Future Design for Composite Airframe structures – The Projects POSICOSS and COCOMAT

Richard Degenhardt

DLR, Institute of Composite Structural and Adaptive Systems, 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

1. 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 *Composite Structural and Adaptive Systems*. 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.

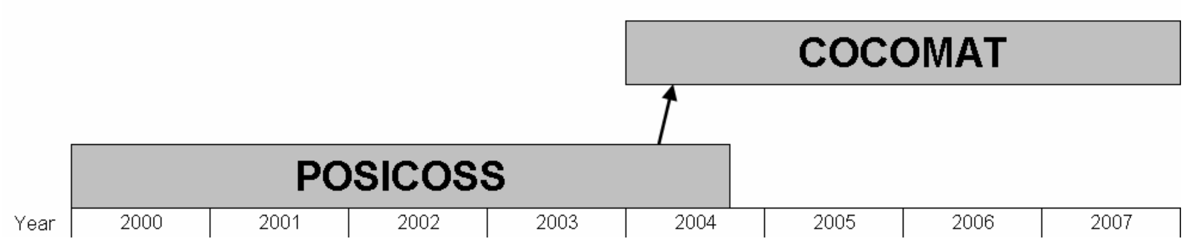

Fig. 1 Timetable of the EU projects POSICOSS and COCOMAT

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.

2. 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.

2.1 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.

2.2 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.

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 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)

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 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.

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. 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.

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.

2.3 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 a list of all published results can be found at www.posicoss.de and [1].

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.

3. 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).

3.1 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.

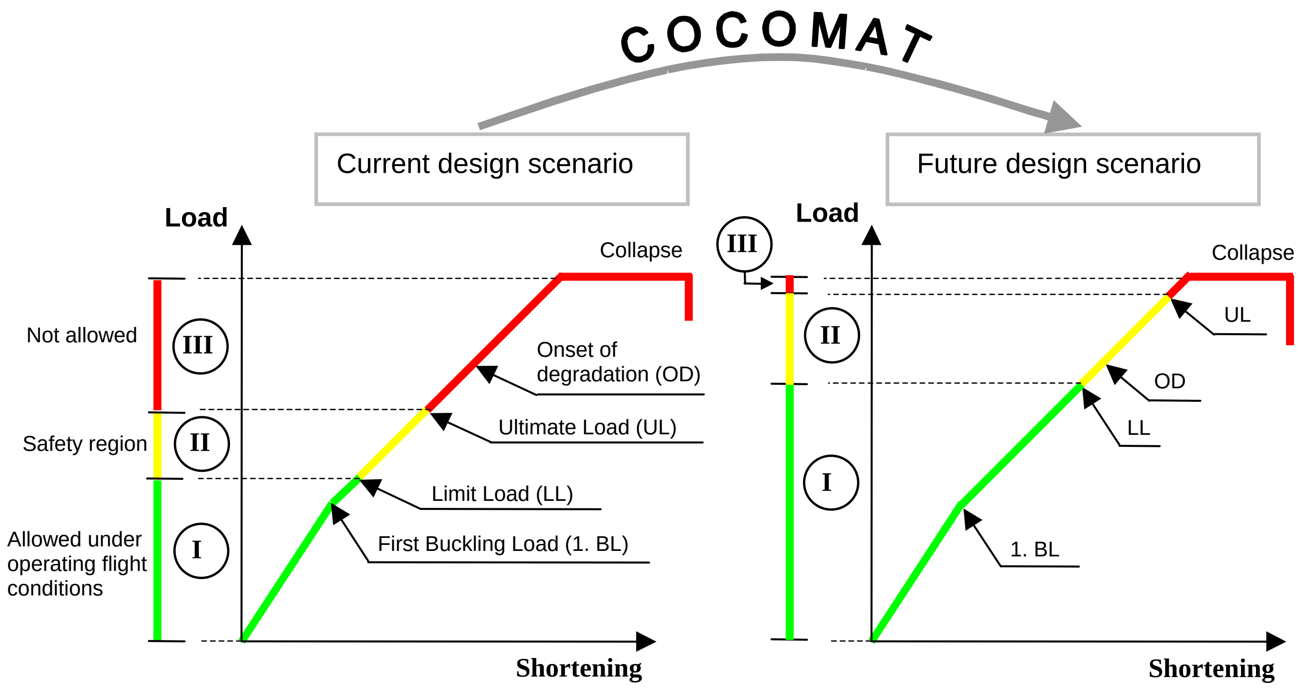

Fig. 2 Current and future design scenarios for typical stringer stiffened composite panels [2]

3.2 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.

3.3 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.

3.4 First results

During the first 2.5 project years the COCOMAT partners worked mainly on the first four technical workpackages. This section gives a general summary of the status of each workpackage and presents some of DLR’s first results. Because workpackage 4 is in a preliminary stage this paper concentrates on the first 3 workpackages. A list of papers published by the partners so far can be found at www.cocomat.de.

3.4.1 Workpackage 1

WP1 is 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 panel from the POSICOSS project was refurbished, a minor damage was fixed, then it was pre-damaged by IAI and tested by TECHNION. In addition, the consortium exchanged test results of pre-damaged benchmark structures with Airbus Germany. The partners applied different finite element tools on the benchmarks in order to simulate the structural behaviour up to collapse. They identified abilities and deficiencies of the simulation of degradation.

Some detailed results on the two undamaged benchmarks are published in [7]. As an example Figure 3 shows the load shortening curve of one undamaged benchmark (axially loaded CFRP panel) provided by DLR and the comparison with simulations by means of the commercial tools ABAQUS and NASTRAN. There is a good agreement of all curves from the prebuckling region up to the first global buckling (at 1.4 mm shortening) where the stringers buckle. From that point there is still a good agreement between the different numerical simulations which take imperfections into account. The agreement with the experiment becomes worse. However, in that deep postbuckling region the simulation is not expected to agree with the test because degradation (e.g. material degradation, skin-stringer separation or the delamination in the stiffener blade) is not taken 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. In addition, the modeling of the lateral boundary conditions largely influences the results in that load region.

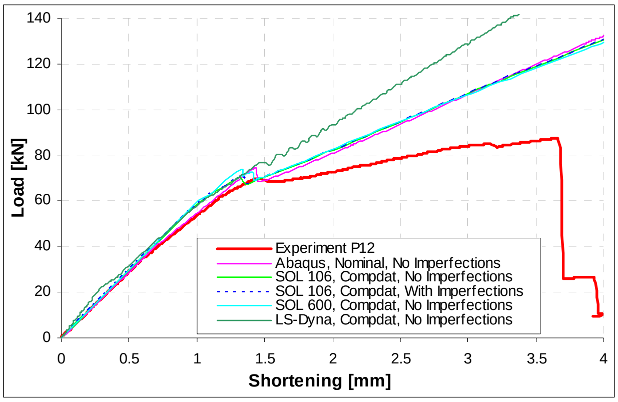

Fig. 3 Selected results from WP 1

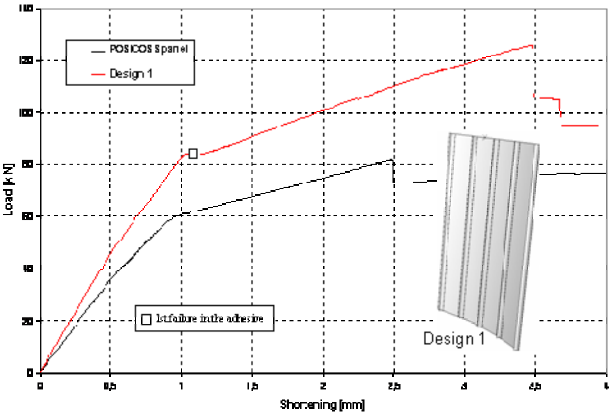

Fig. 4 COCOMAT panel design in comparison to the start design from POSICOSS

3.4.2 Workpackage 2

The work in WP2 is finished.

In *Task 2.1* the partners involved characterised the material properties of the specimens with and without damages, manufactured of the material IM7/8552 UD, 985-GT6-135 and IM7/8552. DLR has determined the material properties of specimens, according to the German standard. The specimens are manufactured of IM7/8552 UD by GAMESA. Additionally, so called small specimen tests, according to compression after impact tests (CAI) have been conducted to examine a possible stiffness reduction as a function of delamination size. All DLR's results are summarized in [8].

The objectives of *Task 2.2* are improved degradation models which are needed for the slow certification tools and fast design tools in WP 3. These will be obtained by test results. Planned specimens for the investigation of degradation are plates or small structures made a skin with one or two stiffeners. Partners involved in the experimental activity are providing tables and graphs to be used for the development of new procedures or the improvement of existing slow and fast numerical codes in order to consider combined effects of damages and compressive loading. Efforts are spent on a critical review of the collected data and on an improvement of the tests in order to characterize degradation onset. Some of the partners also performed numerical simulations of the specimen behaviour in order to better understand degradation mechanisms.

The objective of *Task 2.3* is the design and analysis of stiffened panels which shall be manufactured and tested in WP4. The group designed two kinds of panels: validation panels and industrial panels. The *validation 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.

In co-operation with CRC-ACS and HAI, DLR designed one validation panel (Design 1). The initial configuration for the design process was taken from the POSICOSS project. The objective was to increase further the postbuckling region, especially to have a certain load capacity after the first global buckling. The reason is that the influence of skin-stringer separation on the collapse load should be investigated and this kind of degradation usually occurs after the first global stringer buckling. Several parametric studies for the ariation of the lay-up of the skin and stringer, number stringers, stringer geometry and position of the stringers were performed. During the design process the onset of different kinds of degradation, as skin-stringer separation, delamination in the stringer blade and failure in the composite laminate structure have been estimated by simple extension of the available software tool. In order to check the influence of degradation on collapse the panels with a large postbuckling region and the indication of skin-stringer separation (failure in the adhesive layer) as early failure mode were favoured. There was also a second important change of Design 1 in comparison to the POSICOSS one. For Design 1 the clamping boundary conditions of the lateral edges of the panel, which were applied to all POSICOSS experiments, were released because the modelling of these boundary conditions showed a significant influence on the axial stiffness in the postbuckling region after the first global stringer buckling (cf. Figure 2). However, in order to avoid an early start of skin buckling due to the free lateral edges the stringers were moved in circumferential direction to support these edges. In addition, computations on different designs were performed in order to ensure that the onset of skin-stringer separation starts in the middle stringers and not in the outer ones. Figure 4 illustrates the load-shortening curve of this design in comparison to a POSICOSS design. For the Design 1 there is a large postbuckling region, even after the first global stringer buckling and the stringer buckling starts in the middle of the panel. DLR's experience in the designing of panels within the projects POSICOSS and COCOMAT is explained in more detail in [9].

3.4.3 Workpackage 3

In WP3 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.

Task 3.1 concentrates on the improvement of slow certification simulation tools. Figure 5 illustrates the whole family of slow computational tools including the degradation models considered in that task.

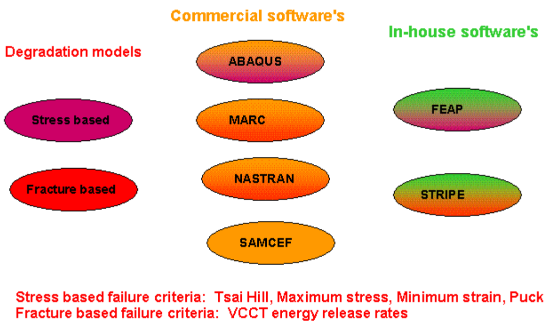

Fig. 5 Family of slow certification computational tools within Task 3.1

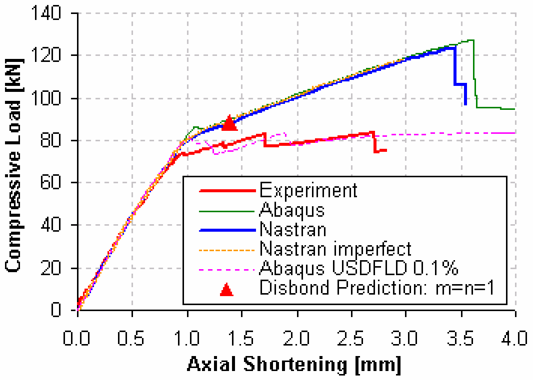

Fig. 6 Some results from Task 3.1 [7]

For simulating the skin-stringer separation of composite structures *DLR* is developing three ABAQUS user subroutines which differ in their numerical approach. The first subroutine, USDFLD, is finished and was applied to calculate the structural behaviour of Design 1 up to collapse. The comparison of the load shortening curves of the simulation with a panel test result show good agreement (cf. Figure 6). However, concerning the buckling shapes there are differences which could not be clarified. Detailed results can be found in [9]. The other two subroutines are not finished yet.

Task 3.2 concentrates on the improvement of design procedures for the fast simulation of collapse behaviour of stringer stiffened fibre composite panels. The tools will be faster at least by a factor of 10 than respective Finite Element (FE) simulations at an accuracy, which is sufficient for design purposes. A graphical model representing overall precision and computing time of fast simulation procedures with degradation between all partners involved in that task is presented in Figure 7.

DLR is considering iBUCK which was developed in a previous project. iBUCK is a tool for the fast simulation of the postbuckling behaviour of aerospace structures [10]. The model is based on the Donnell type shell equations for thin, slightly curved shells that undergo large deflections. Stringers are considered as structural elements with independent degrees of freedom and are not “smeared” onto the skin. 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, where 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. The panel may be loaded axially and bi-axially. In addition, one load case that is of special interest for the aircraft industry is included: the loading by an external bending moment in circumferential direction which may act in an opening or closing mode. All external loads may be applied individually or in combination. In COCOMAT skin-stringer separation is implemented into iBUCK.

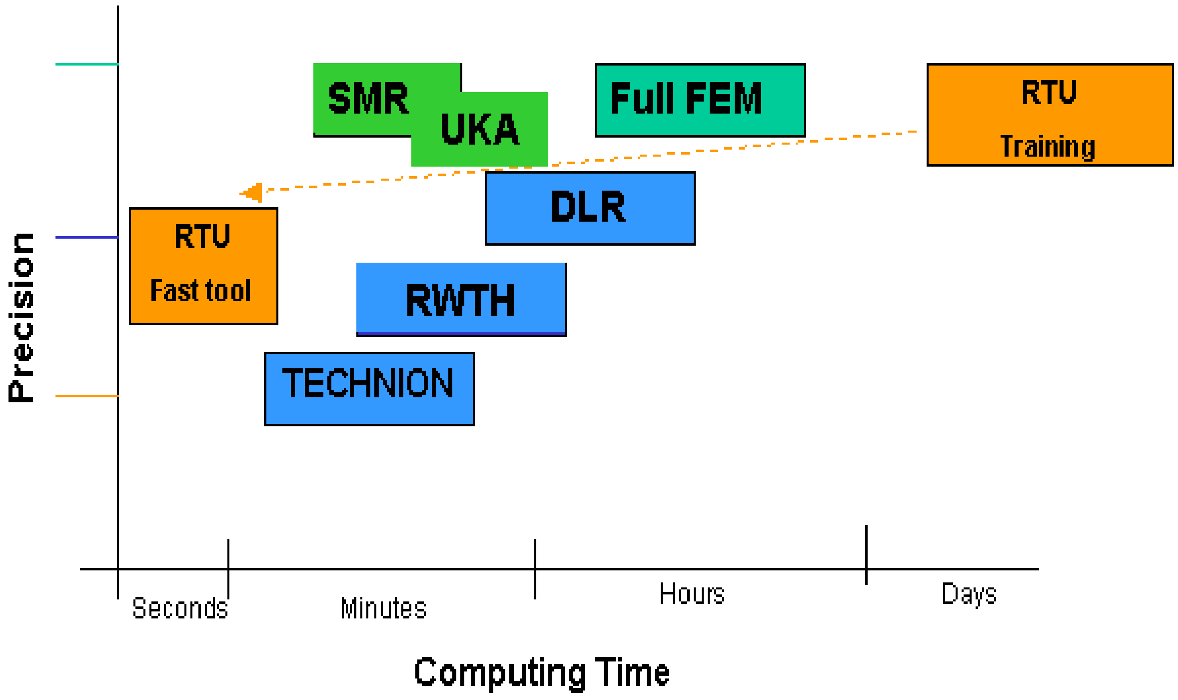

Fig. 7 Family of fast design computational tools within Task 3.2

3.5 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.

4. Acknowledgements

The finished project POSICOSS was supported by the European Commission, Competitive and Sustainable Growth Programme, Contract G4RD-CT-1999-00103. The running project COCOMAT is supported by the European Commission, Priority Aeronautics and Space, Contract AST3-CT-2003-502723. The information in this paper is provided as is and no warranty is given that the information is fit for any particular purpose. The reader thereof uses the information at its sole risk and liability.

5. References

[1] Zimmermann R., Rolfes R., “POSICOSS - Improved postbuckling simulation for design of fibre composite stiffened fuselage structures”, *Composite Structures*, Vol. 73 (2006), pp. 171-174.

[2] Degenhardt R., Rolfes R., Zimmermann R., Rohwer K., “COCOMAT - Improved **MAT**erial exploitation at safe design of **CO**mposite airframe structures by accurate simulation of **CO**llapse”, *Composite Structures*, Vol. 73 (2006), pp. 175-17.

[3] www.cocomat.de

[4] Zimmermann R., Rolfes R., “POSICOSS - Improved postbuckling simulation for design of fibre composite stiffened fuselage structures”, *Composite Structures*, Vol. 73 (2006), pp. 171-174.

[5] Zimmermann R., Klein H., Kling A., “Buckling and Postbuckling analysis of stringer stiffened fibre composite curved panels”, *Composite Structures*, Vol. 73 (2006), pp. 150-161

[6] Kling A., Degenhardt R., Zimmermann R., “A hybrid subspace analysis procedure for non-linear postbuckling calculation”, *Composite Structures*, Vol. 73 (2006), pp. 171-174.

[7] Orifici, A. C., Thomson, R. S., Gunnion, A. J., Degenhardt, R., Abramovich, H., Bayandor, J., “Benchmark finite element simulations of postbuckling composite stiffened panels”, *11th Australian International Aerospace Congress*, Melbourne, Australia, 13-17 March, 2005.

[8] Kling A., Degenhardt R., “Characterization of material properties – Results of the EU project COCOMAT”, April 2006, *Internal DLR report*, IB 131-2006.

[9] Degenhardt R., Kling A., Rohwer K., “Design and analysis of composite panels”, *III European Conference on Computational Mechanics*“, Lissabon, 5-8 June, 2006.

[10] Orifici A. C., Thomson R. S., Degenhardt R., Kling A., Rohwer K., Bayandor J, “Degradation investigation in a postbuckling composite stiffened fuselage panel”, *13th International Conference of Composite Structures“, Melbourne, Australia*, 14-16 November, 2005.

[11] Bürmann P., Rolfes R., Tessmer J., Schagerl M., “A semi-analytical model for local post-buckling analysis of stringer- and frame-stiffened cylindrical panels”, *Thin-Walled Structures*, Vol. 44 (2006), pp. 102-114.