STRINGER STIFFENED PANEL UNDER AXIAL COMPRESSION, SHEAR AND COMBINED LOADING CONDITIONS - TEST AND NUMERICAL ANALYSIS

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Abstract

In this contribution, the experimental and numerical analysis of an omega stringer stiffened panel made of CFRP is treated. The experiment described hereafter is a buckling and post buckling test under axial compression loading. The structure is loaded until collapse. Load shortening data, strain gauges and DIC measurements are available for the validation of the numerical model. The simulation is conducted using Finite Element software ABAQUS/Standard. A shell model is described and the numerical results are compared to the experimental data.

1 Introduction

Physical testing of structures of different scale is vital for the validation of computational models used in the different stages of the design and analysis of structural parts made of composites. Therefore, tests at all levels of the so called Rouchan Pyramid [1] need to be conducted in order to build up a sound basis for validation. Since the predominant limitation for thin walled stiffened structures under in-plane loads in the structural performance is the buckling and post buckling characteristic, it is important to have a good understanding in the phenomenology of the structural response as well as to have a high level of confidence in the simulation models. This is a prerequisite to fully exploit the load carrying capacity of the structure by means of allowing first skin based buckling below limit load and thus utilizing the post buckling regime of a stiffened panel under operation conditions of an aircraft resulting in potential weight saving.

In regard of the validation of a numerical model [2, 4], it is required to know what in the tests is realised, and that the outcome is reliable. Thus on the one hand attempts are made to obtain well known test structure properties and well defined test conditions, and on the other hand at least two nominally equal panels are tested of each design to achieve a minimum redundancy for each load case. In addition, pre-test computations are required in order to increase the confidence in the planning of the tests (e.g. location of strain gauges and appropriated combined loading ratio of compression and shear) as well as the suitability of the test results for validation purposes.

The present contribution comprises the discussion of a test of an omega stringer stiffened panel and the description of the numerical simulation model for the comparison with test results. Load shortening curves and the out of plane displacement are exemplarily provided.

2 Test structure

The test structure described and discussed in the present paper is a curved stiffened panel with five equally spaced omega stringers made of CFRP. It is a sample of a test series of four nominal identical panels. The geometric details of the test structure discussed in this contribution are given in Table 1. Before the test, geometric imperfections of the skin are measured to obtain deviations from the nominal shape (e.g. real radius) and ultra-sonic inspection is conducted to get information of the quality of the laminate as well as of the connection of the skin-stringer interface. This data is of great importance for the evaluation of the test results regarding their suitability in the validation process of the simulation model. This NDI assessment before the test of the panel revealed no noteworthy defects in the laminate that influence the behaviour in the test. It was also found that the geometric deviation from an ideal cylindrical shape is negligible small, although the radius generated by means of a best fit procedure indicated a significant deviation from the nominal radius of 2075mm. The material properties of the CFRP prepreg are known from a characterisation.

Panel length (with potting area) [mm]	825
Free length (buckling length) [mm]	584
Radius [mm]	1680
Thickness [mm]	1.625
Arc length [mm]	750
Number of stringers	5
Distance stringer to stringer [mm]	150
Laminate set-up of skin	[45, -45, 0, 90, -45,45, 0, 45, -45, 90, 0, -45, 45]
Laminate set-up of stringers	[45, 0, -45, 0, 90, 0, -45, 0, 45]
Ply thickness [mm]	0.125
Stringer thickness (web) [mm]	1.125
Stringer height [mm]	24
Width upper web [mm]	27
Angle between upper and side web[°]	80
Stringer foot width [mm]	21

Table 1. Geometry of the panel

A picture of the panel after potting and milling during the test preparation is given in Figure 1 (left).

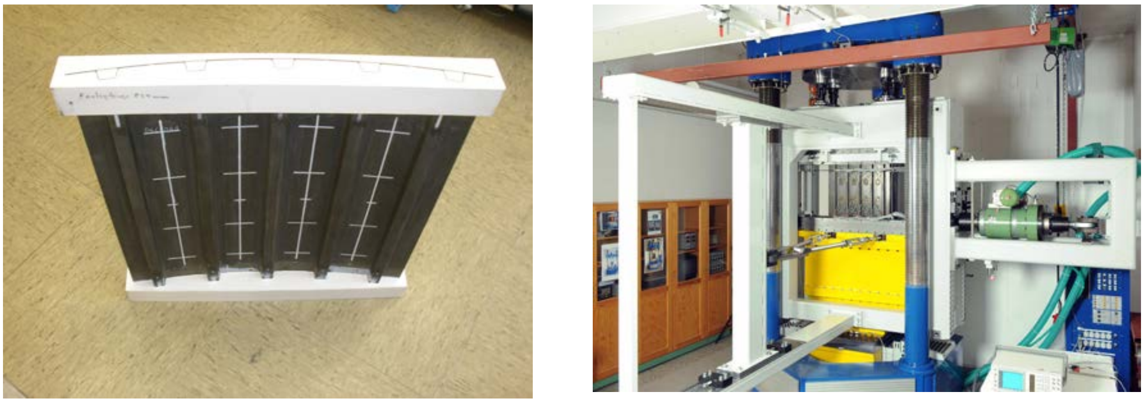


Figure 1. Test panel (left) and buckling test facility (right)

The panel skin also - in addition to the CFRP layers - comprises of a bronze mesh and filler; however, the mechanical properties of these outer layers are considered to be negligible for the structural behaviour and also not taken into account in the numerical simulations.

3 Experiment

The objective of the test is to get a better understanding for the buckling and in particular the post buckling behaviour and the load carrying capacity characteristic under in-plane loading conditions. For this purpose, axial compression, shear dominated and combined load cases are considered in the test series of four omega stiffened panels. All tests are conducted in the buckling test facility of DLR with a test rig capable of introducing shear load into curved panels. The test device that was developed at DLR for the introduction of compression and shear loading at the same time is depicted in Figure 1 (right). The load is introduced displacement controlled for both components, i.e. the axial compression and shear. As shown in the image, the longitudinal edges are free, that means they are neither constrained nor load is introduced. This ensures constant and reproducible boundary conditions along these edges, which are vital for validation purposes of a FE model. The boundary conditions at the potting area, i.e. upper and lower edge, can be approximated as clamped with a fixed axial displacement at the upper panel edge and the displacement controlled load introduction at the lower edge. In all tests, the load is applied in multiple steps first until skin buckling occurs and is subsequently increased into the post buckling regime (Figure 2).

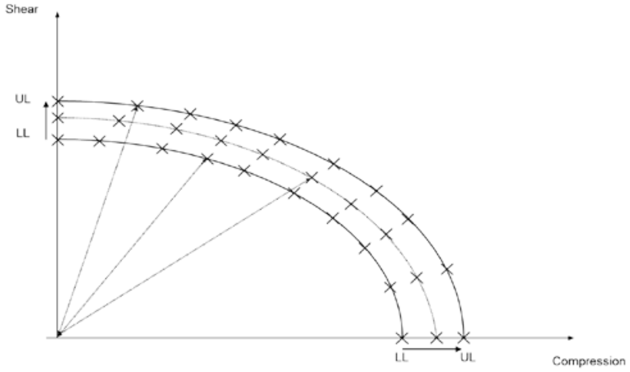


Figure 2. Interaction curve of shear and compression loading

In addition to the NDI measurement mentioned before, the panel is casted into end blocks that are finally milled (Figure 1, left) in order to achieve an equally distributed load introduction along the curved edges into the panel. This procedure was established in previous programmes and found to be adequate for this purpose [3, 5]. After this procedure and the application of strain gauges, the panel is mounted into the buckling test facility through final potting of 120mm height at the lower and upper edge. The measurement during the test comprises the monitoring of the axial and transverse (in shear direction) displacements and forces, strain gauge measurement as well as DIC images to measure the out-of-plane deformations. The DIC pictures were taken from the skin side of the panel.

Exemplarily, a panel test under axial compression is discussed here. The panel was loaded by compression until collapse of the structure. The load shortening curve is depicted in Figure 3. The corresponding DIC images showing the out of plane deformations at characteristic loading stages are given in Figure 4. The slope of the curve is linear up to the point where the first buckles occur at a shortening of u=1.33mm with a compressive force of $F_{buckling}$=254kN. This first buckling that leads to a reduction in structural stiffness initiates in the outer skin fields, although even before the free edges that are not constraint during loading start to buckle. However, this deflection is expected and is not regarded as first buckling of the structure. The buckling pattern is completely developed as a regular pattern with five half waves in each skin field at a shortening of approximately u=1.52mm. Above this load level, the buckling shape does not change until the collapse of the panel, only the amplitude of the buckles increases during further loading. The curve also shows that the post buckling path behaves linearly up to approximately u=2.4mm, where a little degradation in the stiffness can be noticed. This might firstly be due to the growing amplitude of the local skin buckling but secondly also due further deflection of the skin beneath the omega stringer as indicated in the DIC images close before collapse of the panel at u=2.65mm (Figure 4). The actual collapse occurs at u=2.67mm with a load of $F_{collapse}$=441kN. The observed failure mode is the breakage of the omega stringers with a corresponding separation of the skin from the stringer.

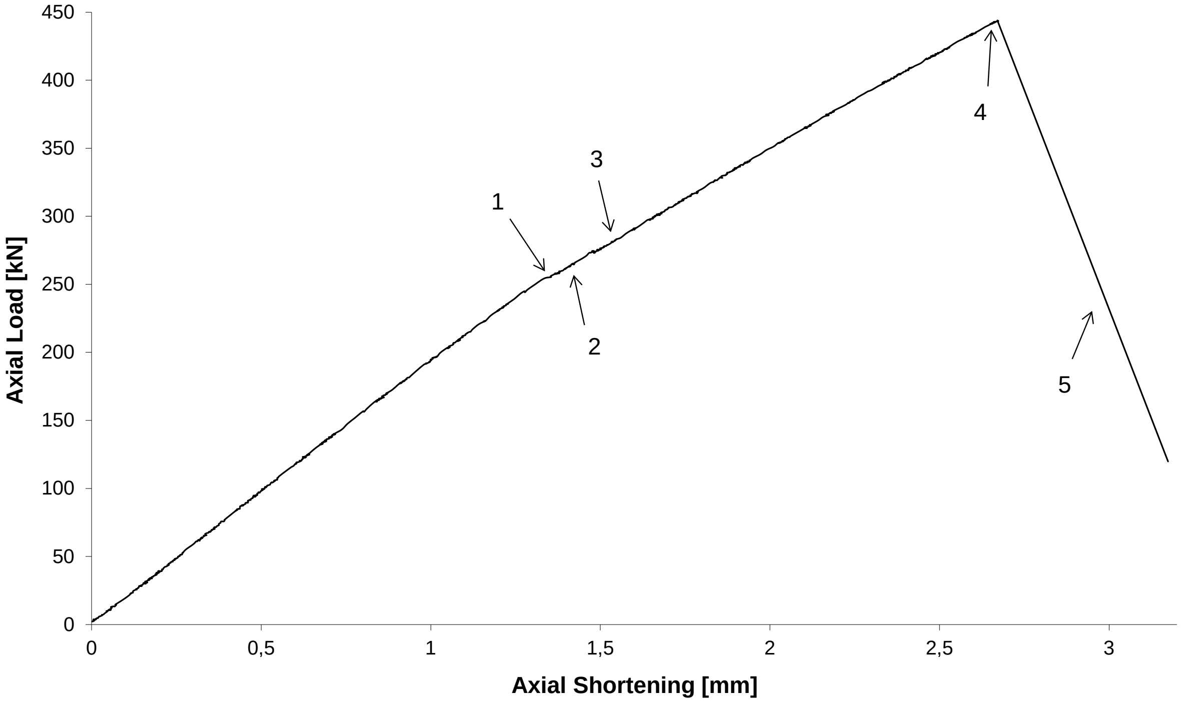
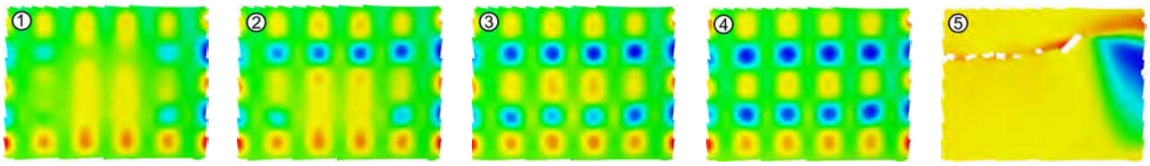


Figure 3. Load shortening curve of the test panel under axial compression until collapse



u = 1.33mm u = 1.39mm u = 1.52mm u = 2.65mm after collapse

Figure 4. DIC images at characteristic load levels

4 Simulation and comparison to test results

The objective of a validation process is to ensure that the numerical model correctly accounts for the phenomenological behaviour of the stiffened panel under the considered loading conditions and to represent the boundary conditions of the test facility. In a validation process, the gained data from an experimental analysis, as outlined in the previous paragraph, can be utilized at two different levels [4]. On the one hand, a comparison of the global structural behaviour by means of global end shortening and transverse displacement, respectively, with their corresponding reaction forces referring to the axial compression and the transverse shear load is made and on the other hand an assessment of rather local quantities such as strains and out-of-plane displacements, i.e. the buckling pattern is conducted.

Figure 5. FEM model of the test panel

For the numerical simulations, the Finite Element software ABAQUS/Standard has been used. The panel components, i.e. the skin and the omega stringers are discretised using four node shell elements (S4R). In order to capture the nonlinear effects, a fine mesh with an overall element length of approximately 6mm is used during the simulations. The stringers are connected to skin via a tie constraint to couple the degrees of freedom of the stringer feet nodes to those of the corresponding nodes of the skin. The load is introduced displacement controlled as in the test procedure. The potting area is approximated by constraining all degrees of freedom for these nodes except of the axial one to allow the shortening of the loaded edge. The longitudinal edges are free as in the experiment. The material properties are known from a material characterisation according to appropriate standards. A picture of the FE model is shown in Figure 5. Imperfections from a linear eigenvalue analysis are included in the non-linear solution procedure. To solve the system, the Newton-Raphson method with artificial stabilization to ensure convergence is applied. A degradation model is not implemented. Consequently the collapse behaviour is not subject of the present analysis.

The result of the numerical analysis and a comparison with the curve obtained from the test described in the previous paragraph is shown in Figure 6. The simulation shows an excellent agreement for the pre- and post buckling stiffness. Also, the buckling load indicated in the load shortening curve as drop in the structural stiffness corresponds quite well with the one from the panel test and is $F_{buckling}$=241kN. Since no failure and degradation model is used in the simulation, the collapse load is not captured in the analysis. The comparison of the buckling pattern reveals that the shape obtained with ABAQUS (Figure 7) matches well with the buckles from the test at selected characteristic loading stages. The development of the buckling shape is slightly different; however this depends also on minimal imperfections in the experiment and also on the numerical parameters in the FE model. In the test and the simulation the buckling shape develops from first buckling to a regular five half wave buckling pattern in all skin fields between a shortening of 1.25mm and 1.52mm.

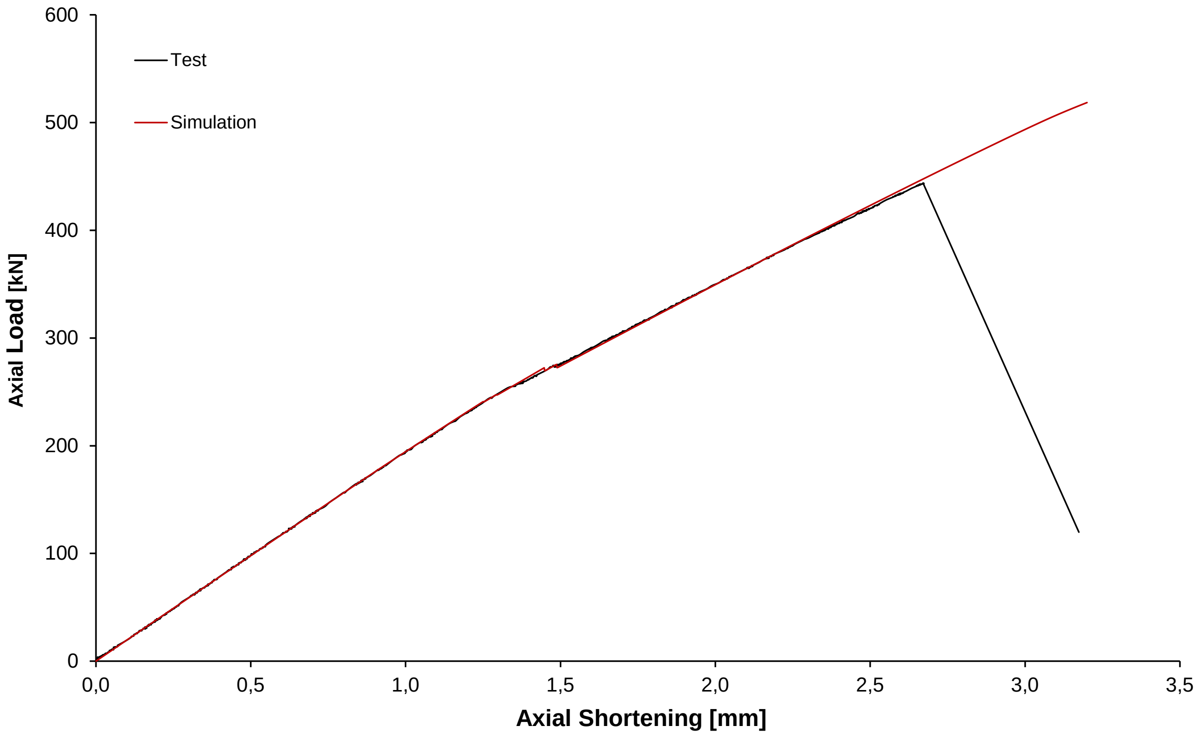


Figure 6. Comparison of load shortening curve from the simulation to the test result

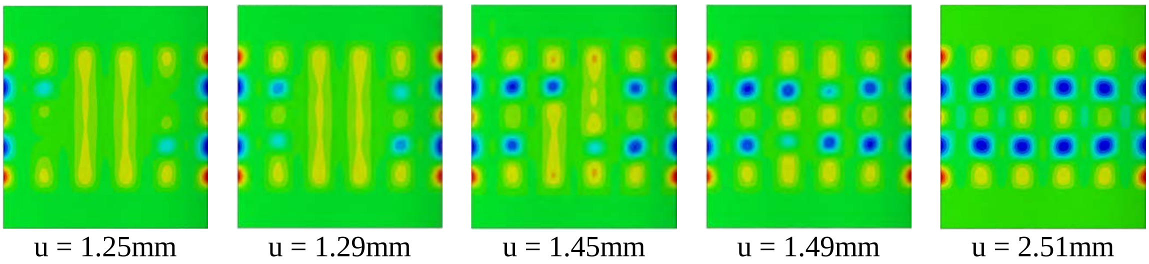


Figure 7. Buckling pattern from simulation for selected load levels

5 Conclusion and outlook

In this contribution, a test of an omega stringer stiffened panel under axial compressive loading until collapse has been described. The load shortening behaviour as well as the out of plane measurement by DIC has been discussed for characteristic points on the load shortening path. Also, a model for the numerical simulation of this panel has been introduced. The simulations were conducted using ABAQUS. It was shown that the results from the numerical model matches well with the results of the experiment for axial compression in terms of pre- and post buckling stiffness and the critical load and can thus be regarded as validated up to the deep post buckling regime. Future work will be focused on loading conditions such as shear loading and combined load cases. Also, the failure mechanism shall be reflected in the simulation.

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