VALIDATION PROCEDURE FOR NONLINEAR ANALYSIS OF STRINGER STIFFENED CFRP PANELS

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Abstract

The allowable load bearing capacity of undamaged thin-walled stringer stiffened carbon fibre reinforced plastic (CFRP) panels loaded in compression is currently limited by its buckling load. The extension to a novel stability design scenario - to permit postbuckling under ultimate load [1, 2] or even more progressive to move ultimate load close to collapse [3,4] - requires validated simulation procedures for this highly nonlinear topic for fast tools in the early design phase up to numerical analysis within the certification process. Different aspects of the validation process with respect to experimental investigations, nonlinear FE analysis as well as the comparison on different levels of detail are highlighted.

1 Introduction

The reduction of weight by about 20% in 10 years without prejudice to costs and structural life is the baseline for current research on primary aircraft structures, like stringer stiffened panels. A possible approach to cope with that demand for fuselage structures is to utilize CFRP material and for the considered thin walled structures, loaded in compression, to permit postbuckling (only small deformations will be allowed) until ultimate load at the same time. However, this approach requires a systematic and reliable nonlinear numerical analysis including collapse prediction with accepted validation procedures using experimental data. In Figure 1 two schematic load shortening curves are depicted with a typical run for the considered CFRP panels. The left one displays the current/typical industrial design scenario. The right graph illustrates a future design scenario utilizing the large unemployed structural reserves between current ultimate load and collapse. In addition, the onset of degradation moved from the not allowed region III (current design scenario) to the safety region II in the new scenario. But it must be ensured, that in any case the onset of degradation must not occur below limit load.

This paper focuses on the validation aspect within the nonlinear analysis up to the deep postbuckling regime, whereas structural degradation is not a main focus. Further information with respect to the currently developed methods to consider structural degradation can be found in [4, 5].

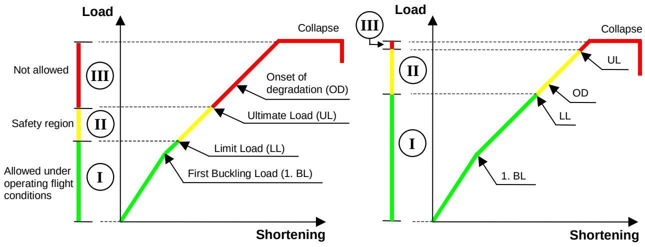

Fig. 1. Current and future design scenario for stiffened CFRP panels [4, 5]

Figure 2, depicting the different phases of modelling and simulation, provides an insight in the interaction of reality/physical experiment, computer and conceptual model. The phenomenological 'Experiment' has to be analyzed to obtain the 'Conceptual Model' (mathematical equations), which describe the physical behaviour accurately. Subsequently, the extracted mathematical equations are coded to obtain the ‘Computer Model’. The main focus within this paper is not to verify the underlying numerical algorithms (e.g. arc-length method or displacement controlled Newton-Raphson Method) or detailed element formulation (“solve the equations right”), rather to validate (“solve the right equations”) the nonlinear analysis containing possible conceptual modeling errors. Therefore the accentuated area ‘Model Validation’ containing experimental planning and testing as well as numerical analysis, which will be the focal point of this paper and described exemplarily for stiffened CFRP panels.

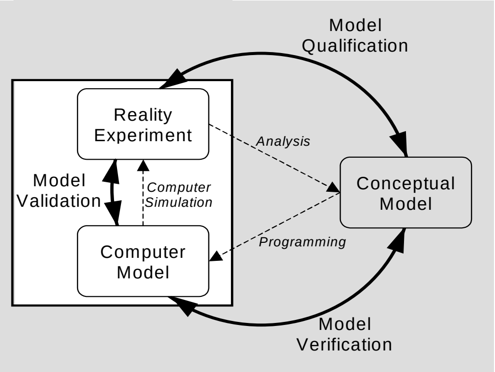

Fig. 2. Phases of modeling and simulation [6]

2 Design of the test structures

Based on several former research projects, a significant number of cylinders and panels have been designed, manufactured and tested. Each of them with a slightly different focus to understand the basic physical behavior (phenomenological) or for validation purposes.
For the design of the test structures ABAQUS (/Standard as well as /Explicit) has been utilized in most cases to trace the buckling and postbuckling behaviour. The purpose of this nonlinear finite element analysis was to evaluate which design (e.g. stringer spacing, skin and stringer wall thickness or lay-up) would show the desired reduction in the axial stiffness at the occurrence of local skin buckling and a significant load carrying capacity in the postbuckling region before collapse emerges. Additional constraints on the design of the panels were the geometric limitations of the in-house buckling facility as well as the proximity to real aircraft fuselage structures.

Subsequently, the influence of initial geometric imperfections on the postbuckling behavior was examined. Therefore a single buckling mode (eigenvalue analysis) as well as their superposition was applied as “artificial” imperfections in the nonlinear analysis. These preliminary calculations indicated a minor imperfection sensitivity for this rather stringer dominant structure. Additionally, the influence of different boundary conditions was investigated to assess critically any impact on the load carrying capacity. It revealed that the clamping width of the longitudinal edge supports has a significant influence on the axial stiffness in the deep postbuckling region. As a result of this, modifications were made to optimize the experimental boundary conditions.

Based on these preliminary nonlinear calculations, a fairly good understanding of the buckling and postbuckling behavior of the CFRP panels was gained.

With regard to the described outcome from these preliminary calculations it is worthwhile to spend time and efforts on pre-test analysis, however, this makes only sense for these relatively complex problems, if there is a sufficient confidence in the analysis process (e.g. based on some experience to simulate similar structures).

For the subsequently detailed panel the goal was to obtain a local, skin based, first buckling between the stringers (change of axial stiffness in the load shortening curve) followed by a significant increase in load carrying capacity up to global, stinger based, buckling (close to a factor of two) and after that a further increase in axial load and shortening up to collapse load.

More details on the design process within the projects POSICOSS and COCOMAT can be found in [7].

3 Experiment

The validation procedure to ensure reliable numerical simulations requires extensive experimental data (not only the subsequently described panel tests, but also as a sound foundation reliable material characterization tests), especially to compare with nonlinear calculations and the possibility of several bifurcation as well as limit points in the postbuckling region.

3.1 Pre-Test Analysis

Each test on so called subcomponent level, like the examined panels, is, due to its time consuming preparation, testing and evaluation, quite expensive. Therefore a substantial amount of work was spent on detailed design analysis and planning.

As soon as the structures were manufactured additional pre-analyses were performed on the real geometrical data which can be slightly different to the nominal one (e.g. measured radius is larger then the nominal one due to spring back effects within the manufacturing process). Therefore, the placement of the sensors (strain gauges and displacement transducers) could be modified according to these tentatively results for validation purposes.

3.2 Test structure

Overall eight test structures have been manufactured and tested at the in house buckling test facility within the POSICOSS [2] project. Subsequently, a four-stringer panel (P12) will be considered exemplarily.

To avoid local buckling along the free edges, longitudinal edge supports have been placed close to the lateral edges of the test structure. Figure 3 displays the panel installed in the clamping boxes on the top and bottom for a homogeneous load introduction. The four T-shaped stringers have been manufactured separately, using a symmetric stacking sequence of prepreg material and have been bonded to the cured skin.

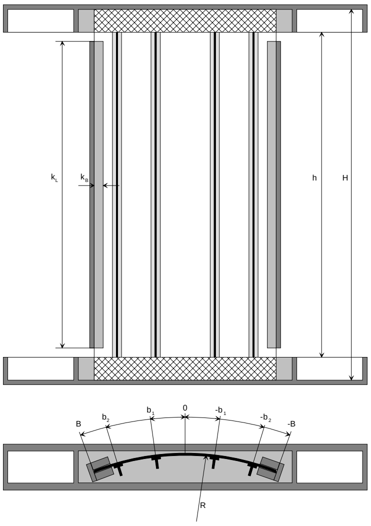

Fig. 3. Test structure with clamping boxes

Ultrasonic inspections have been conducted to examine the quality of the panels. Figure 4 depicts the flaw echo of a panel where almost no inhomogeneity in the lamina as well as at the stringer-skin interface can be found.

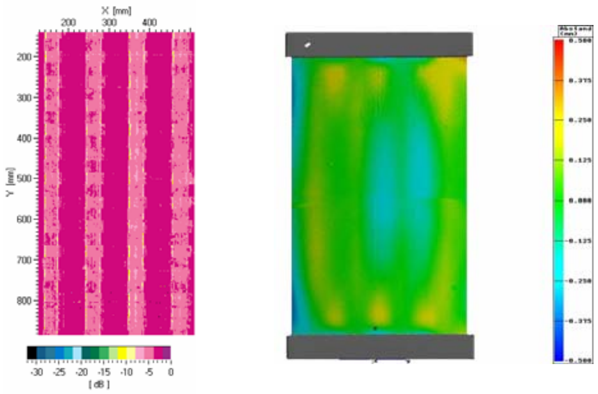

Fig. 4. Ultrasonic flaw echo (left), measure imperfections (right)

In order to identify the real shape of the skin, ATOS, an optical 3D digitizing measurement system (based on photogrammetry), was utilized to extract the actual radius of the panel as well as the initial geometric imperfections of the skin. The small difference between the nominal radius (1000 mm) and the measured one (1071 mm) is due to snap-back effects during the manufacturing process. Figure 4 shows the color rendering as aberration with respect to the perfect panel. This deviation can be not only used as a qualitatively estimate of the panel geometry, but it could be introduced as imperfections within the nonlinear analysis.

Fig. 5. Test setup (in-house buckling test facility)

The placements of sensors to measure local strains (strain gauges) as well the focus of the ARAMIS system (3D digitizing measurement system based on photogrammetry) was based on the afore described pre-test analysis, however the sensor configuration has been selected to cover possible, slightly different, deformation patterns. The test setup at the in-house buckling test facility with the installed ARAMIS system is shown in Figure 5.

3.3 Test results

The afore mentioned optical measurement system (ARAMIS) has been used to capture digital images of the deformed panel at 88 load levels. After postprocessing, the displacements at nodes of a fine mesh (representing the surface of the “skin side” of the panel) are available. Three of these color renderings are shown in Figure 6 at characteristic load levels along the load shortening curve. The pattern A displays the occurrence of local skin buckling, which corresponds to a small change in the axial stiffness of the load shortening curve slightly below 40 kN axial load.

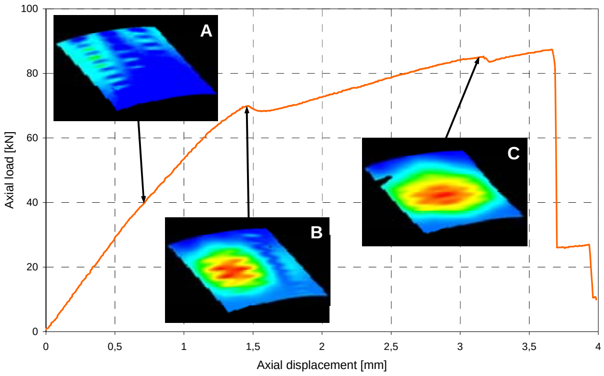

Fig. 6. Load-shortening curve and deformation patterns measured with ARAMIS at characteristic load levels

Subsequently, the global (stringer based) buckling arises as a typical 2/3 versus 1/3 deformation for this type of panel. At the kink of the load shortening curve (1.4 mm axial displacement) the transition from the 2/3 versus 1/3 buckle to a single global one started. This global buckling deformation moves consecutively to the center of the panel and grows as shown in C. At 3.16 mm axial displacement a small, however sudden change in the load carrying capacity is visible, which is most probably due to first/local structural degradation. The structure collapsed at a load of 87.3 kN due to a massive stringer-skin-separation.

4 Analysis

Due to its highly non-linear behavior of the examined stiffened CFRP panels under pure axial pressure a commercial nonlinear finite element tool (ABAQUS) has been employed for analysis. As mentioned before substantial investigations have been undertaken with respect to model generation (e.g. stringer-skin connection, boundary conditions) and analysis procedure which are described subsequently.

4.1 Finite element model

Preliminary examinations (combined with long lasting experience within this type of analysis [8]) have been conducted to ascertain the use of an appropriate shell element, the necessary mesh refinement and the stringer-skin connection. Finally, a four-node shell element (S4R, six degree of freedom at each node, three integration points along the thickness for each ply have been selected, further information can be found in [9]) with a side length of approximately 4 mm has been employed to discretize the panel.

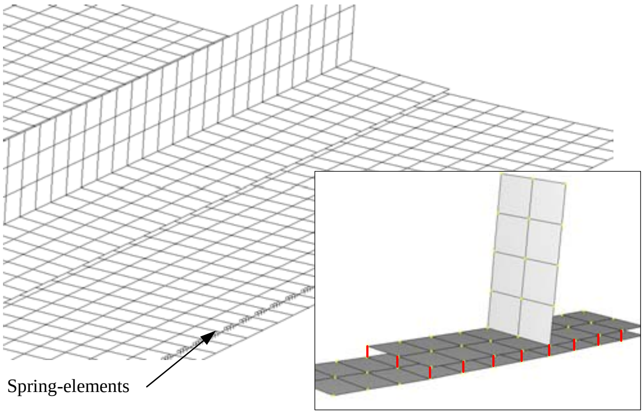

Fig. 7. Finite element model

This relatively fine mesh was mandatory to include all kind of local as well as nonlinear effects in the analysis for validation purposes. Figure 7 depicts a clipping of the FE-model and some detailed information with respect to the stringer-skin connection. The stringer-skin connection (adhesive joint) has been modeled using rigid elements connecting corresponding nodes of the skin and stringer elements. In addition, spring elements are visible, which have been used to model the longitudinal edge supports, which have been attached to the test structure. A slightly refined mesh as well as a coarser one has been utilized as a convergence check. The pure axial loading has been applied displacement controlled.

4.2 Analysis procedure

There are different numerical approaches available in ABAQUS, which can be used to simulate the buckling and postbuckling behavior of the considered CFRP panel type structures. Next to the nonlinear static incremental/iterative methods like the arc-length method or the Newton-Raphson method with or without artificial damping, also nonlinear dynamic methods by implicit or explicit integration have been considered. Extensive studies revealed that the Newton-Raphson method with artificial damping was the most effective way to simulate this type of structures within ABAQUS/Standard. If this solution method is active, a virtual velocity is introduced to be equal to the displacement increment divided by the corresponding time increment. The damping matrix, which is used, is simply the mass matrix with unit density multiplied with a damping coefficient. The damping coefficient should be as small as possible to minimize the dissipative energy, which is taken out of the system. For a converging solution procedure the time incrementation usually decreases as virtual velocity (e.g. at global buckling) increases, which leads to a controlled postbuckling behavior.

The approach which has been used to conduct a FE-analysis in ABAQUS/Standard consists basically of four stages Figure 8):

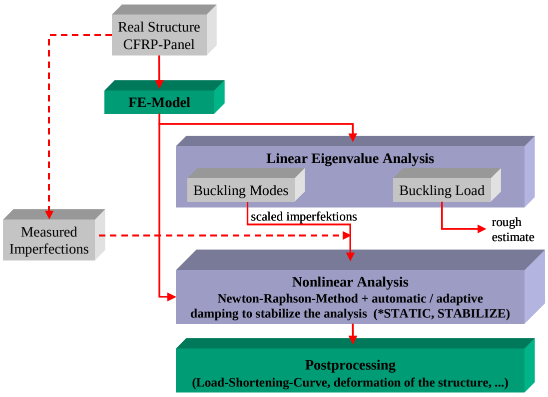

Fig. 8. Analysis procedure

First the preprocessing to generate the FE model, followed by a linear eigenvalue analysis (*BUCKLE) to extract buckling modes. These modes have been used in the subsequent nonlinear analysis as scaled “artificial” imperfections. Alternatively, the results due to the optical digitizing of the skin (measured initial imperfections of the unstressed panel) could be used as “real” imperfections of the panel. For the nonlinear analysis with ABAQUS/Standard the built-in Newton-Raphson technique with adaptive/artificial damping (*STATIC, STABILIZE [9]) and displacement controlled loading has been utilized. However, note that other approaches might be necessary or more efficient for other thin walled structures (e.g. unstiffened cylinders). Finally, the desired results (e.g. deformations, strains) have been extracted with a postprocessing software.

4.3 Results

Figure 9 depicts the load-shortening-curve, which has been extracted from numerical results of the analysis procedure described in the preceding section with and without initial geometric imperfections (scaled buckling modes). The deformation pattern at characteristic displacement levels are shown from the analysis without imperfections, starting with the typical "local" skin buckling (A), followed at the kink with a 2/3 versus 1/3 buckle (B), which changed consecutively to a single global deformation moving to the center of the panel (C).

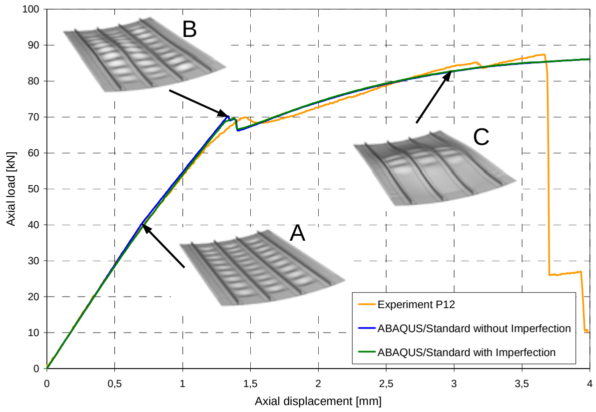

Fig. 9. Load-shortening curves (numerical and experimental) and deformation patterns (numerical)

The differences between the numerically extracted curves are small, the occurrence of characteristic points, represented by the displayed deformation patterns A and B emerge at a slightly lower shortening for the analysis without imperfection. The smother transition from the prebuckling stiffness to the postbuckling one, due to local skin buckling (A), can be explained by the initial geometric imperfections. Based on several parametric studies and the fact that the considered structures are rather stringer dominant, it can be summarized that there exists only a minor geometric imperfection sensitivity.

5 Validation

As described in Section 3.3 a significant amount of test data is available to validate numerical results. Basically, three levels of detail can be distinguished:

In a condensed global level of validation, where e.g. the overall axial load-shortening is considered. This is usually the first step to ensure that for example the axial stiffness in the pre-buckling stage is accurately mapped, subsequently local and global buckling as well as the postbuckling stiffness is compared.

In a full scale level, where the quantitative deformation patterns at different load levels are compared. Improved experimental measurement techniques allow a direct comparison how well the deformation patterns match at different load levels with the numerical ones.

In a local level of validation, where local information like strains from strain gauges or radial displacements from local position encoders are compared with the numerical results. With the purpose to evaluate the correspondence on a rather small scale.

Each level has its individual necessity for a full validated model, due to the fact that with this approach individual, possible shortages in the discretization become obvious.

In the following only the global and full scale level of validation, where the overall displacement and reaction force is compared in the load-shortening curve, as well as a qualitative examination of the deformation patterns will be described.

Figure 6 and 9 show the good accordance of the numerically extracted and experimentally measured data, like the axial stiffness in the pre- and postbuckling region, the appearance of the non-symmetric global buckle and the transition to the centered global buckle in the deep postbuckling region. Smaller deviations between the experimental and numerical results are visible at the occurrence of the sharp kink (non-symmetric global buckle) and the deeper postbuckling region. This is most probably due to the influence of the rigid supports attached to the longitudinal edges of the panel (modeled with spring elements). The deformations at characteristic load levels (A, B, C) match well. For example the global (stringer based) buckling arises as a typical 2/3 versus 1/3 and moves further on to the center as one large buckle, still superposed with a few local buckles in its center.

Note that at this stage of the validation process no degradation model has been implemented in the FE-code, therefore degradation (e.g. stringer-skin separation), was not predictable.

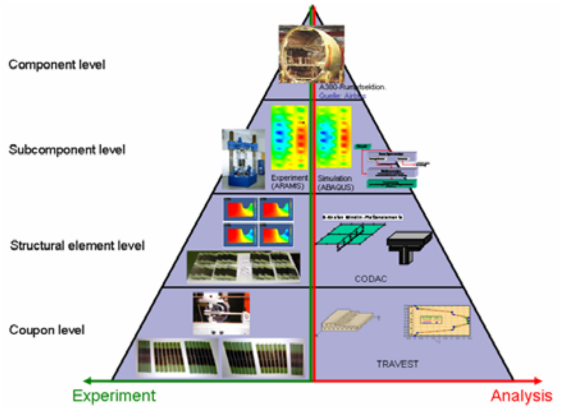

Fig. 10. Structural levels (e.g. for an aircraft fuselage)

An important question which arises for the considered stiffened curved panels is how far the validated model will be applicable within the desired parameter space (e.g. validated small panel to larger panels and finally to barrels). And, are there additional effects within the postbucking range for larger panels (e.g. due to symmetric boundary conditions, mode switches, different load cases) which have not been considered/included for/into the validated small panel model. It has to be kept in mind that due to the highly nonlinear behaviour of stability problems the transfer from a smaller structural level to a larger one as shown in Figure 10 has to be always scrutinized and examined.

6 Summary and outlook

It has been shown that the pre-test planning and analysis is crucial for a reliable and goal oriented validation of numerical results, which finally leads to the need of real validation test rather then phenomenological experiments to obtain a principle physical understanding [10]. The numerical approach detailed allows a sufficient accurate nonlinear calculation of the considered stiffened CFRP structures. Within the validation process it has been pointed out that different levels of detail have to be examined to obtain a broader idea of how well the numerical results represent the experimental data.

The question which now arises is, to which extend the validated results for a specific test specimen allow a transfer to different configurations of stringer stiffened CFRP-panels (e.g. change in lay-up, stringer spacing, radius of curvature or dimension/level of the structural component). Or the other way around, how many predefined test specimens are necessary to validate a desired parametric design space for this aircraft fuselage type of structure.

7 Acknowledgements

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