SIMULATING POSTBUCKLING BEHAVIOUR AND COLLAPSE OF STIFFENED CFRP PANELS

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SUMMARY

Advanced composite materials are well known for their outstanding potential in weight-related stiffness and strength leading to an ever increasing share in aerospace structural components out of Carbon Fibre Reinforced Plastics (CFRP). In order to fully exploit the load-carrying capacity of such structures an accurate and reliable simulation is indispensable. Local buckling is not necessarily the load bearing limit for stiffened panels or shells; their full potential can be tapped only by utilizing the postbuckling region. That, however, requires fast tools which are capable of simulating the structural behaviour beyond bifurcation points including material degradation up to collapse. The most critical structural degradation mode is skin stringer separation; delamination, especially within the stringer, is a critical material degradation. A reliable prediction of collapse requires knowledge of degradation due to static as well as low cycle loading in the postbuckling region.

Earlier projects have shown that it needs considerable experience in simulating the postbuckling behaviour. Though a great deal of knowledge about CFRP structural and material degradation is available its influence on collapse is not yet sufficiently investigated. It is the aim of the project COCOMAT (Improved **MAT**erial exploitation at safe design of **CO**mposite airframe structures by accurate simulation of **CO**llapse) to develop means for and gain experience in fast and accurate simulation of the collapse load of stringer stiffened CFRP curved panels taking degradation and cyclic loading as well as geometric nonlinearity into account. COCOMAT is a Specific Targeted Research Project supported by the EU 6th Framework Programme; it started 2004 and runs for 4 years. Main deliverables are:

- test results for buckling and collapse of undamaged and pre-damaged stiffened CFRP panels under static and cyclic loading,
- improved material properties and degradation models,

- computational tools for design and certification of stiffened fibre composite panels which take postbuckling behaviour, degradation and collapse into account,
- and finally design guidelines and industrial validation.

The work will lead to an extended experimental data base, relevant degradation models and improved simulation tools for certification as well as for design. These results should allow setting up a future design scenario which exploits the existing reserves in primary fibre composite structures. The paper starts out from results provided by the forerunners of COCOMAT, describes the main objectives of the project, gives a general status of the progress reached so far and presents first results.

1: Introduction

Fierce competition between airlines enforces them to ask for a drastic cost reduction for newly developed aircraft. In order to meet this demand aircraft industries strive for reducing development and operating costs by 20% and 50% in the short and long term, respectively. Supported by the European Commission the 4-year project COCOMAT, which started in January 2004, contributes to this aim. COCOMAT stands for Improved MATerial Exploitation at Safe Design of COmposite Airframe Structures by Accurate Simulation of Collapse. It aims at allowing 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 (cf. [1] and [2]). The work is carried out by 15 partners from 11 nations and co-ordinated by DLR, Institute of Composite Structures and Adaptive Systems.

COCOMAT is based upon the results of two forerunners. On one hand there was the GARTEur (Group of Aeronautic Research and Technology in Europe) Structures and Material Action Group 25: Postbuckling and Collapse Analysis. Between 1999 and 2003 the group investigated the abilities and deficiencies of FE codes for simulating the postbuckling behaviour of panels, and defined recommendations for buckling, postbuckling and collapse analysis of aerospace structures [3]. On the other hand there was the EU project POSICOSS, 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 [4]. Some of DLR's results are published in [5] and [6].

The COCOMAT project extends the results of both forerunners. Especially degradation of CFRP panels due to static as well as low cycle loading in the postbuckling range is considered. It is well-known that thin-walled structures made of CFRP are able to tolerate repeated buckling without any change in their buckling behaviour. However, it has to be found out, how deep into the postbuckling regime the loading can be extended without severely damaging the structure, and how the behaviour can be predicted by fast and precise simulation. 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 certification. The results will comprise a substantially extended data base on material properties and on collapse of undamaged and pre-damaged structures subjected to static and low cycle loading, degradation models, improved slow and fast computation tools as well as design guidelines. Therewith the aircraft industry will have tools at its disposal, which substantially contribute to the objectives of reducing development and operating costs.

2: Future design scenario for composite airframe panels – Objective of COCOMAT

COCOMAT mainly strives for accomplishing the large step from the current to a future design scenario of 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 (LL); region II is the safety region and extends up to Ultimate Load (UL); region III comprises the not allowed area which reaches up to Collapse. In aircraft design Ultimate Load amounts to 150% of Limit Load. For stiffened panels there is still a large unexploited structural reserve capacity between the current Ultimate Load and Collapse. The right graph of Figure 1 depicts the design scenario aspired in future, where Ultimate Load is shifted towards Collapse as close as possible. Through that move the onset of degradation appears no longer in the not allowed region III but already in the safety region II. This is comparable to metallic structures where plasticity is 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 cyclic loading to assure its limited progression.

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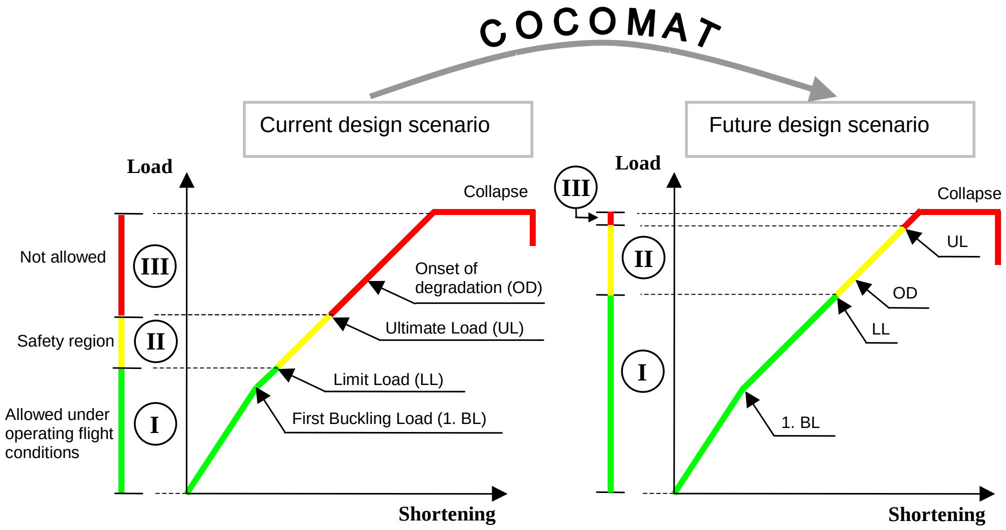

Figure 1: Current and future design scenarios for typical stringer stiffened composite panels [1]

3: Consortium

The COCOMAT 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).

4: Work packages

Within COCOMAT the partners contribute to the following six technical work packages:

- **WP 1**: Benchmarking on collapse analysis of undamaged and damaged panels with existing tools: Knowledge of the partners is compared and the deficiencies of existing software are identified.
- **WP 2**: Material characterisation, degradation investigation and design of panels for static and cyclic tests: Material properties are characterized, degradation models are developed and test panels are designed as to the requirements of research in order to overcome the deficiencies.

- **WP 3**: Development of improved simulation procedures for collapse: Slow certification tools and fast design tools are developed and validated by the tests.
- **WP 4**: Manufacture, inspection and testing by static and cyclic loading of undamaged panels: The experimental data base is extended by testing of undamaged panels.
- **WP 5**: Manufacture, inspection and testing by static and cyclic loading of pre-damaged panels: The experimental data base is extended by testing of pre-damaged panels.
- **WP 6**: Design guidelines and industrial validation: All project results are assembled and final design guidelines are derived. The tools are validated by the industrial partners.

Industrial partners bring in their experience with design and manufacture of real shells; research partners contribute knowledge on testing and on development of simulation tools. Design guidelines are defined in common, and the developed tools are validated by the industrial partners.

5: Expected results and benefits

The project results will comprise a substantially extended data base on material properties and on collapse of undamaged and pre-damaged statically and cyclically loaded structures, degradation models, improved slow and fast computation tools for statically loaded structures as well as design guidelines, which take skin stringer separation and material degradation into account. The experimental data base is indispensable for validation of the analytically developed degradation models, which will be implemented into the new tools and for verification of the computed results as well. Reliable fast tools will allow for an economic design process, whereas very accurate but necessarily slow tools are required for the final certification.

Although, with respect to loads and characteristic dimensions, this project is oriented towards an application in the fields of fuselage structures, the results will be 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. That provides the chance for decisive improvements in competitiveness of future aircraft.

The traditional aircraft design can be replaced by an advanced procedure including degradation models for composite structures. One main benefit of the application of the new tools and design guidelines will be a considerably reduced structural weight at safety not impaired. In addition, the developed tools also reduce the design and analysis time by one order of magnitude and thus, they substantially improve the response-to-market time of industrial developments.

6: First results

Up to now the COCOMAT partners worked mainly on the first four technical work packages. Since work package 4 is in a preliminary stage this paper concentrates on the first 3 work packages. A list of papers published by the partners so far can be found at www.cocomat.de

6.1: Work package 1

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, and 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 regarding the simulation of degradation.

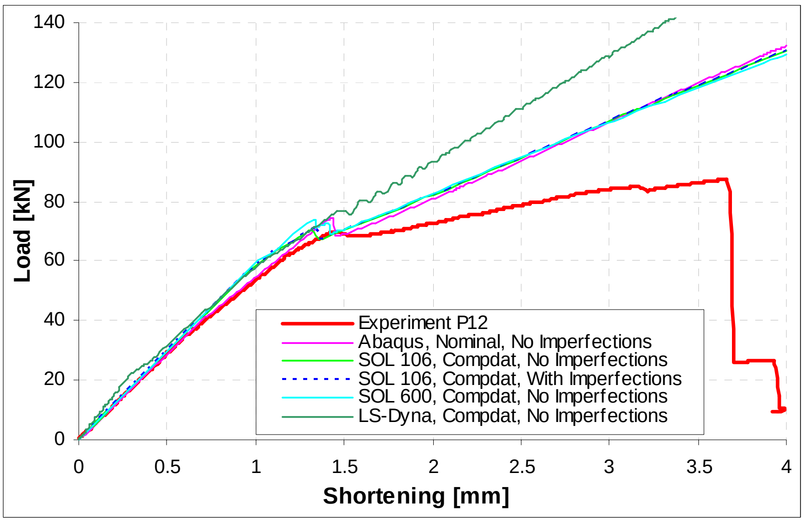

Figure 2: Some results from WP 1 [6]

Some detailed results on undamaged benchmarks are published in [7]. As an example Figure 2 shows the load shortening curve of an axially loaded CFRP panel and the comparison with simulations by means of ABAQUS, NASTRAN and LS-DYNA. There is a good agreement of all curves up to the first global buckling (at 1.4 mm shortening) where the stringers buckle. From that point on 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 cannot be expected to agree with the test because degradation (e.g. material degradation, skin-stringer separation or the delamination in the stiffener blade) is not considered. In the frame of WP3 the simulation procedures will be improved in that way that the effect of most important types of degradation can be considered. More details can be found in [6].

6.2: Workpackage 2

Material properties for IM7/8552 UD, 985-GT6-135 and IM7/8552 are characterised using specimens with and without damages. 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. Fig. 3 illustrates the DLR test set-up for the CAI tests and one of the specimens with applied strain gauges. All DLR results are summarized in [8].

Figure 3: DLR's test set-up for CAI tests and specimens with strain gauges [8]

Further, improved degradation models are developed, which are needed for the slow certification tools and fast design tools in WP 3. These will be obtained using test results. The specimens planned for this investigation are plates or small structures made of 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. The test campaign is almost finished. 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.

Stiffened panels to be manufactured and tested in WP4 are designed and analysed. The partners considered 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 and number of modes prior to postbuckling, mild or strong stiffness reduction in the postbuckling regime. 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 variation of the lay-up of the skin and stringer, number of stringers, stringer geometry and position of the stringers were performed. During the design process the onset of different types of degradation, as skin-stringer separation, delamination in the stringer blade and failure in the composite laminate have been estimated by simple extensions 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 an early failure mode were favoured. There was another 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. However, in order to avoid an early start of skin buckling due to 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 provided in more detail in [9].

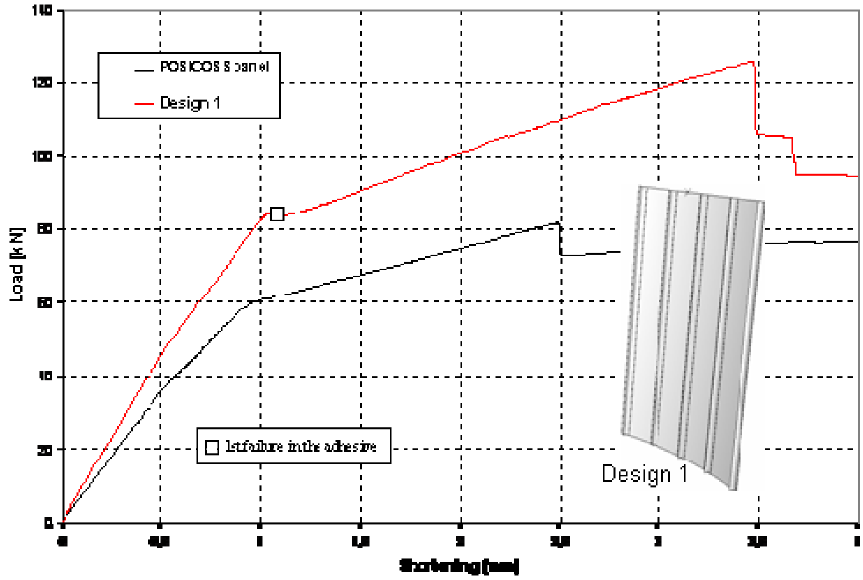

Figure 4: COCOMAT panel design compared with the start design from POSICOSS [9]

6.3: 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.

Figure 5 illustrates the whole family of slow computational tools including the degradation models considered in that task. 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 [10]. The other two subroutines are not finished yet.

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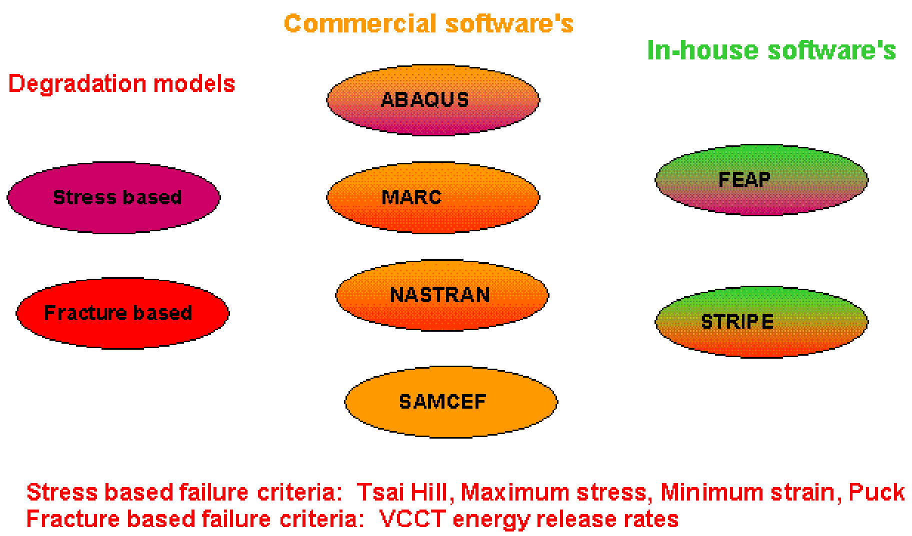

Figure 5: Family of slow certification computational tools within Task 3.1

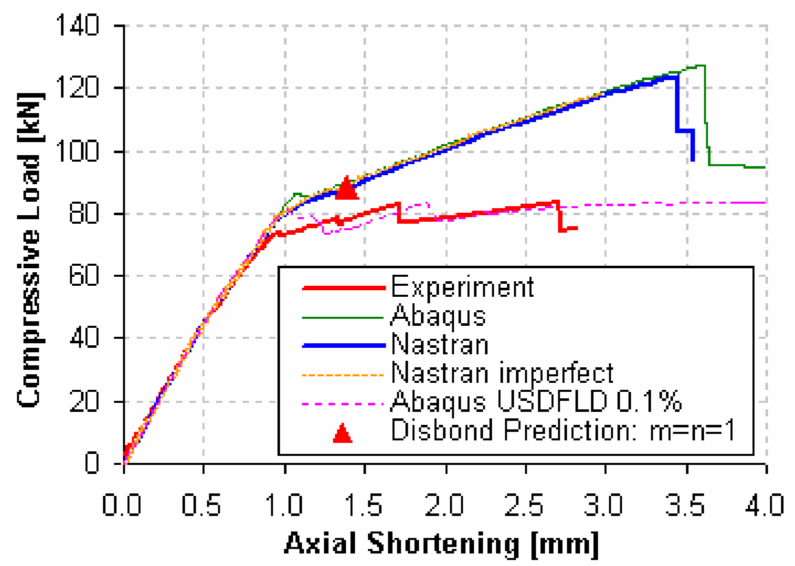

Figure 6: Some results from WP 1 [6]

Fast simulation of the collapse behaviour of stringer stiffened fibre composite panels are needed for improved design procedures. The tools will be faster at least by a factor of 10 than respective Finite Element (FE) simulations at accuracy, which is sufficient for design purposes.

DLR is considering the tool iBUCK [11], which is based on the Donnell type shell equations for thin, slightly curved shells that undergo large deflections. It uses shape functions valid for the complete panel. Stringers are considered as structural elements with independent degrees of freedom and are not "smeared" onto the skin. Local and global buckling modes are superposed, where local buckling is defined as skin buckling and skin-induced stiffener rotation within a bay. The panel may be loaded axially or 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. Figure 8 illustrates one postbuckling shape obtained by iBUCK.

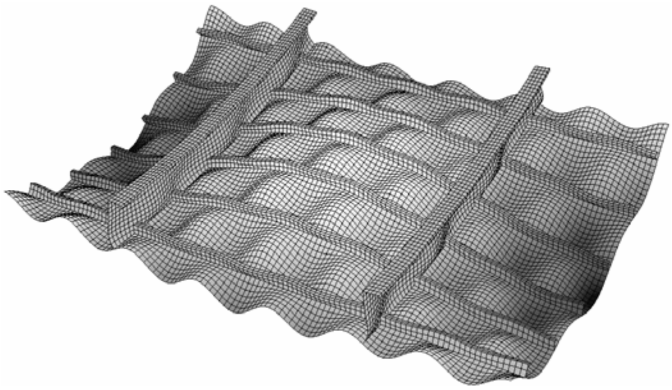

Figure 7: Postbuckling shape obtained by iBUCK [11]

7: Conclusion

The running COCOMAT project intends to pave the way for a future design scenario for stringer stiffened CFRP panels (cf. Fig. 1). Expected results comprise an extended experimental data base, degradation models, improved certification and design tools as well as design guidelines. This paper gives an overview of the main objectives, the partner institutions, the work-package structure and the foreseeable benefit of the outcome. Results obtained so far include extended knowledge about abilities and deficiencies regarding the simulation of postbuckling and degradation with different models and codes, specific experience with respect to testing of stiffened panels up to collapse, and initial results for simulating the collapse behaviour in the design process.

8: Acknowledgement

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REFERENCES

[1] DEGENHARDT, R et al. – COCOMAT - Improved MATerial exploitation at safe design of COmposite airframe structures by accurate simulation of COllapse. Composite Structures, Vol. 73, pp. 175-178, 2006.

[2] www.cocomat.de

[3] VAN HOUTEN, R and ZDUNEK, A – GAREUR (SM) AG-25 Post-buckling and collapse analysis, Final Technical Report, GARTEUR TP-149 NLR-TR-2004-463, Amsterdam, 2004.

[4] ZIMMERMANN, R and ROLFES, R – POSICOSS - Improved postbuckling simulation for design of fibre composite stiffened fuselage structures. Composite Structures, Vol. 73, pp. 171-174, 2006.

[5] ZIMMERMANN, R et al. – Buckling and Postbuckling analysis of stringer stiffened fibre composite curved panels. Composite Structures, Vol. 73, pp. 150-161, 2006.

[6] KLING, A et al. – A hybrid subspace analysis procedure for non-linear postbuckling calculation. Composite Structures, Vol. 73, pp. 171-174, 2006.

[7] ORIFICI, A C et al. – Benchmark finite element simulations of postbuckling composite stiffened panels, 11th Australian International Aerospace Congress, Melbourne, Australia, 13-17 March, 2005.

[8] KLING, A and DEGENHARDT, R – Characterization of material properties – Results of the EU project COCOMAT. Internal DLR report, IB 131-2006, April 2006.

[9] DEGENHARDT, R et al. – Design and analysis of composite panels, III European Conference on Computational Mechanics, Lisboa, 5-8 June, 2006.

[10] ORIFICI, A C et al. – Degradation investigation in a postbuckling composite stiffened fuselage panel, 13th International Conference of Composite Structures, Melbourne, Australia, 14-16 November, 2005.

[11] BÜRMANN, P et al. – A semi-analytical model for local post-buckling analysis of stringer- and frame-stiffened cylindrical panels. Thin-Walled Structures, Vol. 44, pp. 102-114, 2006.

