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DESIGN AND ANALYSIS OF COMPOSITE PANELS

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Abstract. *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 (5thFP) and the running follow-up project COCOMAT (6thFP), 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 up to collapse. The POSICOSS team developed fast procedures for postbuckling analysis of stiffened fibre composite 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.*

The projects POSICOSS and COCOMAT develop improved tools which are validated by experimental results obtained during the projects. Because the new tools must consider a wide range of different aspects a lot of different structures had to be tested. These structures were designed under different design objectives. For the design process the consortium applied already available simulation tools and brought in their own design experience. This paper deals with the design process within both projects and the analysis procedure applied within this task. It focuses on the experience of DLR on the design and analysis of stringer stiffened CFRP panels gained in the frame of these projects.

1 INTRODUCTION

European aircraft industry demands for reduced development and operating costs, by 20% and 50% in the short and long term, respectively. The European Commission project POSICOSS, which lasted from January 2000 to September 2004 and the 4-year follow-up project COCOMAT, which started in January 2004 (cf. Figure 1), contribute to this aim [1- 4]. Both projects are under the co-ordination of DLR, Institute of Composite Structures and Adaptive Systems. The main goal is the exploitation of considerable reserves in primary fibre composite fuselage structures through an accurate and reliable simulation of postbuckling up to collapse. Collapse is specified by that point of the load-displacement-curve where a sharp decrease occurs thus limiting the load carrying capacity. The POSICOSS team developed fast and reliable procedures for postbuckling analysis of fibre composite stiffened panels, created experimental data bases and derived design guidelines [1-2]. The COCOMAT project builds up on the POSICOSS results and goes beyond by simulation of collapse. The project improves existing tools as well as design guidelines for stiffened panels taking skin stringer separation and material degradation into account and it creates a comprehensive experimental data base [3-4].

The improved tools, developed within the POSICOSS and COCOMAT project, have to be validated by test results. Since appropriate test data bases were not available, both projects were constrained to create new experimental data bases for curved stringer stiffened CFRP panels as well as cylinders. To that end suitable panels and cylinders were designed under own project objectives. Some of them were already manufactured, inspected and tested. Each project differentiates between validation panels and industrial structures. The validation structures are designed as to specific limiting aspects of application of the software to be validated, e.g. small or large stiffness reduction in the postbuckling regime. The industrial structures were designed in regard to industrial applications, mainly by existing procedures used in day-to-day industrial design practice.

For the analysis of the structures the partners utilized different available software tools and brought in their own design experience. Two different kinds of tools were applied; fast tools suitable an economic design process and very accurate but necessarily slow tools required for the final certification. Geometrical nonlinear computations up to collapse were performed. The material was assumed linear elastic. The onset of degradation of the structure and the skin-stringer connection was determined using different failure criteria.

This paper focuses on the experience of DLR on the design and analysis of stringer stiffened CFRP panels gained in the frame of the POSICOSS and COCOMAT projects.

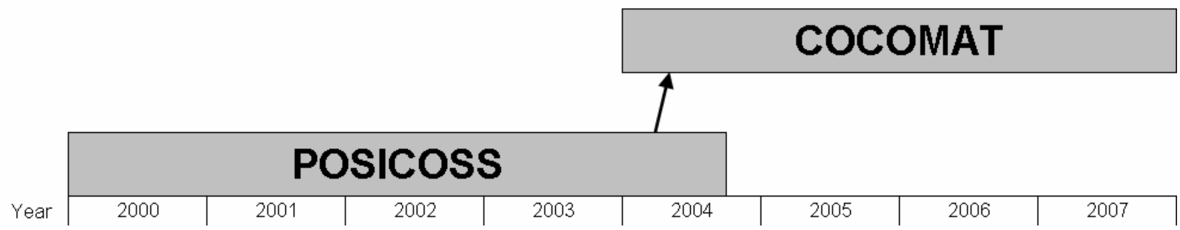

Figure 1: Timetable of the EU projects POSICOSS and COCOMAT

2 DESIGN OF COMPOSITE PANELS

2.1 Introduction

The objectives to design a structure, independent of the material, kind of structure or application, depend on the purpose the structure shall have. In general, one can distinguish between *industrial structures* and *validation structures*. The validation structures are designed as to specific limiting aspects of application of the software to be validated, e.g. type of shell theory (design going into the limits of the theory), type of buckling before postbuckling (local or global), mild or strong stiffness reduction in postbuckling regime, multiple or single modes of buckling limit before postbuckling. Industrial structures are designed in regard to industrial applications, mainly by existing procedures and requirements used in day-to-day industrial design practice. For these structures there exist usually multi-objective requirements concerning weight, load carrying capacity and costs.

Figure 2 illustrates a realistic (experimentally measured) load-shortening curve of an axially compressed stiffened CFRP panel, which represents a stringer dominant design, and explains the terminology of three remarkable load levels. The first one is usually first local buckling where the buckling mode are local skin buckles between the stringers, the second one is first global buckling which is stringer based-buckling and the last is the collapse load level which is the maximum load. The red curve is a simplified representation of the realistic load-shortening curve with knees at these load levels.

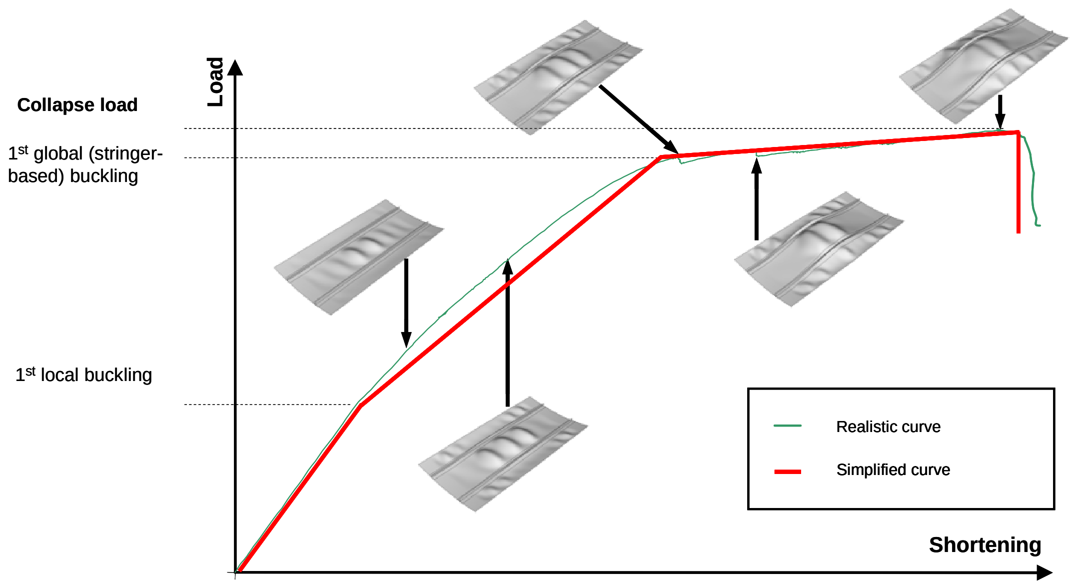

Figure 2: Definition of first local and global buckling load and collapse load

This paper concentrates on the description of the design process made within the EC projects POSICOSS and COCOMAT. The structures considered are curved stringer-stiffened panels and cylinders made of carbon fibre reinforced plastics (CFRP) material. Within each project a large number of structures was designed. Because the maximum number of tests was limited only appropriate designs for manufacturing and testing were selected. The selection criterion was to have a wide range of different designs. The new test results build a large experimental data base which is necessary for the validation of the new tools developed to simulate the buckling and postbuckling behaviour up to collapse. Two kinds of tools are considered; 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. For the industrial applicability these tools must be on the one hand side validated by appropriate experiments and on the other hand their applicability must be proved on real industrial panels.

The following section describes the design process of DLR as partner within the projects POSICOSS and COCOMAT. It starts with a description of a benchmark which was taken as initial design for the POSICOSS structures. Then the design process within the POSICOSS project is described. The panels designed within COCOMAT build up on the experience on POSICOSS and are described finally.

2.2 Start design

The design of the POSICOSS structures takes the results of the following pre-damaged benchmark, which was tested at DLR, as basis. It was intensively investigated within the GARTEUR SM Action Group 25 “Postbuckling and Collapse Analysis” [5] and at the beginning of the POSICOSS project and will be subsequently detailed.

This benchmark is an axially compressed CFRP panel as depicted in Figure 3. The panel consisted of a skin with nominally cylindrical shape, stiffened by T-shaped stringers. The stringers were partially separated from the skin by impacting prior to the tests. The damaged areas were measured by ultrasonic inspection to allow for an accurate numerical simulation. Finally, the panel was axially compressed until collapse.

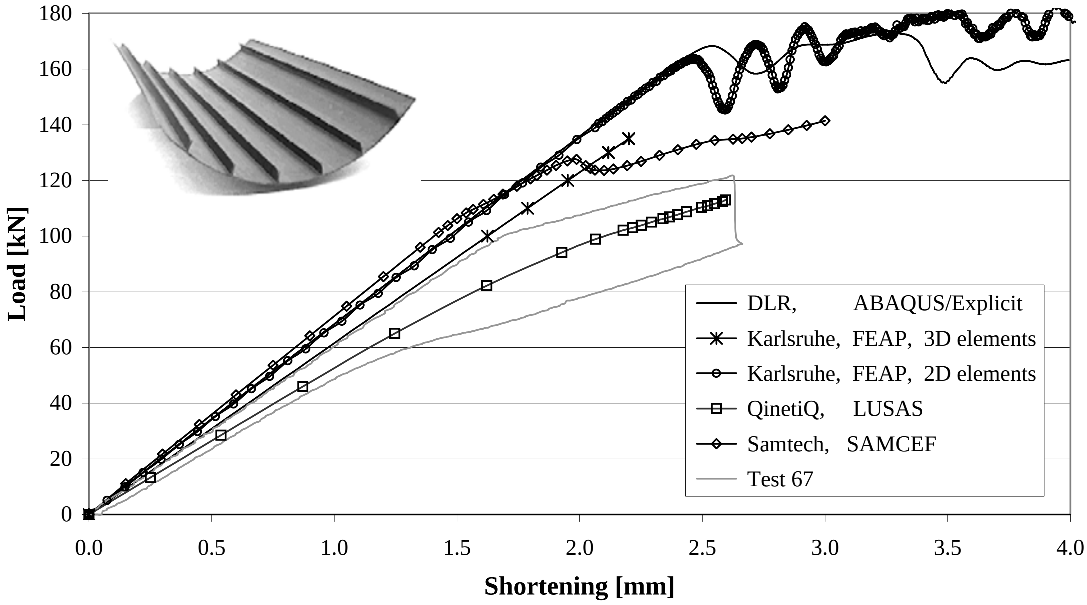

Figure 3: Finite element analyses of the undamaged DLR benchmark taken as start design [5]

Different commercial and self-developed finite element tools were applied to simulate the behaviour of this panel during loading up to collapse. Linear and nonlinear analyses as well as buckling analyses were performed in order to observe the axial stiffness in the pre-buckling region, the buckling loads of the panel and the structural behaviour in the post-buckling region. A major challenge of this benchmark was the simulation of the damaged region through contact elements. Furthermore, a considerable number of parameters like skin stringer connection, stringer flange modelling, number of finite elements, damping, imperfections, loading velocity, boundary conditions, numerical method or kind of finite elements were investigated. Figure 3 illustrates some load-shortening curves obtained by numerical simulations of the undamaged panel. As a main result all FE-software tools considered turned out to be suitable in general for the simulation of buckling, post-buckling or collapse behaviour of such panels. Specific abilities and deficiencies of the finite element tools were evaluated. Recommendations with respect to the influence of parameters, the initial buckling load, the convergence behaviour, the simulation of load introduction and boundary conditions as well as the imperfection sensitivity were derived.

In order to check the influence of the pre-damage this benchmark was also calculated without any damage. The result was that this undamaged panel has almost no reserve capacity in the postbuckling region because its local skin buckling load and global stringer buckling load are very close. The reason is that this is a more skin dominant design. This undamaged panel was therefore taken as start design for the POSICOSS project because it represented under the design objective “large postbuckling region” the worst case of design.

2.3 Design process within POSICOSS

The main design objective within POSICOSS was to obtain a significant postbuckling area before collapse. DLR aimed to design 4 panels and 2 cylinders which should be considered as validation structures for the validation of the software. The undamaged benchmark described in the previous section has almost no postbuckling region and represents therefore with respect to that the worst case. It was therefore taken as start design and was modified in the following way in order to increase the postbuckling region. Here were also cylinders designed which are understood as the continuation of panels:

1) For the first cylinder design, a smaller number of stringers was taken to trigger the local buckling at a lower level as first buckling mode and to increase the load carrying capacity in the postbuckling region.
2) In the second cylinder design, the number of stringers was decreased and the 90°-layers of the skin were removed in order to increase the sensitivities to torsion loading as second effect. The radius of both cylinders was fixed to 400 mm due to reasons from testing.
3) For the purpose of comparison, the panels should be as similar as possible to the cylinders. Therefore, the first two panel designs were taken as 60° sections from the cylinder designs.
4) Two additional panel designs were defined which differ from the first two, only by increase in the radius from 400 mm to 1000 mm in order to examine the influence of the parametric radius and to get closer to the real aircraft fuselage structures.

This design process resulted in four different stiffened panels and two different cylinders illustrated in Figure 4. Except one panel, which has the smallest postbuckling region, all designs were manufactured, however some of them two or three times each in order to increase the reliability, and tested at the DLR testing buckling facility until collapse. Figure 5 illustrates the comparison of the test and simulation of one tested panel. It can be seen that the panel design has a large postbuckling region as it was planned. There is a good agreement between simulation and test up to the first global buckling. From that point there differences become larger. However, because degradation is not considered within that simulation a better agreement in the deep postbuckling region is not expected. In addition, the modelling of the boundary conditions for the clamping of the lateral edges of the panel showed a significant influence on the axial stiffness in the postbuckling region after the first global stringer buckling. More details are given in [6]. The consideration of degradation is topic of the project COCOMAT.

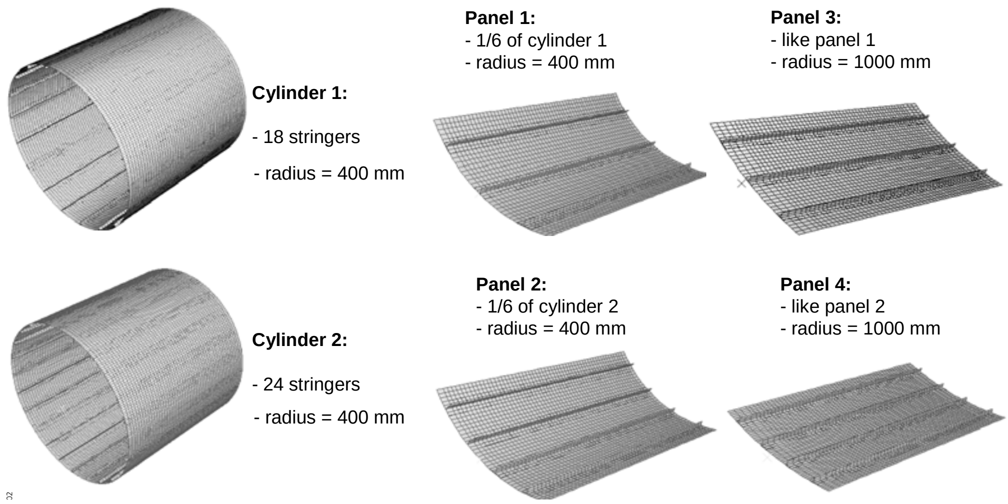

Figure 4: POSICOSS designs (DLR)

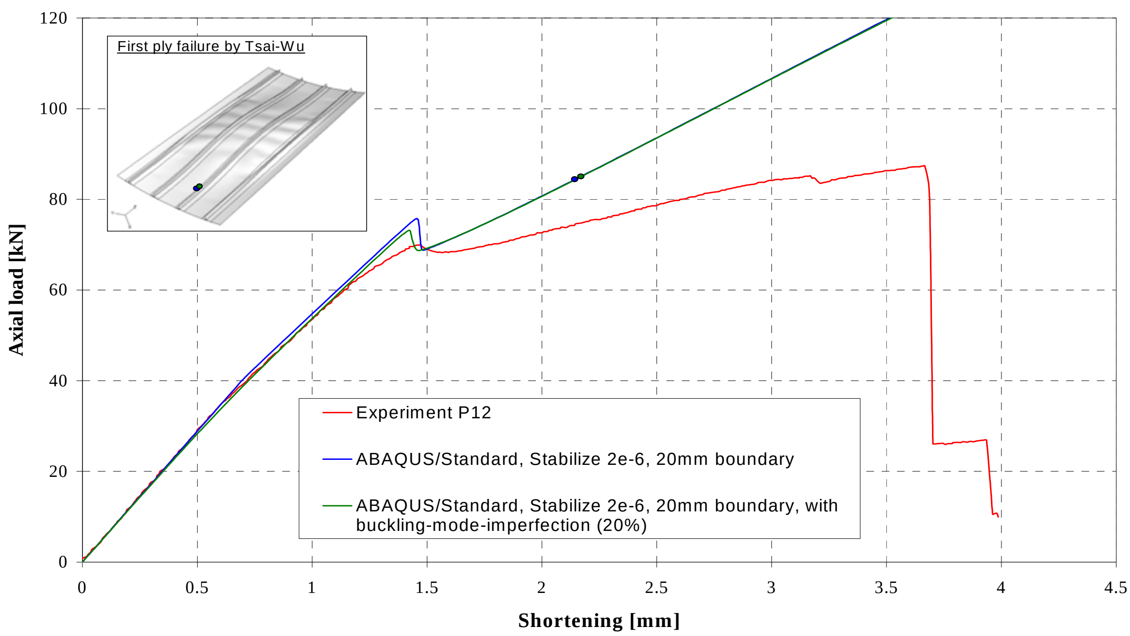

Figure 5: POSICOSS design panel P12 – Comparison test and simulation

2.4 Design process within COCOMAT

To simulate the collapse load of stringer stiffened CFRP panels accurately the COCOMAT group improves slow certification tools and fast design tools which are capable to take degradation into account. The group considers the following degradation modes: skin-stringer separation, delamination in the stringer blade and degradation on the composite structure itself. Because for the validation of the tools an appropriate test data base is not available (the POSICOSS test data base could not be taken because degradation was not measured during the project) new curved stringer stiffend CFRP panels, which shall be manufactured and tested, were designed. The group designed two kinds of panels: validation panels and industrial panels. DLR as research establishment concentrated to design one validation panel which is called in the following Design 1. The objective was similar as for the POSICOSS project a large postbuckling region and an early onset of stringer-separation.

The design process for Design 1 started with a panel configuration with the radius 1000 mm tested within POSICOSS. 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 variation 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.

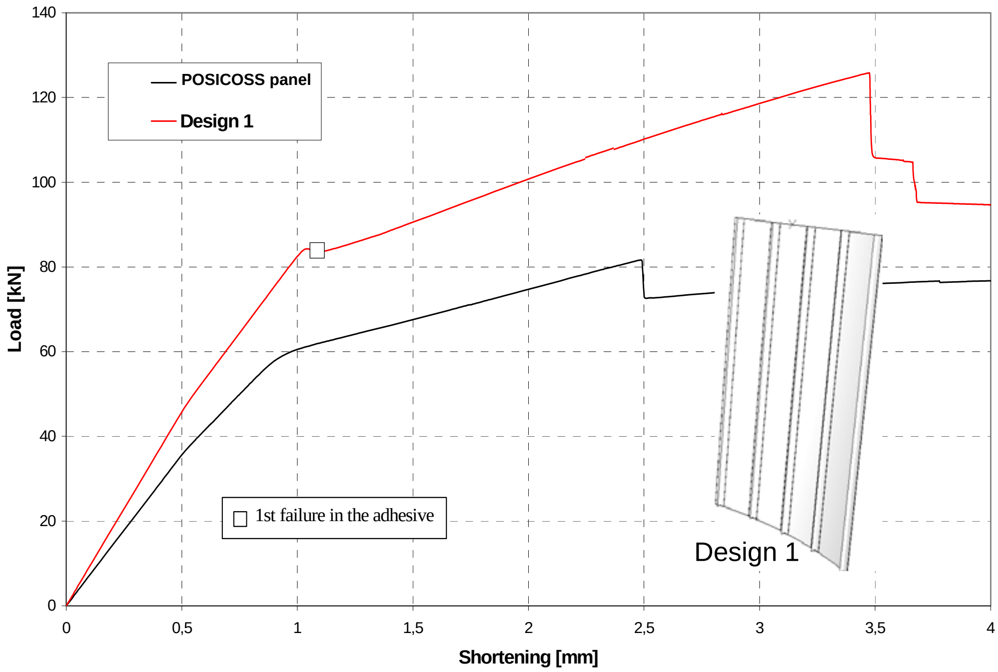

Figure 6: Load shortening curve of the COCOMAT panel design in comparison to the start design from POSICOSS

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 on 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 5). However, in order to avoid a start of skin buckling in that free lateral area the stringers were moved in circumferential direction to the end of the lateral edges. In addition, computations on different designs were performed in order to ensure that the onset of skin-stringer separation starts in the stringers in the middle and not in the outer stringers.

On the basis of the structural and fracture mechanics analyses one design (Design 1) was selected as being the most suitable for the experimental investigation into degradation and collapse of stiffened composite panels. Figure 6 illustrates the load-shortening curve of this design in comparison to a POSICOSS design which was taken as start design for COCOMAT. There is a large postbuckling region, even after the first global stringer buckling and the stringer buckling starts in the middle of the panel.

3 ANALYSIS OF COMPOSITE PANELS

For the design of the panels, described in the previous chapter, DLR applied the Finite Element Software ABAQUS/Standard. Geometrical nonlinear computations with an incremental iterative Newton/Raphson method with artificial damping (Stabilize-Method) up to collapse were performed. The material is linear elastic. Within POSICOSS no degradation was considered. Within COCOMAT DLR develops ABAQUS/User subroutines, which consider the skin-stringer debonding using stress-based failure criteria.

3.1 Nonlinear Finite Element Analysis - without degradation

To analyse the pre- and postbuckling behavior of the panels the commercial nonlinear finite element tool ABAQUS/Standard has been employed by DLR. The four-node shell element (S4R) has been used to discretize the panel. Figure 8a depicts some details of the FE-model (e.g. spring elements, which have been used to introduce the stiffness of the longitudinal edge supports in the computer model).

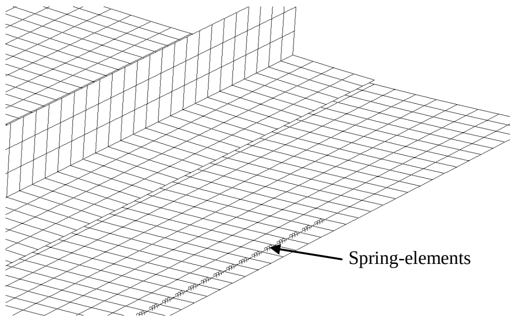

Figure 8a: Details of the FE model

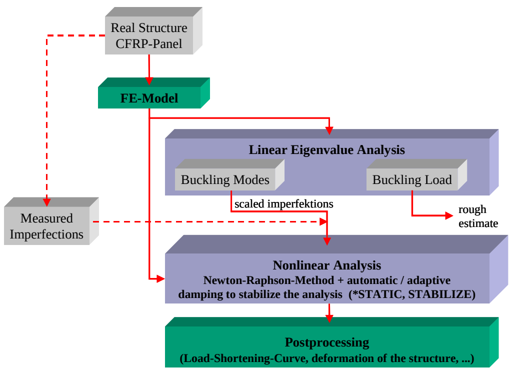

Figure 8b: Analysis procedure in ABAQUS

The approach to conduct the FE-analysis consists basically of four stages (Figure 8b): The preprocessing, a linear eigenvalue analysis to extract buckling modes, which are subsequently used as initial imperfections in the nonlinear analysis utilizing the built-in Newton-Raphson technique with adaptive/artificial damping, and finally the postprocessing. This nonlinear solution method has been proved to be relatively stable for the considered stringer-stiffened panels. Figures 5 and 6 depict the load-displacement curves, which have been obtained utilizing the analysis procedure described in Figure 8b with and without initial geometric imperfections.

The validation of the numerical simulation is performed by a comparison with experimental results on a so-called “global” and “local” level. On the “global” level of validation the overall load-shortening as well as the full scale deformation patterns are compared. Figure 8 shows such a comparison of buckling patterns obtained by experiment and simulation. The experimental data was obtained using ARAMIS - a 3D-optical measurement system which is based on photogrammetry. On the “local” level e.g. measurements from strain gauges are considered and compared to numerically calculated strains. Details to this concept can be found in [7]. Figure 5 shows a comparison of the load-shortening curves of simulation and experiment of one POSICOSS panel [6]. Up to the first global buckling load a very good agreement can be observed. From that point the simulation and experiment began to differ. There are two explainations for that. Firtsly, no degradation is taken into account, so in the deep postbuckling region a good agreement is not expected. The second reason is high sensitivity of the modelling of the lateral clamping boundary conditions. It has been investigated in detail and caused most probably the starting of divergence shortly before global buckling.

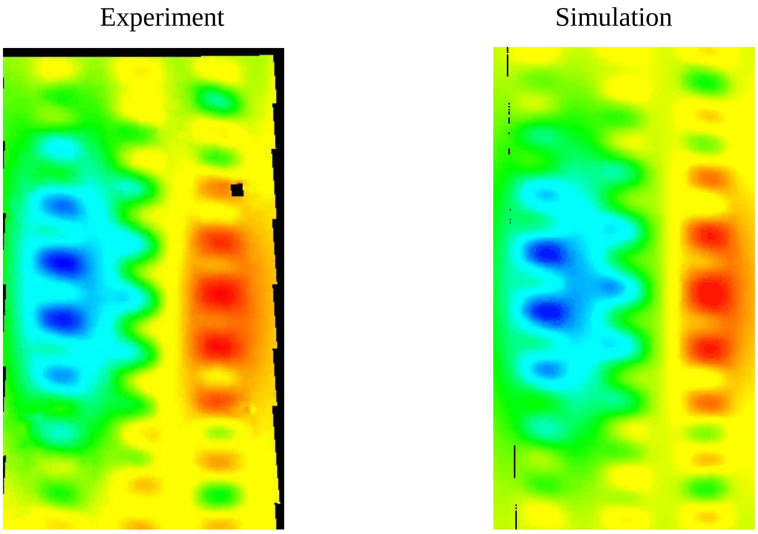

Figure 8: Out-of-plane deformations of one tested POSICOSS panel

The objective for the design of the panels within COCOMAT was a large postbuckling region and an early onset of skin-stringer debondig. To that stage of the project no tools were available which take this kind of degradation into account. However, for the design process the knowledge on the onset of degradation is sufficient. As workaround the available tool ABAQUS/Standard was utilized in following way. To obtain the onset of degradation of the composite lamina structure itself failure criteria which are available in ABAQUS (e.g. Tsai-Wu, Tsai-Hill, etc.) were applied. The adhesive, which connects the skin with the stringers, was modeled with 3D solid elements. The occurrence of the maximum allowable stress in the adhesive was taken as indication for the onset of degradation. Detailed results can be found it [8]. The load-shortening in Figure 6 was calculated using this approach. One can see that the onset of skin-stringer debondig is almost at the same stage as beginning of global stringer buckling. This behaviour is plausible and was expected because the onset of stringer buckling causes also significantly higher stresses in the adhesive layer.

3.2 Nonlinear Finite Element Analysis - with degradation

One main task within COCOMAT is to improve slow certification tools. DLR as partner concentrates in this task on the improvement of ABAQUS in order to allow the skin-stringer separation. To solve this problem the mechanical behaviour of the 3D solid element is described by new self-developed ABAQUS-User subroutines. Three different User-subroutines, which different in their numerical approach, were developed and use at this stage simple stress-based failure criteria. However, it is possible to implement in two of these three subroutines more complicated and probably more accurate degradation models. Within COCOMAT new degradation models, which are based on experimental investigations, are currently developed and it is planned to implement them into the subroutines. The three subroutines can be described as follows:

1) USDFLD (User Defined Field): Allows defining only of simple failure criteria which reduce selected material properties.
2) UMAT*explicit*: The stresses are calculated from the previous increment results *explicitly*. Has the advantage to control the failure propagation and the degradation of the adhesive layer.
3) UMAT*implicit*: The stresses are calculated from the current stiffness matrix *implicitly*. This version was also extended for finding the first element failing in each increment. This increases the analysis time dramatically.

The last two user-subroutines allow the monitoring the propagation of the failure in the adhesive and the implementation of complicated user-defined degradation models. As first approach a simple stress based failure criterion for the adhesive was implemented for all three user-subroutines. The degradation of the adhesive is simulated by decreasing the Young's modulus to a small fraction of the initial value of this finite element of which the maximum allowable stress is reached.

All three user subroutines were tested and compared on small and large models and showed a good agreement between each other. The application of one User-subroutine on the COCOMAT panel Design 1 and the comparison with the experiment and other software tools without degradation is shown in Figure 9. This figure illustrates the load-shortening curve of Design 1 and shows up to the first global buckling at about 1mm shortening an excellent agreement between all curves. From that point only the ABAQUS analysis with the User Subroutines shows a good agreement with the experiment. However, it must be noted that the comparison of only the load-shortening curve is not sufficient because the global buckling pattern of the simulation and experiment are different. In addition, the subroutines calculated more damaged adhesive areas than observed in the experiment. This demonstrates that further improved degradation models - as under development within COCOMAT - are needed.

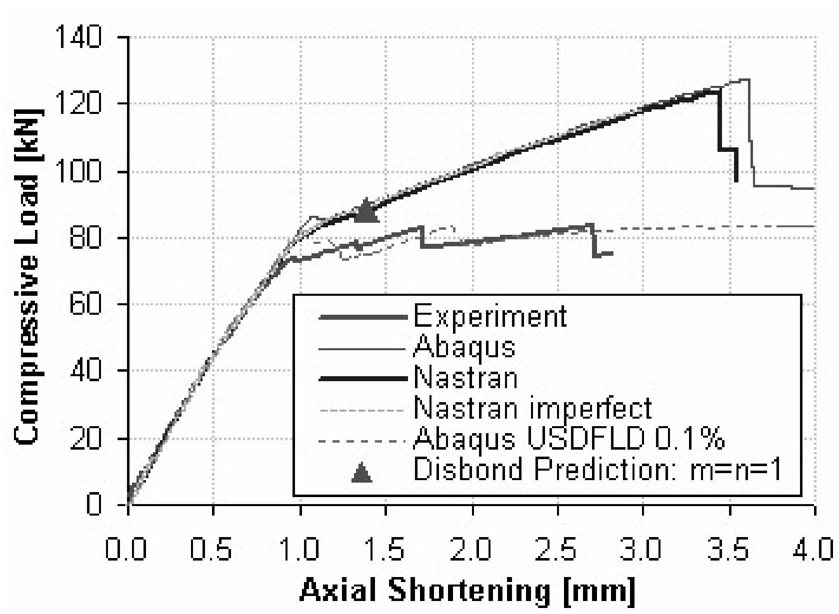

Figure 9: Comparison of experiment and different simulation tools [9]

4 SUMMARY AND CONCLUSIONS

This paper illustrates the design process and experience of DLR on stringer stiffened panels and cylinders within the finished EU project POSICOSS and the running EU project COCOMAT. The tool ABAQUS/Standard was applied for the design process and is extended by means of self-developed User-subroutines which simulate the order of degradation of the skin-stringer separation. It was shown that the numerical calculations have been validated with experimental data up to the first global buckling successfully. For the simulation of the deep postbuckling region degradation must be taken into account. Here ABAQUS-User-subroutines, which consider stringer debonding using simple stress based failure criteria, were developed. First application of the ABAQUS-User subroutines version is promising. However, improved degradation models – which are currently under development within the COCOMAT project – are needed.

This design and analysis experience described in that paper may be helpful for the design real composite fuselage structures.

ACKNOWLEDGEMENTS

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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] www.posicoss.de

[3] Degenhardt R., Rolfes R., Zimmermann R., Rohwer K., "COCOMAT - Improved **MA**-**T**erial Exploitation at Safe Design of **CO**mposite Airframe Structures by Accurate Simulation of **CO**llapse", Composite Structures, Vol. 73 (2006), pp. 175-178

[4] www.cocomat.de

[5] Degenhardt R., Rohwer K., Wagner W., Delsemme J.-P., "Postbuckling and collapse analysis of stringer stiffened panels – A GARTEUR activity", Proceedings of the *4^{th} International Conference on Thin-Walled Structures*", Loughborough, England, 22-24 June 2004

[6] Klein H., Zimmermann R., Kling A, "Buckling and Postbuckling of Stringer Stiffened Fibre Composite Curved Panels - Tests and Computations", Composite Structures, Vol. 73 (2006), pp. 150-161

[7] Kling A., Degenhardt R., Klein H., Tessmer J., Zimmermann R., "Novel stability design scenario for aircraft structures – simulation and experimental validation", Proceedings of the *5th International Conference on Computation of Shell and Spatial Structures*, 1-4 June, 2005 Salzburg, Austria

[8] Hansen L., Degenhardt R., Kling A., "F Auslegung von axial gedrückten, versteiften Paneelen", Internal DLR Report, IB 131-2004/37, November 2004

[9] Orifici A. C., Thomson R. S., Degenhardt R., Kling A., Rohwer K., Bayandor J, "Design of a Postbuckling Composite Stiffened Panel for Degradation Investigation", Proceedings of the *13th International Conference of Composite Structures*", Melbourne, Australia, 14-16 November, 2005