# COMPONENT TESTING OF SANDWICH STRUCTURES WITH MORE REALISTIC BOUNDARY CONDITIONS

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## ABSTRACT

As part of the design process for aircraft cabin monuments, the loads on the fasteners, like inserts are determined using global FEM and are compared with allowables of the fasteners. The allowables are determined in component tests, which currently have highly idealized boundary conditions, resulting in high safety factors being added. In this paper, application-oriented component tests with realistic boundary conditions for insert systems are proposed, experimental investigations are performed on them, and virtual models are implemented. The studies show that the boundary conditions have a great influence on the structural behavior and the failure mechanisms of the sandwich structure and the insert system. The results further prove that tests with application-oriented loading situations should be used to validate detailed virtual models, e.g. to ensure their use as submodels in the global FEM analysis of large sandwich structures. In addition, an example is given to show how such a component test with realistic boundary conditions can be used in the design optimization of the load introduction.

## 1 INTRODUCTION

Due to their good weight-specific material properties, sandwich structures are used in lightweight design, especially in aircraft design [1, 2]. A light core is used to keep two face sheets apart in order to obtain a lightweight and stiff structure. In aircraft cabin applications, phenolic resin-impregnated aramid paper (Nomex) is mostly used for the core and glass fiber prepreg for the face sheets [2]. Further, inserts are used for local load introduction, which are usually inserted *cold-bonded* into the structure via a potting compound [3]. The verification process for aircraft cabin interior involves the use of global finite element method (FEM) calculations to determine the maximum loads occurring on the fasteners [4, 5]. Corresponding component tests are then carried out for the insert system, in which the permissible forces (so-called allowables) of the respective configuration are calculated for a specific load type. This is followed by a comparison with the globally and product-specifically calculated FEM values and verification of whether the insert system will withstand [4, 5].

Tensile load in particular represents a critical loading situation for the inserts, which in most cases leads to local shear failure of the core as the initial damage mechanism [3]. The pull-out test recommended in the Insert Design Handbook (IDH) [3] is the quasi-standard tensile test currently used to determine the strength and stiffness behavior and thus also the allowables of insert systems. The clamping is realized via a circular hole with a diameter of 70 mm. This clamping situation is idealized, and in the real product there are usually superimposed loads at the fasteners. As a result, high safety factors are added to the allowables so that the inserts also resist load situations close to the real-life application. Hartwich et al. [6] as well as Rodriguez et al. [7] compared component tests performed in the literature, in particular the pull-out test. It became apparent that in the different literature sources different hole diameters were chosen for the clamping and also the specimen dimensions differed from the IDH recommendations. However, the exact influence of the hole diameter of the clamping and thus the influence of the test boundary conditions on the structural behavior of insert systems were not

investigated. In this context, these test boundary conditions can have a considerable influence on the load situation that occurs and thus affect the failure behavior of the insert systems.
In order to be able to investigate the structural behavior efficiently, the use of virtual tests based on the FEM is suitable. This has the advantage that detailed models can also be used to investigate the behavior of the individual cell walls of the sandwich structure, which are hidden by the face sheets during experimental testing. Meso models, in which the geometry of the honeycombs is represented in the model, are particularly suitable for such investigations. Corresponding models have been successfully implemented for the pull-out test by various authors [8-10]. However, in order to use such models e.g. as submodels in larger structures to accurately investigate local areas in a global model, it must be ensured that the models also provide adequate results under application-oriented boundary conditions and loading situations. Standard component tests, such as the pull-out test, have their limitations here due to the idealized boundary conditions.
Such limitations of existing component tests do also occur in the designing of insert systems. Approaches to optimize the design of individual constituents, especially inserts, exist in the literature [11-13]. An overview of the different design concepts for the various constituents of a sandwich structure is presented by Schwenke et al. [14]. Schwenke and Krause [15] show an approach and corresponding results for integrating the load introduction point into the core in order to introduce local loads into the structure in a way that is suitable for the load path. A topology optimization is performed here on a 3D-printed core and it is shown that the boundary conditions have a significant influence on the optimization results and must be considered accordingly in the design and layout of sandwich structures and their constituents [14].

This paper aims first to characterize and quantify the influence of boundary conditions in component tests on the structural and failure behavior of insert systems in sandwich structures by experimental and numerical investigations. Test setups for square specimens on the one hand and test setups for rectangular, elongated specimens on the other hand are developed and considered. With the help of the application-oriented boundary conditions, load situations that are close to the product can already be implemented in the component test. The findings from the investigations should help to take the load situation more into account in future when determining the allowables of the insert systems, in order to select low safety factors. Furthermore, it will be investigated to what extent detailed virtual models are able to reproduce the structural behavior also in application-oriented component tests with superimposed loads, in order to be able to use them also as submodels for local damage prediction in large sandwich structures. Finally, with the example of the optimization of the load introduction in one of the new tests, the practical relevance of application-oriented component tests for the design of sandwich structures and insert systems is shown.

## 2 METHODS AND MATERIALS

First, suitable test setups with product-near boundary conditions are developed. Two basic approaches are taken here. On the one hand, test setups with square specimens are considered following the pull-out test, on the other hand, a test setup for rectangular, elongated specimens, which in the following is referred to as the bending pull-out test, is also developed in order to be able to apply higher bending loads to the specimen.
For the test setups with quadratic specimens, the pull-out test with a clamping diameter as proposed in the IDH is the starting point [3]. In order to investigate the influence of the clamping diameter, another test setup is considered which is similar to the pull-out test but has a diameter of 140 mm with a circular clamping and thus leads to a higher bending of the sandwich structure. In the physical product, the load is applied individually via fasteners. Since the use of multiple inserts can result in a reduction of the load-barring capacities due to a superposition of their stress fields [3, 16], a test setup with octagonal clamping was developed. This abstracts the case of a clamping via inserts in the corners without having any effects or punctual load introduction. Finally, the test setup with clamping via inserts as a generic test setup with product-specific boundary conditions, which was introduced by Hartwich et al. [6] and Schwenke et al. [14] is also investigated. With this test setup, it is also possible to compare different designs, which use the advantages of topology optimization and do not need inserts.

The basis for the test setup with rectangular, elongated specimens is again the pull-out test, which is combined with the clamping from a classic 3P or 4P bending test. This allows the influence of a global bending load on the local behavior of the insert system to be investigated, which is a common superimposed loading situation in cabin applications. The test setups and their boundary conditions considered in this paper are summarized in Figure 1.

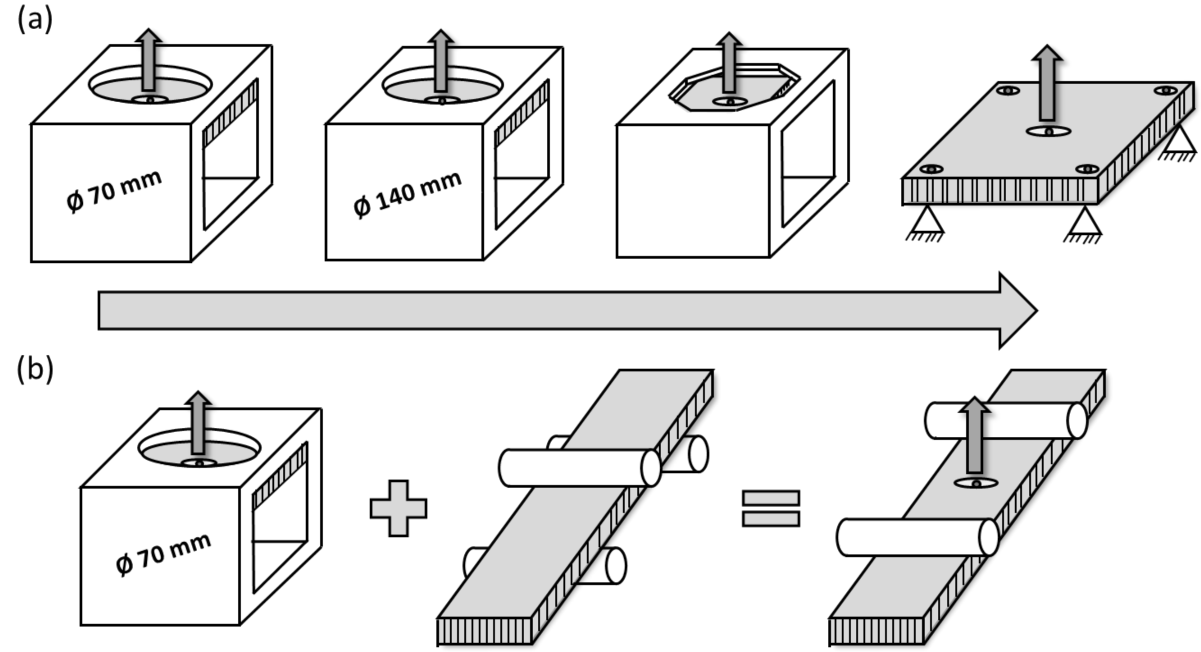


Figure 1: Test setup with different boundary conditions for pull-out tests; (a) Test setups for quadratic specimens; (b) Test setup for bending pull-out test with rectangular, elongated specimens.

The investigations are carried out both experimentally and numerically for each test setup. The specimen layout is shown in Figure 2. Here, 19.5 mm thick sandwich panels are used with a Nomex honeycomb core in accordance with the Airbus specification ABS 5035-A4. One layer of glass fiber prepreg in accordance with the Airbus specification ABS 5047-07 is used for the face sheet. The SL608-3-6S inserts were each cold-bonded in the sandwich structure with Scotch-Weld™ 9323 B/A potting compound, with a potting height of 15 mm, making it a partially potted insert configuration. While the specimen size in the pull-out test with a 70 mm clamping diameter is 100 x 100 mm, specimen sizes of 200 x 200 mm are used for the other tests with quadratic specimens conducted. The specimen size for the combined pull-out and bending test is 700 x 80 mm, while the long side of the specimen is in the warp direction. The diameter of the clamping roll is 20 mm and roll distances of 160 mm and 360 mm are tested and also simulated.

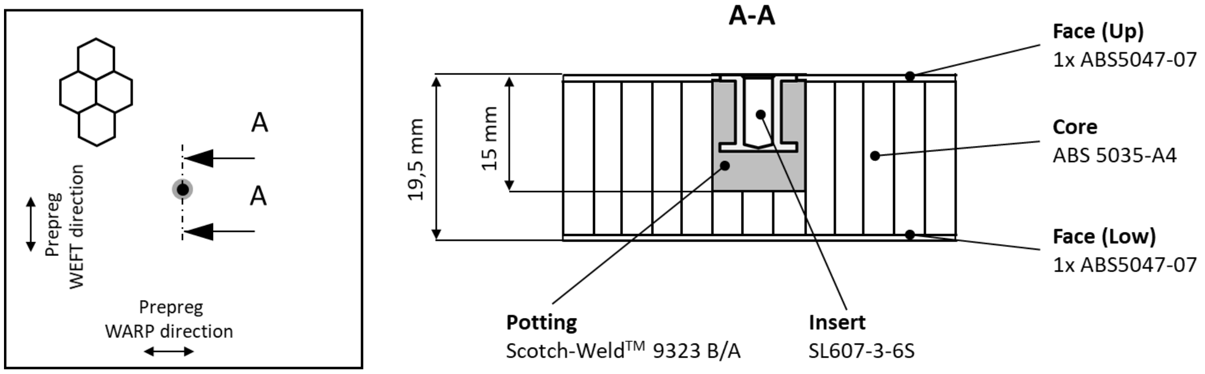


Figure 2: Materials used for experimental and numerical study.

## 3 EXPERIMENTAL AND NUMERICAL STUDIES

The experimental tests were all carried out on the same Galdabini Quasar 100 universal testing machine. The loading rate was set at 1.5 mm/min and the force was measured in the insert tests using a 10 kN HBM S9M load cell. The displacement was measured via the testing machine crosshead, and the machine and test stiffnesses were determined in each test setup and calculated from the test data. The experimental setups are shown and summarized in Figure 3 and Figure 4.

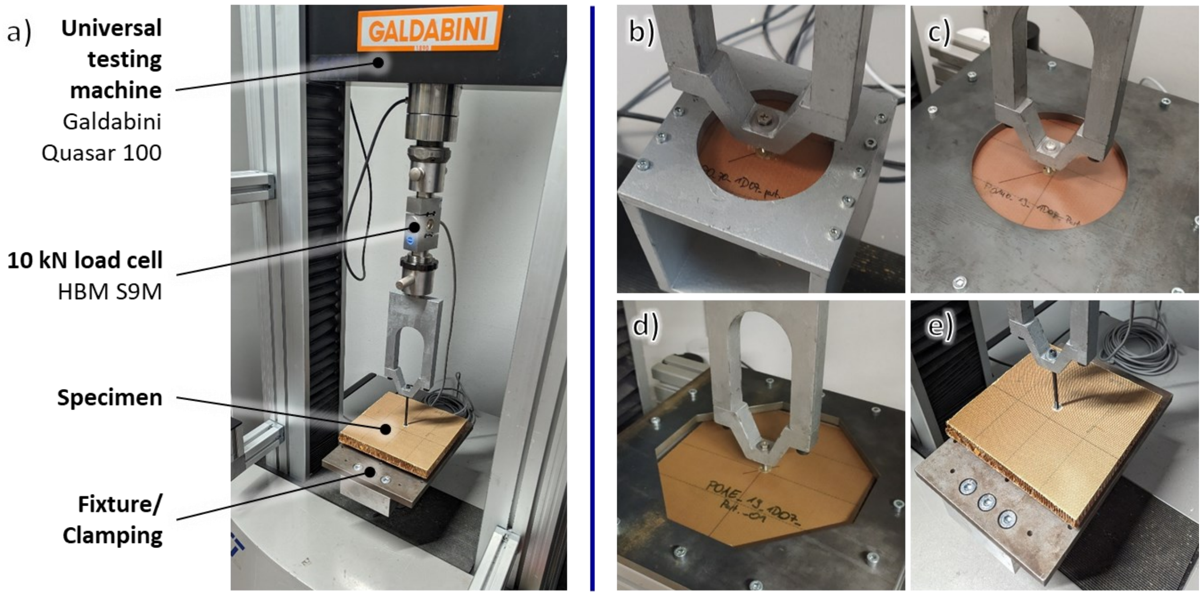


Figure 3: (a) Test setup; (b) Round clamping of standard pull-out test with 70 mm diameter; (c) Round clamping with 140 mm diameter; (d) Octagonal clamping; (e) Clamping with four inserts.

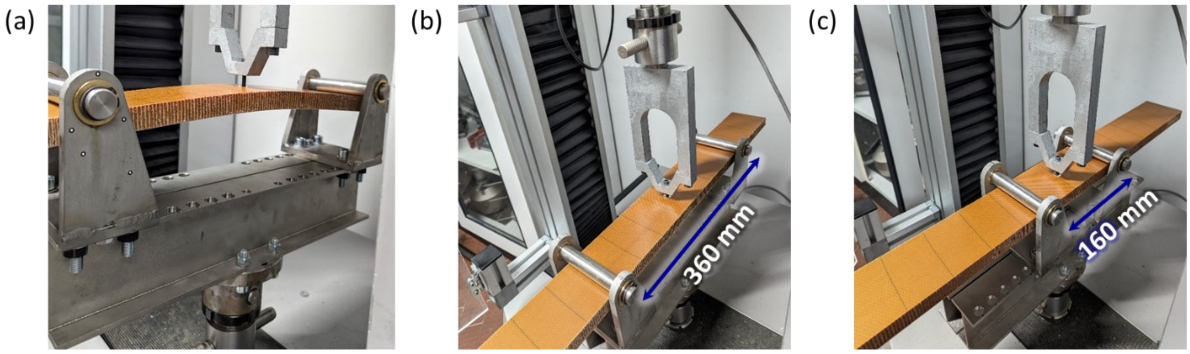


Figure 4: (a) Side view on bending pull-out test setup; (b) Test setup with roll distance of 360 mm; (c) Test setup with roll distance of 160 mm.

The numerical models are shown in Figure 5 and Figure 6 and were implemented in ABAQUS/Explicit 6.14-1. While for the test setups with the quadratic specimens meso models were used, for the bending pull-out tests hybrid models, which exist of a detailed representation of the core in the area around the insert and a solid core representation in the rest of the sandwich specimen were used (cf. Figure 6). Due to the symmetries, quarter models were used to save computation time. The material models for the face sheet, the potting, the solid core as well as the honeycomb geometries for the Nomex core were used from Seemann [11]. For the Nomex paper, the material properties according to Schwan et al. [16] were used, which agree well with values from other literature sources. The contacts between the constituents were defined as tied-contacts, with the exception of the connection between the core and the top face sheet. To model the adhesive contact between the face sheet and the core, an additional phenolic adhesive layer was implemented into the model (cf. Figure 5). Only the contact between the phenolic layer and the upper face sheet was modeled as an adhesive contact and the other contacts were implemented as fixed, since no damage was assumed in these areas. The material properties for the material model of the phenol adhesive layer were taken from Redjel [17].

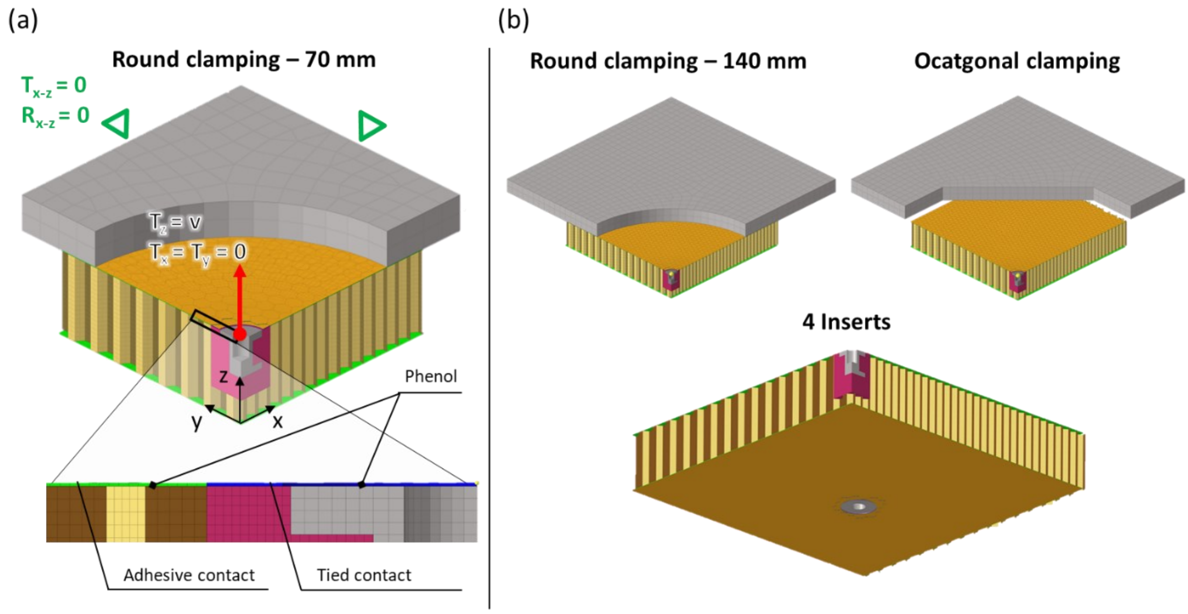


Figure 5: Virtual models for numerical study; (a) Model for standard pull-out test with implemented adhesive contact between core and face sheet; (b) Models for the test with application-oriented boundary conditions.

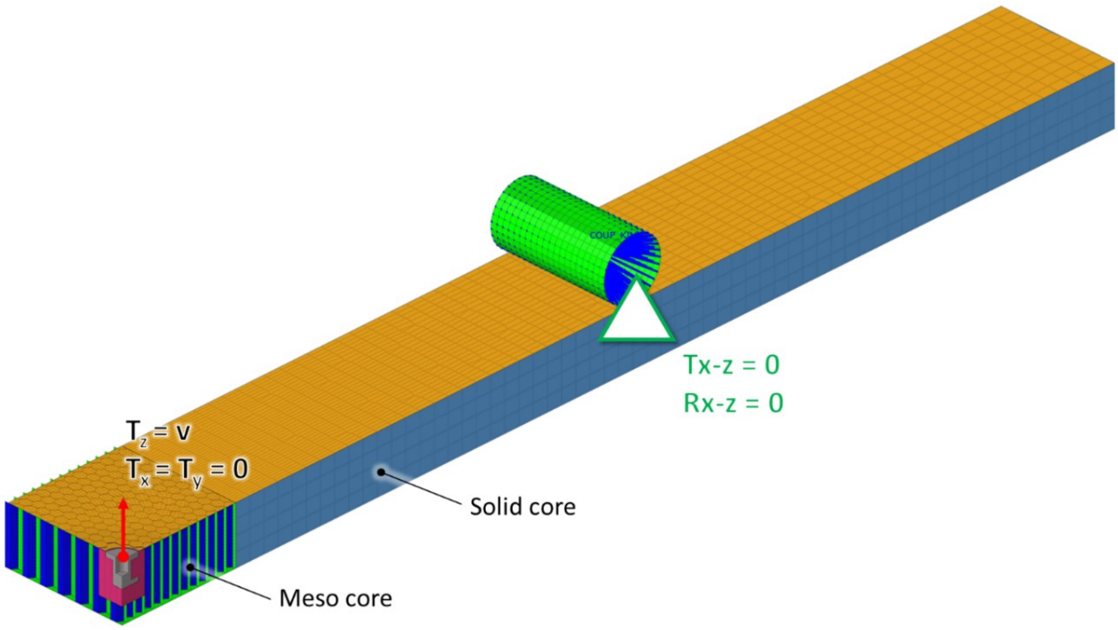


Figure 6: Virtual model of bending pull-out test with roll distance of 360 mm.

## 4 RESULTS AND DISCUSSION

Figure 7 shows the results of the experimental and numerical studies for the quadratic specimens. The damage mechanisms evident are similar in the different tests and are shown exemplarily in Figure 8 for the pull-out test. Overall, the structural behavior can be divided into different phases. First, linear-elastic deformation of the specimen occurs, before shear buckling of the core walls appears, which leads to the nonlinear behavior of the force-displacement diagram. Subsequently, initial delamination between the upper face sheet and the core occurs at the first local maximum, resulting in a small force drop. The face sheet then continues to successively detach from the core and the cell walls continue to buckle until an abrupt force drop occurs as a larger area of the adhesive contact fails at once.

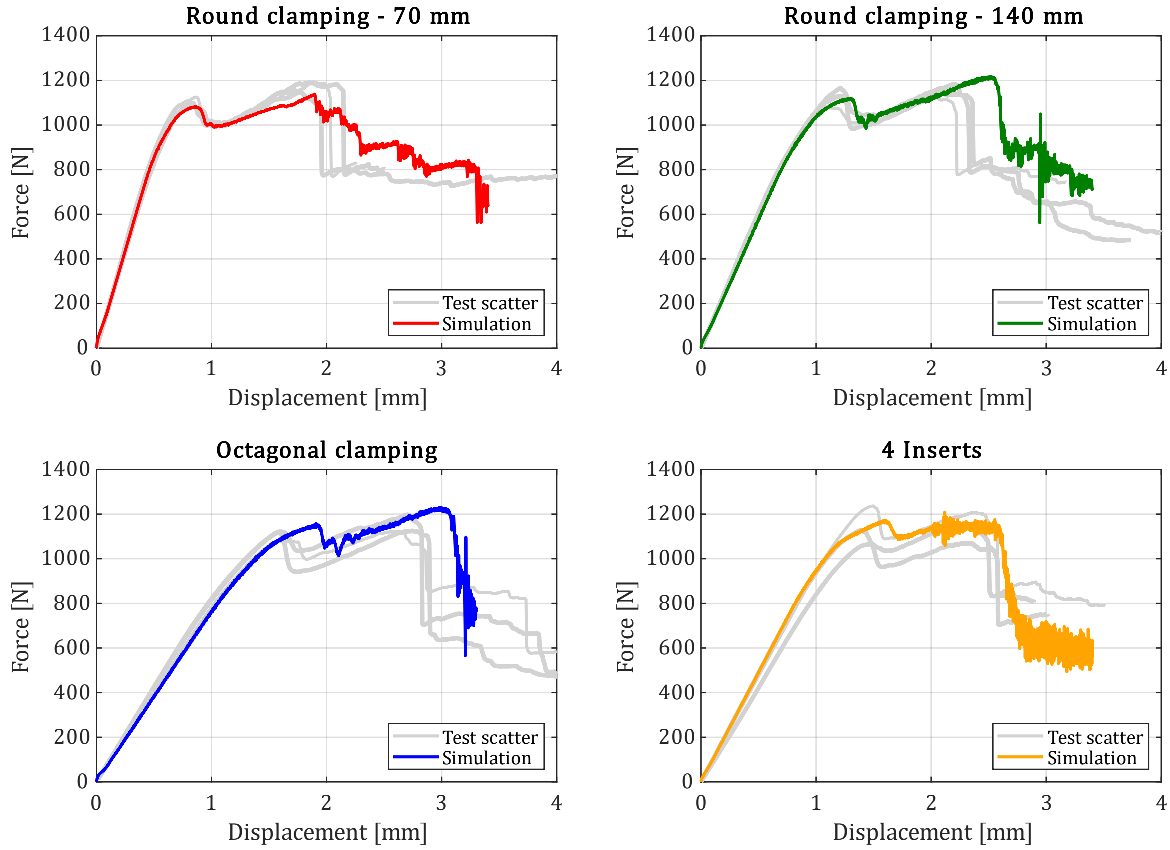


Figure 7: Experimental and numerical results of the tests of quadratic specimens.

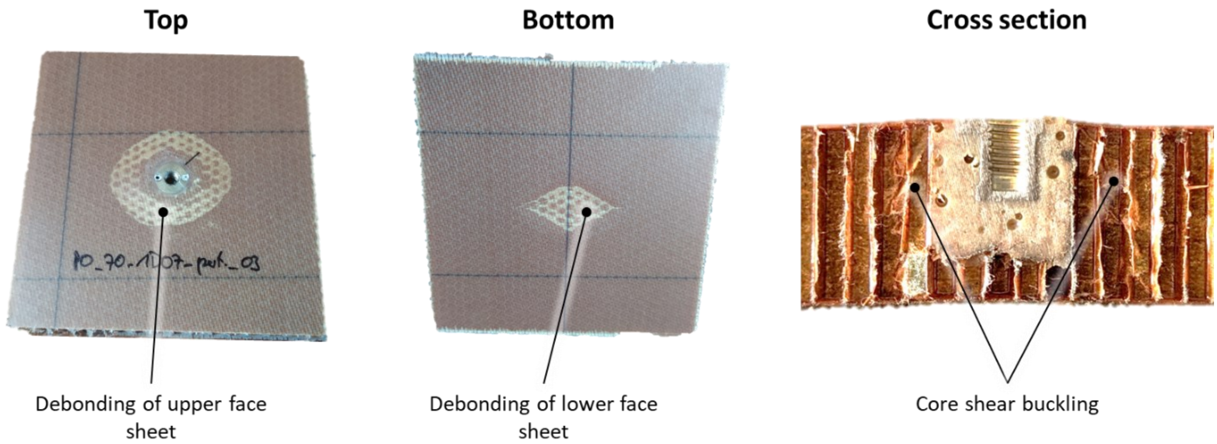


Figure 8: Damage mechanisms in the pull-out test.

Figure 9 shows the results of the experimental and numerical studies for the bending pull-out tests. The damage mechanisms evident differ for the different roll distances and are shown in Figure 10. In the test setup with a 160 mm roll distance, like in the tests of the quadratic specimens, first also local shear damage of the core and delamination between face sheet and core around the insert occurs. Further loading leads to total failure of the structure in form of global compressive failure of the lower face sheet. In contrast to that, in the tests with a 360 mm roll distance a linear progression in the force-displacements diagrams can be determined, after global compressive failure of the lower face sheet directly occurs.

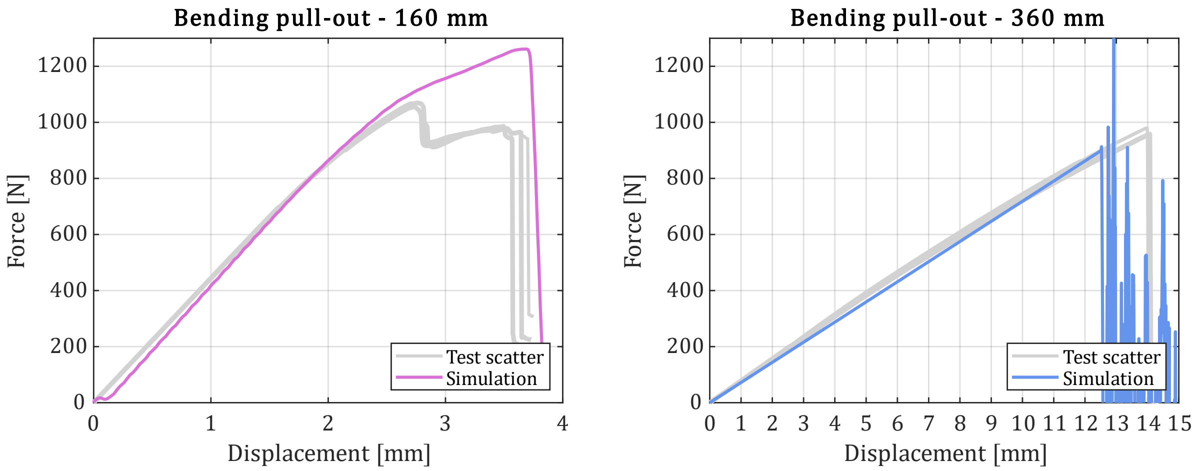


Figure 9: Experimental and numerical results of the bending pull-out tests.

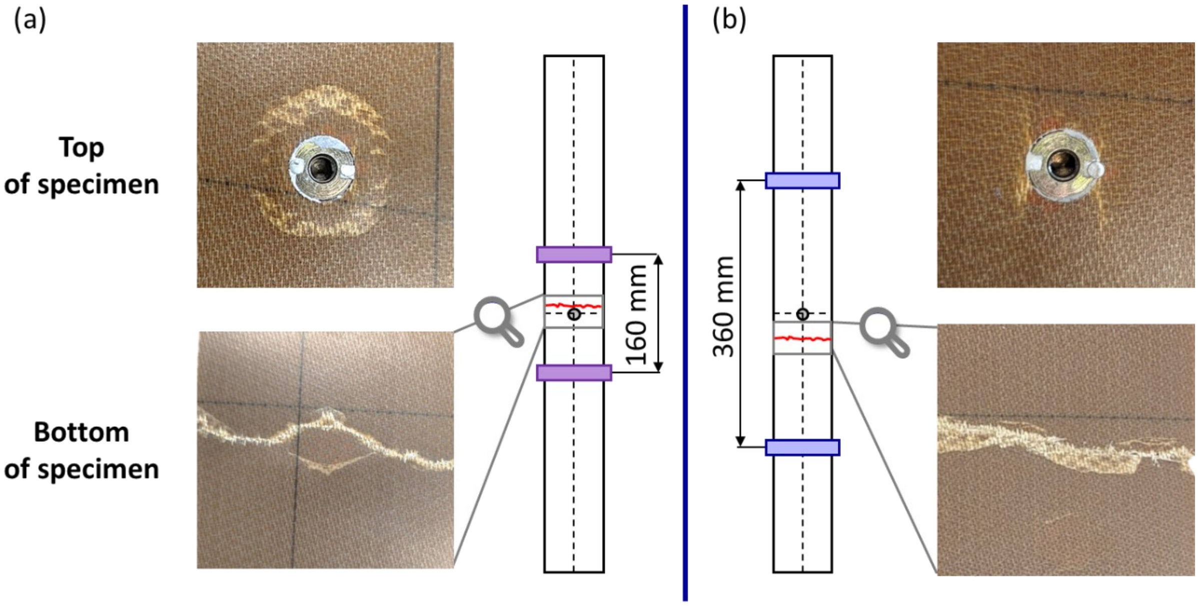


Figure 10: Damage mechanisms in bending pull-out test; (a) Damage in tests with 160 mm roll distance; (b) Damage in tests with 360 mm roll distance.

In Figure 11 (a), a representative measurement was taken from each test setup for the square specimens to compare and contrast the different boundary conditions. The stiffness differs in the tests, which can be attributed to the difference in specimen length due to the different clampings. This is well illustrated in Figure 11 (b), where the different clampings are compared graphically. However, the pull-out forces and basic progression of the curves are similar and indicate the same damage mechanisms, as it could also be determined visually in the experimental tests.

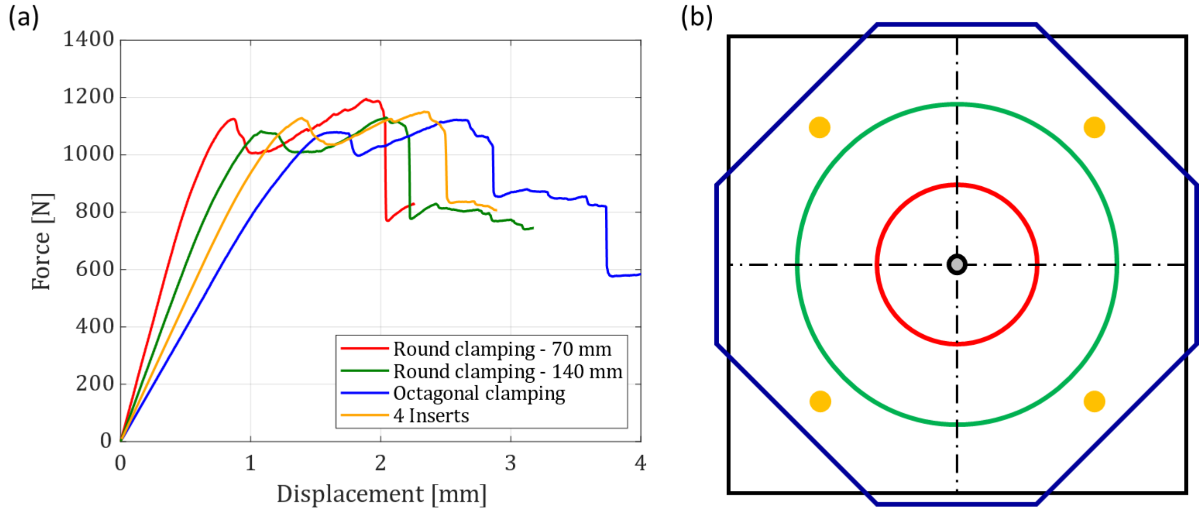


Figure 11: (a) Comparison of testing results for the different boundary conditions with quadratic specimens; (b) Visualization of the different clampings with the colors from the plot.

In Figure 12 (a), also a representative measurement was taken from the tests with the two different roll distances as well as from the standard pull-out test for comparison. The different boundary conditions are visualized in Figure 12 (b). It can be seen that the progression of the test with a roll distance of 160 mm initially shows a similar progression to the standard pull-out test. As expected, the stiffness in the test is slightly reduced due to the larger specimen span width. Also, the pull-out force is reduced and post-failure behavior is significantly shortened compared to the standard pull-out test. Both are due to the superimposed loading situation and the higher bending fractions that cause both the premature local insert failure and the global abrupt face sheet failure. The stiffness in the test with a roll distance of 360 mm is again significantly lower and the global face sheet failure at about 1000 N is visible. This corresponds approximately to the load level of the global failure in the test with a roll distance of 160 mm as it depends on the compressive strength of the prepreg. With increasing distance of the clamping rolls, the influence of the local effects of the insert system on the structural and failure behavior thus decreases and is replaced by the global effects and damage mechanisms of the sandwich composite.

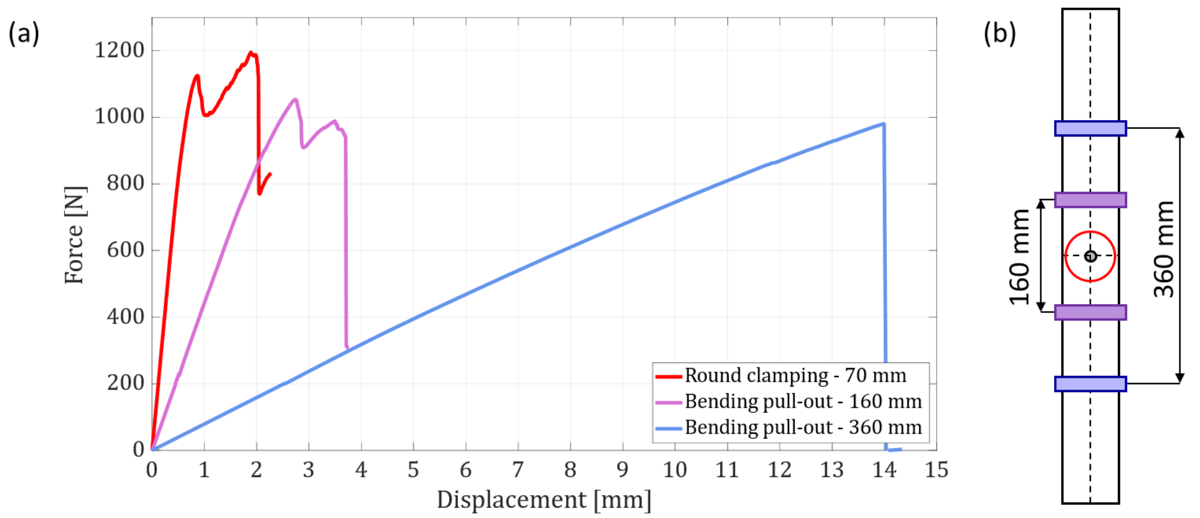


Figure 12: (a) Comparison of testing results for the different boundary conditions in bending pull-out tests; (b) Visualization of the different clampings and roll distances with the colors from the plot.

Overall, especially the simulations with the quadratic specimens agree well with the experimental results and reproduce the damage mechanisms closely. Nevertheless, while the simulation adequately represents the pull-out test with 70 mm diameter clamping, there are slight deviations in the prediction of the abrupt failure in the pull-out tests with 140 mm and octagonal clamping. This is due to the different loading conditions in the tests under application-oriented boundary conditions. Also in the bending pull-out tests deviations between simulation and test become evident and show the importance of validating numerical models on appropriate tests. In the test with a 160 mm roll distance the first damage mechanism, which is the initial delamination from core and face sheet is not correctly reproduced and leads to an overestimation of the pull-out force. On the other hand, the strength in the 360 mm is slightly underestimated. Although the models have been tested and validated under various loading conditions in appropriate component tests, the boundary conditions in these tests are highly idealized and therefore do not result in a superimposed load that is close to the application. However, for use in larger structures, for example in the form of submodels, it must be ensured that the structural and damage behavior are adequately reproduced by the detailed models even under superimposed loads, as they usually occur in the use of products. Therefore validating and testing the numerical models in tests with realistic boundary conditions as purposed in this paper is recommended.

## 5 APPLICATION OF NEW TEST SETUP ON AM-SANDWICH DESIGN

In the previous chapters, it was shown that the boundary conditions in component tests have an influence on the structural behavior of the sandwich structures. The new test setups lead to superimposed loading situations in the sandwich structure, which must also be taken into account in the insert design. In this chapter, the application of the new test setup for the design of the load introduction in sandwich structures is shown. Additively manufactured sandwich cores are used as an example, as they offer a high degree of design freedom and these optimized designs are easier to manufacture. But the test setup can also be used for other design concepts and in particular for the load-path optimized design of sandwich structures with aramid cores.

The method and materials used in this section are the design approach described by Schwenke and Krause [15], as it was also used by Wegner et al. [18] for a small octagonal clamping. In this paper, the new test setup with load introduction points as test boundary conditions is investigated. The design space for optimization can then be extended to the complete sandwich structure. With this new test setup, the optimized structure for these boundary conditions is compared with a reference design, where the reinforcement is concentrated around the load introduction point. The two designs have the same mass and are additively manufactured with the stereolithography printer Form 3L (Formlabs) from a photopolymer synthetic resin (Clear Resin FLGPCL02). The additively manufactured cores are bonded with aluminum face sheets to form sandwich structures of approximately 200 x 200 mm in size. Holes are drilled at the load application points and the load is applied directly via the bolt heads as a simplification in the test. Both designs are shown together with the set-up with new clamping and the results of the pull-out test in Figure 13.

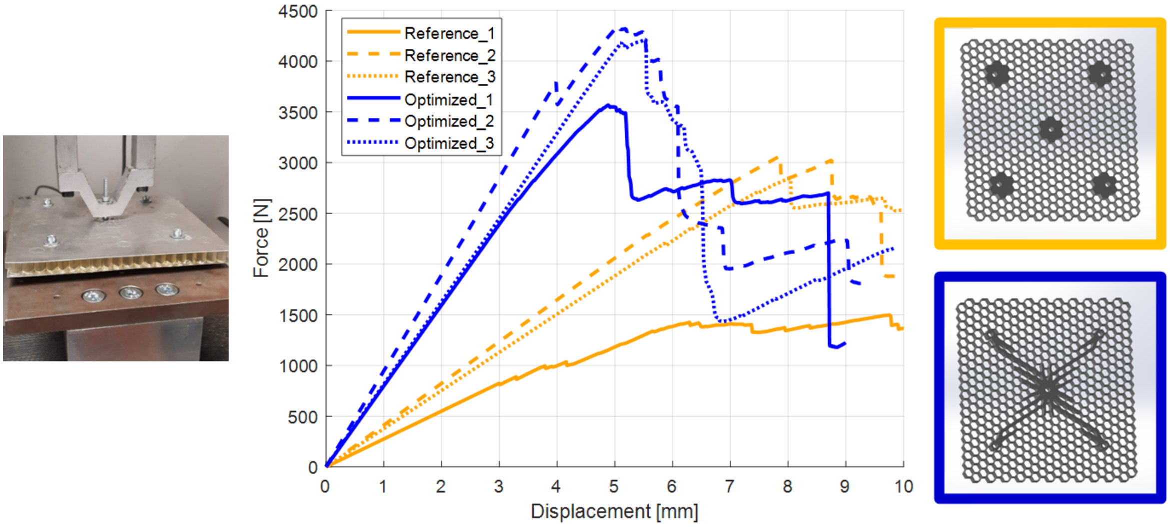


Figure 13: Tested designs, test setup and results in force-displacement diagram.

Three identical sandwich specimens are tested for the reference design and the optimized design. The force-displacement diagram shows slight variations in the stiffness of the specimens for each design, with the optimized design being noticeably stiffer. There is some variation in the maximum force for both designs, mainly due to manufacturing, but all the maximum forces of the optimized design are greater than those of the reference design. The stiffness and maximum force values obtained for the six specimens are shown in Table 1.

Table 1: Test results for stiffness and maximum force.

| Specimen | Stiffness [N/mm] | Mean and standard deviation of stiffness [N/mm] | Max. force [N] | Mean and standard deviation of max. force [N] |
|---|---|---|---|---|
| Reference_1 | 275 | 355 ± 71 | 1497 | 2468 ± 848 |
| Reference_2 | 412 | | 3065 | |
| Reference_3 | 377 | | 2843 | |
| Optimized_1 | 797 | 852 ± 82 | 3568 | 4044 ± 417 |
| Optimized_2 | 946 | | 4349 | |
| Optimized_3 | 814 | | 4214 | |

The optimized design performs 240 % better than the old design in terms of average stiffness and 153 % better in terms of maximum force.
Since there is a strongly defined direct connection to the supported corners in the optimized design due to the relatively small sandwich specimen, verification on larger sandwich structures is recommended.

## 6 CONCLUSION AND OUTLOOK

Current component tests of sandwich structures and fasteners have idealized boundary conditions and do not take into account product-orientated load conditions, resulting in high safety factors being added. In this paper, application-oriented component test setups with realistic boundary conditions for insert systems were introduced and experimental, numerical and design optimization studies on these have been performed. On the one side tests for quadratic specimens, like proposed in the quasi-standard pull-out test, and on the other side test setups with rectangular, elongated specimens to take combined pull-out and bending load into account have been proposed. The investigations have shown that the boundary conditions have a great influence on the structural behavior and the damage mechanisms of the sandwich structure and the insert system. Especially in the proposed bending pull-out test, it has been determined that local failure of the inserts is replaced by global failure mechanisms if the bending load is being increased. While the implemented virtual models represented the tests with the quadratic specimens well, there have been deviations in the bending pull-out tests. Tests with application-orientated loading situations should therefore be further investigated and used to test and validate detailed virtual models, e.g. to ensure their use as submodels in the global FEM analysis of large sandwich structures. Also, for the design optimization, it becomes clear that new test setups are necessary and that test setups like the presented one can be used for this purpose.

## ACKNOWLEDGEMENTS

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