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Precisely Adjustable Inserts for Stiffness-Driven CFRP Sandwich Structures

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Abstract

Carbon fiber reinforced plastic application, as a substitute for more traditionally applied materials like steel and aluminum, allows for combining lower mass with higher stiffness, and thus an increase in performance of highly-dynamic multiaxial testing machines. A novel through-the-thickness insert was developed to allow load transfer in stiffness-driven CFRP sandwich structures. The insert consists of two parts, is machined with an economical turning process, and features a fine thread which allows it to be accurately tuned, compensating for any potential CFRP sandwich thickness variations. The insert's external surfaces can be milled, meeting the tolerances needed for mating with other components.

Keywords: CFRP sandwich panels; inserts; stiffness-driven design; shear load; joining technology.

1. Introduction

Carbon fiber reinforced plastic (CFRP) is a well-established material in the industry due to its high strength and stiffness to weight ratio. It is widely used in aerospace applications because of its lightweight and excellent mechanical performance. In the automotive industry the demand for lower CO_2 emissions is pushing automakers towards lighter materials; this translates into reduced fuel consumption with improved levels of performance. CFRP have more recently also made their way into the machine tool (MT) and multiaxial testing machine (MATM) industries. There are two main differences in the application of CFRP between the aerospace and automotive, and the MT industries. The first difference regards the precision of the parts: the machine tool industry standard is in the micrometer range, hence one or two orders of magnitude higher precision than typically needed in aerospace or automotive industries. Secondly, the design of machine tools and multiaxial testing machines is rather stiffness than strength-driven. MT and MATMs demand rapid, precise movements and positioning, great speed, accelerations and high eigenfrequencies, which can be achieved by high dynamic stiffness and low weight. Another potentially attractive property of CFRP is the low thermal expansion coefficient of carbon fiber.

Sandwich structures are a combination of strong and stiff materials on the outermost layers with a supportive yet lightweight core [1]. Similar to I-beams, they concentrate material in highly loaded areas, and thus optimize the second moment of area. This allows the achievement of stiff and strong structures at a low weight. Sandwich structures are typically made of solid metal or CFRP panels on the external layers with a foam or honeycomb core in between. The latter outperforms the former in terms of stiffness to weight ratio, but foam is more economical and easier to apply in complex shapes. The crucial problem of sandwiches is load introduction, for two reasons: firstly, the load must be introduced in both surface panels but the distance between the surface panels is not necessarily precise. Secondly, both foam and honeycomb can't withstand high local pressure [2].

A conventional approach of connecting the two surface panels is via the use of a flange. Though, flanges have several

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disadvantages: their massive design leads to high weight, and they are not scalable, i.e. each interfacing requires a specific flange that must be individually adjusted in regard to hole diameter and placement. Therefore, a common way of both joining sandwich panels and transferring local loads is via the use of inserts [3], as visible in Fig. 1. Inserts have a comparably low mass, more compact dimensions and high freedom of design. By increasing the number and the distance of the inserts, hole diameter, stiffness and strength can be adjusted.

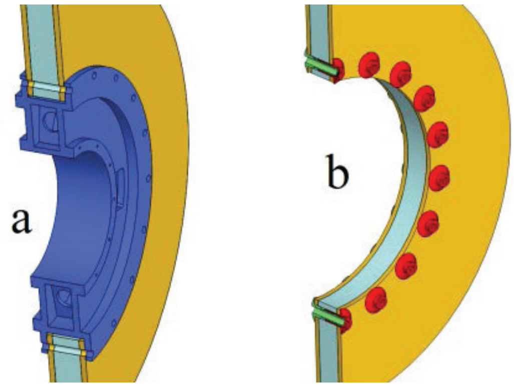


Fig. 1. Cut view of sandwich panels with use of: (a) flange; (b) inserts.

Three basic types of inserts in sandwich structures are known: partially potted, fully potted, and through-the-thickness [4], as depicted in Fig. 2.

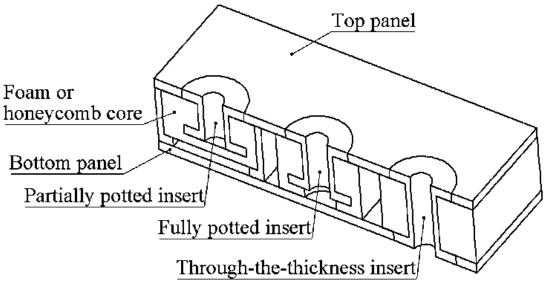


Fig. 2. Partially potted, fully potted and through-the-thickness inserts in a sandwich structure.

The loads introduced by inserts are of three forms: tensile/compressive, both normal or in-plane, and bending/torsional moments. Moments are usually converted into forces by the use of several inserts. The most critical failure mode in the case of through-the-thickness inserts was identified by Nguyen et al. [5] as shear cracking in the foam core. In the region of the bore holes the ideal load transfer mechanism is strongly disturbed: the face sheets, instead of bending about the middle surface of the sandwich panel, bend locally about their own middle surface, leading to stress concentrations. Inserts prevent premature failure by transferring loads on the structure in a distributed manner as demonstrated in [6]. By implementing the geometry optimization of the inserts carried out by Shipsha et al. [7], an increase of the loads with reduced stress concentrations is possible.

Higher production numbers and cost savings caused the automotive industry to focus on the integration of the inserts directly during sandwich manufacturing according to [8]. In the aerospace industry with lower production numbers and higher safety standards, the inserts are bonded in an additional production step as described in [9], unless the application requires very high strength. When producing CFRP structures, thermal influences and chemical processes cause shrinkage and other geometrical deviations. High precision is usually achieved by secondary operations such as machining or replication, well known in the field of polymer concrete [10]. The precision requirements in the MT and MATM industries also need a secondary and eventually a third process step in order to achieve tolerances in the micrometer range.

The original application of the inserts has its origin in the automotive and aerospace industries. For safety reasons, structural and material failure is a major concern in the aforementioned fields [11], hence inserts were designed with a focus on strength rather than stiffness requirements, and research was oriented accordingly. Thomsen et al. [12] formulated a set of guidelines for the design of sandwich plates with through-the-thickness inserts. The following guiding principles were followed: the minimum radial extension of the potting compound, as well as the ratio of the potting stiffness to the honeycomb stiffness was guaranteed, external bending moment loading was avoided by applying load through groups of inserts, and lastly, reinforcements were added to the face sheets where the inserts were mounted. The load transfer characteristics of the through-the-thickness inserts for stiffness-driven composite sandwich panels were investigated experimentally with respect to the insert shape. Burchardt evaluated fatigue in sandwich structures with inserts. The stiffness of the inserts was used as a design parameter and the investigation in [13] showed that it had almost no influence on fatigue crack propagation.

2. Methodology

In this study the development of the inserts was stiffness-driven with minimum strength to withstand a 4 kN in-plane shear load case. Stiffness can be accurately and reliably calculated with both analytic considerations and FEM software, whereas for strength simulation it is more complex and needs failure criteria and validation. Therefore, right from the beginning, utilizing prototype inserts, it was fundamental to first of all guarantee the minimum strength requirement and understand how the different geometry variations influence the strength of the insert because if the bonding fails, the whole solution fails, and the stiffness is lost too (Section 3). Following the strength requirements, a stiffness optimization was carried out on newly designed inserts in the 4th section of the paper. Finally, in order to ensure the essential strength requirement of the optimized inserts, a conclusive pull-out test, as well as fatigue tests were conducted (Section 5).

3. Prototype inserts

The chosen approach was the use of a through-the-thickness insert consisting of two pieces, with two concentric tubes, as depicted in Fig. 3. Each of these two parts was designed to incorporate an external flange, which distributes more evenly the load on the sandwich structure. The inner diameter of the inserts had a dimension of 22 mm, while the material employed was steel (42CrMo4), suitable in terms of stiffness.

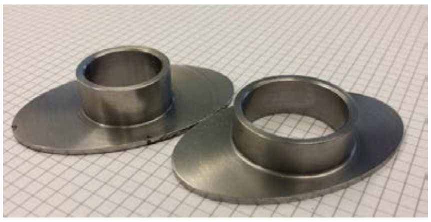


Fig. 3. Prototype insert.

Different geometric parameters were investigated for the design of the inserts: the edges can be circular, oval parallel or oval perpendicular to the load case direction (Fig. 4a). Two thickness variations of the flanges were also considered: constant flange thickness and linear thickness variation. It was assumed the latter would reduce stress concentrations around the insert-laminate interface (Fig. 4b).

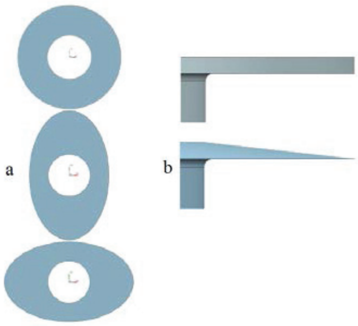


Fig. 4. (a) Circular vs. oval flanges; (b) Thickness adaptation for a smooth takeover of stresses.

The samples employed to test the prototype inserts, had a length of 300 mm and a width of 200 mm, and consisted of two CFRP plates and an 8 mm Rohacell 51 foam core. The total sample thickness was 9.8 mm. Each plate was composed of three layers (0°/90°/0° with respect to the load direction) of unidirectional carbon fiber prepreg with a thickness of 0.26 mm. The plates, the cores and later the inserts were joined together with Hexion MGS 233-238 epoxy resin, with a bond-line thickness of typ. 0.1 mm. On one end of the sample, a steel plate was positioned between the CFRP plates instead of the foam core, resulting in improved sample clamping. The pull-out tests were performed with a displacement velocity of 2 mm/min, using a Zwick 1474 machine. The measured parameters were the force and the displacement between the grips as showed in Fig. 5.

Fig. 5. CFRP sample with insert during the pull-out test.

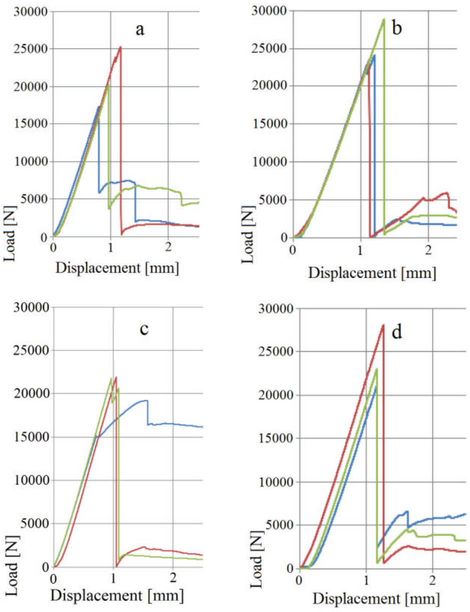


Fig. 6. Prototype inserts pull-out tests on preliminary samples described in Table 1.

The strength difference between the oval and the circular shaped flange inserts showed negligible differences, thus the latter design was chosen since it is easier to manufacture and assemble. The linear thickness variation of the flanges showed a considerable enhancement (18%) of load bearing due to a better distributed load introduction on the sandwich structure.

Table 1. Sandwich samples with prototype inserts

Insert type	Average Failure Load (kN)	Standard deviation (kN)
(a) Oval flange with orthogonal load/constant thickness	20.7	3.3
(b) Oval flange with orthogonal load /linear thickness variation	25.1	2.2
(c) Oval flange with parallel load/constant thickness	22	1
(d) Circular flange/constant thickness	23.7	2.8

4. Optimized insert design

The insert requirements for stiffness-driven structures were the following: adjustability in thickness, scalability of the design, high stiffness, low mass, ease of manufacture and cost effective price. In order to comply with this, firstly the choice of material was steel (1.4305), which assured the desired Young's modulus. Secondly, the axial-symmetric design allowed them to be turned using an automatic lathe. The lower diameter limit was imposed by the through hole for the connecting bolt (M12), while the upper one was determined upon an economical consideration: bars up to 52 mm (2 inches) were found to be more cost-effective. The next important characteristic was the utilization of a fine thread for better adjustability and minimum play between the two components of the insert, which when locked with a bolted joint leads to negligible compression of the sandwich. Additionally, both parts were designed with wide flanges, which had a linear varying thickness, both characteristics resulted in a distributed load introduction. In order to more effectively balance the load on the sandwich panel, stiff and strong overhangs were added on one side. Overhangs could be added on the other side as well, in particular in case load introduction on both sides. Lastly, spacers on the back of both flanges ensure the optimal bonding layer thickness.

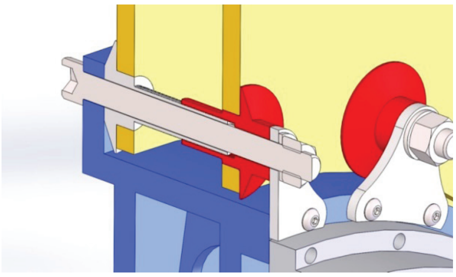
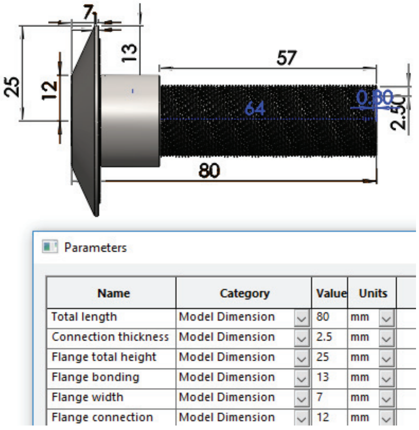


Fig. 7: Load introduction from ring elements to inserts.

The load introduction for several inserts is supposed to be realized by ring elements, as illustrated in Fig. 7. In order to ensure the necessary flatness, machining of the connecting faces of the inserts might be necessary.



Name	Category	Value	Units
Total length	Model Dimension	80	mm
Connection thickness	Model Dimension	2.5	mm
Flange total height	Model Dimension	25	mm
Flange bonding	Model Dimension	13	mm
Flange width	Model Dimension	7	mm
Flange connection	Model Dimension	12	mm

Fig. 8. Parametric study on inner-side of the insert.

To achieve superior eigenfrequencies in MATMs, low weight and high stiffness are fundamental. After the final geometric design was determined, a dimensional optimization with respect to high stiffness and low mass was carried out in the case of shear load, calibrated to a value of 4 kN.

A parametric study of the insert's dimensions was performed with SolidWorks Design Study package (Fig. 8). The optimization target that had to be met was a tradeoff between stiffness and weight: a maximum mass of 300 g and a displacement inferior to 1 μm. A tensile load of 4 kN was applied in-plane on both the front faces. The results of the simulation are visible below (Fig. 9).

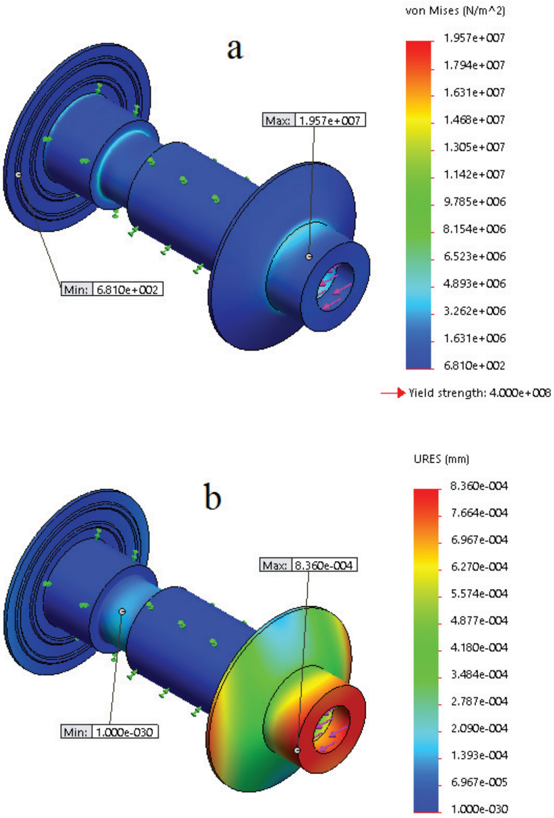


Fig. 9. (a) Von Mises stress and (b) displacement in a 4 kN in-plane loaded optimized insert.

The maximum Von Mises stress (Fig. 9a) in the insert was of 20 MPa on the middle shaft at the connection with the flanges, where stress concentration occurs. This resulted in a displacement (Fig. 9b) of almost 1 μm in the direction of the load. The geometrical optimization allowed for low stresses in the bonding areas, which led to low and homogeneously distributed stresses on the on the back sides of the flanges, that represent the joining areas to the CFRP sandwich. Consequently, as desired, the resulting displacements are minimal in the most delicate areas.

The total weight of the insert is of 298 g which fully meets the requirements. The length of the inserts was selected so that they could be used for sandwich thicknesses from 60 mm to 110 mm. This feature results in a "one size fits all" standardized solution. The fine thread of the insert presents several advantages. Firstly, the two parts can be precisely screwed in together to a desired torque that does not overstress or damage the sandwich core. Secondly, it can compensate for undesired thickness variations of the core and CFRP face sheets that can occur during their manufacturing. Lastly, since reinforcements of the face sheets with the role of locally strengthening the structure are common additions to CFRP (Fig. 10), the same insert type can be implemented within the same structure with thickness variations. The insert is pre-stressed once locked with a bolted joint, which along with the load bearing nature of the insert itself avoids an overload of the foam core.

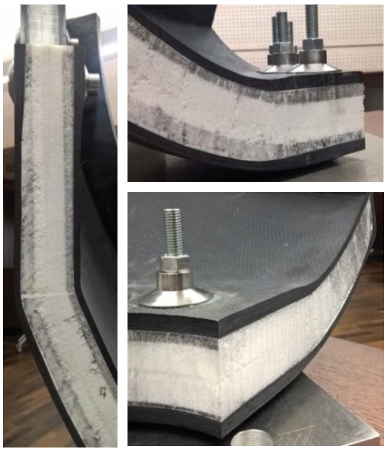


Fig. 10. Cutaway of a CFRP sandwich frame with local reinforcement areas for multiaxial testing machines.

5. Validation

FEM calculations for static tests return precise, accurate and reliable results. Unlike strength tests, where the failure mode requires physical validation, the validation of the stiffness was not necessary, the FEM results above suffice. Consequently, only static and fatigue tests were performed on a 70 mm thick stiffness-oriented sandwich structure composed of two laminates of CFRP with a foam core and two optimized through-the-thickness stainless steel inserts. The sandwich structure was manufactured with a vacuum infusion process, due to its cost effectiveness and suitability for thicker plate dimension production. The 10 mm thick CFRP face sheets were produced with Sigratex's 80/20 plain weave C W400-PL1/1 (warp: Carbon-HT 12k, weft: Carbon-HT 3k). The fabric weight was of 400 g/m^2 resulting in a total layer thickness of 0.45 mm. The fiber to volume content was of about 50%. The resin used was Hexion RIM235, while the 50 mm thick core was Airex T92.100 foam.

The holes were bored through the CFRP plates using the 068HOPC080-DIP5 tool from Hufschmied, while the holes through the foam were completed with the 103DFOXL100 from the same manufacturer. Tolerances of a tenth of a millimeter were achieved. To improve the bonding quality, the surfaces of the steel parts and those of the sandwich were sandblasted and then degreased with acetone. 2K Hysol EA 9394 epoxy paste adhesive was applied around the sandwich holes and on the flanges. The curing occurred at 65°C, as recommended by the supplier of the adhesive.

5.1. Static tests

The sandwich specimen was mounted on a specially designed jig, as visible in Fig. 11. It consisted of two U shapes, composed of steel plates screwed in together. The sandwich panel was locked in place through the use of two M12 jointed bolts.

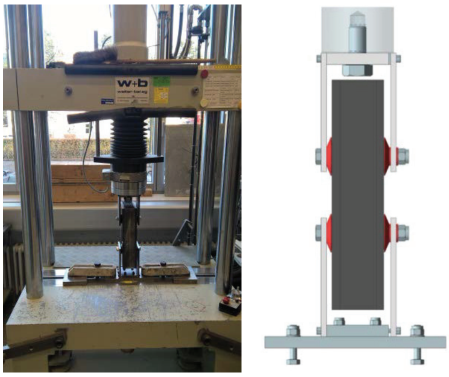


Fig. 11. Static test employing a jig for mounting the sandwich.

According to calculations, the strength was limited by the 12 mm bolted joints, and not by the bonding between the sandwich and the inserts. Considering the 4 kN shear strength requirement for the insert, static tests were performed on a Walter+Bai AG pull-out machine, which has a 160 kN maximum pulling force. At the 45 kN mark the jig on which the sandwich was mounted started deforming, as visible in Fig. 12, and the test was stopped since a higher than 10 safety factor was accomplished.

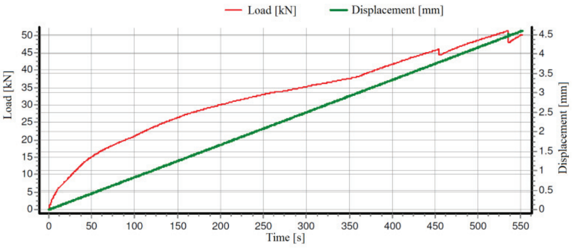


Fig. 12. Result of the pull-out test.

5.2. Dynamic tests

Fatigue tests were also conducted on the composite sandwich with inserts. The tests were carried out at room temperature with a sinusoidal load at 2 Hz on a hydropusler machine (Fig. 13). Initially one million cycles were carried out with a load of +/-2.5 kN, after which the load was doubled to +/-5 kN and another million cycles was performed. No damage was assumed to have occurred since no change in amplitude on the hydropulser machine could be observed.

Fig. 13. Fatigue testing in the hydropulser machine.

6. Conclusion and outlook

The design of inserts for stiffness-driven CFRP sandwich structures with a foam core was developed in this study. In the first phase, the most influential geometric parameters for strength were experimentally quantified through pull-out testing. Preliminary sandwich samples and prototype inserts were manufactured. The results indicated that the flange thickness variation leads to a considerably better load introduction in the structure. Since an oval shape of the flanges showed just a minor advantage, a circular shape was preferred for the ease of manufacturing and assembly. Considering the geometrical and dimensional tolerances in the micrometer range needed for MATMs, the direct integration of the inserts in the sandwich manufacturing was not pursued. Instead, the addition of a second manufacturing step was justified by the smaller production numbers, by higher precision and by tighter tolerances achievable with this type of inserts.

In the second phase, the results from the pre-study were applied to a parametrically designed insert. The inserts were developed with respect to high stiffness and low mass while subjected to in-plane forces. The optimization process was carried out utilizing the Design Step SolidWorks algorithm.

The static and dynamic characteristics of optimized through-the-thickness stainless steel inserts for stiffness-oriented CFRP sandwich structure with a foam core were also investigated.

Theoretical and experimental investigations indicate that due to their high stiffness and strength, the inserts allow for an increase in performance of MATMs by ensuring high stiffness and a low mass (Fig. 14). A distributed load case transfer on the CFRP sandwich is made possible by the inserts, avoiding stress concentration around the bore holes. Finally, the required accuracy is achieved by the precise placement of the inserts and their final machining, which allows achieving dimensional and geometric tolerances for mating with other parts. Overall, these through-the-thickness inserts for stiffness-driven CFRP sandwiches with an in-plane load resulted in all the desired objectives being met: high stiffness, contained mass, scalability and adjustability, ease of manufacture, and cost effectiveness.

Further research could be done on the aspect of load distribution for a one sided ring element, and on the limits of scalability in respect of the ring element diameter and the number of inserts, since stiffness is scalable, while strength is not. Another aspect that could be additionally evaluated is a possible integration of the first strength testing and stiffness optimization in a one-step process, which would lead to only one final strength validation.

Fig. 14. CFRP structural part for highly-dynamic multiaxial testing machine with optimized inserts.

Acknowledgement

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