with 0.125mm prepreg plies. The interface coupling is arranged with aluminium rings with a one-row bolted joint design. The facesheets are locally reinforced by means of a one-sided bonded 2mm thick GFRP-doubler within the sandwich laminate to provide for sufficient bearing capabilities and facesheet support.

FIG 5. ATV SDC module (Contraves Space)

The feasibility of a local reinforcement using ply substitution techniques is generally much more challenging for sandwich shells than it is for monolithic laminates due to the use of thin facesheets, which results in important disadvantages in terms of the design flexibility of a ply substitution strategy. Moreover, to eliminate a local facesheet pad-up by the use of a local laminate hybridization increases the risk of a laminate failure by stability loss at the bolt loaded hole prior to the full nominal bearing capability of the laminate being reached if not enough lateral support is ensured.

5. POTENTIAL ESTIMATIONS

The potential of the local hybrid reinforcement can be exemplarily demonstrated on the Ariane Booster Intersegment joint. Figure 6 shows the reference monolithic design featuring a Clevis-Tang joint of the steel connecting rings.

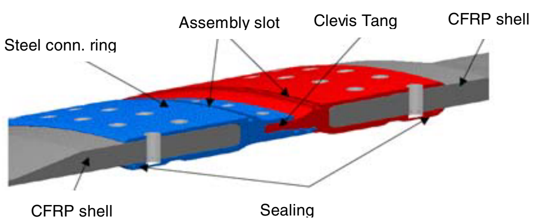

FIG 6. Intersegment joint design

The bearing capabilities of the reference skin are increased by the use of a one-sided laminate thickening of 40mm against 18mm of the main cylinder skin.

5.1. Advanced design

Using analytical methods it has been demonstrated that a local hybridization of the main cylinder skin with 45% of titanium enables the elimination of any local thickening, as well as a single-row bolted joint design (Figure 7). The evaluation was performed with regard to estimated ultimate bearing capabilities of hybrid material using high-strength titanium alloy Ti-15-3-3-3 based on previous research results.

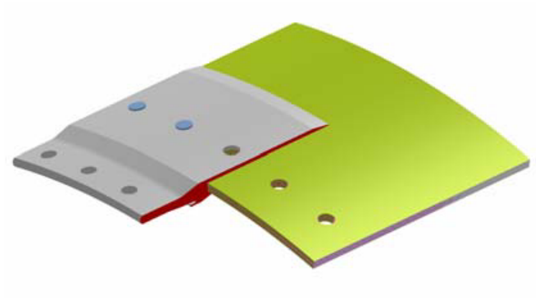

FIG 7. Advanced design using local CFRP/Ti laminate reinforcement without thickening

As a result, the additional structural mass required for the intersegment joint is 37% less than the original reference design, thus allowing an estimated mass saving of 280kg for each intersegment joint. This is a consequence of the elimination of the local thickening, smaller bolt lengths due to reduced grip lengths, the reduction of the steel ring width – as a result of the single bolt row design – and a reduction of the number of bolts of 68%.

5.2. Reinforcement strategy

The local hybridization is arranged by means of the substitution of 50% of 90°-plies and 11% of 0°-plies. The associated strength loss of the hybrid region in hoop direction can be compensated by the load carrying contribution of the stiff steel connecting rings. The remaining 90°-plies in combination with the titanium content provide for enough 90°-off-axis hybrid laminate strength, which is required by the hoop stresses that result from the inner operational pressure.

One important issue for pressurized vessels is the impact of the stiffness discontinuities that arise from a local reinforcement. Hoop stiffness discontinuities result in a “necking effect”, which describes the radial elongation constraint at the stiffer area, and excites considerable local bending stresses.

Due to the substitution of 90°-plies at the coupling region and the thickness reduction, the total hoop stiffness of the advanced solution is even slightly lower in comparison to the reference design, which, on the contrary, increases the hoop stress level of both, the connecting ring and the hybrid laminate.

In view of the “necking effect” the ply substitution is designed to start close to the laminate midplane and progressively grow in a staggered manner to the laminate outer surfaces, in order to ensure a smooth change from both, the longitudinal and the flexural stiffness along the transition region, thus alleviating stiffness discontinuities.

The change of longitudinal and flexural stiffness is plotted in Figure 8. Due to the gradual increase in longitudinal stiffness, the stress state of each ply decreases with increasingly titanium content. For that reason, the substitution of the 0°-plies are arranged last (Points Z1 and Z2), thus alleviating the stress concentrations at the corresponding substitution points.

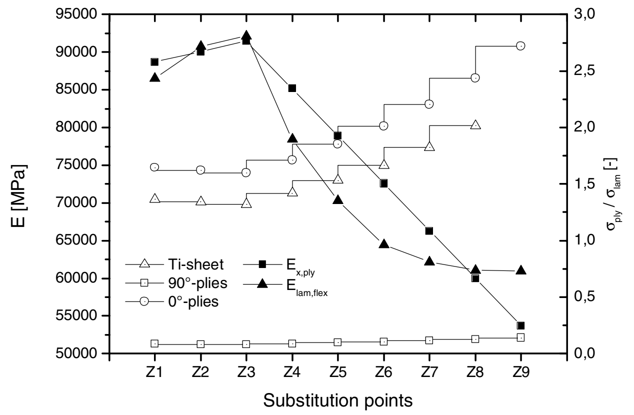

FIG 8. Stiffness and stress level change along transition region

5.3. Stress analysis

The stress state of the pressurized booster at the intersegment joint has been analytically estimated (and numerically validated) for both the reference design with local thickening and the advanced hybridized joint.

The hoop stress and the maximum total longitudinal stress – which includes tensile and bending stresses – are shown in Figure 9 and Figure 10 respectively. The hoop stress state of the laminate within the coupling region (Z1) increases for the advanced design due to its lower hoop stiffness and lower total thickness.

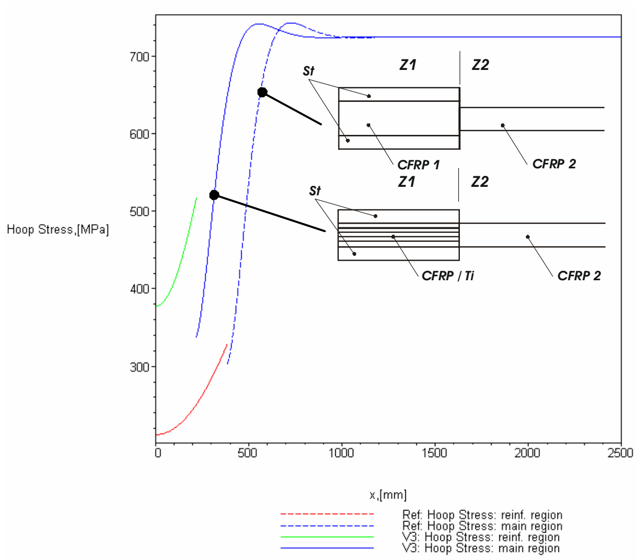

FIG 9. Hoop stress of reference and advanced design

On the contrary, the total stress at the critical location – border between basis skin and the steel ring stiffened coupling region – is lower for the advanced design, as a result of the attenuated necking effect, which leads to 20% smaller bending stresses. Moreover, the region affected by the necking effect is lower due to the reduced coupling area that results from the single-row bolted joint design.

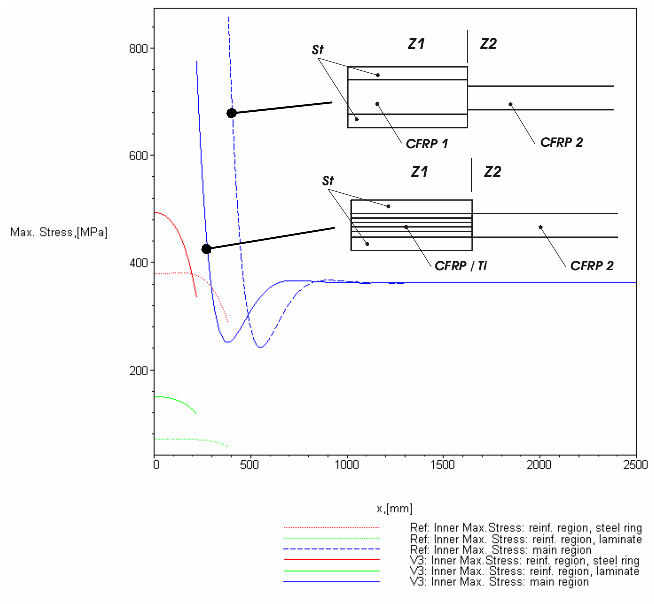

FIG 10. Maximum total stress of reference and advanced design

In view of the high stress concentration at the critical location, the reinforced area is extended beyond the steel ring stiffened coupling area as schematically shown in Figure 11, thus considerably increasing the laminate strength at that point. The effect on the stress state is negligible.

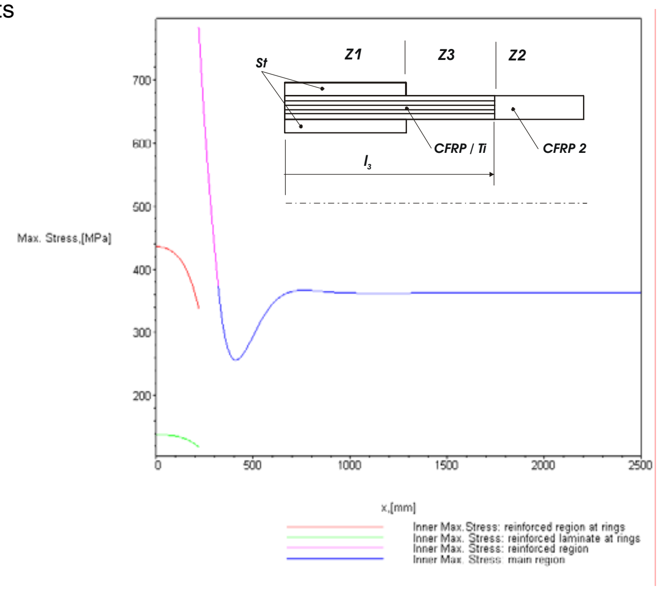

FIG 11. Maximum total stress of advanced design with extended reinforced region

5.4. Geometrical distortion

The local laminate reinforcement leads to a gradient material with varying material's properties. Since the composite structure generally is cured at elevated temperatures, the implementation of titanium sheets results in structural deformations after curing and cooling down to room temperature. The geometrical distortions and the associated thermal residual stresses are dependant on the materials mismatch in terms of CTE and stiffness, as well as on the operational temperature.

The radial displacement after curing and cooling of the advanced Ariane 5 composite booster case is plotted in figure 12 along the axis. The reinforced region contracts during the cooling down to RT and excites a maximum radial relative displacement of about 1mm, which is deemed to lead to certain assembly difficulties and may require special design adaptations. The associated laminate residual stresses are negligible.

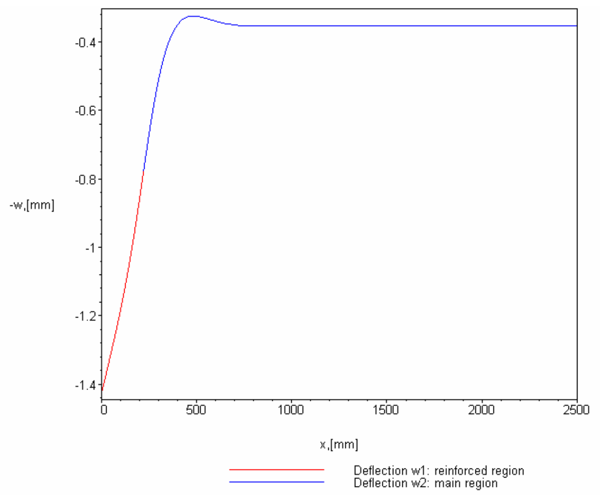

FIG 12. Radial displacement of locally reinforced Ariane 5 composite case after curing and cooling down to RT

The geometrical distortions of the ACU VEGA and the ATV SDC applications have been determined to be low; the latter is, however about twice as high as the former, due to the relatively low total hoop stiffness of the sandwich laminate. This leads also to a considerably larger region affected by the geometrical distortions.

6. PARAMETRIC AND SENSITIVITY STUDY

In the frame of a parametric and sensitivity study, detailed fundamental research activities have been performed based on generic and non-generic, application oriented configurations with the intention of obtaining basic dependencies to better understand and exploit the potential of local hybrid reinforcement techniques.

Two mechanisms act on the mechanical efficiency of local hybrid reinforcement techniques: the bearing capability of a bolt loaded hole, and the load capability of the transition region. The latter is limited on the one hand by the ply overstressing of adjacent plies due to local stress concentrations at each ply substitution point and by the delamination of the interrupted plies on the other. Of course, the coupling efficiency of the transition region has to be higher than the coupling efficiency of the bolt loaded hybrid laminate; otherwise, the potential of the hybrid material would not be fully exploited.

6.1. Bearing capacity

The load capacity in terms of first ply failure and the occurrence of yielding of the metallic layers has been analytically studied using the software tool Fastcomp, once specially adapted for its use on hybrid materials in order to account for thermal residual stresses and the yielding of metal. Using the Larc03 failure criteria for matrix cracking for the composite plies and the Von Mises criteria for the metal foils, the first ply failure loads were determined by searching for damage in the hole boundary.

Fastcomp has also been used for the estimation of the bearing strength applying a failure criteria in a characteristic curve which is located in a region away from the hole boundary. The predicted ultimate strength is reached once fibre fracture is determined within the characteristic curve and represents the first non-linearity of the bearing response. This approach, validated for pure composite laminates, can be extended to hybrid metal laminates assuming that metal yielding does not occur but in the characteristic curve, which means that the joint's mechanical response is linear up to the first failure event in the characteristic curve. Furthermore it is assumed that the characteristic curve approach is also valid for hybrid materials and may be derived from data of pure composite laminates. The analytical tool does not simulate elasto-plastic behaviour of the metal, nor the damage process beyond the first point of non-linearity. For that reason, the ultimate bearing strength in terms of maximum bearing capability can not be determined.

The impact of varying metal stiffness, operational temperature, metal yield strength and metal content on the FPF and ultimate bearing strength has been studied with regard to the VEGA adaptor reference laminate and the variety of possible reinforcement materials. The effect of the thermal residual stresses on the first ply failure (FPF) of a reference laminate reinforced with 33.3% of metal is exemplarily shown in Figure 13.

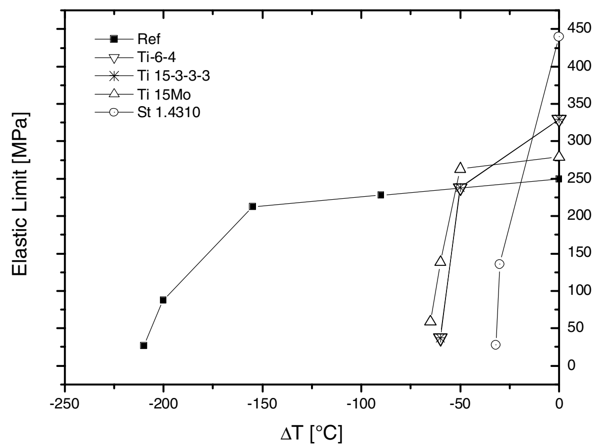

FIG 13. Effect of operational temperature on FPF

Thermal residual stresses arise due to the CTE mismatch and increase with decreasing operational temperatures. First ply failure at the hole boundary is expected at low ΔT, which means that matrix crack already occurs at cooling down from curing temperature to RT (ΔT=-155°C) as a consequence of the thermally induced ply stresses. However, matrix cracking is not to be considered a limiting criterion for the load capacity of a bolt loaded hole. Other laminate configurations have shown, however, no sensitivity to thermal residual stresses in terms of FPF; thus, the occurrence of FPF is strongly dependant on the laminate stacking configuration.

The effect of ΔT on the bearing strength of the same laminate is shown in Figure 14. Contrary to the FPF, bearing strength is characterized by a low sensitivity to applied temperature and is dominated by yielding of the metallic plies.

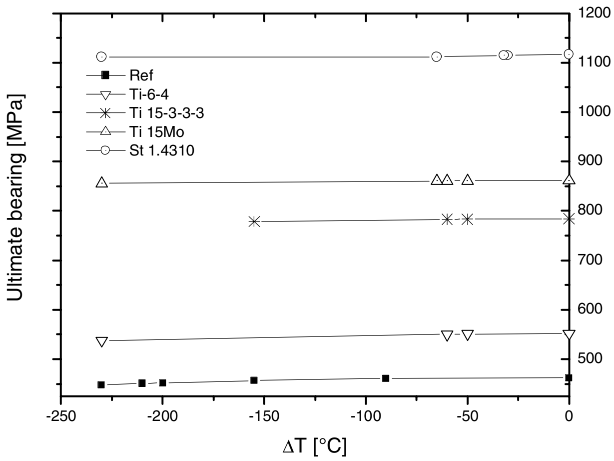

FIG 14. Effect of operational temperature on ultimate failure

The strength increase as a function of the metal content for the VEGA adaptor laminate for ΔT=0 is plotted in Figure 15.

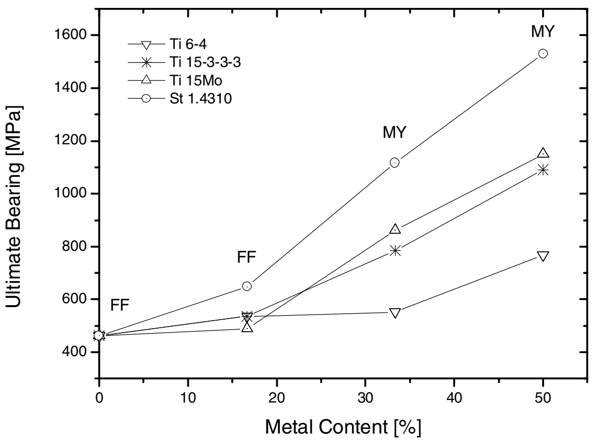

FIG 15. Estimated bearing strength for VEGA reference laminate in relation to the metal content

The bearing failure of the reference laminate and the laminates with low metal content is triggered by fibre compressive fracture (FF), whereas those laminates with higher metal content feature yielding failure (MY) of the metal sheet.

Table 2 shows the expected improvement in bearing strength for the VEGA laminate being reinforced with different materials and metal contents. Due to its relatively low strength, Ti 6-4 does not provide for sufficiently high improvements. High metal contents and higher metal strengths lead to considerable reinforcement effects, reaching improvements up to 150% for titanium and 230% for high-strength steel. Lower titanium stiffness is deemed to have a positive effect on bearing strength.

Met. content	Ti 6-4	Ti 15-3-3-3	Ti 15Mo	St 1.4310
16,7%	16%	16%	6%	40%
33,4%	19%	70%	86%	142%
50%	66%	136%	149%	231%

TAB 2. Estimated bearing strength improvement for different metal contents and reinforcement materials

The calculation of the bearing strength under offset loads results in a lower sensitivity of hybrid material in comparison to the reference pure composite laminate, which demonstrates a general improvement of robustness.

6.2. Delamination resistance

The mechanical efficiency of local hybridization approaches is dependant not only on the bearing capabilities of the hybrid material, but also on the load capability of the transition region, which is characterized by ply substitution points at which overstressing of adjacent plies on the one hand, and delamination failure on the other may occur. The delamination response of generic and non-generic, application-oriented ply substitution configurations has been numerically analyzed. Some generic parameters of interest are, among others, the orientation of the replaced plies, the orientation of the adjacent plies and the thickness of the titanium sheets.

A three-dimensional-generalized plain strain model was used to perform the parametric analysis. Each model consists of a line of 8-node three-dimensional elements, using kinematic constraints to impose a generalized plain strain state.

Delamination between the plies has been simulated using zero-thickness cohesive finite elements, which combine strength and fracture mechanics approaches, and can be used to simulate both the onset and propagation of delamination. The onset of delamination is predicted using stress-based criteria, and the delamination propagation is predicted using fracture mechanics. Cohesive elements do not require pre-cracks. The ply damage resulting from the overstressing of the adjacent plies is predicted applying the LaRC04 failure criteria. ABAQUS user subroutine UVARM was used to postprocess both delamination damage and ply overstressing.

The modelling of one ply substitution point is exemplarily shown in Figure 16, which features a fine meshing in the vincinity of the substitution point and cohesive elements located at the ply top, bottom and transverse interfaces.

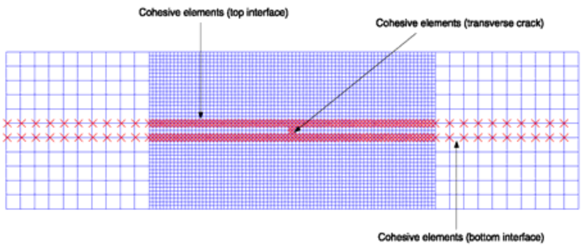

FIG 16. Ply substitution point modelling

Generic analysis deals with the impact of basic parameters on the mechanical behaviour of ply substitution points. Those are e.g. the orientation of the replaced composite plies, the orientation of the adjacent plies, the total laminate thickness, the thickness of the metal sheet and the length of the resin rich zone.

The analysis of actual joint configurations describes the effects of step distance, thermal residual stresses and loading direction (tension vs. compression) for the proposed laminate configurations.

The analysis results of a ply substitution point with a 0°-ply being replaced by a titanium sheet are given in Figure 17, where the value of the failure criterion for fibre tensile failure is post-processed at the onset of fibre failure.

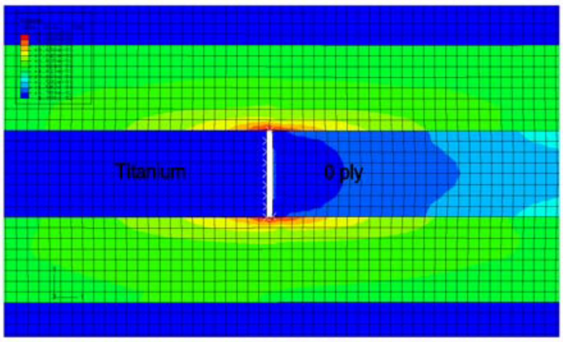

FIG 17. Ply substitution point stress state at the onset of fibre failure

The stress concentrations at the ply substitution point are clearly visible, as well as the transversal crack at the vertical interface between the dropped 0°-ply and the added titanium sheet, which triggers the occurrence of delamination fracture process zones at the longitudinal ply interfaces.

The corresponding evolution of the delamination fracture process zone along the interfaces between the titanium insert and the 0°-composite ply and the adjoining plies is shown in Figure 18 in relation to the percentage of the applied remote stress against the ultimate stress at the onset of fibre fracture. The damage variable d describes the damage state and the load capability at the interface: for d=0, the material is undamaged, for 0<d<1 the interface is strain-softened and still capable to transfer loads until d=1, at which crack occurs.

It is observed that there is no delamination before fibre fracture, but rather a fracture process zone since the damage variable is less than unity at a remote stress corresponding to fibre fracture.

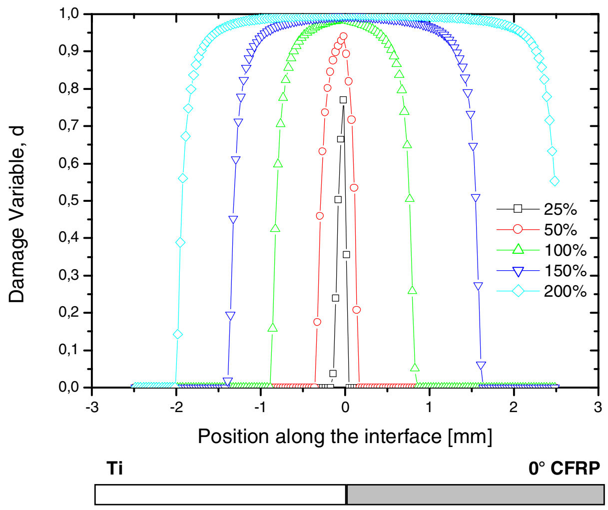

FIG 18. Evolution of fracture process zone

The orientation of the replaced composite plies affects the ultimate failure load of the transition region: more compliant plies result in a higher remote stress at the onset of fibre tensile failure. In addition, the fracture process zone at the interface with the adjoining layers is unsymmetrical when 90° or 45° plies are replaced. The orientation of the adjacent plies affects both the failure stress and the type of inelastic behaviour that occurs after the propagation of the transversal crack. For all configurations investigated, the fracture process zone is small until ultimate fibre failure. Thus overstressing has been deemed to be the driving failure mode of all configurations regarding the actual material's properties.

7. MANUFACTURING

A preparatory phase to the test campaign aimed to verify and optimize the manufacturablity and inspectability of locally hybridized laminates. The tack capabilities, the process integration and the machinability (drilling, milling) are some issues which have been successfully analyzed and optimized regarding conventional industrial processes.

Due to the material combination and the hardness of titanium the tool has to be carefully chosen. In any case, the machining operations are characterized by a considerable tool wear. The NDI-capability has been successfully demonstrated on samples containing typical defects in accordance with the inspection methods used for Ariane 5 structures. A scan of the analyzed panels using through-transmission ultrasonic inspection techniques is shown in Figure 19. Pulse-echo ultrasonic inspections were deemed to be unfeasible.

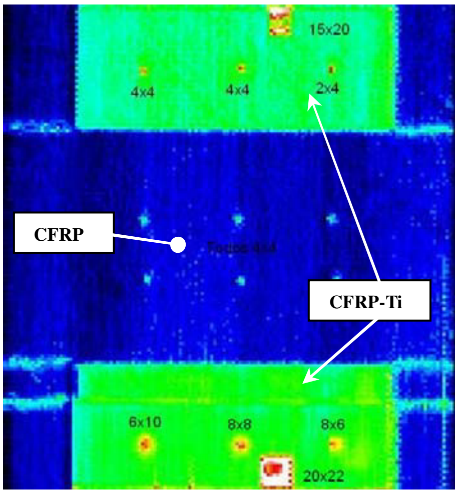

FIG 19. Transmission ultrasonic scan of test panel containing artificial failures

8. TEST CAMPAIGN

The planned test campaign includes an extensive coupon test phase and a breadboard test phase. During the coupon test phase simple flat coupons are tested in order to obtain basic mechanical performance data on hybrid material in terms of tension, compression, bearing and fracture toughness. The laminate configurations are chosen with regard to the selected applications. Some joint samples with a higher degree of detail are designed based on the actual reference design and statically as well as dynamically (for one selected application) tested. Figure 20 shows one exemplary bearing specimen (previous DLR research work), Figure 21 a planned detail sample of the advanced ATV SDC joint.

FIG 20. Hybrid bearing specimen

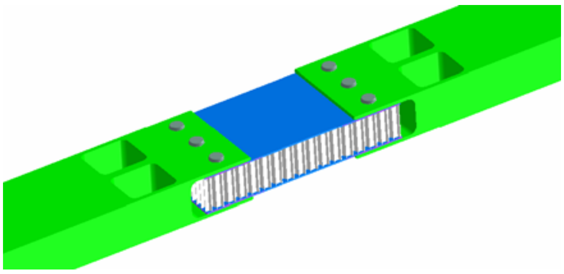

FIG 21. ATV SDC sandwich joint sample

The compatibility of the hybrid technology with a nominal industrial process is planned to be demonstrated by means of a full-scale breadboard manufacturing. The structure selected for this purpose is based on the ACU VEGA adaptor which is shown in Figure 22 in its original design.

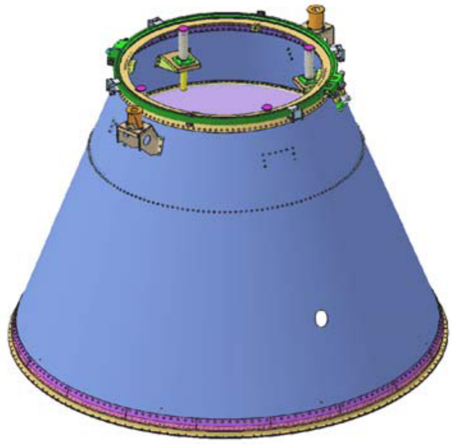

FIG 22. ACU VEGA payload adaptor: original design

In order to extend the applicability of a local hybrid reinforcement, some design variations are planned to study a wide diversity of solutions on the cone surface. Thus, the breadboard represents a generic demonstrator that collects several types of possible joints that are found for actual adaptors.

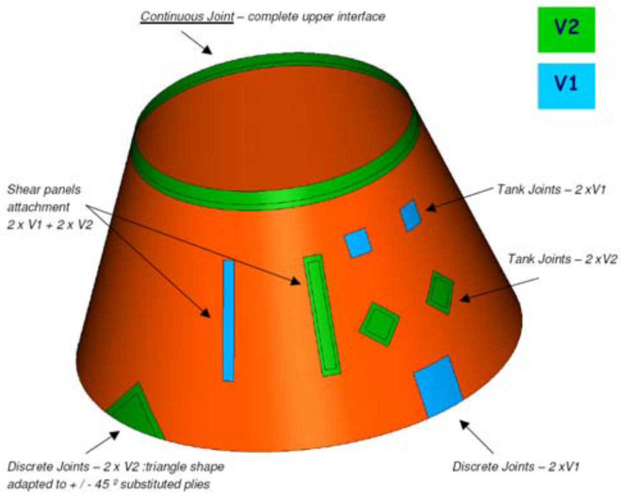

FIG 23. Modified adaptor cone with continuous and discrete root joints, equipment attachments

The following objectives are planned within the breadboard manufacturing and test phase:

- Compatibility with Fibre Placement industrial process, achieving required skills in terms of NDI and machinability.
- Verification of possible dimensional distortions due to CTE mismatch
- Verification of solution flexibility: CFRP titanium reinforcement for continuous (along the whole cone

circumference) and discrete root joints, as well as discrete local attachments for heavy equipment.

- Verification of the mechanical performance of real laminates. For that purpose, samples are being cut from the hybrid cone and tested up to rupture.

9. CONCLUSIONS

Local hybrid laminates have been demonstrated to provide for a considerable improvement in terms of the coupling efficiency of composite bolted joints. The technology transfer to real reference structures requires adapted experimental and numerical performance evaluations considering real laminate configurations, materials, design concepts and loads, as well as structural and manufacturing integrability evaluations. In the frame of the current ESA-TRP project “Increase of Bolted Joint Performance for CFRP” the suitability and feasibility of the advanced reinforcement technique is being extensively studied with regard to selected representative spacecraft applications and all relevant requirements in view of its industrial use.