SHEAR–COMPRESSION BUCKLING TEST METHOD ON CURVED STIFFENED COMPOSITE PANELS

F. Odermann[a]*, A. Kling[b]

[a] *Institute of Composite Structures and Adaptive Systems, Department of Structural Mechanics, German Aerospace Center (DLR), Braunschweig, Lilienthalplatz 7, D - 38108 Braunschweig, Germany*
[b] *former Institute of Composite Structures and Adaptive Systems, Department of Structural Mechanics, German Aerospace Center (DLR), Braunschweig, Lilienthalplatz 7, D - 38108 Braunschweig, Germany*
**falk.odermann@dlr.de*

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Abstract

A test method is described to experimentally investigate curved stiffened composite panels with respect to their buckling and post-buckling behavior up to collapse. The test method utilizes a new test rig with which stringer and frame stiffened curved panels can be tested under uniaxial compression loads, in-plane shear loads as well as a combination of both. During shear loading the panel is guided according to its radius. The whole test rig can be adjusted to cover a large range of geometric shell parameters.

Results will be presented for different stiffened composite panel designs. Effects of the chosen load introduction and the boundary conditions will be discussed, which have a considerable influence on the panel behavior. In addition, procedures and measurement techniques used during the tests will be explained. The findings confirm that the test method and in particular the new test rig is suitable to investigate representative stiffened structures under in-plane loading conditions relevant for stability analysis.

1. Introduction

Within aircraft design composite structures are gaining in importance. Although composite materials are already widely used for primary aircraft structures, the inherent structural reserves of these materials are not fully exploited. Due to their thin walled design, those aircraft structures are prone to buckling under compressive and shear loading, which is one of the key sizing criterion within the design process. However, the complex mechanism of post-buckling behavior of thin walled stiffened composite structures is dependent on a great variety of parameters, especially when considering also mechanisms of damage initiation. Thus, further research is required in order to provide reliable methods for structural design, and hence, to fully exploit the lightweight potential of composite structures.

Experimental tests are essential to investigate buckling and post-buckling phenomena on different aircraft structure designs and different loading conditions. Stiffened curved panels are considered as a representative section of an aircraft fuselage and allow a practicable and valid investigation. Moreover, this level allows the experimental analysis of the interaction of stringers, frames and skin with a reasonable effort.

2. Brief overview of existing shear-compression test methods on panels

In general different kinds of in-plane shear and shear-compression test methods can be found in literature. Most of them deal with testing of flat panels with simple load frames or load rigs, which can be adapted to existing standard servo-hydraulic test machines, e.g. picture shear frame test rigs. For special issues, e.g. curved structures or combined loading, different test rigs and test machines with unique characteristics are developed. Some of them are described briefly in the following.

Agarwal [1] describes shear tests on composite shear web panels, which are assembled in a cantilever beam structure. In this I-section cantilever beam a composite panel with two stiffeners forms the web. The chord material is steel. The beam is clamped at one edge. Load is applied with an eccentric arm at the opposite edge to reach a state of shear stress free from bending in the center of the panel. Static tests and cyclic fatigue tests are conducted. For fatigue loading, delamination in the diagonal tension corners between skin and stiffeners of the panel are reported.

In the contribution by Castanié [2] a test rig is presented to test asymmetric sandwich specimens under combined compression-shear loads. The test specimen is mounted between a cross beam like structure. Different actuators at the ends of these cross beams introduce the respective loading, i.e. compression, shear or a combination of both, into the sandwich specimen. With this test procedure, the loads acting on the specimen cannot be obtained; only strains and displacements are measured.

A test machine for combined compression, tension and shear loads on flat panels is presented by Romeo et al., [3]. The loads can be applied independently from each other. The machine can apply a longitudinal compression load, a transverse compression or tension load as well as positive or negative shear load on panels up to 1000 mm x 700 mm. The panel is mounted to the test rig at all four edges. The corners of the panel are chamfered and left free. The axial compression and shear loads are decoupled by a hinge device. Transverse shear is introduced through an eccentric beam whereas the compression load is applied on the lower part of the load introduction unit.

In the work by Ambur [4] a test machine for combined loadings of curved stiffened panels is described. The test machine is able to apply axial compression loads, bending and torsion to a D-box structure. The panel is connected to the upper part of the D-box, whereas the curved box structure provides support to the edges of the test article. This set-up is used to ensure boundary conditions representative for a real fuselage or wing structure. One end of the D-box is clamped whereas the opposite end is mounted on a loading platen that is driven by actuators.

A modified picture shear frame test device is presented by Wolf, [5]. A picture frame is used to apply shear loads on shallow unstiffened panels. The thickness to radius ratio reaches from 1/2000 to 1/4000. The panel size is fixed to an area of 400 mm x 400 mm. That means, that the curvature, compared to the panel dimensions is very low.

In addition, a short description of a complex test rig from former MBB can be found (original source not available), where a curved panel is mounted vertically. The axial compression load can be applied on the curved edges independent to shear loads. Shear loads are introduced on horizontal and lateral edges. The panel is guided by rods on a circular path for shear movement.

Klein [6] presents a test set-up, procedure and results for axial tests on curved stiffened panels with impact. Especially the boundary conditions, aroused by the assembly of the panels into the test facility, are described. Stiff tubes and gliding planes support the straight lateral edges of a panel. The upper and lower curved edge of the panel are casted into a clamping box with a mixture of epoxy and quartz-powder as well as gypsum. The panel together with the clamping boxes is fitted with equalizing layers into the facility.

3. Test method for curved stiffened panels under compression and shear

3.1. Test rig built-up

To apply compression, shear or combined compression-shear loads on a curved stiffened panel, an existing buckling test facility, which is capable to apply axial loads on cylindrical shells, is extended by a shear compression device (figure 1).

Figure 1. Buckling test facility: axial compression configuration (left); extended facility in shear compression test rig configuration (right)

At first, the design of the test rig, led by several test requirements (table 1), is basically defined by a kinematic principle. Within the intended test method, a curved panel should be loaded by axial compression and in-plane shear independent from each other. The radius should be adapted continuously within a specific range. In-plane shear load should be transferred on a circular path adapted to the panel radius. Panels of different height and length should be tested, as well as panels with different structural designs according to frames,

criteria	**requirement**	**current parameters**
max. axial force	1 MN	380 kN, extendable to 1 MN
max. shear force	500 kN	210 kN, extendable to 500 kN
min. free panel height	584,2 mm (one frame pitch)	584,2 mm
max. free panel height	1168,4 mm (two frame pitch)	1168,4 mm
max. free panel width	1200 mm	1200 mm
radius	radius of single aisle fuselage	1550 mm … 2300 mm

Table 1. Comparison between requirements and realized design of shear compression test rig

stringer geometry and number of stringer. The design of the test rig follows specific criteria to fulfill the intended requirements.

According to these requirements the test rig is configured as shown in figure 2. The shear compression test rig consists of a shear frame (1), a load transmission unit (2), a shear load cylinder bracket (3), an extension arm for the guiding rods (4) and a slide bearing adapter for the existing buckling test facility (5). The adapter decouples the axial movement from the horizontal one and is guided on bearings at the frame of the buckling test facility (8). Further, the axial cylinder (9), which is mounted on the ground plate of the buckling test facility, acts on the adapter. Load cells (10) connect the shear frame to the top plate of the buckling test facility. The shear load cylinder bracket contains a hydraulic cylinder (11) with rear mounted load cell (12). The panel (6) is assembled between the upper panel box at the shear frame and the lower panel box of the load transmission unit. It is assembled to these boxes by casting the curved edges 120 mm deep into the box. The casting material is a mixture material, which consists of milled soapstone in a polyurethane matrix. Thus, it is possible to homogeneously introduce the load for any given geometry. Lateral edges of the panel are kept free for following reasons:

1. Since the experimental finding is subsequently utilized to validate numerical simulations, a defined modelling of boundary conditions is mandatory. When edge stiffeners or sliding bearings are applied undefined friction forces together with normal forces appear. They significantly change during loading up to the deep post-buckling regime, which complicates the modelling.
2. Shear load introduction at lateral edges would need complicated stepwise mounted actuators that must not stiffen the panel under compression loading. Those actuators, which should be load controlled, need to follow the movement of the main actuator, which is displacement controlled. In addition, such actuators would have to follow the circular movement of the curved panel.

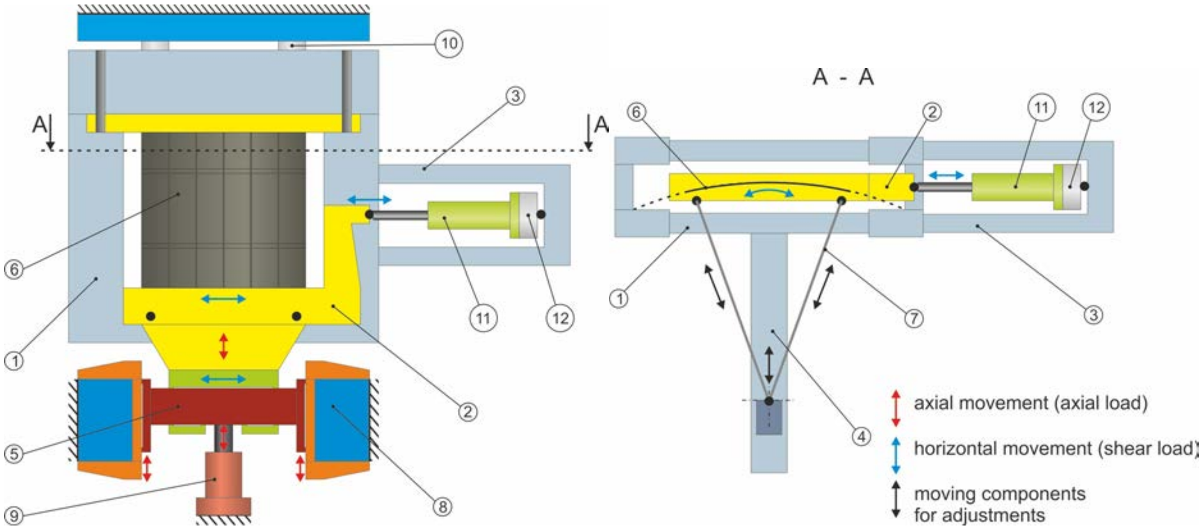


Figure 2. Principal of shear compression test rig: front view (left); top view (right)

3.2. Function and characteristics of the shear compression test rig

As described before the panel is loaded at the lower horizontal edge and clamped at the upper horizontal edge. The axial load is applied by the vertical hydraulic servo-cylinder, which acts on the slide bearing. From the bearing unit the axial load is introduced through the load transmission unit to the panel. Axial load is measured by four load cells at the top of the shear frame. The shear load is applied by a horizontal hydraulic servo-cylinder directly at the load transmission unit and into the lower edge of the panel. The shear load is measured by a load cell mounted at the rear of the servo-cylinder. The measured force contains not only the reaction forces of the panel but also the friction force of the slide bearing. Yet, the comparison of the loading and unloading path of the undamaged panel allows determining the reaction force of the panel. Since the slide bearing allows a free movement in horizontal plane of the load transmission unit, the exact circular path is given by guiding rods. These rods are mounted on a common axis of the extension arm. By changing the distance of the axis to the load transmission unit and changing the length of the guiding rods, the path can be adapted to the existing curvature of the panel since the actual radius of the panel was measured via static DIC (digital image correlation) system ATOS. Additional guiding rods support the radial position of the frames in case of frame-stiffened panels.

Axial displacement is measured by two inductive displacement transducers at the lateral edges of the panel, and horizontal displacement for shear is measured by laser triangulation sensors at one plane of the load transmission unit near the lower panel box. A second laser sensor measures the horizontal displacement of the sliding bearing. Panels are equipped with linear strain gages and rosettes of strain gages. The unstiffened back side of the curved panel and the stiffened center area are used for DIC measurements utilizing the ARAMIS system.

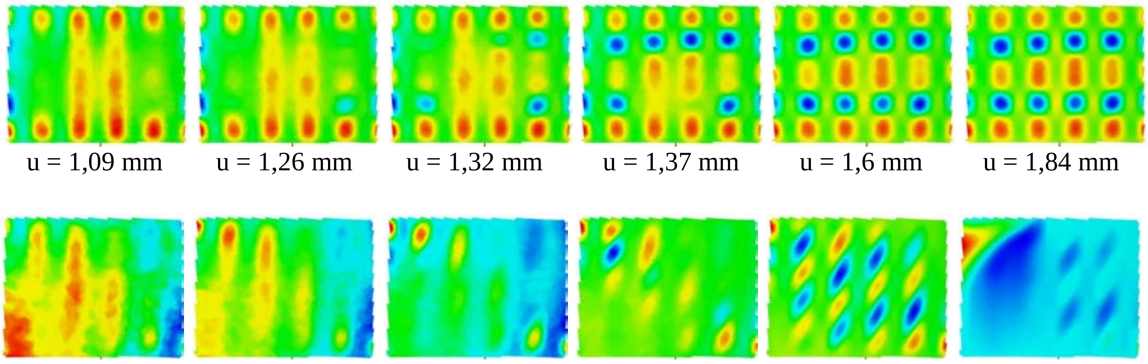
4. Exemplary experimental results

4.1. Short panel without frames

In the following experimental results from DIC measurements of radial displacements of a panel are given. A curved CFRP panel, stiffened with omega stringers, is loaded axially and horizontally. The panel, which geometrical details are given in table 2, has a free buckling length of 584 mm, which compares to a stiffened skin area of a fuselage between two frames with a pitch of 23 inches. Axial loading without shear influence shows an equal load distribution over the panel width at the edges of load introduction; depicted in figure 3a for different axial displacement “u”. There the panel is loaded axially in the region of elastic material behavior. Noticeable radial displacement appears first at the two inner skin bays and might be an effect of free lateral edges. All panels of this type showed largest radial displacement at two inner bays at low axial displacements. However, radial displacement is nearly symmetrically, even if buckling pattern appears at the right skin at a lower displacement of 1,09 mm compared to 1,26 mm at left side. This may be an effect of geometric tolerances of the panel in some extent. Further panels, which were tested with the identical set–up, revealed an evenly distributed symmetric pattern. At 1,6 mm of axial displacement a buckling pattern is fully developed which reaches over all skin bays. At that load skin buckling under the omega stringers is also developing; compare small buckles with

radius	1978 mm	**stringer pitch**	151 mm
free length	584 mm	**skin thickness**	1,625 mm
width	718 mm	**stringer thickness**	1,125 mm
circular width	744 mm	**stringer height**	24,9 mm
type of stringer	omega	**stringer feet width**	77 mm
number of stringers	5		

Table 2. Geometrical data of short omega stringer stiffened panel


a) u = 1,09 mm u = 1,26 mm u = 1,32 mm u = 1,37 mm u = 1,6 mm u = 1,84 mm

b) v = 1,55 mm v = 2,25 mm v = 3,26 mm v = 3,55 mm v = 7,18 m v = 7,47 mm

Figure 3. DIC radial displacement (autoscaled) of omega-stiffened panel, skin side; a) stages of axial displacements u under axial loading; b) transverse displacement v under horizontal shear loading

a larger longitudinal dimension than transverse dimension between circular shaped skin buckles. In figure 3b the development of a buckling pattern of a shear dominant stress field until failure is depicted. Due to the loading principal the upper left and lower right corner of the panel are loaded with compression forces whereas the two other corners are loaded with tension forces in addition to the shear force. Therefore, the upper left and lower right corner show the largest radial displacement. Also the buckling pattern develops along this diagonal direction starting at a displacement of 2,25 mm. However, a full shear buckling pattern is developed at all four skin bays shortly before failure at 7,18 mm. Failure occurs at the upper left corner because of the afore mentioned normal forces superposed to the shear force. This can be seen in figure 4 (stringer side) at the upper right corner.

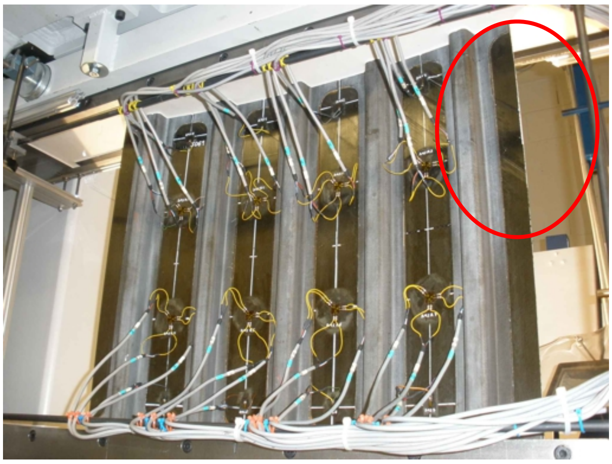


Figure 4. A typical short panel after failure at right upper corner, front side with omega stringers

4.2. Long panel with frames

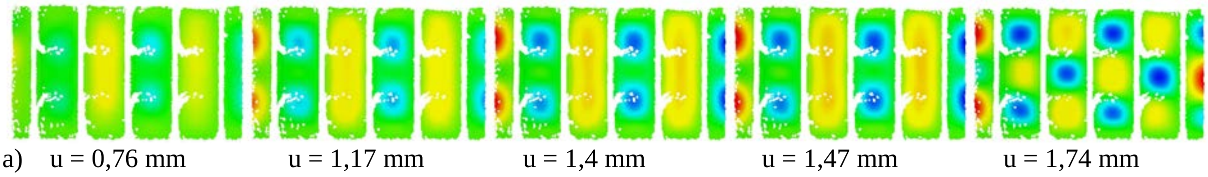
Within the following selected DIC measurement results are presented for a curved CFRP panel, stiffened with T-stringer and simple I-frames made of aluminum (table 3). Guiding rods support the two frames of the panel and keep them in radial position (figure 5). ARAMIS DIC is applied on both sides of the panel. Since the panel has a free length of two frame pitches, one skin section is located in the center between two frames. A half skin section is enclosed to the center section. This half section helps to equalize the load distribution from

radius	2097 mm	**skin thickness**	1,375 mm
free length	1173 mm	**stringer thickness (web)**	3,25 mm
width	990 mm	**stringer height**	32 mm
circular width	1000 mm	**stringer feet width**	56 mm
type of stringer	T-stringer	**type of frame**	Al I-frame
number of stringers	5	**number of frames**	2
stringer pitch	200 mm	**frame pitch**	584 mm

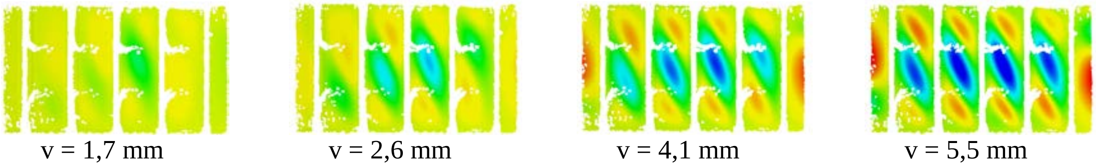
Table 3. Geometrical data of long T - stringer stiffened panel with Al - frames

Figure 5. Test rig with frame stiffened panel, frames supported by guiding rods, ARAMIS-DIC in front and rear (not visible)

the panel boxes to the center skin section. In figure 6a the buckling pattern under axial loading is depicted for different axial displacements “u”. Equal development over the width of all four skins is noticeable. Outward cambered buckles (yellow) appear at first and stay joined until mode switch at u = 1,74 mm. Inward cambered buckles (blue) develop at larger displacements and are separated from the beginning. Different shapes between inward and outward cambered buckles may be due to the curvature of the panel, which makes it easier for outward directed buckles to develop. Within figure 6b the buckling pattern under in-plane shear loading for transverse displacement “v” is depicted. At first, the largest radial displacement



a) u = 0,76 mm u = 1,17 mm u = 1,4 mm u = 1,47 mm u = 1,74 mm



b) v = 1,7 mm v = 2,6 mm v = 4,1 mm v = 5,5 mm

Figure 6. DIC radial displacement of T-stringer and frame stiffened panel, stringer side, center area, fixed scale a) stages of axial displacements u under axial loading; b) transverse displacement v under horizontal shear loading

appears at the two inner skin bays which can be noticed at a displacement of 2,6 mm and 4,1 mm. After that a more even shear pattern develops at a displacement of 5,5 mm. Compared to the shear buckling pattern of the short panel the high radial displacement at the diagonal corners is avoided.

5. Summary and conclusion

A new shear-compression buckling test method on curved stiffened composite panels is presented in form of a new shear-compression test rig. Different local measurement technics like load cells, displacement transducers, laser triangulation sensors and strain gages are applied. In order to measure the global deformation of the test structure digital image correlation (DIC) is used. It provides important information about the test rig and test structure interaction. Within the paper it is shown, that the presented test rig provides reliable load conditions for axial and shear dominant loads. Although lateral edges left free without stiffening or load introduction, an equal developed buckling pattern for axial compression as well as shear load can be achieved.

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References

[1] B. L. Agarwal. Postbuckling Behavior of Composite Shear Webs, *AIAA Journal*, volume(19), Issue 7: 933-939, July 1981

[2] B. Castanié, J. J. Barrau, J. P. Jaouen, S. Rivallant. Combined shear/compression structural testing of asymmetric sandwich structures, *Experimental Mechanics*, volume(44) Issue 5:461-472, October 2004

[3] G. Romeo and G. Frulla. Nonlinear analysis of anisotropic plates with initial imperfections and various boundary conditions subjected to combined biaxial compression and shear loads, *International Journal of Solids and Structures*, volume(31) Issue 6:763-783, March 1994

[4] D. R. Ambur, J. A. Cerro, J. Dickson. D-Box Fixture for Testing Stiffened Panels in Compression and Pressure, *Journal of Aircraft*, volume (32), Issue 6: 1382-1389, 1995

[5] K. Wolf, H. Kossira. An efficient test method for the experimental investigation of the postbuckling behaviour of curved composite shear panels, In *Proceedings of ECCM-CTS, European Conf. on Composites Testing and Standardisation*, Amsterdam, September 1992.

[6] H. Klein, B. Geier, H. C. Goetting, et.al. Buckling testing with curved, stiffened CFRP panels damaged by impact. *Proc. Conference on Spacecraft Structures Materials and Mechanical Testing*, ESA/CNES/DARA SP-386. June 1996.