

# New Achievements in Stability of Composite Airframe Structures

Richard Degenhardt, Jan Tessmer

*DLR, Institute of Composite Structures and Adaptive Systems, Braunschweig, Germany*

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

**Abstract:** 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 new achievements from the area of computational and experimental stability research of composite aerospace structures which contribute to that field. The first four topics focus on stringer stiffened panels and the last one on imperfection sensitive unstiffened cylinders.

*Section 1* presents new results achieved so far in the running EU (European) project COCOMAT, which deals with an accurate and reliable simulation of collapse. The main objective of COCOMAT is a future design scenario which exploits considerable reserves in fibre composite fuselage structures by accurate simulation of collapse. The project results comprise an experimental data base, improved slow and fast computational tools as well as design guidelines.

*Section 2* 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 3* presents the fast tool IBuck for the simulation of the postbuckling behaviour. It is a semi-analytical tool for the simulation of axially loaded panels that are stiffened in both axial and circumferential direction.

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. *Section 4* shows that rapidly applied loading of stiffened panels can yield critical dynamic behavior in the postbuckling regime. When applying the new design philosophy it has either to be assured that these critical interactions do not occur under the loading velocities to be expected, or they have to be taken into consideration.

*Section 5* presents a recently developed approach for unstiffened shells which are usually susceptible to imperfections. This robust design approach is based on a single buckle as the worst imperfection mode leading directly to the load carrying capacity of a cylinder. It also promises to improve the knock-down factors which are according the current guidelines very conservative.

Future work should facilitate full applicability of the analysis methods in preliminary design. For that purpose speed of the collapse 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 stiffened shells (skin-dominant designs).

## 1. 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 [1,2]. 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 COCOMAT project is fully based upon the results of the POSICOSS project, which lasted from January 2000 to September 2004. POSICOSS is the acronym of Improved POSTbuckling SIMulation for Design of Fibre COMposite Stiffened Fuselage Structures. The POSICOSS team has developed improved, fast and reliable procedures for buckling and postbuckling analysis of fibre composite stiffened panels of future fuselage structures. For the purpose of validation comprehensive experimental data bases were created. Finally, design guidelines were derived. An overview about the POSICOSS project can be found in [3]. Some of DLR's results are published in [4] and [5].

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.

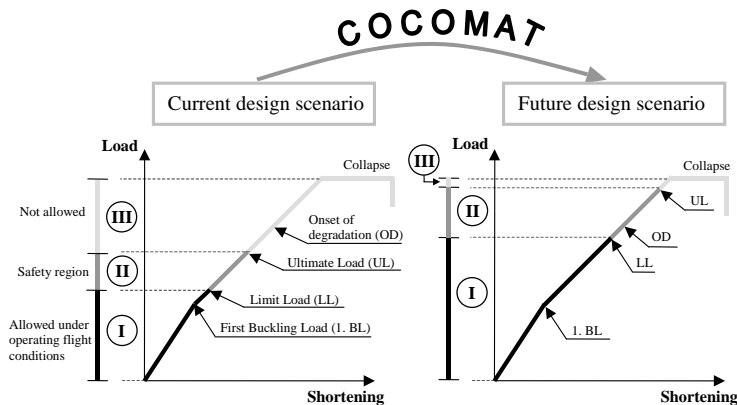


Figure 1: Main objective of the COCOMAT project [1]

tools, and for validation 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

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 verification of the analytically developed degradation models, which will be implemented into the new

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 (almost 50 panel tests), 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. It is not aim of the project to do stochastic investigations, however, the large experimental data base will build a good basis for activities in follow-up projects.

During the first three project years the COCOMAT partners finished benchmarking of available simulation tools on panel test results to define abilities and deficiencies, they characterized material properties on small specimens, performed tests on stiffened strips, developed degradation models, designed panels [6] which shall be manufactured and tested, performed the first panel tests and finished almost the improvement of the simulation tools.

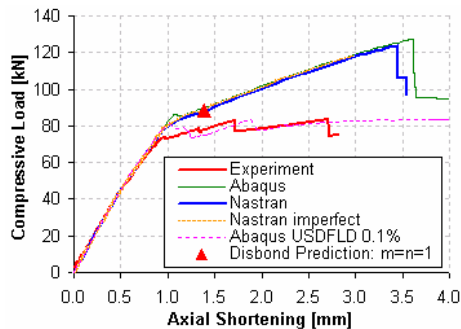


Figure 2: Comparison Simulation with test [7]

because these tools do not consider degradation. For simulating the skin-stringer separation of stiffened structures DLR developed in co-operation with CRC-ACS from Australia an ABAQUS user subroutine, which simulates the degradation of the adhesive. The User subroutine decreases the stiffness of the adhesive to 0.1 % of the original value in the case the maximum stress is reached. Figure 2 shows also the application of the improved ABAQUS version on that test which shows a good agreement. However, it must be noted that it is not sufficient to compare only the load-shortening curve, because the global buckling pattern of the simulation and experiment are in that case different. In addition, the subroutines predicted more damaged adhesive areas than observed in the experiment. This demonstrates that further improved degradation models – which are currently implemented into the simulation tools by the partners - are needed.

A list of papers published by the partners so far and more details can be found at [www.cocomat.de](http://www.cocomat.de).

## 2. Validated Postbuckling Simulation of Stiffened CFRP-Panels by Experiments

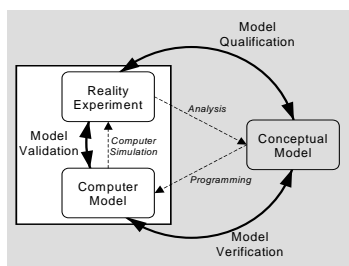


Figure 3: Phases of modelling and simulation [9]

stiffened CFRP panels.

Figure 2 shows exemplary some project results. It illustrates a comparison of the simulation tools ABAQUS and NASTRAN with a test result of a panel loaded by axial compression. Different solvers were used in order to get information about the abilities and deficiencies of these tools. The comparison between all simulation curves and the test result shows a good agreement up to global buckling which occurs at about 1 mm shortening. From that point the simulation results of the conventional tools disagree with the test results. However it is plausible

because these tools do not consider degradation. For simulating the skin-stringer separation of stiffened structures DLR developed in co-operation with CRC-ACS from Australia an ABAQUS user subroutine, which simulates the degradation of the adhesive. The User subroutine decreases the stiffness of the adhesive to 0.1 % of the original value in the case the maximum stress is reached. Figure 2 shows also the application of the improved ABAQUS version on that test which shows a good agreement. However, it must be noted that it is not sufficient to compare only the load-shortening curve, because the global buckling pattern of the simulation and experiment are in that case different. In addition, the subroutines predicted more damaged adhesive areas than observed in the experiment. This demonstrates that further improved degradation models – which are currently implemented into the simulation tools by the partners - are needed.

Finite element calculations or new tools developed (cf. Section 3 and 4) must be validated by experimental data because analytical solutions are usually not available. Figure 3, 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



Figure 4: Buckling test facility at DLR

The Institute of Composite Structures and Adaptive Systems at DLR runs a buckling test facility (cf. Figure 4) 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 these 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 spent 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 [8]. 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 5), the numerical analysis and the validation procedure is detailed.

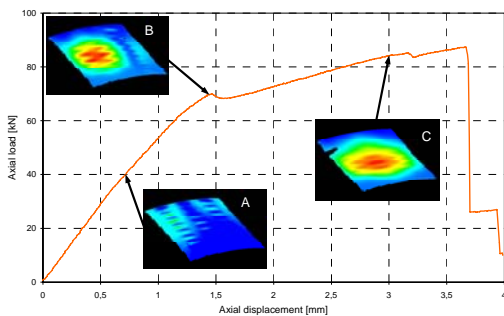


Figure 5: Load-shortening curve and selected deformation patterns (experimental data) [8]

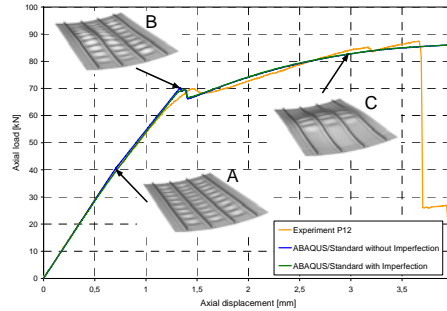


Figure 6: Load-displacement curve, nonlinear finite element analysis versus experiment [8]

The numerical calculations, as shown in Figure 6 (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 an optical measurement system) have been compared. Figure 5 and 6 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).

### 3. Hybrid subspace analysis procedure

This fast tool is a hybrid subspace analysis procedure and was developed by DLR within the POSICOSS project [3]. It simulates the postbuckling behaviour significantly faster than respective finite element tools. 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 (e.g. load-shortening) in the pre- and postbuckling region and the deformed structure up to the onset of degradation. Additionally, a survey of bifurcation and limit points will be provided.

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 7. 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.

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.

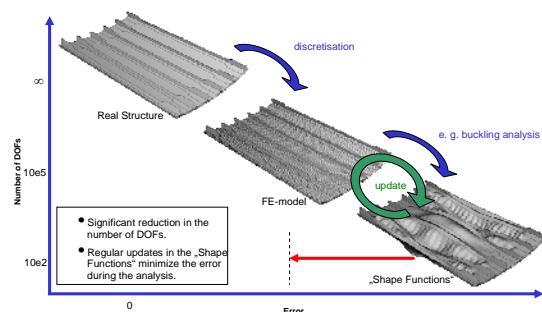


Figure 7: Basic idea of the concept [5]

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. Calculations 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.

#### 4. iBuck - Semi-analytical design tool for stiffened panels

The fast tool iBuck, recently developed by DLR, may be used to assess to post-buckling behaviour of bi-axially stiffened cylindrical shells under axial or transverse load, in-plane shear load, or lateral pressure [10, 11]. In addition, the loading by an external bending moment may be considered.

The panels are assumed to 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 superimposed. 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.

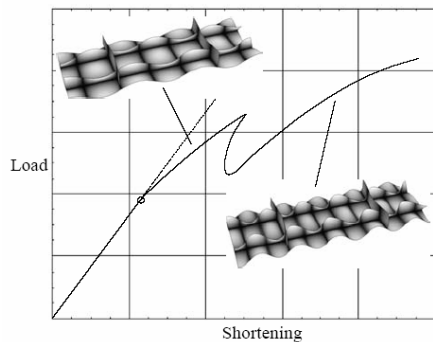


Figure 8: Snap-back behaviour of a panel under axial load [10].

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 some 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. In Figure 8, snapback behaviour of a stiffened panel is depicted. 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.

## 5. 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. In contrast to the current practice 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. 12]. 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 [13]. 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.

Figure 9 and 10 show investigations on a rapidly loaded, stringer stiffened cylindrical composite panel [14]. 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 9. 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 10 the critical dynamic buckling (the transient transition to a lower load level state) 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.

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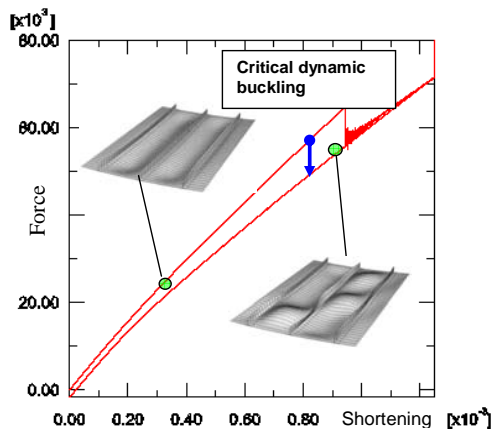


Figure 9: Load-shortening-curve for quasi-static cyclic loading and two characteristic buckling patterns. In addition, the path of a critical dynamic buckling transition is given [13]

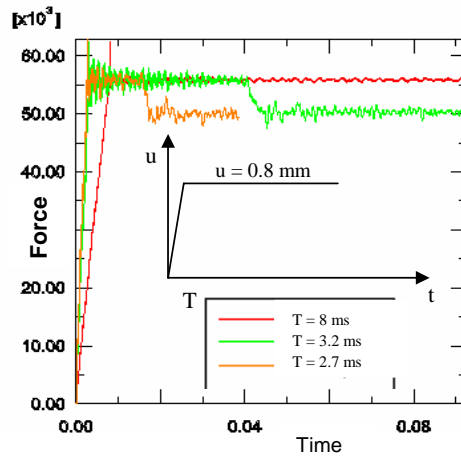


Figure 10: Time history of the reaction force for different ramp times T. Onset of critical behaviour at a ramp time  $T=3.2$  ms [13]

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).

## 6. Robust design of cylindrical shells using a Single Perturbation Load Approach

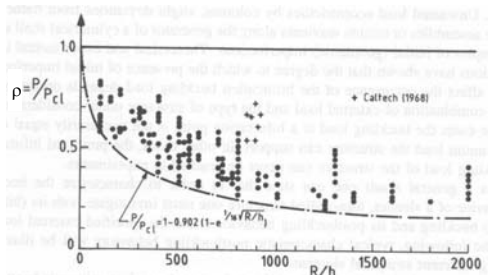


Figure 11: Distribution of test data for cylinders subjected to axial compression [16]

In Figure 11 knock-down factors are shown for axially compressed cylindrical shells depending on the slenderness. The results of tests are presented by dots and show the large variance. The knock-down factors decrease with increasing slenderness. The discrepancy between test and classical buckling theory shown in Figure 11 has stimulated scientists and engineers on this subject during the past 50 years. These works focused on postbuckling, load-deflection behaviour of perfect shells, various boundary conditions and its effect on bifurcation buckling, empirically derived

design formulas and initial geometric imperfections. Koiter was the first to develop a theory which provides the most rational explanation of the large discrepancy between test and theory for the buckling of axially compressed cylindrical shells. In his doctoral thesis published in 1945 Koiter revealed the extreme sensitivity of buckling loads to initial geometric imperfections. His work received little attention until the early 1960's, because the thesis was written in Dutch language. An English translation by Riks was given 1967 in [15].

Based on large test series in the 1950s and 60s the determination of lower bounds led to design regulations like NASA SP-8007 [17], but the given knock-down factors are very conservative. To improve the ratio of weight and stiffness and to reduce time and cost, numerical simulations could be used during the design process. The consideration of imperfections in the numerical simulation is

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essential for safe constructions. Usually, these imperfections are unknown in the design phase, thus pattern and amplitude have to be assumed.

In general, one can distinguish between loading imperfections and geometrical imperfections. Both kinds of imperfections have a significant influence on the buckling behaviour and their state of the art is described in the following.

Loading imperfections mean any deviations from perfect uniformly distributed loading, independent of the reason of the perturbation. Geier [18] tested composite cylindrical shells, applied thin metal plates locally between test shell and supporting structure to perturb the applied loads and performed the so-called shim tests [19]. Later, numerical investigations were performed and compared to the test results; the importance was verified [20]. The need of investigations of loading imperfections for practical use was shown for instance by Albus et al. by the example of Ariane 5 [21].

Deviations from the ideal shape of the shell structure are often regarded the main source for the differences between computed and tested buckling loads. Winterstetter [22] suggest three approaches for the numerical simulation of geometrically imperfect shell structures: “realistic”, “worst” and “stimulating” geometric imperfections. Stimulating geometric imperfections like welded seams are local perturbations which “stimulate” the characteristic physical shell buckling behaviour [23]. “Worst” geometric imperfections have a mathematically determined worst possible imperfection pattern like the single buckle [24]. “Realistic” geometric imperfections are determined by measurement after fabrication and installation. This concept of measured imperfections is primarily based on the work of Arboocz [25]; a large number of test data is needed, which has to be classified and analysed in an imperfection data bank. Within this proposal real geometric imperfections measured at test shells are taken into account.

Hühne showed that for both, loading imperfections and geometrical imperfections the loss of stability is initiated by a local single buckle [26]. Therefore unification of imperfection sensitivity is allowed; systems sensitive to geometric imperfections are also sensitive to loading imperfections. Single buckles are realistic, stimulating and worst geometric imperfections.

Hühne developed recently an approach [26] which also promises to improve the knock-down factors. This approach assumes that a larger single buckle is the worst imperfection mode and leads directly to the load carrying capacity of a cylinder.

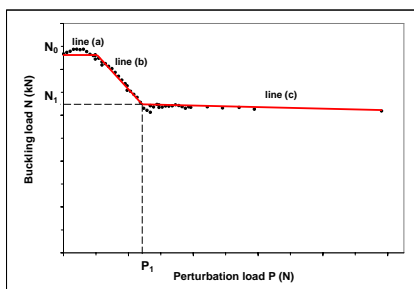


Figure 12: Single-perturbation load approach [25]

## 7. 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 running EU project COCOMAT are given. COCOMAT aims to exploit considerable reserves in fibre composite fuselage structures by 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 single perturbation load is suggested. Future work should facilitate full applicability of the analysis methods in preliminary design. For that purpose speed of the postbuckling analysis of stiffened

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### **Acknowledgements**

The running project COCOMAT is supported by the European Commission, Priority Aeronautics and Space, Contract AST3-CT-2003-502723. The investigations on dynamic buckling were supported by GIF German-Israeli Foundation for Scientific Research and Development, Grant No. I-532-49.10/1997. iBuck was developed as part of a sponsorship contract between Airbus Germany and DLR. All support is gratefully acknowledged.

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