Advances in Computational Stability Analysis of Composite Aerospace Structures

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Summary

European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Structural weight reduction by exploitation of structural reserves in composite aerospace structures contributes to this aim, however, it requires accurate and experimentally validated stability analysis of real structures under realistic loading conditions. This paper presents different advances from the area of computational stability analysis of composite aerospace structures which contribute to that field. For stringer stiffened panels main results of the finished EU project POSICOSS and the running follow-up EU project COCOMAT are given. Both projects deal with exploitation of reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling and collapse. Next, experimental validation of postbuckling analyses, development of two different fast tools for the postbuckling simulation and findings on the structural behaviour under dynamic loading is presented. Finally, for unstiffened cylindrical shells problems of a robust design method are.

Keywords

Composite Structures, Buckling, Stability, Postbuckling, Collapse, Imperfection, Dynamic Loading, Robust Design

0. Introduction

Reduction of development and operating costs, by 20% and 50% in the short and long term, respectively, is one main objective of the European aircraft industry. The continuous demand for cost reduction of aerospace structures leads to high efforts of weight reduction by increasing the use of composite materials and by exploiting considerable reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling and collapse. Collapse is specified by that point of the load-displacement-curve where a sharp decrease occurs thus limiting the load carrying capacity. Since this may not impair safety of aerospace structures, the structural response needs to be predicted with very high reliability. This comprises accuracy of simulation, experimental validation of simulation tools for the whole realistic parameter space as well as coverage of real geometry and all realistic loading conditions. Moreover, speed of simulation tools becomes an important issue since structural reserves shall be revealed already during the preliminary design phase. Many aerospace structures are thin-walled and therefore prone to loss of stability. For example, the design of major parts of aircraft fuselage structures is driven by stability constraints. This paper deals with advances of computational stability analysis which contribute to structural weight reduction by exploitation of structural reserves in composite aerospace structures.

Postbuckling and collapse analysis of stiffened fuselage panels offers a significant weight saving potential since it allows for shifting ultimate load very closely towards collapse load. Different approaches and contributions to this aim are presented. Main results of the completed project POSICOSS and the running follow-up project COCOMAT, both supported by the European Commission and co-ordinated by DLR, Institute of Composite Structures and Adaptive Systems, are given in Section 1 and 2, respectively. The *POSICOSS* team developed fast procedures for postbuckling analysis of fibre composite stiffened panels, created comprehensive experimental data bases and derived design guidelines. *COCOMAT* builds up on the POSICOSS results and considers in addition the simulation of collapse by taking degradation into account. The results comprise an extended experimental data base, degradation models, improved certification and design tools as well as design guidelines. Section 3 deals with validated postbuckling simulation of stiffened CFRP-panels by experiments. The *validation* procedure to ensure reliable numerical simulations requires extensive experimental data, especially in the case of nonlinear calculations with the possibility of several bifurcation and limit points in the postbuckling region. Therefore, the experiments have to be planned carefully, to ensure a reliable and goal-oriented validation with respect to the numerical analysis. Section 4 and 5 present two different fast tools for the simulation of the postbuckling behaviour. The analysis of the first tool – a hybrid subspace procedure - starts with a conventional FE model. The number of degrees of freedom is reduced with a limited number of special shape functions. Due to the reduced system the computation is running significantly faster. However, the shape functions have to be updated during the run of the nonlinear path regularely. The second tool, iBuck, is a a semi-analytical tool for the simulation of axially loaded panels that are stiffened in both axial and circumferential direction. Section 6 shows that rapidly applied loading of stiffened panels can yield critical dynamic behavior in the postbuckling regime. In today´s design process dynamic loading, e.g. due to gusts or landing impact, is assumed to be uncritical, since the dynamic process increases buckling stability. When applying a new design philosophy with less reserves in structural load bearing capacity, these dynamic effects have to be taken into consideration. In sections 1 to 6 stringer dominant panel designs are considered. For this type of structure geometrical imperfections are of minor importance. However, skin dominant panels or unstiffened shells can be susceptible to imperfections. In composite structures the design parameter stacking sequence can be utilized for achieving rather low sensitivity at high buckling load. In that case the question arises, how to predict efficiently the load carrying capacity of the real imperfect shell, and furthermore, how to perform the analysis rapidly, so that it can be used for robust design. In Section 7 Koiter´s b-factor method is adopted to composite cylindrical shells and compared to numerical analyses of imperfect shells. It turns out that the b-factor gives at least useful qualitative information which can be applied within a pre-design procedure for a fast pre-selection of shells with low sensitivity.

1. The EU project POSICOSS

Supported by the European Commission the project POSICOSS [1], which lasted from January 2000 to September 2004 contributed to this aim of structural weight reduction by exploiting considerable reserves in primary fibre composite fuselage structures through a fast and reliable simulation of postbuckling. POSICOSS stands for *Improved POstbuckling SImulation for Design of Fibre COmposite Stiffened Fuselage Structures* and was co-ordinated by DLR, Institute of Composite Structures and Adaptive Systems. It has merged knowledge and capabilities of seven partners from industry and research: DLR, AGUSTA from Italy, IAI from Israel, the Politecnico di Milano from Italy (POLIMI), the Technical University of Riga from Latvia (RTU), the Technical University RWTH Aachen from Germany, and the TECHNION from Israel.

The main *objective* was the development of improved - not only reliable but also fast - procedures for analysis and design of fibre composite stiffened panels of future fuselage structures. Such procedures were desperately needed, because postbuckling calculations are extremely time consuming, which makes them useless for application in the design process. In addition, a comprehensive experimental data basis was created for the purpose of validation.

The project provided four main *results*:
1) Material Properties: IM7/8552 prepreg tape and 98-GF3-5H1000 fabric (CYNAMID) materials were used and characterized by means of small specimens as to their elastic constants and strengths, each with consideration of tension, compression and shear. ASTM standards, DIN 29971, and IEPG-CTP-TA21 were applied.

2) Test Results for Buckling and Postbuckling of Stiffened CFRP Panels and Cylinders: The partners AGUSTA, IAI and DLR manufactured 42 stiffened panels and 9 stiffened cylinders; many different designs were realised. AGUSTA used CYNAMID material, whereas IAI and DLR applied IM7/8552. The structures manufactured by AGUSTA, IAI and DLR were tested by POLIMI, TECHNION and DLR, respectively. Before testing, nominal data and shape imperfections were recorded, and non-destructive inspection was performed. During testing, load-shortening curves, strains, single displacements, deformation patterns and videos were taken.

3) Improved Simulation Procedures for Postbuckling of Stiffened Fibre Composite Panels: The following five different concepts for the improved simulation procedures were considered:

- TECHNION developed three procedures for simulation of skin buckling load and collapse load, based on an analytical model for skin buckling, and beam with effective width as well as beam on elastic foundation for collapse.
- The approach of RWTH is based on the derivation of the total stiffness matrix of stiffened panels. The stiffness matrix represents the analytical solution of a second order shell theory. It is obtained by dividing the structure into elements; one element in longitudinal direction - trigonometric functions are used to describe the displacements in this direction - and an arbitrary number of elements in the circumferential direction.
- DLR used a hybrid reduced basis technique (cf. Section 4).
- POLIMI's and RTU's procedures are based on response surface optimisation theory. They developed fast methods for global approximation of the structural behaviour, and for the approximation they used a limited number of finite element computations. Their procedures can not only be applied to optimisation tasks, but also to structural analysis problems. POLIMI used two different methods to build the response surfaces - Neural Networks and Radial Basis Functions, and performed finite element analyses for training and testing the response surfaces. RTU used methods of Experiment Design in order to find the sample points of the response surfaces for which then the finite element analyses were performed.

4) Design Guidelines for Stiffened Fibre Composite Panels: Parametric studies were performed in order to derive preliminary design guidelines, which were checked by the experience obtained through testing of the industrial panels. The lessons learned from the project work were combined with the experience and practice of the industrial partners in order to derive at final design guidelines.

As an *outcome* of the project work improved fast and reliable simulation procedures for the postbuckling analysis of stiffened fibre composite panels and corresponding design guidelines are available, along with a vast number of test data concerning material properties and, in particular, the buckling and postbuckling behaviour of stiffened CFRP panels and cylinders. On overview about the project, its main results and an overview about all published papers can be found at www.posicoss.de.

2. Running EU project COCOMAT

The 4-year running project COCOMAT (Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of COllapse) aims to reduce structural weight at safe design; it exploits considerable reserves in primary fibre composite fuselage structures by accurate and reliable simulation of collapse [2]. The project, which is supported by the European Commission within the 6th Framework Programme and co-ordinated by DLR, Institute of Composite Structures and Adaptive Systems, started on 1 January 2004. The consortium merges knowledge from 5 large industrial partners (AGUSTA from Italy, GAMESA from Spain, HAI from Greece, IAI from Israel and PZL from Poland), 2 Small and Medium Enterprises (SAMTECH from Belgium and SMR from Switzerland), 3 research establishments (DLR from Germany, FOI from Sweden and CRC-ACS from Australia) and 5 universities (Politecnico di Milano from Italy, RWTH Aachen and University of Karlsruhe from Germany, TECHNION from Israel and Technical University of Riga from Latvia).

The main objective of COCOMAT is the large step from the current to a future design scenario for typical stringer stiffened composite panels demonstrated in Figure 1. The left graph illustrates a simplified load-shortening curve and highlights the current industrial design scenario. Three different regions can be specified. Region I covers loads allowed under operating flight conditions and is bounded by limit load; region II is the safety region and extends up to ultimate load; region III comprises the not allowed area and reaches up to collapse. In aircraft design ultimate load amounts to

150% of limit load. There is still a large unemployed structural reserve capacity between current ultimate load and collapse. The right graph of Figure 1 depicts the future design scenario where ultimate load is shifted towards collapse as close as possible. Another difference to the current design scenario is, that the onset of degradation moved from the not allowed region III to the safety region II. This is comparable to metallic structures where plasticity is already permitted in the safety region. However, it must be guaranteed that in any case the onset of degradation must not occur below limit load. Moreover, the extension requires a reliable simulation of collapse, which means to take degradation under static as well as low cycle loading into account, in addition to geometrical nonlinearity.

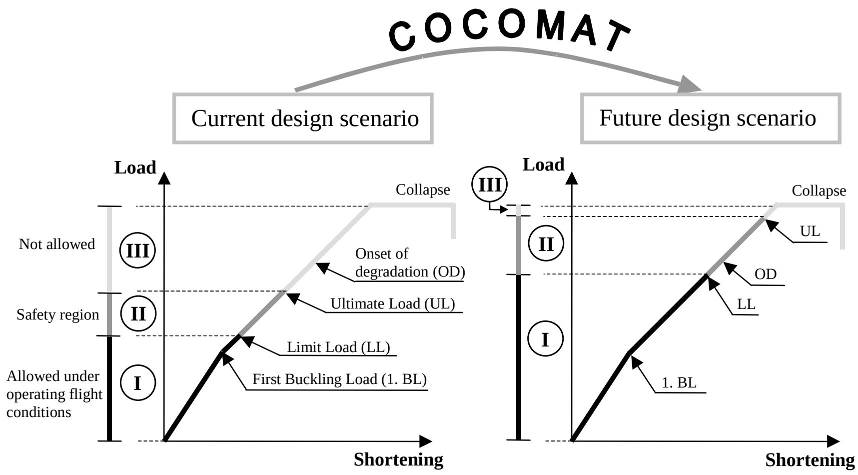

Figure 1: Main objective of the COCOMAT project [2]

To reach this main objective, improved slow and fast simulation tools, experimental data bases as well as design guidelines for stiffened panels are needed, which take skin stringer separation as well as material degradation into account. The experimental data base is indispensable for validation of the analytically developed degradation models, which will be implemented into the new tools, and for verification of the new tools as well. Reliable fast tools reducing design and analysis time by an order of magnitude, will allow for an economic design process, whereas very accurate but necessarily slow tools are required for the final certification. The project will provide both types of tools, ready for industrial application. Industry brings in experience with design and manufacture of real shells; research contributes knowledge on testing and on development of simulation tools. Design guidelines are defined in common, and the developed tools are validated by industry.

The project results will comprise a substantially extended data base on material properties and on collapse of undamaged and pre-damaged statically and cyclically loaded structures, degradation models, improved slow and fast computation tools for statically loaded structures as well as design guidelines. The knowledge, the experience, the results and especially the fast tools of the project POSICOSS form an excellent basis for COCOMAT and allow for starting work at a very high level. More details on the project can be found at www.cocomat.de.

3. Validated Postbuckling Simulation of Stiffened CFRP-Panels by Experiments

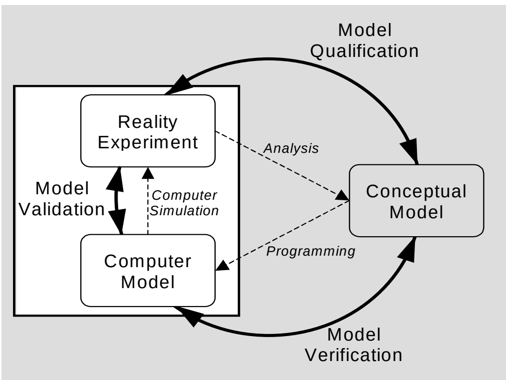

Figure 2: Phases of modelling and simulation [4]

New computational methods must be validated in order to prove the right mathematical equations are applied for the considered physical problem. 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 physical 'Experiment' has to be analyzed to obtain the 'Conceptual Model' (mathematical equations, which describe the physical behaviour). Subsequently, the extracted mathematical equations are coded to obtain the 'Computer Model'. The accentuated area of 'Model Validation' containing experimental planning and testing as well as numerical analysis will be the main focus and described exemplarily for stiffened CFRP panels

Figure 3: Buckling test facility at DLR

The Institute of Composite Structures and Adaptive Systems at DLR runs a buckling test facility (cf. Figure 3) which has the capability to test panels and cylinders by axial compression, torsion or internal pressure by static or dynamic loading up to collapse. The main focus of the experiments is to obtain a better physical understanding of the structural behaviour in the postbuckling region as well as the validation of the computations. In order to identify the real shape of the test structure, ATOS, an optical 3D digitizing measurement system, is utilized to extract the actual radius of the panel as well as the initial geometric imperfections of the skin. During the test an optical measurement system (ARAMIS) is used to capture digital images of the deformed panel at several load levels. Using this powerful optical systems a qualitative and quantitative comparison between the experimentally extracted deformation pattern and the numerically (FEM) calculated displacement is possible. All DLR experiments of the POSICOSS and COCOMAT project were or will be tested by this facility.

Due to the time consuming and therefore expensive experiments a substantial amount of time was spend on detailed pre-test analysis and planning for this so called "validation" tests with a clear focus to obtain test data for comparison with numerical results [3]. Several nonlinear analyses have been conducted with ABAQUS/Standard up to the deep postbuckling regime to obtain a better understanding of the structural behaviour. This contains the assessment of imperfection sensitivity – not only geometrically variations should be considered, the focus should be also on loading imperfections. Additional investigations with respect to experimental boundary conditions along the longitudinal edges of the panels revealed that the clamping width of the attached longitudinal supports have a significant influence on the postbuckling behaviour. These numerical studies provide a deeper understanding on possible "sensitivities" of the planed test structure. In addition, the numerical results influence the placement of sensors (e.g. strain gauges) to examine critical areas of the test structure. By means of experimental results of a four stringer stiffened panel (cf. Figure 4), the numerical analysis and the validation procedure is detailed.

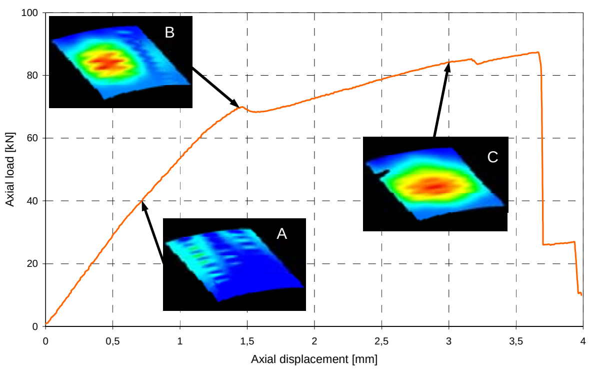

Figure 4: Load-shortening curve and selected deformation patterns (experimental data) [3]

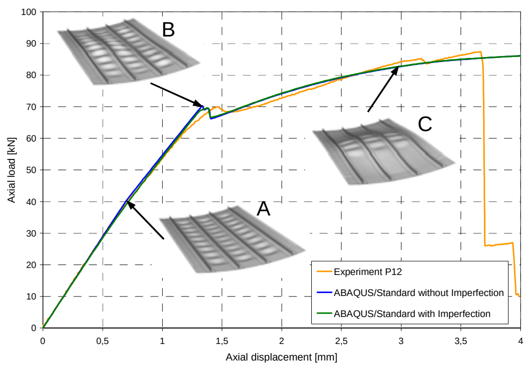

Figure 5: Load-displacement curve, nonlinear finite element analysis versus experiment [3]

The numerical calculations, as shown in Figure 5 (with and without imperfections), have been conducted with ABAQUS/Standard. On the so called "global" level of validation the overall load-shortening curve as well as the deformation patterns (experimentally extracted with ARAMIS) have been compared. Figure 4 and 5 show a good agreement between the experimentally measured and numerically extracted data (e.g. local skin buckling at A, first global 2/3 versus 1/3 buckle at B and the symmetric global buckling pattern marked with C).

4. Hybrid subspace analysis procedure

Using a hybrid subspace analysis Kling et al. [5] developed a fast computational method within the POSICOSS project. It simulates the postbuckling behaviour significantly faster than respective finite element applications with constant meshing. It considers an ideal stringer-skin connection, pure axial, pure shear and combined load cases, initial geometric imperfections and laminates made of unidirectional orthotropic prepreg material. The requested output of the analysis is the axial stiffness in the pre- and postbuckling region and the deformed structure up to the onset of degradation.

The basic idea of the fast tool – to reduce the number of degrees of freedom (DOF) significantly – can be best characterized as a hybrid reduced basis technique, which is clarified in Figure 6. The real composite panel (with an infinite number of DOFs) will be discretized, to obtain a conventional FE model. The horizontal axis depicts the increasing error due to the reduction in the number of DOFs (vertical axis). This FE model will be used to extract a small number of “shape functions” (e.g. buckling modes), which can be utilized subsequently to analyze the structural behaviour. The shape functions will be updated regularly, based on a predetermined error limit, to restrict the error during the nonlinear analysis. Therefore error sensing and error control will be an important part during the calculation.

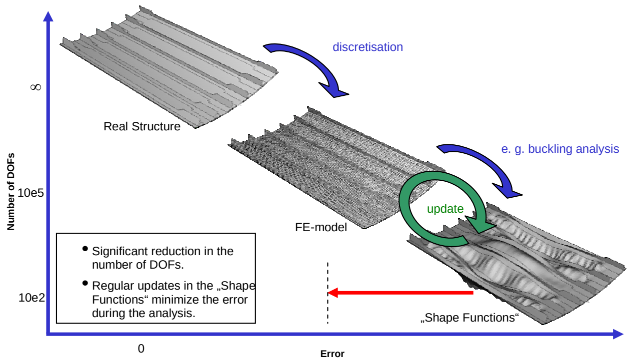

Figure 6: Basic idea of the concept [5]

The analysis starts with a conventional finite element model of the examined structure. Initial geometric imperfections can be superposed before the analysis starts. In a next step the number of DOFs will be reduced with a limited number of shape functions. Subsequently, the reduced system will be solved using a conventional incremental / iterative solution procedure to obtain the deformed structure as well as the load-shortening curve. Some preliminary results of simple beam structures showed the potential of the concept with respect to shorter computational time and appropriate accuracy of the results for design purposes. B2000, an open source finite element program, will be used to implement the algorithm for shell-type structures.

5. iBuck - Semi-analytical design tool for stiffened panels

Even faster but also more restricted to special panel configurations is the fast tool iBuck, recently developed at DLR by Buermann et. al. [14]. It may be used to assess the post-buckling behaviour of bi-axially stiffened cylindrical shells under axial or transverse load, in-plane shear load, or lateral pressure. In addition, the loading by an external bending moment may be considered.

The panels are assumed to be representative for a fuselage section and are comprised of a skin (shell) and stiffeners in both longitudinal (stringers) and circumferential direction (frames). In addition, aircraft-specific components such as doublers (used to reinforce the skin underneath the stiffeners) and clips (providing lateral support for the frames) are included in the model. Stringers and frames are considered as structural elements with independent degrees of freedom, where continuity in terms of rotation at the interface skin/stiffeners and in terms of end-shortening is enforced.

Local and global buckling modes are superposed. Local buckling is defined as skin buckling and skin-induced stiffener rotation within a bay. During local buckling, the stiffeners themselves are not allowed to deflect in out-of-plane direction. During global buckling, that is, buckling across several bays, the stringers may deflect in out-of-plane direction, whereas the frames, being much heavier than the stringers, are fixed in out-of-plane direction.

IBUCK is a semi-analytical tool, which means that the problem formulation is based on the foundations of analytical continuum mechanics and that numerical methods are used to discretize the problem and to solve the resulting equations. The potential energy of the structure is stated, where finite deflections and thus non-linear strain-displacement relations of skin and stiffeners are taken into account. At each load step, stationary values of the potential are sought. The resulting set of third-order equations is discretized using a Ritz approach, that is, by selecting appropriate deflection functions for the skin and the stiffeners. The equations are solved by applying incremental perturbation theory in the form of an arc-length method.

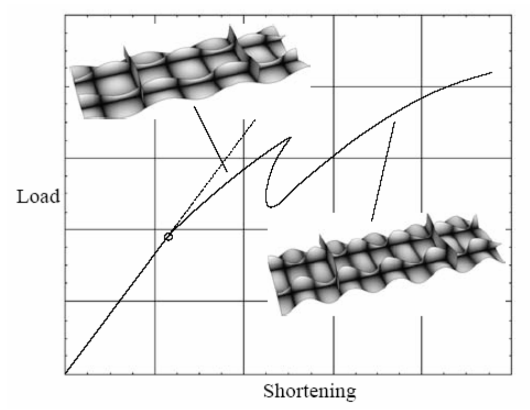

Figure 7: Snap-back behaviour of a panel under axial load [6].

Imperfect panels with initial deflections of skin, stringers and frames are considered. Prior to starting the load history, a buckling eigenvalue analysis is carried out and a combination of buckling eigenshapes is selected as imperfection. By including imperfections, the abrupt onset of buckling is transferred to the gradual growth of out-of-plane deflections. However, instability phenomena may still be observed. Figure 7 shows as an example a snapback behaviour of a stiffened panel. The snap-back is caused by the panel's desire to assume an energetically optimal deflection shape and is typically associated with a load reduction. Due to its curve-tracing algorithm, IBUCK is capable of tracing snap-back behaviour.

6. Influence of dynamic loading on buckling and postbuckling of stiffened shells

Presently, in the design process of dynamically loaded light-weight structures the quasi-static load carrying capacity is the relevant design criterion. It is based on the assumption (which is not generally valid) that a dynamic process increases buckling stability. When applying a short duration pulse load to a cylindrical shell structure, the buckling load is usually higher than under quasi-static conditions. However, if an axial load is rapidly applied to a shell and subsequently held fixed, then the load carrying capacity of the shell might be reduced, which is critical for design aspects. For example, such a loading scenario is given in a landing impact of an aircraft or during gust loading. If in a future design concept structural reserves are more exploited, this critical dynamic behaviour - the reduction of the load carrying capacity - must be taken into account in a safe design.

Concerning the critical dynamic effect most of the work concentrates on structures with unstable buckling response such as unstiffened shells [e.g. 7]. While a multitude of analytical approaches to this topic are proposed, only a limited number of experimental observations are reported. In unstiffened shells, a resonant excitation of the higher frequency in-plane modes and their nonlinear interaction with the low-frequency out-of plane modes is a precondition for the described critical dynamic behaviour [8]. However, it is shown that stiffener-dominant shells without imperfections will display critical dynamic behaviour, even when they are excited at lower frequency out-of plane modes. The usual assumption of a step loading is an idealisation of a more realistic ramp-like loading.

In Figure 8 and 9 Temmen at. [9] show investigations on a rapidly loaded, stringer stiffened cylindrical composite panel. The shortening is raised up to a maximum value within a relatively short time and then the displacement is held fixed. Ramp-time and maximum of the shortening are varied. Results for a given maximum shortening of u = 0.8 mm and three different ramp-times are shown in Figure 8. If the ramp time is chosen short enough (in this example shorter than T=3.2 ms) a transition from a dynamically excited postbuckling state to the postbuckling path with lower load level is calculated. In Figure 8 the critical dynamic buckling (the transient transition to lower load level states) is plotted. For larger ramp-times the structure remains in a postbuckling state, defined by static conditions. Using a simplified, linear modal picture for the considered structure one can show that the ramp-time T = 3.2 ms is able to excite the lowest bending modes.

The results demonstrate that for ramp times similar to the time period of the lowest eigenfrequency out-of-plane modes were excited and resulted in a significant drop of the postbuckling load. Switching occurred to a secondary load path which in quasi-static computations refers to unloading from a deep postbuckling state. Thus, when exploiting the structural postbuckling reserve for economic design of future aircraft fuselage structures it has to be assured that critical dynamic behavior does not occur under the loading velocities to be expected or it needs to be taken into account. In future, additional investigations are necessary to understand the critical dynamic interaction, to include more details of structure and material, to get an experimental validation and to extend considerations to global stiffened shell structures (e.g. aircraft fuselage).

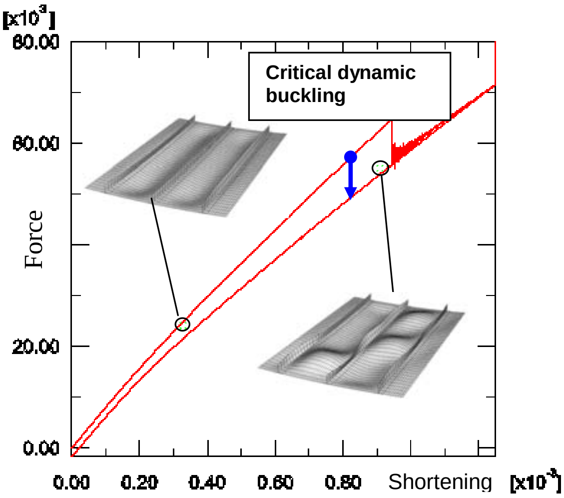

Figure 8: Load-shortening-curve for quasi-static cyclic loading and two characteristic buckling patterns. In addition, the path of a critical dynamic buckling transition is given [9]

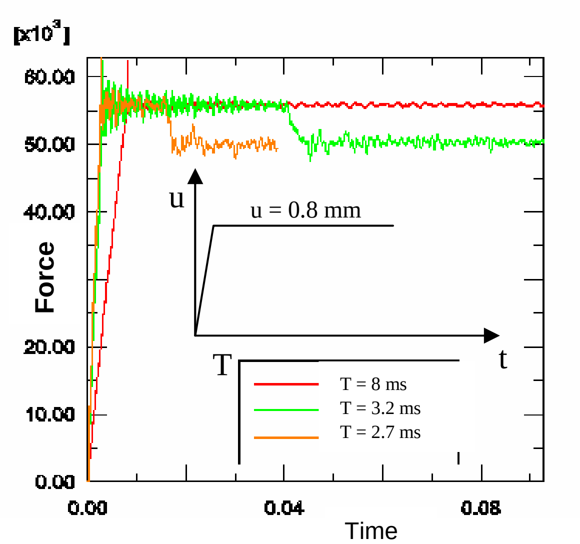

Figure 9: Time history of the reaction force for different ramp times T. Onset of critical behaviour at a ramp time T=3.2 ms [9]

7. Robust design of cylindrical shells using Koiters b-factor

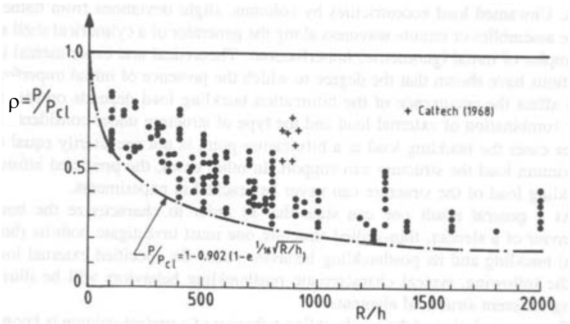

Figure 10: Distribution of test data for cylinders subjected to axial compression [11]

In Figure 10 knock-down factors ρ of axially compressed cylindrical shells (the ratio of buckling loads of imperfect and perfect cylindrical shell) are shown depending on the slenderness (the ratio of radius and wall thickness). The results of tests are presented by dots and show the large variance of tests. The knock-down factors decrease with increasing slenderness. Koiter developed in 1945 as first a theory which provides the most rational explanation of the large discrepancy between test and theory for the buckling of axially compressed cylindrical shells [10]. The KOITER type asymptotic analysis consists basically of perturbation expansion about the lowest (critical) eigenvalue of the structure.

$$\lambda / \lambda_c = 1 + a\xi + b\xi^2 + \dots, \tag{1}$$

where a and b are first and second postbuckling coefficients. Figure 11 illustrates equilibrium paths for different combinations of coefficients: Asymmetric equilibrium path for a<0 and b>0 in Figure 11a and symmetric equilibrium paths (a=0) for cases b>0 in Figure 11b and b<0 in Figure 11c.

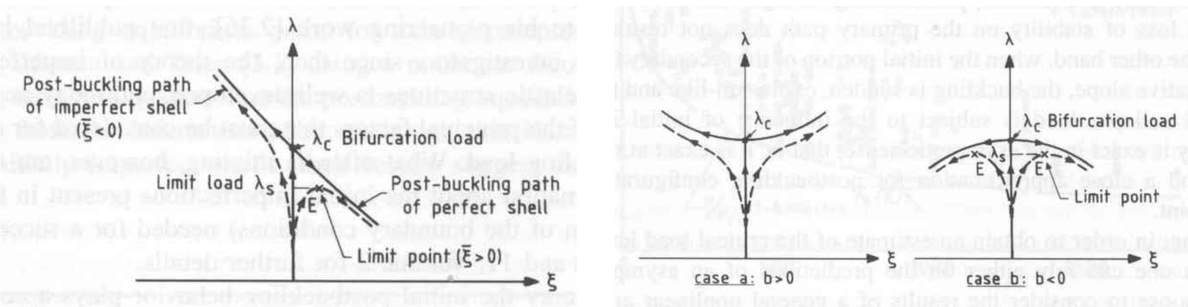

Figure 11: Equilibrium paths for different types of stability [12]

Figure 11 points out that the shape of secondary equilibrium path plays an important role in determining the influence of initial imperfections. For symmetric equilibrium path the sign of second coefficient, the so-called *Koiter's b-factor*, gives information about initial postbuckling behavior, for case b>0 the load can be increased after critical load, for case b<0 the structure fails when increasing load. What makes use of asymptotic methods so attractive is that the postbuckling coefficients a and b are properties of the perfect shell. Hence their computation does not involve the shape and the size of the expected initial imperfections. With the knowledge of the postbuckling coefficients one can make predictions about the nature of the experimental results. If the initial imperfection is assumed to have the shape of the critical buckling mode and one uses a membrane prebuckling analysis then Koiter (1945) showed that the relation between limit load λ_s of the imperfect structure and the bifurcation load λ_c of the perfect structure yields

$$\left(1-\frac{\lambda_s}{\lambda_c}\right)^{3/2}=\frac{3}{2}\sqrt{-3b}\,\mu\frac{\lambda_s}{\lambda_c} \qquad (2)$$

The question of quality of information given by b-factor is still not clearly answered. Qualitative information gives ranking of sensitivity of different shells, whereas quantitative information gives additionally the knock-down factor ρ to determine maximum load. Investigations on cylindrical shells were performed by Huehne et al [9] in order to answer the following questions:

- Is the b-factor suitable for providing qualitative and quantitative imperfection sensitivity?
- Is the information restricted to eigenform-affine imperfection pattern or also valid for realistic imperfection pattern?
- What kind of quality does the b-factor have when using simplifying assumptions like membrane-prebuckling state and classical boundary conditions?

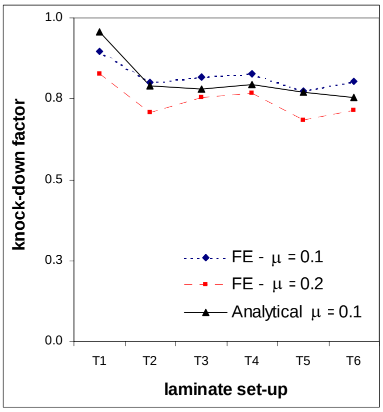

Figure 12: Comparison of analytical and numerical results on Tennyson shells [9]

Koiter´s b-factor method was adopted in order to provide a realistic design load. Nonlinear FE computations of different shells (e.g. Tennyson [13]) with measured imperfections were performed. Koiter explains that equation (2) is valid for asymmetric imperfections. To derive this equation the first eigenmode, which includes information of sensitivity to general imperfection, is used. The knock-down factor depending on analytical b-factor is compared to FE results using eigenform-affine imperfection pattern in Figure 12. The resemblance is quite good for same μ=0.1. The reason why congruence using eigenform-affine imperfections is moderate and quite well for realistic imperfections is not clear. Further investigations are needed. The assumption of membrane prebuckling state can be one reason for differences.

For orthotropic shells the b-factor turned out to give qualitative information of sensitivity. Since the sensitivity ranking of different laminate set-ups could be reflected properly a pre-selection of robust laminate set-ups during the design phase becomes feasible. Furthermore, the b-factor for orthotropic shells provided good knock-down factors for approximation of the realistic buckling load. For anisotropic shells the b-factor delivered qualitative information. This means that the amplitude of the imperfection had to be fitted to the FE analysis in order to determine a realistic knock-down factor. However, the sensitivity ranking, which is valuable information for robust design, was still reliable. The application field of the robust design method should be widened towards imperfection sensitive stiffened shells (skin-dominant designs).

Conclusions

This paper presents different advances from the area of computational stability analysis of composite aerospace structures which aims to reduce structural weight. For stringer stiffened panels main results of the finished EU project POSICOSS and the running follow-up EU project COCOMAT are given. Both projects deal with an accurate and reliable simulation of postbuckling and collapse. Next, experimental validation of postbuckling analyses, development of two different fast tools for the postbuckling simulation and findings on the structural behaviour under dynamic loading is presented.

Finally, for unstiffened cylindrical shells a robust design method relying on Koiter's b-factors is suggested. Future work should facilitate full applicability of these analysis methods in preliminary design. For that purpose speed of the postbuckling analysis of stiffened panels needs to be increased and for collapse simulation degradation must be taken into account. The application field of the robust design method should be widened towards imperfection sensitive (skin-dominant) stiffened shells.

References

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