RESEARCH ON THE INTERFERING EFFECT OF METAL INSERTS IN CARBON FIBER REINFORCED PLASTICS MANUFACTURED BY THE RTM PROCESS

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Abstract

One of the most efficient implementation of lightweight design is the use of carbon-fiber-reinforced-plastics (CFRP) due to their outstanding specific mechanical properties. Inserts are integrated metal elements which can be used to join attachments to structural parts. Such elements differ from other mechanical joining technologies. In particular, the fiber continuity is not interrupted and local bearing stress does not occur for this reason. Nevertheless, interfering effects can result from using inserts on the basis of the fiber deflection. This negative characteristic is especially important when load transfer on structural parts is not carried out by the insert itself.

This paper aims on the systematic research on the interfering effects of inserts in CFRP parts. The specimens are tested under quasi-static tensile loads, while the load transfer is carried out by the laminate itself instead of the insert. The interfering effect of two different insert geometries is evaluated in comparison with specimens of regular used laminate. The research reveals that each tested insert embedded in thin-walled CFRP structures weakens the laminate, but the interfering effect on the laminate is controllable.

1. Introduction

Carbon fiber reinforced plastics (CFRP), especially thin-walled and continuous fiber reinforced laminates are often used in lightweight design to produce components that are subject to high structural loads. In order to deal with the load transfer in structural parts, embedded metal elements, so called inserts, are often used. Such inserts consist of a base plate with a bushing and have striking advantages in comparison to other joining technologies. A detachable connection can be established, however the fiber continuity is not interrupted and the CFRP parts are not subsequently drilled, so local bearing stress does not occur [1]. The inserts are integrated into CFRP parts during the preforming and are produced by the resin transfer molding (RTM) process. One remarkable feature of the RTM process is the great design freedom which can be used for integration of functional elements during manufacturing [2]. Due to the fact that no fibers are harmed in this process, insert joints might have higher load bearing capacities than conventional boltet joints. Therefore detachable connections with those inserts have already been investigated by various authors:

Ferret et al. [3] explored two different BigHead© type metal inserts which differ in shape and number of holes in the base plate under tensile (pull-out), bending and pressure (push-in) loads. It has been

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shown that the load bearing capacity depends on the inserts' size and failure occurs either directly at the stud or by lack of the co-cured bonding of CFRP and insert. Schwarz et. al. [4] investigated inserts with several geometrical parameters and their influence for bending loads. Thereby pre-dimensioning models for the designer could be given. In addition, Schwarz et. al. [5] carried out bending tests with embedded or attached inserts and could improve the co-cured bonding of CFRP and insert. The co-cured bonding of CFRP and inserts under pull-out and bending loads could also be improved by Gebhardt et. al. [6]. The co-cured bonding was strengthened by surface treatments and coating. Further, the inserts' failure behavior was improved by increasing the bending stiffness of the base plate due to adding a bead pattern to it. Furthermore Gebhardt et. al. [2] examined the correlation between load bearing capacity and failure behaviour of metal inserts and the insert's geometry as well as the thickness of the used laminates. It was pointed out that the inserts' load bearing capacities under tensile, pressure, shear, bending and torsion loads strongly depend on the thickness of the base plates and the related increased bending stiffness.
These previous works show, that destruction of the composite was always initiated by the inserts' interfering effects and thus motivates investigation of the weakening of the surrounding CFRP material due to an insert. So far, the influence of an insert on the surrounding material has not been analyzed although the embedded insert causes deviations in the orientation of the fibers. Influence of the insert on the material properties of CFRP cannot be excluded for this reason but has not been examined yet. In this paper a systematic research on the interfering effects of inserts in CFRP parts is performed. Several specimen types are investigated. They have the same dimensions but either an insert or other interference at the same position in the laminate. The specimens are tested under quasi-static tensile load with a load transfer directly into the CFRP laminate. Load-displacement diagrams are evaluated as well as the material characteristics of tensile strength. That way, the interfering effects of the described insert and an improved type of insert are characterized and compared to a reference specimen which is out of regular used laminate.

2. Manufacturing of the CFRP specimens

In this research, the interfering effect in the area of an embedded insert is investigated. Selection and comparison of different specimen types with several interferences aim to an estimation of the insert's interfering effect. Drawings of all specimen types are illustrated in Figure 1.

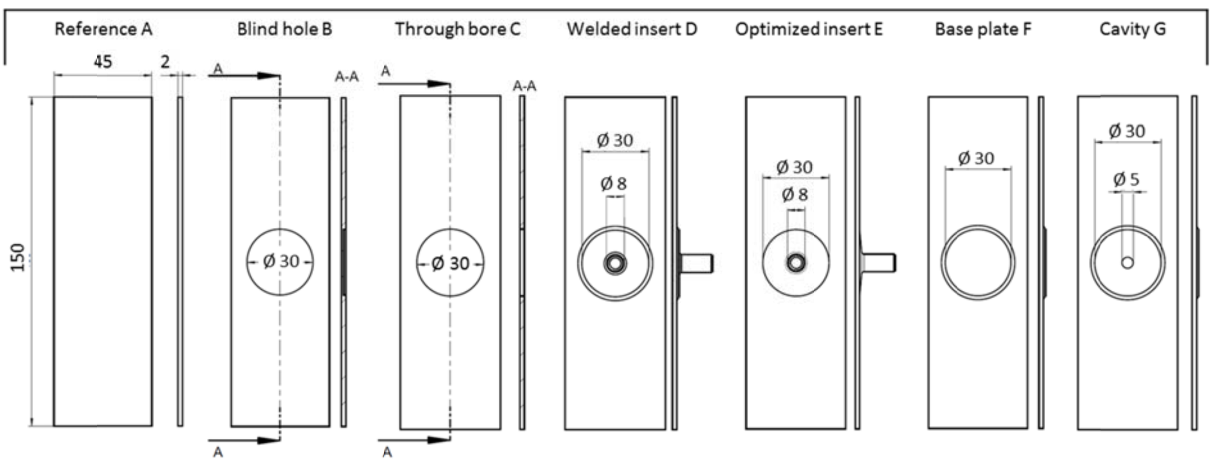

Figure 1: Drawings of all specimen types A to G.

A reference specimen "A" is defined to determine the material properties of CFRP without any interferences. Specimen type "D" has an embedded welded insert, whose interfering effect is to be

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examined. The inserts are made out of stainless steel (1.4301) and consist of a flat sheet (base plate) with a welded bushing (Figure 2 a).

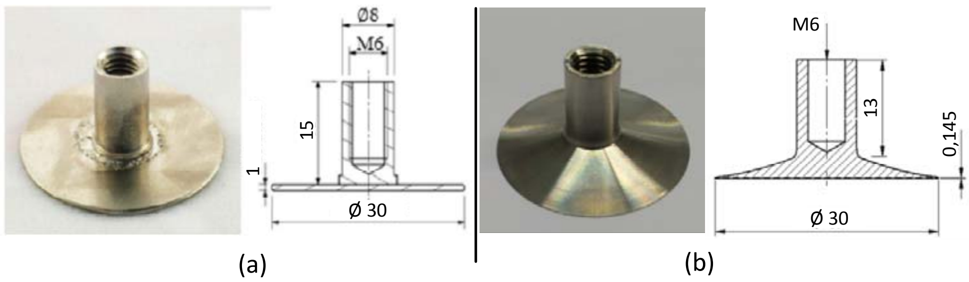

Figure 2: Exemplary picture and dimensions of a welded insert used for type D (a) [2] and of a optimized insert used for type F (b).

Type "E" is defined to investigate the interfering effect of another type of insert whose shape has been optimized to improve the load transfer from the metal insert to the CFRP material (Figure 2 b). This insert is of equal material and equal weight as the insert used for type D.

Further, a "worst case" experiment is carried out by specimen type "C" with a through bore located at the insert's position. This interference influence is also exposed in classic bolted connections. Type "B" is defined to investigate the effect of fiber interruption in the same area as fibers are deviated due to using an insert in type D and type E. Therefore blind holes with equal depths as the thickness of the insert's base plate are located in the specimens' center. Specimen type "F" is defined to investigate only the interfering effect of the bushing. Therefore specimens with embedded metal sheets are produced and then compared to the specimens which contain a complete insert. A final interfering parameter is given by a cavity in the laminate, and is associated with a further specimen type "G". In that way, the influence of the co-cured bonding CFRP and insert can be investigated due to a comparison with the other specimen types.

Preparation of all specimens was carried out in three process steps: preforming, manufacturing in the RTM process and specimen cutting. Each specimen consists of eight plies of a non-woven carbon fiber fabric by Hexcel (0°/90°, 200 g/m^2). The specimens were partially different in structure depending on the specimen type. This is why preforming was divided into two variants:

Initially identical preforms were prepared for the types A, B and C: eight plies were put on top of each other and then fixed with spray adhesive. The preforms of the specimen types D, E, F and G consisted also of eight plies, but inserts respectively base plates were embedded between the four lower and the four upper plies in the center of the carbon fiber fabric. The fibers of the upper plies were guided around the insert's bushing to avoid interruption of fiber continuity. The base plates of specimens type F was made out of stainless steel, the ones of type G was made out of aluminum which will be etched after production. All specimens were finally manufactured at "wbk – Institute of Production Science at KIT" in the RTM process. For this purpose, the preforms were placed in a specially adapted RTM mold with interchangeable cartridge, which was heated to 70 °C. The mold was closed with a press (Laufer) and a closing pressure of 55 bar was set up. The reaction mixture was an epoxy resin system from Sika (Biresin® CR170 / CH150-3) and infiltration was carried out with a mixing machine (Tartler). The reaction mixture was injected into the cavity with a velocity of 170 g/min and a control pressure of 9 bar was built. Subsequently, the components cured at 70 °C for 90 minutes and had now a fiber volume fracture of 0.46. To ensure a reliable research on the specimens' area where the interference is located, dimensions of all tested specimens were set to 150 x 45 mm^2 and the interferences were in the center of each specimen. After manufacturing, the specimen types B and C were additionally provided with a blind hole (B) and a through bore (C) and the upper plies of the specimens of type G were drilled (5 mm in diameter) to the aluminum base plate. In a sodium hydroxide solution etch bath (concentration: 40%), the G-type specimens were etched for five days to solubilize the integrated aluminum.

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3. Experimental

The specimens were tested under quasi-static tensile load with a universal material testing machine (Zwick). All tests were performed at room temperature with a crosshead velocity of 2 mm / minute. The initial gauge length of each specimen was 45 mm and the interference (drilled hole/ insert/ base plate/ cavity) was set in the middle of the section of measurement. At least five specimens of each type were tested and load-displacement-curves were measured because the specimens do not have standardized dimensions. For later discussion the breaking strengths were additionally converted into stresses to take missing cross-section of several specimen types into consideration.

4. Results

The following Figures 3 to 7 show the results of the tensile tests with the different specimen types. Figure 3 shows one examplary picture of a failed sample for each specimen type.

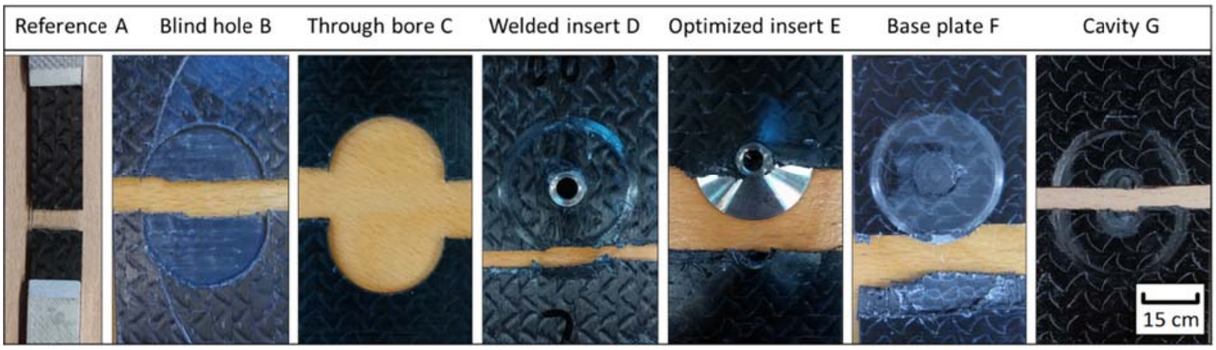

Figure 3: Exemplary pictures of the failed specimens with different interferences

In Figure 4 the measurements of the reference specimens type A are illustrated. Because none of the 45 mm wide specimens failed in the section of measurement and therefore no reliable results could be obtained this way, addidional tests had been carried out: Specimens which were only 15 mm wide and provided with cap strips have been tested. Cap strips are metal plates that are glued in the area of clamping on the CFRP specimen and have a phase in order to achieve a more homogeneous application of force into the CFRP laminate. The cap strips were fixed with 'UHU endfest' and cured for one hour at 85 °C.

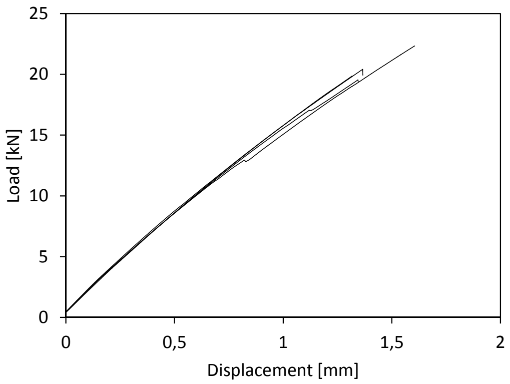

Figure 4: Load-displacement diagram of a failed specimen of the reference type A.

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The courses of the curves in the load-displacement diagram in Figure 4 show elastic behavior of the CFRP material. Especially one curve reaches a plateau at about 13 kN that probably marks the failure of the fiber plies which are orientated across the direction of the stress. The fibers which are orientated into the direction of stress fail at approximately 20 kN.

Each Figure 5 to 7 shows two different specimen types in part (a) and (b). For each type, a load-displacement diagram of all evaluated specimens is shown.

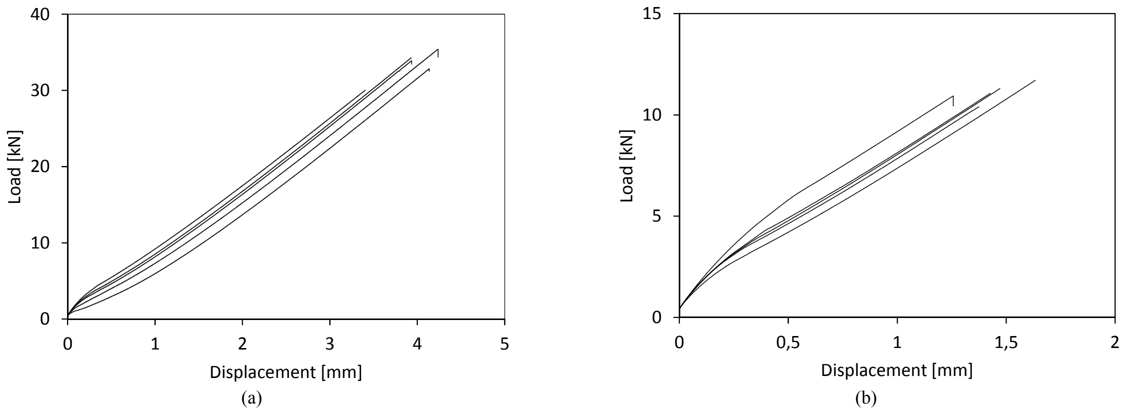

Figure 5: Load-displacement diagram of a failed specimen for the specimens with a blind hole (a) and for the specimens with a through bore (b).

The courses of all curves in Figure 5 (a) show a brittle failure at 33 kN on average. The specimens with a blind hole always failed in the area of the blind hole. The fracture runs across the direction of the stress (Figure 3). The courses of all curves of the specimens with a through bore show failure already at 11 kN on average (Figure 5 b). The specimens failed at the smallest cross section (Figure 3).

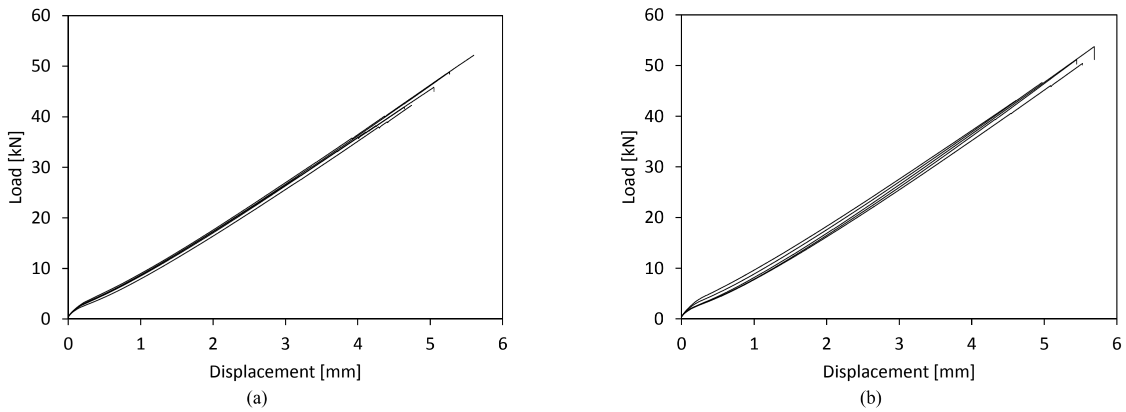

Figure 6: Load-displacement diagram of a failed specimen for the specimens with an welded insert (a) and for the specimens with an improved insert (b).

The specimens with an embedded insert also failed by fiber fracture. In Figure 6 both diagrams show a linear displacement in the elastic area until the specimens fail abruptly by brittle fracture. The load bearing capacity of both specimen types is at about 45 to 55 kN. As Figure 3 shows, the fracture of the specimens with a welded insert construction is located at the transition from the pure CFRP to the metal base plate of the insert (a) whereas the specimens with an improved insert fail directly at the bushing (b).

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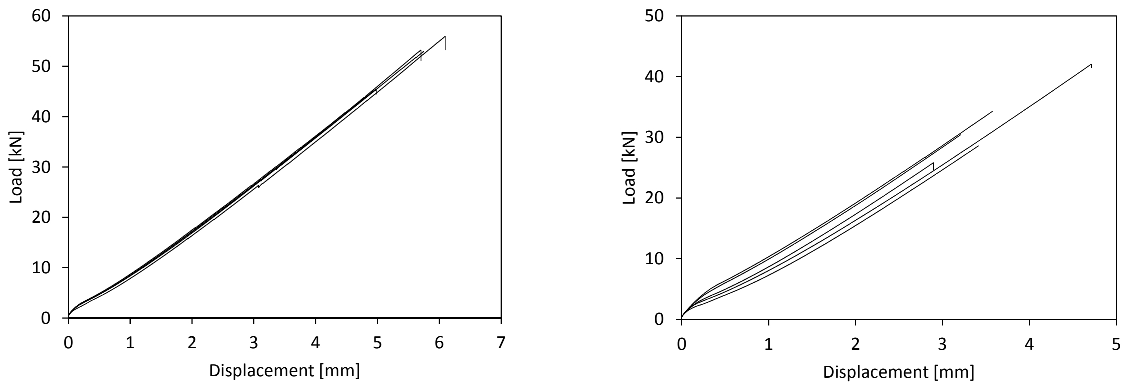

(a) (b)

Figure 7: Load-displacement diagram of a failed specimen for the specimens with an embedded base plate (a) and for the specimens with a cavity (b).

The courses of the curves in Figure 7 both show an elastic behavior of the specimens until fracture. The specimens with a metal base plate failed at approximately 50 kN and their fracture was at the transition CFRP/ base plate (Figure 3). Strikingly, the fracture is divided into two sections; the upper plies of the CFRP material fail directly at the transition CFRP/ base plate but the lower plies fail underneath the base plate and slide from it. The specimens with a cavity failed already at distinctly lower forces at about 30 kN on average. The fracture runs across the direction of the stress and the specimens failed at the smallest cross section (Figure 3).

5. Discussion

Comparing the load-displacement curves, it is noticeable that the runs of curves are similar between the various types of specimens. To ensure comparability of the specimens' load bearing capacity among themselves, the failure forces are transformed into stresses. This way, the effects of missing cross section due to the interferences at some specimen types are included. All results of the tensile tests are summarized in Table 1. The tensile strengths of the various specimen types differ which means that various interferences cause different notch effects.

Table 1: Load bearing capacity of the different specimen types.

	Reference A	Blind hole B	Through bore C	Welded insert D	Optimized Insert E	Base plate F	Cavity G
Average load capacity [kN]	20,54	33,29	11,08	46,20	49,02	48,97	32,23
Standard deviaton [kN]	1,25	2,04	0,48	4,38	4,17	5,87	6,30
Average displacement [mm]	1,41	3,93	1,48	5,06	5,25	4,58	3,56
Standard deviation [mm]	0,13	0,32	0,15	0,39	0,45	2,29	0,69
Average stress [MPa]	649,05	514,01	343,47	490,32	504,01	493,96	344,18
Standard deviation [MPa]	44,23	36,88	23,84	46,63	48,36	55,43	67,55

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First, the worst-case specimen type C shows that the tensile strength is reduced if all fibers are interrupted in the researched area. Obviously, a significant notch effect occurs at the edge of the hole.
The results of the tensile tests with specimen type B illustrate that the specimens avaragely reach a higher tensile strength than the specimens with a through bore but a lower tensile strength than the reference specimens. The tensile strength of the laminate type B is probably weakend by the blind hole and obviously a notch effect occurs. Therefore, part of the flow of force can not be transferred optimally in the fiber plies that are interrupted due to the blind hole. However, the flow of force can be transmitted ideally through the laminate below the blind hole. That's why the average tensile strength of the B-type specimens is still significantly higher than the tensile strength of the specimens with through bore.
The specimens with an embedded welded insert type D have a lower tensile strength than the reference specimens (≈ 25%). But it can be determined that the specimens with an embedded insert are distinctly stronger than specimens with a through bore (Type C).
Comparison of specimen types D and F shows that specimens with an integrated base-plate (F) reach similar tensile strengths than laminates with embedded inserts (Types D and E). This means that the welded studs do probably not affect the laminate's strength additionally. However, the failure at the laminates with optimized inserts (type E) is not located at the transition zone CFRP/ base plate but directly at the bushing. Nevertheless this effect does not hardly raise the tensile strength. This phenomenon leads to the assumption that a fiber deviation into parts of the CFRP component always has a similar effect on the tensile strength of the laminate. For this reason it does not seem to matter whether the fibers are deviated only due to the base plate or additionally turned around the bushing.
Comparing these three specimen types to the B-type specimen shows that the tensile strengths of all four types are in a similar range. This means that the load bearing capacities of the laminates are comparable. It leads to the assumption that the deviation of fibers around an embedded insert has a similar influence on the laminate's strength as a blind hole of the base plate's depth in this area. Nevertheless deviated fibers are not the only influence on the specimen types D, E and F but also a new bonding of CFRP and insert is created. The influences of this co-cured bonding are discussed in comparison with specimens type G.
In the researched area, the G-type specimens with a cavity have an identical fiber deviation as type F but they differ from the specimen types D, E and F because no metal element is embedded. The measured tensile strengths of type G are significantly lower than the tensile strengths of the specimens with embedded base plates. This result indicates that the CFRP laminate is considerably weakened by a bare fiber deviation and only the newly created bonding CFRP/ insert compensates the weakening of the laminate. This assumption matches to the torsion tests described in [2] in which the torque to the insert's bushing is almost completely transmitted by the co-cured bonding. In these tests Gebhardt et. al. showed clearly the importance of this bonding of CFRP and insert. The achieved torque in the torsion tests was higher than the tightening torque of a M6 screw, so the specimens reveal a strong plastically torsion of the bolts. In the present investigation lack of the co-cured bonding of CFRP and insert explains a decrease of the tensile strengths of the G-type specimens. One approach to explain the decrease up to the range of the worst-case specimens which do not have any material in the researched area is the phenomenon that the G-type specimens do not only have an interference due to the bare cavity but the upper plies of the laminates are also drilled to etch the cavity. This drilling might have significant influence on the tensile strength of the G-type specimens so that the single influence of the fiber deviation without a co-cured bonding of CFRP and insert can not be analyzed exactly.

6. Conclusion

In conclusion, it can be determined that the use of inserts causes an interference to the surrounding CFRP laminate which is reflected in the tensile strength of the laminate: Laminates with an embedded insert have an approximately 25% lower tensile strength than laminates without any interferences. But if an insert is embedded in the laminate, both, the bushing's diameter and the shape and geometry of the base plate does not affect the strength of the laminate essentially. To achieve high tensile strengths

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of the laminates with embedded inserts, the co-cured bonding of CFRP and insert is particularly important. Laminates with embedded inserts have approximately the same load bearing capacity as laminates with blind holes. However, the interfering effect caused by an insert remains probably controllable because the main task of an insert is usually the application of force into the laminate. Especially compared to bolted joints which require a through bore in the laminate, the inserts affect the laminates' properties only slightly. Nevertheless, a detailed characterization of individual interfering effects to the laminate caused by the embedded insert is only partly possible because the various combined interfering effects can not be examined completely detached from each other.
The critical failure area is located at the transition zone from CFRP to the metal base plate if welded inserts are used. This transition zone can be improved by an optimization of the base plate (conical base). Thus, the critical failure area moves directly to the bushing to which the fibers are guided around. However, this optimization does not gain the tensile strength of the laminate.

7. Summary

Various specimens with either inserts or other different interferences were produced by the RTM process and were tested under quasi-static tensile loads. To analyze the interfering effect of an insert to the surrounding material, the load transfer was set up directly into the laminate.
The investigation shows that each tested insert weakens the laminate. Nevertheless, the interfering effect of the insert on the laminate is controllable and can be compared to the interfering effect of a blind hole with the insert's size. The results of this work provide evidence that thin-walled CFRP structures with embedded inserts have higher tensile strengths than those with a through-hole if the application of force is given directly into the laminate.

Acknowledgments

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