IMPERFECTION INVESTIGATION OF COMPOSITE STIFFENED FUSELAGE PANELS FOR POSTBUCKLING ANALYSES

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Abstract: Project COCOMAT is an ongoing four year European Commission project aimed at exploiting the large reserve of strength in composite structures through more accurate prediction of collapse. As part of the research program, curved stiffened composite panels have been manufactured and tested in compression. During the experiments, it was noted that the panels were highly imperfection sensitive. Imperfections in the structure contributed to variations in the postbuckling mode shape as well as the collapse load. The inability of deterministic finite element analyses to easily capture these variations means that it is difficult to match simulation with experiment. Therefore the use of stochastic finite element analyses has been proposed. In order for realistic stochastic simulations to be conducted, there is a need to investigate the actual variability and imperfections that exist in the manufactured panels. A library of imperfections and variations has been collated and the initial geometrical imperfections that exist before testing have been accounted for.

Keywords: *Postbuckling, Collapse, Stiffened Structures, Variability, Imperfection Sensitive, COCOMAT.*

1. INTRODUCTION

The European Commission 6th Framework project COCOMAT (Improved **MAT**erial exploitation at Safe Design of **CO**mposite Airframe Structures by Accurate Simulation of **CO**llapse) is a four year project aimed at exploiting the large reserve of strength in composite structures through more accurate prediction of collapse. A summary of project COCOMAT has been presented by Degenhardt et al. (2006). The Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) is one of the 15 international partners involved in this project headed by the German Aerospace Centre (DLR).

Curved panels such as those modelled numerically and tested physically in COCOMAT are suitable examples of how imperfection sensitive stiffened curved composite panels can be. It is worth noting that the structures used for research are designed with imperfection sensitivity in mind to show the worst case scenarios through a spread of results, cf. Degenhardt et al. (2006). However using deterministic solvers, a spread of results will not be generated. Validations are done by comparing the results of a perfect simulation with experiments that contain inherent imperfections. In the initial benchmarking both the physical experiments and numerical simulations exhibited different postbuckling mode shapes during compression. This difference in postbuckling mode shapes directly affects the loading capability of the stiffened panel, and the manner in which the stiffeners fail in global buckling. Figure 1 shows the difference in postbuckling mode shapes achieved through experimentation and numerical simulations in the initial benchmarking. The FEMs shown below by Orifici et al. (2008) have included this imperfection feature in order to match the experiments. Unfortunately it is difficult to match the load-shortening curves if the postbuckling mode shapes are not similar. It was stated in the discussion that the asymmetrical postbuckling mode shapes achieved through physical testing were possibly due to imperfections in the panel.

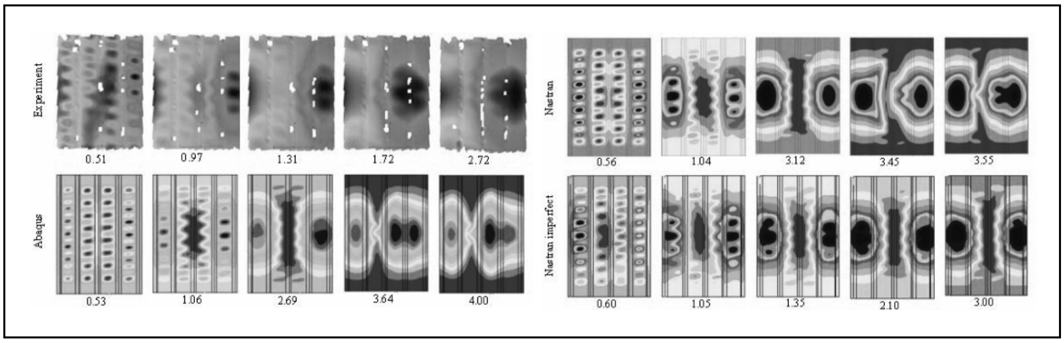

Figure 1: Variation between postbuckling mode shapes observed in experiments and FEA.

With regards to accounting for variation in real structures, attempts have been made in the recent years to introduce imperfections via stochastic modelling so as to achieve plausible knock down factors. This can be seen in the work by Chryssanthopoulos and Poggi (1995). Raj et al. (1998) acknowledge that it is impossible to control all the variables in a manufacturing process, and hence for better understanding of structural behaviour, all material properties should be considered stochastic. Spagnoli et al. (2001) measured points on the surface of real panels using a laser scanning system and used a two-dimensional Fourier analysis to create a mathematical model for the real imperfect surface. This was applied to the numerical model, where the nodes were then offset. It can be seen from the authors above that various attempts have been made to account for variations in both material and geometry. Lee et al. (2007) have previously presented the possibility of asymmetrical postbuckling mode shapes due to imperfections in loading and boundary conditions. The range of the input values that were used was arbitrary and hence data on the actual imperfection and variability resulting from manufacture had to be obtained.

A Stochastic Finite Element Analysis (SFEA) procedure has already been developed in COCOMAT. In order for realistic simulations to be conducted, the actually imperfections and variations that occur on the manufactured panel have be found. In the following section an example of the SFEA procedure used will be presented. Following this there will be a section showing the nominal design of the panels, as well as the variations observed once manufacture was completed. It was found that variations in certain plies within the laminate were significant contributors to the initial geometrical imperfections observed in the panels; the imperfections were caused by the panel deforming due residual stress during curing. Finite element models with and without the initial imperfections were then subjected to compression and compared. The geometrical imperfections cause significant differences in the load-shortening curve.

2. EXAMPLE OF STOCHASTIC ANALYSIS

Consider a simple cantilevered beam with an edge loading as shown in Figure 2 below.

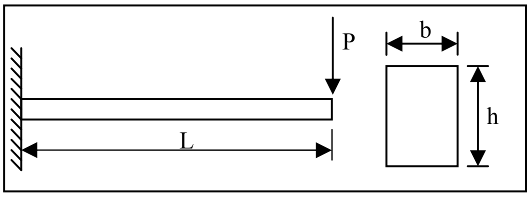

Figure 2: Cantilevered beam with edge loading

From simple beam theory, the expected deflection of the cantilevered beam is:

Deflection, $\delta = \frac{PL^3}{3EI}$ and Moment of Inertia, $I = \frac{bh^3}{12}$

Table 1: Stochastic Boundary of Input Variables

Input Variable	Mean	Defined Range		
Load, P (N)	1 000	850	-	1 150
Length, L (mm)	1 000	850	-	1 150
Young’s Modulus, E (MPa)	72 000	61 200	-	82 800
Breadth, b (mm)	50	42.5	-	57.5
Depth, d (mm)	100	85	-	115

A sample size of 100 was used for the stochastic analysis. All the variables in Table 1 were varied simultaneously. This allowed the following plots to be produced. Each plot is the response plotted with respect to one input variable. The right hand plot in the figure indicates that depth has a strong influence on the deflection and a structure appears in the cloud of points. The left hand figure is less structured indicating that the influence of Young’s modulus is less strong. Table 2 gives the influence of all the input variables over the deflection of the beam. It can be seen that in this instance, the height of beam has the greatest influence over the deflection. This is due to the inverse cube effect of the height in the deflection equation. Young’s modulus has the weakest influence.

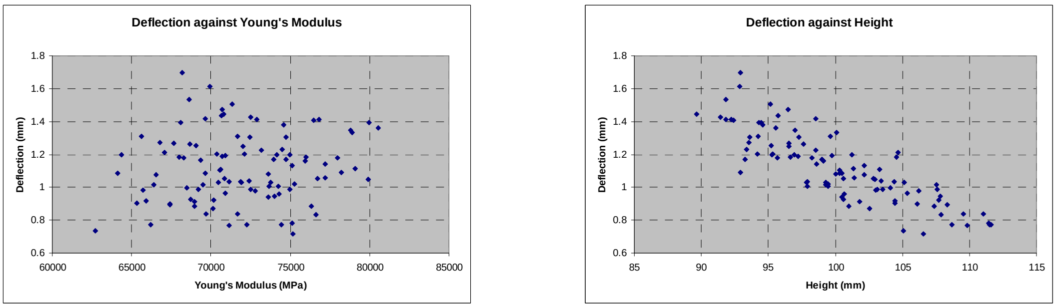

Figure 3: Metamodels of deflection against Young’s modulus and cross-sectional height

Table 2: Results from stochastic analysis

Relationship	Influence
Displacement and Load	0.258
Displacement and Length	0.572
Displacement and Young's Modulus	-0.106
Displacement and Breadth	-0.266
Displacement and Height	-0.772

3. VARIABILITY BETWEEN NOMINAL DESIGN AND MANUFACTURED PANEL

This section describes the panel design being used in project COCOMAT. The panel is curved, with five equally spaced T–stiffeners in the axial direction. This arrangement is representative of the stiffened structures employed in aircraft fuselages. This section provides an insight into the variability and imperfections that exist in the manufactured panels. This includes results from material characterization, measurements against the nominal designs and some noted differences between the manufactured panel and the panel modelled using finite elements.

3.1 Variations in material properties

The data presented in this section are results obtained from the material characterization of Hexcel IM7/8553 unidirectional carbon fibre epoxy used in COCOMAT. This material was also used in the forerunner project POSICOSS (Improved **PO**stbuckling **SI**mulation for Design of Fibre **Co**mposite **S**tiffened Fuselage **S**tructures) and hence the material characterisation includes data obtained that project. This enables a larger population size to be considered. The table below shows the results of the material characterization. The manufacturer's data was obtained from Hexcel (2005). Note that there is a significant difference between the mean values obtained from project COCOMAT and POSICOSS. Nevertheless it is important to detail the full range of possible values and standard deviations for future use so that realistic values can be input into the stochastic analyses. The range of possible values as shown below shows the minima and maxima for each material property.

Table 3: Nominal material properties

	POSICOSS		COCOMAT		Range of Possible Values			Hexcel Data
	Mean value / Standard deviation							
Stiffness	(GPa)	(%)	(GPa)	(%)				(GPa)
$E_{t\,L}$	192.3	1.17	164.1	3.01	155.8	-	197.4	164
$E_{c\,L}$	146.5	1.84	142.5	1.69	138.6	-	150.8	150
$E_{t\,T}$	10.6	2.36	8.7	3.91	8.3	-	10.9	12
$E_{c\,T}$	9.7	6.77	9.7	4.85	9.0	-	10.4	-
$G_{L\,T}$	6.1	2.28	5.1	13.73	3.7	-	6.3	-
Poisson's Ratio	-	(%)	-	(%)				-
$\upsilon_{L\,T\,(t)}$	0.31	5.55	0.28	14.44	0.22	-	0.33	-
Strength	(MPa)	(%)	(MPa)	(%)				(MPa)
$R_{t\,L}$	2 715	3.42	1 741	11.92	1 523	-	2 836	2 724
$R_{c\,L}$	1 400	4.93	854.7	9.04	472	-	1530	1 690
$R_{t\,T}$	56	18.56	28.8	5.23	19.3	-	69.3	111
$R_{c\,T}$	250	6.6	282.5	18.16	229.9	-	310.1	-
t = tension, c = compression, L = longitudinal direction, T = transverse direction								

3.2 Variations in geometry of stiffened panel

Shown below are the geometrical specifications of the panel being considered in this paper followed by the measured values. Within project COCOMAT, a few panel designs were created for analysis and experimentation so that parametric studies could be conducted once experimentation was complete. The panel shown below was one of two designed by the CRC-ACS and DLR for the COCOMAT project.

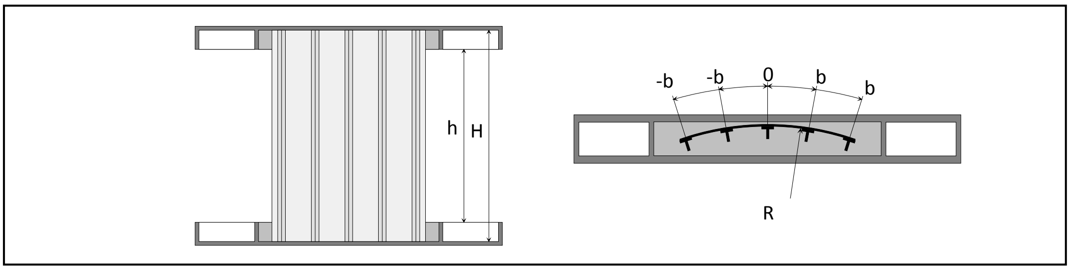

Figure 4: Geometrical representation of stiffened panel

One of the obvious disparities between the manufactured panel and the panels analysed using finite elements is the difference in the initial geometry. The panels which are manufactured have been subjected to residual stresses caused by the curing process while those in the finite element environment are perfect, with exception to minor geometrical variation caused by numerical rounding in the pre-processor. The curing process has resulted in the panels taking on varying nominal radii or curvature, thereby affecting the buckling behaviour and final collapse load. This variation in radius has been noted above in Table 4. The measurement of geometrical imperfections and actual radius was performed at the DLR using a sensor head system known as ATOS. For more information on the measurement systems used in Project COCOMAT, refer to Degenhardt et al. (2007).

Table 4: Nominal panel geometry

	Measured					Nominal Design
	Mean Value	Standard Deviation (%)	Range of Possible Values			
Panel Length, H (mm)	-	-	-	-	-	780
Panel Free Length, h (mm)	658.63	0.067	657.5	-	659	660
Panel Radius, R (mm)	937.25	11.87	864	-	1 034	1 000
Stiffener Pitch, b (mm)	132.65	0.49	132	-	133	132
Number of Stiffeners	-	-	-	-	-	5
Panel Arc Length (mm)	560.4	0.24	558	-	561	560
Stiffener Flange Width (mm)	32.37	1.40	31.5	-	33.0	32
Stiffener Blade Height (mm)	14.36	0.82	14.1	-	14.5	14
Skin Lay-up	-	-	-	-	-	$[90, \pm 45, 0]_s$
Stiffener Web Lay-up	-	-	-	-	-	$[(45,-45)_3, 0_6]_s$
Stiffener Flange Lay-up	-	-	-	-	-	$[0_6, (45,-45)_3]$
Lamina Thickness (mm)	-	-	-	-	-	0.125

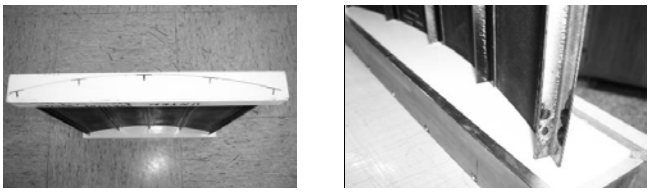

Figure 5: Images of stiffened panel encased in potting

3.3 Other noted variations and imperfections in the stiffened panel

Figure 6 presents the differences between the nominal stiffener design, the idealized finite element representation modelled using QUAD4 shell elements and the actual manufactured stiffener. The forming procedure also resulted in a resin-rich area at the middle of the stiffener flange where it is bonded onto the panel skin. The effect of this local resin-rich area cannot be captured by the shell element representation used in these analyses and its effect on the failure initiation and progression therefore warrants further investigation cf. Orifici et al (2007).

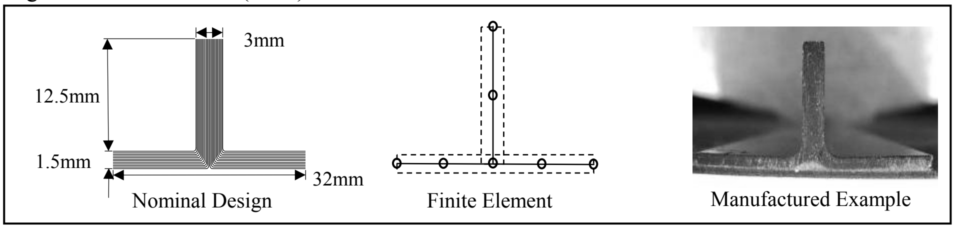

Figure 6: Comparison between modelled and manufactured stiffener (not to scale)

Another critical imperfection that affects the collapse loading is the skin-stiffener bonding. Slight imperfections will ultimately affect how the delaminations grow. Symmetric postbuckling mode shapes provide higher collapse loads compared to asymmetric ones as the failure involves the symmetrical delamination of the stiffeners from the skin. The delamination between the skin and the stiffener is highly dependent on the final quality of the bonding process. It was noted by the project COCOMAT partner and manufacturer of the stiffened panels, AERNNOVA, that interpretation of the bond quality from C-scans that were done was a very difficult due to the variations on adhesive thicknesses along the bonded joints. These variations in the bonding will result in different loads for separation due to changes in the strength and fracture toughness of the joint. Some of the imperfections from manufacturing are shown in Figure 7.

Figure 7: Defects from the bonding process

4. STOCHASTIC ANALYSIS OF CURING PROCESS WITH VARIATION IN MATERIAL PROPERTIES

In order to understand the effect of residual stress, finite element models of the stiffened panels were created and subject to a curing simulation. This resulted in the plots as shown in Figure 8. The data for the coefficient of thermal expansion (CTE) was taken from Kulkarni and Ochoa (2006). The longitudinal CTE was taken to be -0.4 x $10^{-6}/^{o}C$ and the transverse CTE was 5.6 x $10^{-6}/^{o}C$. The finite element panel was subjected to an initial temperature of $177^{o}C$ as per the Hexcel (2005) data sheet and cooled to room temperature. The panels were numerically modelled using the variability and imperfections found in the manufactured panels. A total of 41 panels were created in finite elements using the methodology as described in Section 2.

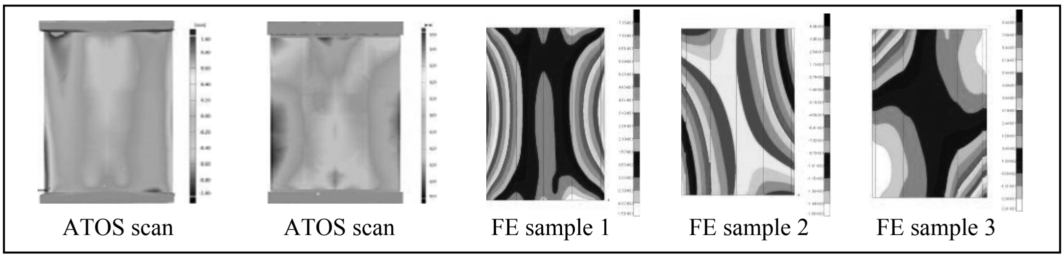

Figure 8: Deformation of panels due to residual stresses from curing process

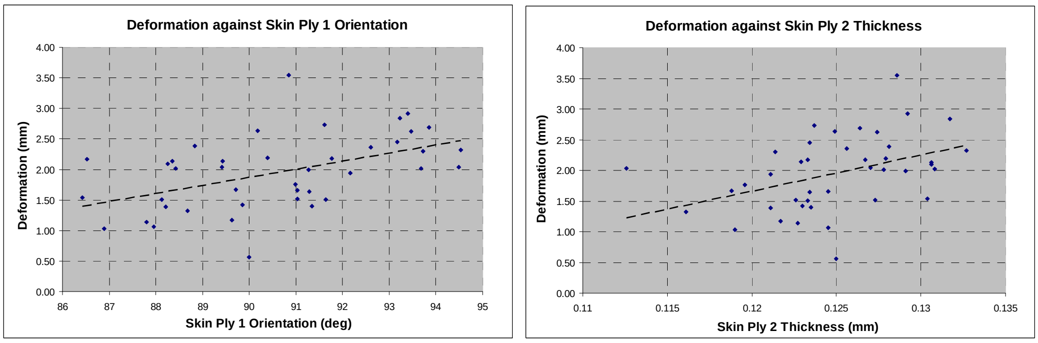

Figure 9: Metamodels of deformation against Ply 1 Orientation and Ply 2 Thickness

From the stochastic analysis as shown in Figure 9, it was noted that the amount of deformation was significantly larger once variation was applied. The nominal panel had a net deformation of 0.57 mm while the net mean deformation obtained from the analyses was 1.95 mm. It was found that the stiffness of the first two skin plies were significant in affecting the curing deformation; the influence was 0.516 and 0.458 respectively. The basis for these two plies highly influencing the curing deformation is due their positioning as the plies furthest from the neutral axis.

5. DISCUSSION

It can be seen from the metamodels Figure 7 that it is possible to reduce the magnitude of the deformation due to curing process in the panels by controlling the quality of plies 1 and 2. This involves stringent quality control during the layup process and also the requirement that the material has less scatter. The purpose of reducing the initial geometric imperfections can be seen in Figure 10 where the load-shortening curves can be seen. This is a preliminary investigation into the effects of imperfections for the stiffened panels. The finite element models have been solved on MSC.Marc using a subroutine created by Orifici et al. (2007) as part of COCOMAT. It can be seen that the plots are in good agreement up to local buckling at about 0.5 mm shortening. The curves appear to diverge after the local buckling stage and both finite element models have a higher collapse load compared to the benchmark. The finite element model with the cure deformations appears to have a higher collapse load and this occurs at a higher shortening load compared to the nominal finite element panel.

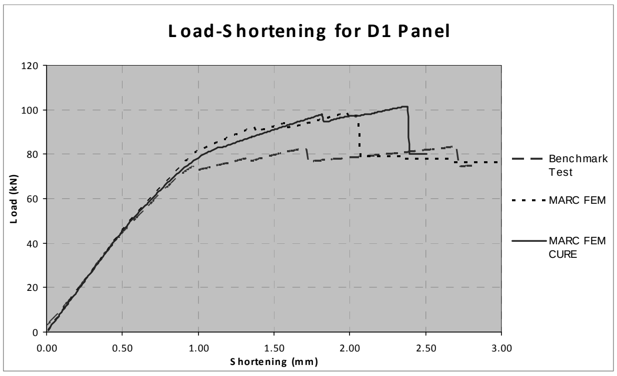

Figure 10: Load-shortening plots for stiffened panels compressed to collapse

6. CONCLUSION

This investigation has provided a suitable database by which to conduct the stochastic analyses for the postbuckling of the stiffened composite panels. The purpose of these inputs is to show the best and worst case scenarios that can possibly occur when the experiments are completed. The panels have been manufactured under ‘best practice’ manufacturing tolerances and specifications. Once the experiments have been completed, it is expected that there will be scatter in the results. Hence a methodology needs to be developed so that in the future imperfection insensitive structures can be designed and built.

The variations observed in these panels will contribute to the scatter that is expected in the experiments once they have been completed. The next step is to determine the contribution of each variation and how it affects the final collapse load of the panel. Two parameters, Influence and Sensitivity, have been identified Lee et al. (2007) as factors affecting the robustness of structures. The parameters will be derived from both numerical simulations and experiments for comparison. This study will later be expanded to include data from other panel designs.

7. ACKNOWLEDGEMENTS

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