NUMERICAL INVESTIGATION ON THE STRUCTURAL MECHANICS OF A JOINING TECHNIQUE FOR COMPOSITE MATERIALS: THE REDUNDANT HIGH EFFICIENCY ASSEMBLY

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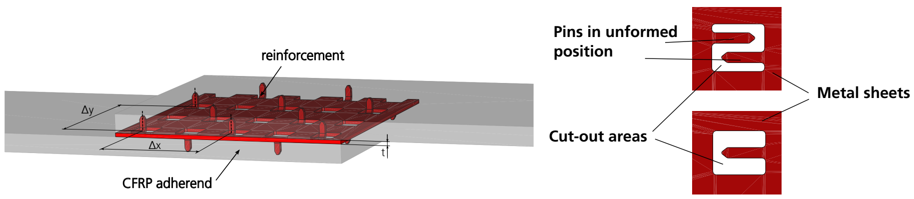
Abstract
This paper deals with the Redundant High Efficiency Assembly (RHEA), an interlaminar reinforcement for bonded composite structures as an improvement of the joining characteristics. The presented concept is based on the implementation of additional metallic three-dimensionally bent elements on meso-scale. The influence of significant design parameters on the structural mechanics of the joint is analyzed with numerical investigations on single-lap shear joint test specimens. The material of the reinforcements belongs to the investigated parameters as well as the distance between the pins. The analyses were performed using finite element models on two different levels of detail.

1. Introduction

Carbon fiber reinforced plastics (CFRP) feature an enormous potential relating to lightweight design especially in transport applications such as aerospace. To benefit from all the possibilities of this material class, a suitable design of the structure is essential. This especially applies to joining techniques. Composites gain most of the mechanical properties from the load carrying fibers. An ideal joining technique should be able to preserve the integrity of the material as does e.g. adhesively bonding. However, the use in structurally loaded aerospace applications often demands a secondary mechanical load path, which means that rivets or bolts, which were originally developed for metallic structures, must be applied in addition to adhesive. The present joining concept is based on the implementation of three-dimensionally bent, custom-designed metal inserts between two composite structures before the curing process. In this way, a secondary load path and a fiber interlocking in a meso-scale is generated. This joining concept is able to preserve the integrity of the fiber structure with just a slight fiber misalignment. The RHEA technology constitutes a continuance of several reinforcement methods presented in different research activities. In [1] an approach using carbon rods is shown. In practice, this kind of reinforcement suffers on a limited shear strength due to the anisotropy of the applied carbon fibers. The concept shown in [2] avoids this difficulty by the use of isotropic metal materials. The main focus of this technology has to be seen on joining metal and composite structures. The RHEA technology [3, 4] dealt with in this work is based on the implementation of custom-formed metal inserts. In a first manufacturing step the shape of the pin is cut out by laser or stamped from a metal sheet. Next, the reinforcement is bent to a 90° angle. As shown in [5], this bending process must also consider the spring back effect, which releases the elastic energy of the metal. The three-dimensionally bent RHEA reinforcements are integrated into the composite structures before the curing process. During the implementation, the homogeneous fiber orientation is disturbed as they are draped around the pins. In contrast to conventional joints as riveting, the integrity of the fiber structure can be maintained though the mechanical performance is slightly weakened. During the curing of the composite, the resin of the prepreg material creates an adhesive bond between composite and metal. The main principle is illustrated in figure 1. The RHEA technology offers several design variables.



(a) Scheme of the RHEA joining concept (b) Cut-out configurations

Figure 1. Overview of the reinforcement concept with investigated variables

Within this paper, the ones illustrated in figure 1 as well as the material choice were analyzed with numerical investigations performed in ABAQUS. The studies are based on a single-lap shear (SLS) test specimens according to the ASTM standard 5868 [6]. The overlapping area of the specimens of 25.4 x 25.4 mm includes different reinforcement configurations. Additionally, the influence of the ratio of the cut-out areas on the whole area is investigated by a variation of the pin density in dependence of those areas. The results are interpreted by comparing the reaction forces and the elongation measured at a distance of 80 mm around the overlap, cf. figure 2.

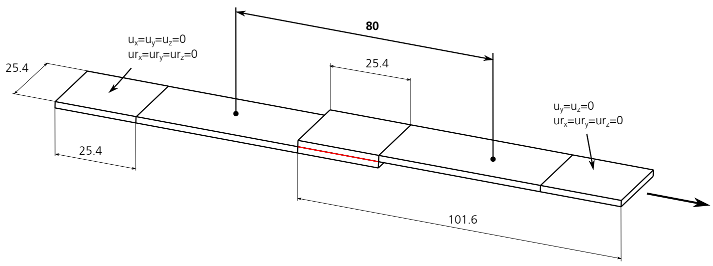


Figure 2. Single-lap-shear test specimen

2. Finite element model of the RHEA concept

2.1. General approach

The numerical implementation of the RHEA joints was performed on two scale levels. An extensive implementation of a reinforced joint is described in [7] and [5]. This model considers each RHEA reinforcement as a particular three-dimensional part consisting of C3D8 solid elements. The interface properties between reinforcements and composite are modeled with cohesive zones. Due to the high effort concerning model generation, as well as calculation time, this approach could not be used for specimens according to ASTM 5868 [6]. For the implementation of those, an abstracted model of the pins was developed. This simplified model includes an implementation of the metal sheet and the CFRP adherends as S4 shell elements. The adhesive is modeled with three-dimensional cohesive-elements COH3D8. The pins were reduced to connectors of type CONN3D2 including structural mechanics along the translational degrees of freedom, which were calibrated with single-pin simulations.

2.2. Material and interface models

In the present work, reinforcements of titanium Ti-15-3-3-3 and stainless steel 1.4301 were investigated. The stress-strain curves of these metals were determined experimentally. Their implementation in ABAQUS consists of an elastic behavior, plastic deformation and a ductile failure criterion with damage evolution. Figure 3 summarizes the respective engineering stress-strain curves, the true ones used as basis for the numerical implementation and the result of one-element-tests under tensile load.

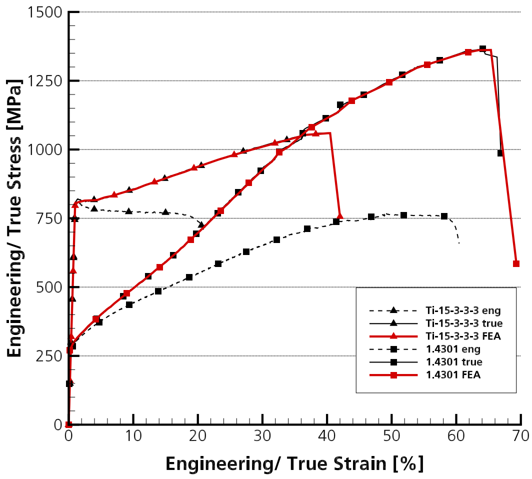


Figure 3. Comparison of experimental and numerical stress-strain curves used for the investigations

The CFRP structure consists of a quasi-isotropic layup of unidirectional prepreg material. The material properties used in the numerical implementation are shown in table 1.

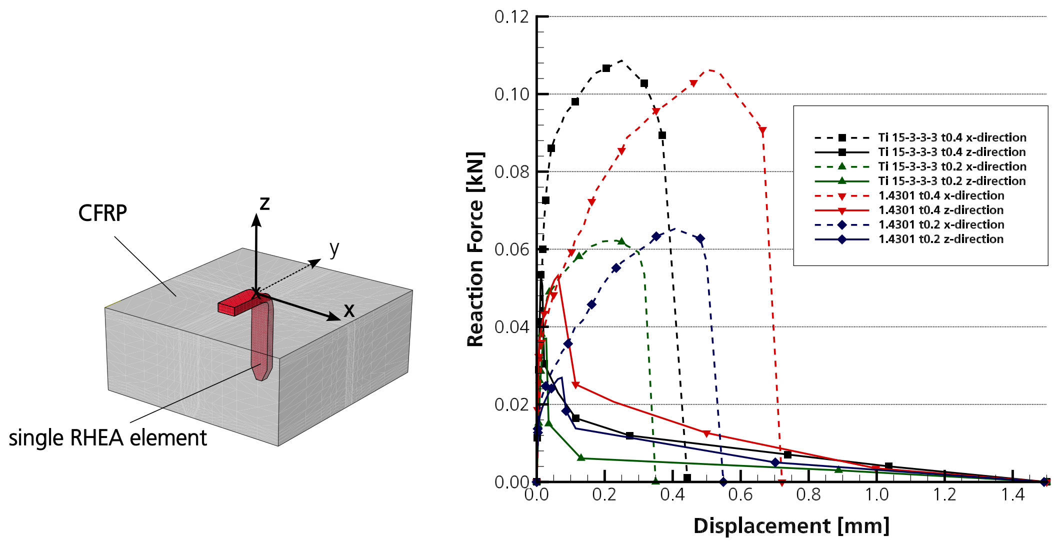
$E_{\|\|}$	$E_{\perp}$	$\nu_{\perp\|\|}$	$R_{\|\|}^{+}$	$R_{\|\|}^{-}$	$R_{\perp}^{+}$	$R_{\perp}^{-}$	ρ
[GPa]	[GPa]	[-]	[MPa]	[MPa]	[MPa]	[MPa]	[g/cm^3]
172	10	0.3	2981	1669	50	250	1.6

Table 1. Material data of CFRP Hexply® M21 with T800S fibers

The structural mechanics were implemented into ABAQUS using a user subroutine. This employed Puck's action plane failure criterion [8] to be integrated as well as the post failure degradation of the elastic material properties depending on the failure mechanism. A detailed description of the implementation is given in [7]. The interface between CFRP and the metallic inserts is numerically implemented using cohesive zones. The calibration of the underlying traction-separation-law that defines the cohesive zones was realized by end notched flexure and double cantilever beam tests [7]. Concerning the bond between the RHEA pin and the surrounding composite structure a weakening of the cohesive zone was implemented to match experimental test results. Furthermore, a degradation of the bonding characteristics concerning the cut-out areas was integrated into the FE model.

2.3. Multi scale modeling of the RHEA reinforcements

The reinforcement elements of the SLS specimens were modeled using CONN3D2 elements in the simplified FE model. The calibration of the structural behaviour was performed by detailed single pin simulations cut-out of the three-dimensional model of the joint, where the reinforcements were loaded along each translatational direction, cf. figure 4 (a). The resulting load-displacement curves were used as input data for the characteristics of the connector elements, split into elastic, plastic and failure definitions. The degradation behaviour of the connector element was implemented using degradation variables, which also allow a determination of the occuring failure mode of the reinforcement pin. In figure 4 (b) a comparison of the essential loading curves along the x- and z-direction for the analyzed metals and pin/sheet thicknesses t=0.2 mm and t=0.4 mm is given. As expected, the higher yield strength of the titanium increases the elastic response of the reinforcement in contrast to the steel pin. On the other hand, the higher failure strain of 1.4301 steel enhances the damage tolerance of the single pin. The pullout mechanism of the reinforcement is seen to be dominated by the bonding surface between CFRP and the metal. Therefore, the geometric parameter of the thickness increasing also the bonding surface shows an even more significant influence on the behaviour than the material selection. The geometric parameters have a substantial influence on the modulus of resistance concerning loading in x-direction.



(a) Schematic of the single pin simulations (b) Input data of connector behaviour

Figure 4. Calibration of the reinforcing RHEA elements using single pin simulations

A comparison of the detailed and the simplified model numerical results is shown in figure 5. The simulations were conducted on a single-lap shear geometry with a reduced overlap area in contrast to ASTM 5868 [6]. The reinforcement characteristics after the first failure are reproduced by both modeling techniques with an adequate precision.

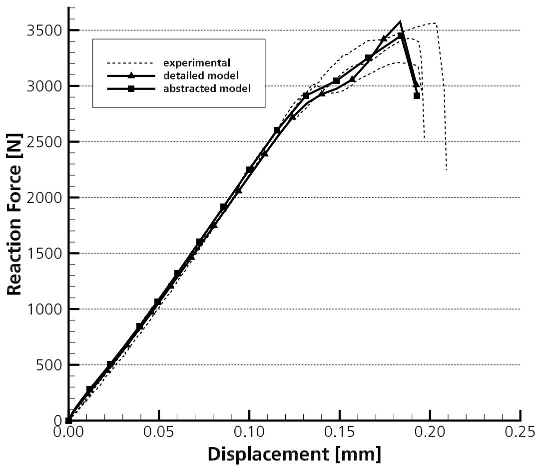


Figure 5. Comparison of detailed and abstracted numerical implementation

Concerning the implementation of the ASTM standard based SLS geometries, the influence of the additional metal inserts on the composite material was taken into account. In [9] and [10] the in-plane properties including the weakening of the composite material due to stitching were analysed. It shows that not only the geometrical properties, but also the distance between them, influence the mechanical properties. Also based on adapted filled hole experiments, the knock-down factors α of elastic and strength parameters of CFRP, which are shown in table 2, were used. An interdependancy of density and thickness on the knock-down factor could not be observed.

t [mm]	Δx [mm]	Δy [mm]	α [-]	t [mm]	Δx [mm]	Δy [mm]	α [-]
0.2	10.0	14.8	0.96	0.4	10.0	14.8	0.93
0.2	8.0	14.8	0.95	0.4	8.0	14.8	0.92
0.2	8.0	11.0	0.94	0.4	8.0	11.0	0.91
0.2	4.0	5.5	0.89	0.4	4.0	5.5	0.86

Table 2. Degradation parameters of the composite material in dependance of the geometrical properties of the reinforcement

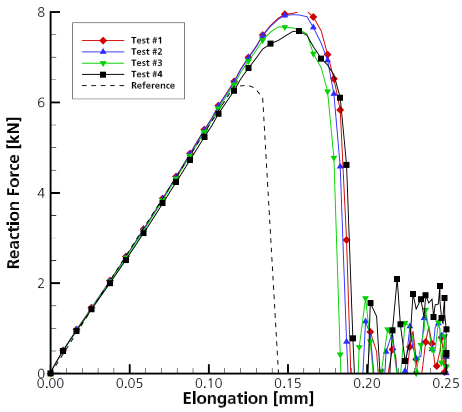
2.4. Results of the numerical analysis and discussion

Table 3 includes investigated parameters of the tested single-lap shear geometries. The analyses were carried out using the FE code ABAQUS 6.13-2, including the bonding characteristics determined in [7] and [5]. These include among others a weakening of the bonding characteristics of the cut-out areas shown in figure 1. The results are included in figure 6 containing reaction force versus elongation measured according to figure 2. The general structural characteristics include a linear elastic behavior at the beginning of loading. Just small differences in the stiffness are observed. All configurations featuring a high density of pins (#4, #8, #12, #16) suffer on smaller slopes resulting from the stiffness loss of the composite material. In addition, the configurations with pin thicknesses t=0.2 mm show a minor influence on the material characteristics of CFRP as the disorientation of the homogeneous fiber architecture is less evident as that with t=0.4 mm reinforcements. The elastic part is followed by a non-linear behavior.

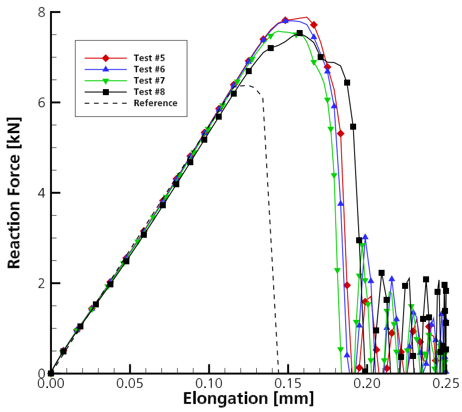
Test #	**Material**	**t** [mm]	**Δx** [mm]	**Δy** [mm]	**Test #**	**Material**	**t** [mm]	**Δx** [mm]	**Δy** [mm]
1	1.4301	0.2	10.0	14.8	9	1.4301	0.4	10.0	14.8
2	1.4301	0.2	8.0	14.8	10	1.4301	0.4	8.0	14.8
3	1.4301	0.2	8.0	11.0	11	1.4301	0.4	8.0	11.0
4	1.4301	0.2	4.0	5.5	12	1.4301	0.4	4.0	5.5
5	Ti-15-3-3-3	0.2	10.0	14.8	13	Ti-15-3-3-3	0.4	10.0	14.8
6	Ti-15-3-3-3	0.2	8.0	14.8	14	Ti-15-3-3-3	0.4	8.0	14.8
7	Ti-15-3-3-3	0.2	8.0	11.0	15	Ti-15-3-3-3	0.4	8.0	11.0
8	Ti-15-3-3-3	0.2	4.0	5.5	16	Ti-15-3-3-3	0.4	4.0	5.5

Table 3. Essential data of the investigated single-lap-shear test specimen

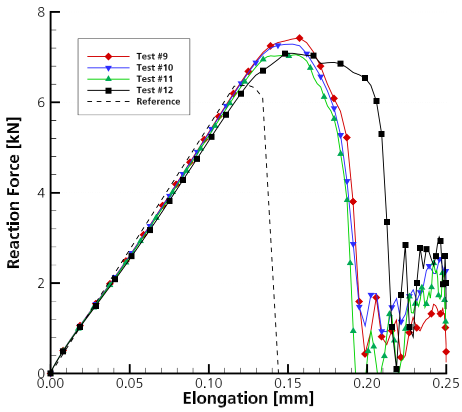
The initiation shows a dependency on the reinforcement thickness. In general, the configurations with t=0.2 mm achieve a first damage of up to 7.8 kN, the maximum damage initiation of variants with t=0.4 mm is observed at 7.0 kN. The material choice influences the maximum load as well as the damage tolerance. Configurations including steel reinforcements feature a higher strength compared to the respective titanium ones.



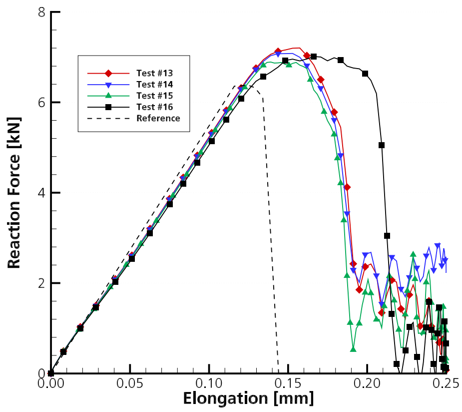
(a) Steel 1.4301 with thickness t=0.2 mm



(b) Titanium 15-3-3-3 with thickness t=0.2 mm



(c) Steel 1.4301 with thickness t=0.4 mm



(d) Titanium 15-3-3-3 with thickness t=0.4 mm

Figure 6. Numerical results of the SLS test specimens of table 3

Otherwise, titanium reinforced joints exhibit an enhanced eleongation of up to 0.01 mm compared to the correspondant steel reinforced. This effect is particularly significant concerning variants with a thickness of t=0.4 mm. Furthermore, an effect of the density of the reinforcements is visible, though a differentiation between the results of the distance along the x-direction and the y-direction has to be considered. It can be concluded, that the distance Δy shows a more significant influence concerning damage initiation as the distance Δx. A performance weakening in dependance of pin density could be observed as a result of the cut-out areas between the elements leading to a degradation of the bonding quality [5], cf. figure 1. Considering the damage tolerance, the pin reinforced test specimens show a more tolerant behavior than the reference SLS joint. A dependancy on the reinforcement density is evident, a difference in the effects of the two directions is not obvious. The effect, that a higher pin density does not extend the damage tolerance in the same way, could be seen as a result from the weakening of the bonding surface due to the cut-out areas, cf. figure 1. Just variants #4, #8,#12 and #16 show a clear improvement compared to the corresponding variants as they include two pins per cut out area, which reduces the cut-out area per pin and alters the position in x-direction of the initial pins. As a result of this it can be seen that the amount of the cut-out areas on the whole bonding surface has to be taken into account in the engineering process and should be designed as small as possible. Furthermore, the position of the initial pin row should be determined exactly.

3. Conclusions

In this research work 3D-reinforced CFRP SLS-joints were numerically implemented with ABAQUS. Based on a detailed FE model a simplified implementation was developed. The verification of this modeling technique was proved on the example of a geometrically reduced SLS-joint in comparison to experimental results. The abstracted model was used to investigate the influence of material choice, sheet/pin thickness and distribution of the reinforcements. The following conclusions were observed:

- In general, the pin reinforcement results in an enhancement of the damage tolerance and strength, especially concerning the pins with a thickness t= 0.4 mm, in comparison to the reference test. An additional positive effect was observed due to the higher yield strength of titanium. The pin density did not show a significant influence since the degradation of the bonding due to the cut-out areas counter-effects this performance improvement. Just the configurations showing two pins per cut-out area result in an improvement of the damage tolerance with a higher pin density.
- The pin density of the reinforcement influences the global stiffness of the reinforced joint resulting from a degradation of the composite material.
- The reinforcement thickness influences the ultimate load of the reinforced joints. Thick metal sheets reduce the strength of the joint.
- The initiation of the non-linearity is mostly affected by the distance Δy between the pins; the higher the space between them, the higher the initial point of failure.

For a further description of the structural mechanics of the present joining technology the effects of the initial row of pins' position in the overlap has to be analyzed, as well as the position and quantity of the cut-out areas.

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