Improved Material Exploitation of Composite Airframe Structures by Accurate Simulation of Postbuckling and Collapse – The Projects POSICOSS and COCOMAT

Richard Degenhardt, Rolf Zimmermann, Raimund Rolfes, Klaus Rohwer

DLR, Institute of Structural Mechanics, Braunschweig, Germany

Summary: European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Contributions to this aim are provided by the completed project POSICOSS and the running follow-up project COCOMAT, both supported by the European Commission. As an important contribution to cost reduction a decrease in structural weight can be reached by exploiting considerable reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling and collapse. 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. This paper presents an overview of major results from the POSICOSS project as well as the objectives and planned tasks of COCOMAT. In addition, DLR's first findings of the COCOMAT project are given.

Keywords: Collapse, Buckling, Postbuckling, Composites, Simulation tools, Experiments, Degradation, Skin stringer separation

Introduction

European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. Supported by the European Commission the project POSICOSS, which lasted from January 2000 to September 2004 and the 4-year follow-up project COCOMAT, which started in January 2004 (cf. Fig. 1), contribute to this aim. POSICOSS stands for *Improved POstbuckling SImulation for Design of Fibre COmposite Stiffened Fuselage Structures* and COCOMAT is the acronym of *Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of COllapse*. Both projects are co-ordinated by DLR, Institute of Structural Mechanics. They allow for a structural weight reduction by exploiting considerable reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling and collapse.

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. The COCOMAT project builds up on the POSICOSS results and goes beyond by a simulation of collapse. That requires knowing about degradation due to static as well as low cycle loading in the postbuckling range. COCOMAT will improve existing slow and fast simulation tools and will set up design guidelines for stiffened panels which take skin stringer separation and material degradation into account. Reliable fast tools

allow for an economic design process, whereas very accurate but necessarily slow tools are required for the final certification. The results will comprise a substantially extended data base on material properties and on collapse of undamaged and pre-damaged statically and low cyclically loaded structures, degradation models, improved slow and fast computation tools as well as design guidelines.
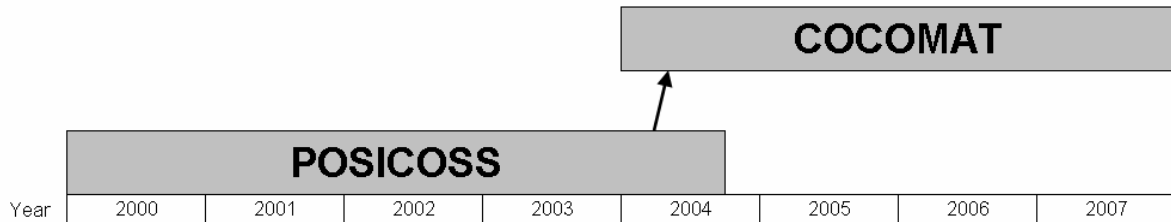
Fig. 1: Timetable of the EU projects POSICOSS and COCOMAT

Regarding loads and characteristic dimensions, the projects POSICOSS and COCOMAT are oriented towards an application in the field of fuselage structures, but the results are transferable to other airframe structures as well. With the new design guidelines the aircraft industry will have a tool at its disposal, which substantially contributes to the objectives of reducing development and operating costs, by 20% and 50% in the short and long term, respectively.

This paper presents an overview of major results from the POSICOSS project as well as the objectives and planned tasks of COCOMAT. In addition, DLR's first findings of the COCOMAT project will be given.

The Project POSICOSS

POSICOSS has merged knowledge and capabilities of seven partners from industry and research: The German Aerospace Center (DLR) - which also acted as co-ordinator, AGUSTA from Italy, IAI from Israel, the Politecnico di Milano (POLIMI) from Italy, the Technical University of Riga (RTU) from Latvia, the Technical University RWTH Aachen (RWTH) from Germany, and the TECHNION from Israel. The project was running from January 2000 until September 2004.

Objectives

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.

Workpackages

The partners co-operated in the following six technical work packages:

- *WP1: Benchmarking for postbuckling and collapse analysis*: This work was performed in order to collect existing benchmarks for software evaluation purposes, as well as to identify in detail the abilities and deficiencies of the tools available.

- *WP2: Design of stiffened, fibre composite verification structures*: The objectives and constraints were mainly defined in view of the requirements from benchmarking according to the shortcomings of existing tools and benchmarks. For designing, material properties have to be known. Hence the required properties were characterized by coupon testing for the fibre composite materials used.

- *WP3: Manufacturing and testing of verification structures*: The objective was to extend the data base for evaluation of improved software tools by results of buckling tests until collapse. A total of 32 verification structures were manufactured and inspected non-destructively. The tests were carried out with shortening control, thus enabling control of how far to go into the postbuckling regime. Different loading conditions were applied (compression, torsion or shear, and critical combinations of them). In general, a basic problem in testing as reference to computations is, that the material properties realized in the structure may vary from those found by coupon testing. Thus efforts were taken to identify material properties as they have been realized in the verification structures.

- *WP4: Development of improved simulation procedures and preliminary design guidelines:* New tools were developed and existing ones for metallic structures were modified. These tools as well as general purpose Finite Element programmes then were used for parametric studies in order to derive preliminary design guidelines for stringer stiffened fibre composite panels.

- *WP5: Design, analysis, manufacture, inspection and testing of fibre composite industrial panels*: The industrial panels were designed in regard to pure industrial aspects, to being best for application as part of real industrial fuselage structures, thus taking full advantage of experience of the industrial partners. At the end, 19 industrial panels were manufactured, inspected and tested. Again, realized material properties were identified.

- *WP6: Design guidelines for stiffened fibre composite panels*: Existing experience and practice of industry, as well as the lessons learned from the project work, were combined in order to carry out final design guidelines.

Results

The project provided four main results:
1) Material properties
2) Test results for buckling and postbuckling of stiffened CFRP panels and cylinders
3) Improved simulation procedures for buckling and postbuckling of stiffened fibre composite panels
4) Design guidelines for stiffened fibre composite panels.

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. In addition, attempts were made to measure elastic constants as they have been realised in the test panels [18] and [20].

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. The partners published their results in [8], [11-13], [15], [17], [21-26] and [28-30].

3) Improved Simulation Procedures for Buckling and Postbuckling of Stiffened Fibre Composite Panels

The following five different concepts for the improved simulation procedures were considered:
- Modelling by consideration of basic structural elements (TECHNION)
- Semi-analytical procedure, discretisation by strip elements (RWTH)
- FE basis, reduction of degrees of freedom by shape functions, regular updating (DLR)
- Response surface method: Neural Networks and Radial Basis Functions (POLIMI)
- Response surface method: Experiment Design (RTU)

An overview was presented by RWTH in [32].

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 [34].

The approach of RWTH is based on the derivation of the total stiffness matrix of stringer stiffened panels. The total 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 buckling and postbuckling displacements in this direction - and an arbitrary number of elements in the circumferential direction. The concept and the results were published in [16], [31] and [33].

DLR used a hybrid reduced basis technique. At first, a conventional finite element model was developed, and was applied to derive a small number of 'shape functions' (e.g. buckling modes), which are utilised subsequently for the analysis of the structure [27]. Thus the number of degrees of freedom can be reduced substantially. The shape functions are updated regularly, based on a predetermined error limit; error sensing and error control take a major part during the calculations.

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. POLIMI published its results in [2], [7] and [14-15], the RTU findings are presented in [1], [3-4], [6], [9], [19], [35] and [36].

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.

Summary

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 and its main results was published by DLR in [5], [10] and [37-38]. More details can be found at www.posicoss.de.

It is well-known that thin-walled structures made of carbon fibre reinforced plastics are able to tolerate repeated buckling without any change in their buckling behaviour. However, it has to be found out, how far into the postbuckling regime loading can go without severe damage of the structure, and how this can be predicted by fast and precise simulation procedures. This issue is dealt with by COCOMAT, the follower project to POSICOSS.

The Project COCOMAT

The 4-year project COCOMAT, which is also co-ordinated by DLR, started in January 2004. Within the consortium knowledge and skills are comprised from 5 large industrial partners (AGUSTA from Italy, GAMESA from Spain, HAI from Greece, IAI from Israel and PZL from Poland), 2 small 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).

Objectives

COCOMAT mainly strives for accomplishing the large step from the current to a future design scenario of typical stringer stiffened composite panels demonstrated in Fig. 2. 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 which 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 the current ultimate load and collapse. The right graph of Fig. 2 depicts the design scenario aspired in future, where ultimate load is shifted towards collapse as close as possible. Another difference to the current design scenario is, that the onset of degradation is 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 an accurate and reliable simulation of collapse, which means to take into account degradation under static as well as under low cycle loading, in addition to geometrical nonlinearity.
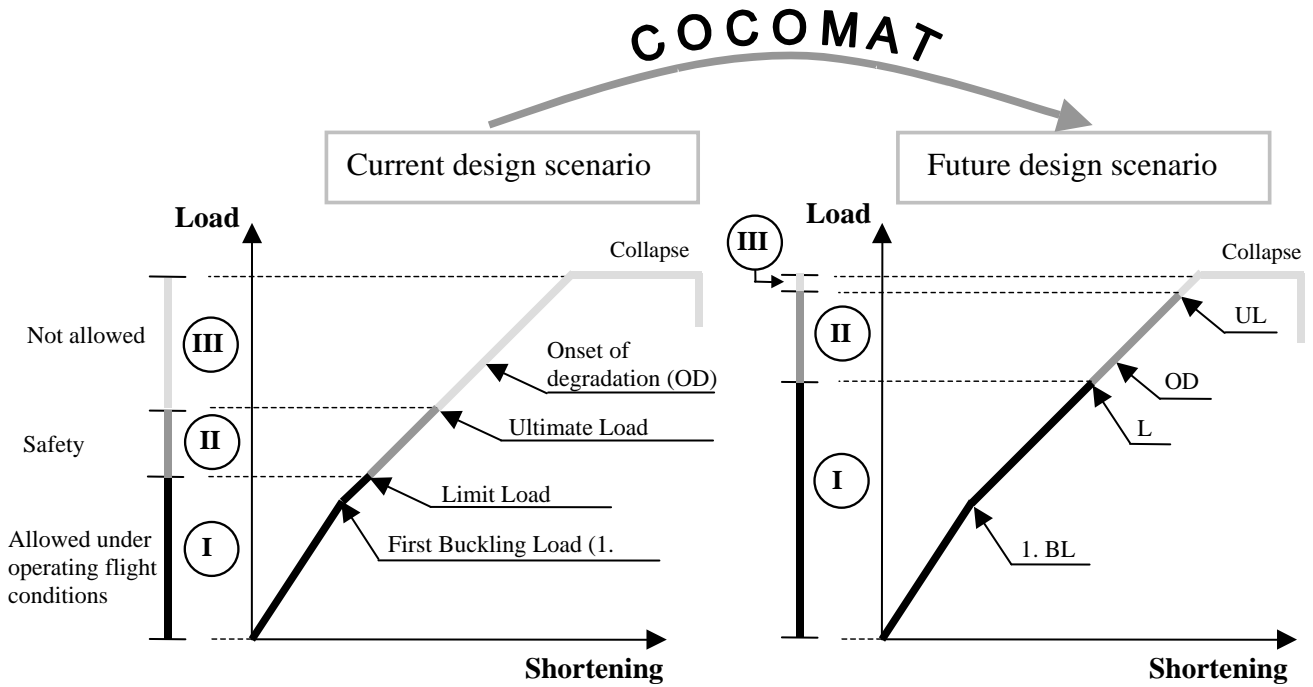
Fig. 2: Current and future design scenarios for typical stringer stiffened composite panel

Expected results

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 and material degradation into account. The experimental data bases are indispensable for verification of the analytically developed degradation models, which will be implemented into the new tools, as well as for validation of the new tools. 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 the 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 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.

Workpackages

The partners co-operate in the following six technical work packages:

- *WP1: Benchmarking on collapse analysis of undamaged and damaged panels with existing tools:* Benchmarks are defined for software evaluation purposes. The objectives are results of selected benchmarks with and without degradation as well as the knowledge of the abilities and deficiencies of the tools available.

- *WP2: Material characterisation, degradation investigation and design of panels for static and cyclic tests*: The first focus is on the design of panels which will be manufactured and tested in WP4. For that purpose, small specimens will be built and tested in order to characterise the specific composite material properties. Another need is the knowledge of experimental degradation models. This will be investigated in the second task on small test

structures (e.g. stiffened strips). The focus will be on the growth of skin-stringer separation and delaminations. In this task, these models will also be verified analytically.

- *WP3: Development of improved simulation procedures for collapse*: In this workpackage slow and fast computational tools, which take degradation into account, are developed and improved. Very accurate but necessarily slow tools are required for the final certification, whereas reliable fast tools reducing design and analysis time by an order of magnitude, will allow for an economic design process. Finally, all tools are validated by means of the experimental results obtained from the other workpackages.

- *WP4: Manufacture, inspection and testing by static and cyclic loading of undamaged panels from WP2*: This workpackage deals with the manufacturing and testing of undamaged panels. The objective is to extend the data base on collapse of undamaged panels under static and low cycle loading for evaluation of improved software tools. Based on the documentation of the designs for the panels from WP2 as input, a total of 22 undamaged prepreg panels, each with blade stiffeners, will be manufactured: 14 single panels and 8 additional panels combined to 4 closed sections.

- *WP5: Manufacture, inspection and testing by static and cyclic loading of pre-damaged panels from WP2*: This workpackage contains the manufacturing and testing of pre-damaged panels. The structural designs are the same as in the previous workpackage, but now the panels are artificially damaged before testing. The selection of the same designs allows a better assessment of the influence of damage on collapse. The objective is to extend the data base on collapse of pre-damaged panels under static and low cycle loading in order to evaluate the improved software tools. A total of 25 pre-damaged prepreg panels, each with blade stiffeners, will be manufactured: 13 single panels and 12 additional ones combined to 6 closed sections.

- *WP6: Design guidelines and industrial validation*: WP6 comprises the final technical part; all the results of the project are assembled in order to derive the final design guidelines and to validate them as well as the new tools. The input is summarized in the improved simulation procedures, the documentation of the designs as well as the documentation of the experiments and their evaluated results.

First results

WP1 is nearly finished. The partners selected two panel tests from the POSICOSS projects as benchmarks on undamaged structures. In order to obtain test results of a comparable pre-damaged panel one of these nominal identical panels was manufactured again, pre-damaged by IAI and tested by TECHNION. All partners applied different software tools on the benchmarks in order to simulate the structural behaviour up to collapse. They identified abilities and deficiencies of the simulation of degradation. More detailed results on the two undamaged benchmarks are published in [40]. As an example Fig. 3 shows the load shortening curve of one undamaged benchmark (axially loaded CFRP panel) provided by DLR and the comparison with two simulations by means of the commercial tool ABAQUS. There is a good agreement between simulation and experiment up to the first global buckling where the stringers buckle. From that point on the agreement becomes worse. However, in that deep postbuckling region the simulation is not expected to agree with the test because currently ABAQUS cannot take degradation (e.g. material degradation, skin-stringer separation or the delamination in the stiffener blade) into account. In the frame of WP3 the simulation tools will be improved in that way that the effect of most important types of degradation can be simulated.
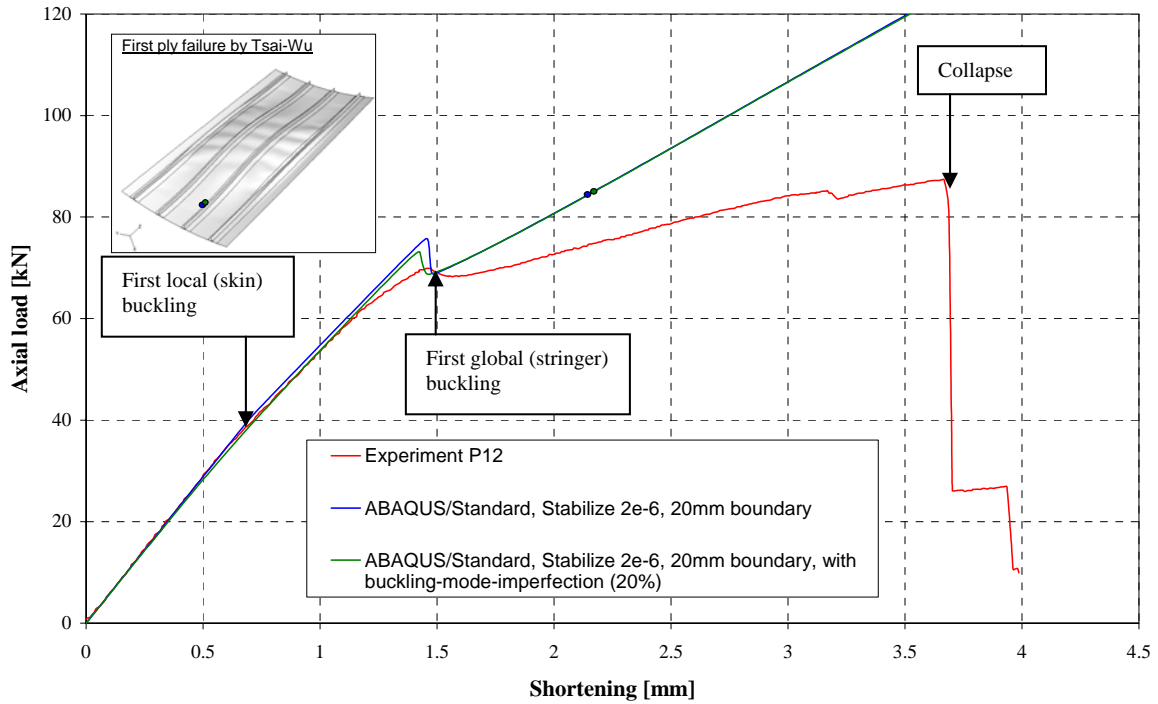
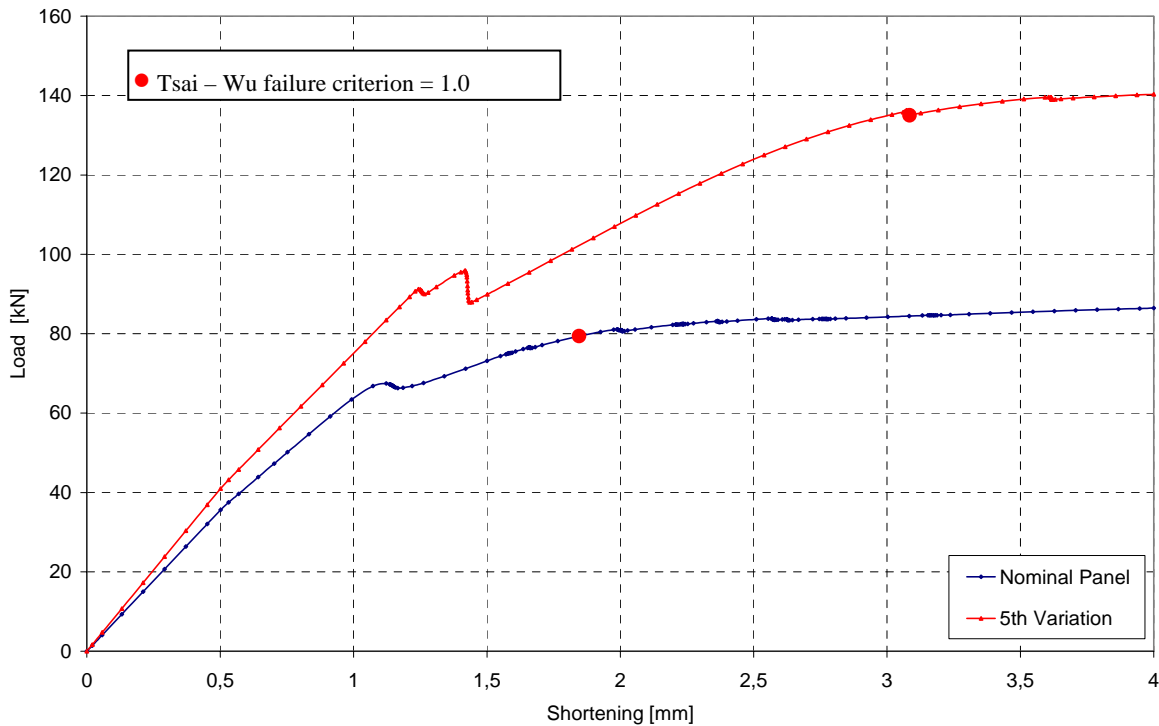*Fig. 3:* Load shortening curve of one benchmark panel

Fig. 4: Load shortening of first panel designs

The work in WP2 is in progress. The first task to characterise the material is almost finished. In the second task the first tests on small structures (e.g. stiffened strips or plates), which build the basis for the development of improved degradation models, has started. In the third task panels are currently designed, which shall be manufactured and tested in WP4. The group designs two kinds of panels: verification panels and industrial panels. The *verification panels* are designed as to specific limiting aspects of application of the software to be verified, e.g.

type of shell theory, type of buckling before postbuckling, mild or strong stiffness reduction in the postbuckling regime, multiple or single modes of buckling before postbuckling. These panels should have a significant postbuckling range up to collapse and an early onset of degradation. The *industrial panels* are designed in regard to industrial applications, mainly by existing procedures used in day-to-day industrial design practice. Fig. 4 shows the predicted load-shortening curves of two different verification panels which are currently in the design process at DLR. The designs by all partners will be finished mid of 2005. The first tests will start at the end of 2005.

The work of WP3 has started mid of 2004. The partners improve slow certification tools and fast design tools in order to have the capability to take different aspects of degradation into account. First results were presented in [41] and [42], or will be presented soon in [43].

Summary

The main objective of the running COCOMAT project is the future design scenario for stringer stiffened CFRP panels (cf. Fig. 2). COCOMAT builds up on the results of the finished POSICOSS project and considers in addition 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. On overview about the project and main results was published by DLR in [39]. More details can be found at www.cocomat.de.

Acknowledgements

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