Probabilistic Assessment of a Stiffened Carbon Fibre Composite Panel Operating in its Postbuckled Region

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ABSTRACT:

This paper presents a probabilistic study on the behaviour and buckling capacity of a thin shell carbon fibre stiffened panel operating in its postbuckling region. The paper is a part of the ongoing world wide research into this phenomena being conducted by the CRC-ACS and many other interested parties including the EU FP6 Project COCOMAT. The aim of the research is to develop proven design methods that will allow an increased specific strength of stiffened composite structures commonly used in the civil aviation industry. Unlike their metal counterparts which can be reliably designed to operate with postbuckled loads, the use of similar composite parts for primary structures has not yet been widely adopted by industry. This is mainly due to the relatively brittle nature of composites which prevents significant yield based load paths being developed local to the stiffened regions of the structure. Using LS-OPT and LS-DYNA the study explores the probabilistic variations of a COCOMAT panel using a stochastic analysis. The response of the panel was the peak buckling load and the design variables included uncertainties in material properties, manufacturing tolerances and geometric imperfections. It was concluded that three of the four ply angles require accurate orientation during placement to produce a panel that will exhibit good repeatability for experimental testing. In addition the available computational methods in LS-DYNA to simulate buckling are reviewed and compared through the testing of a small baseline model.

Keywords:

Buckling, Postbuckling, LS-OPT, LS-DYNA, Stochastic analysis, Composite materials

INTRODUCTION

The requirement for cheaper and more efficient civil aviation transport has seen that that each new generation of aircraft is constructed with an increasing amount of carbon fibre composites which in general out perform their metal counter parts with respect to specific strength, corrosion resistance and fatigue. However one significant drawback of this material is its brittle nature and complex failure mechanisms. These attributes have led to the current design practices where for slender components prone to buckling, no material degradation is acceptable under the ultimate load condition as per figure 1 (a). The aim of the current European research initiative "MATerial exploitation at safe design of Composite airframe structures through more accurate simulation of COllape" (COCOMAT) is to improve the understanding of slender composite panels such that material degradation is permitted as per figure 1(b) [1]. This paper first investigates the available computational methods available in LS-DYNA to simulate a nonlinear buckling analysis and compares the results of each method on a baseline model. This is followed by the analysis of a COCOMAT composite stiffened panel (fuselage section) under a uniform quasi-static compressive loading and compares the experimental results to a LS-DYNA simulation. Finally, the paper presents a stochastic investigation into the panel and the contribution of eleven parameters into its buckling capacity using LS-OPT.

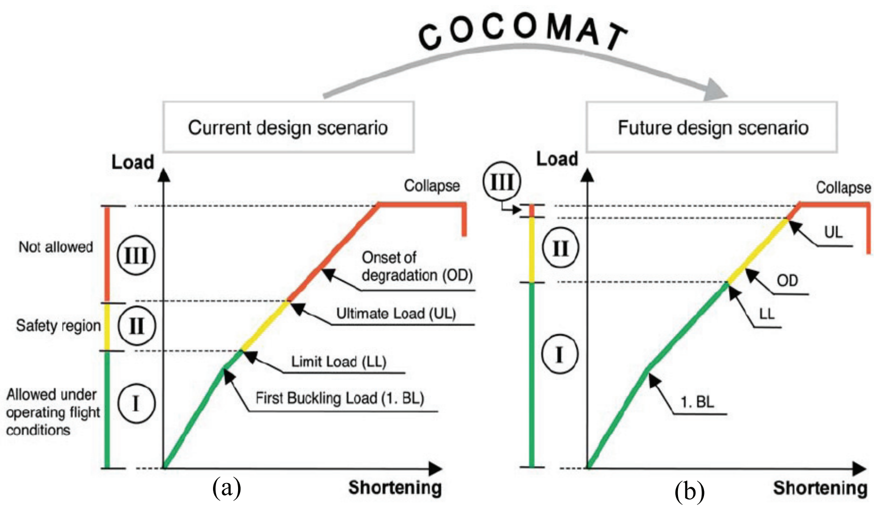

Figure 1: (a) Current design limits and (b) COCOMAT aim to improved strength [2]

BUCKLING CONSIDERATIONS in LS-DYNA

As a baseline, some fundamentals on elastic buckling shall first be considered. To progress this topic a simple baseline model as per figure 2 was analysed by the four different methods available in LS-DYNA. All simulations in this section used the highest order of accuracy possible, with selectively reduced integrated Hughes-Liu shell elements, double precision LS-DYNA code, tight convergences tolerances for implicit simulations and suitably slow loading rates for dynamic analyses. All dynamic models had appropriate damping and one of the two nonlinear static models included initial perturbations as this analysis method proved particularly sensitive to this attribute. From these analyses a number of recommendation are presented at the end of this section.

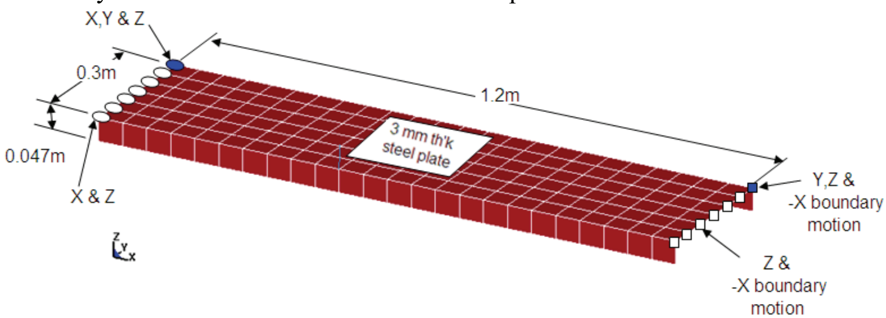

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Figure 2: Baseline model

ANALYSIS METHOD 1 (Linear Eigen Extraction)

A linear elastic eigen buckling solution indicated that a first local buckle occurred at 84 kN with a deformation mode of two wave lengths as per figure 3 and the eighth mode (global collapse) at 160 kN with a half wave length mode.

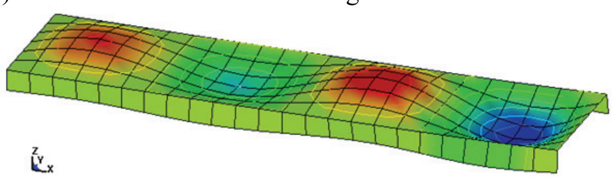

Figure 3: First local buckling mode

ANALYSIS METHOD 2 (Nonlinear Static)

Two buckling modes were observed, a local buckling occurring at 82 kN as per figure 4, and the global collapse mode at 122 kN (with no perturbations) and 115 kN with perturbations as per figure 5. A half wave length deformation mode occurred at global buckling.

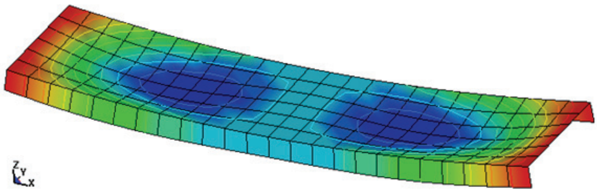

Figure 4: First local buckling mode using nonlinear static analysis

ANALYSIS METHOD 3 (Nonlinear Dynamic)

Two dynamic simulations were completed, one explicit and an implicit, which gave similar local and global buckling modes and values to that of method 2. In addition one extra local mode shape (three in total) developed after the first local, with a deformation similar to that in figure 3. The peak buckling load estimates were 117 kN for implicit and 119 kN for explicit analyses as per figure 5.

COMPARISON OF THE FOUR BUCKLING METHODS

The four computational methods are compared, in an X-Y plot with the axial shortening shown on the X axis and the resultant compressive load on the Y axis as per figure 5.

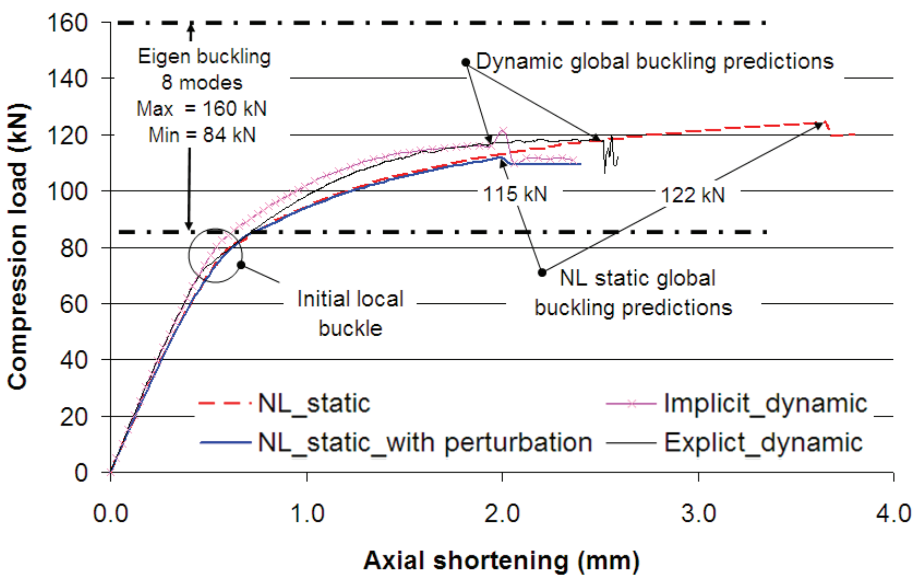

Figure 5: Comparison of linear, nonlinear static and nonlinear dynamic buckling

RECOMMENDATIONS FROM THE BUCKLING STUDY

The recommendations for LS-DYNA buckling simulations are as per below:

- A linear eigen[1] value extraction is approximate only due to the methods assumptions of linear stress distribution and zero deformation. The method is inexpensive and useful for initial investigations using LS-DYNA and LS-OPT.
- Nonlinear static[1] was sensitive to very small initial perturbations with respect to buckling shortening estimates. The inclusion of a full wave length perturbation with a magnitude of 0.1 mm reduced the buckled shortening length to that of approximately 50% of the non perturbed model. In comparison the dynamic model experienced no reduction in the shortening length with the same perturbation. The shortening magnitudes correspond to significant variations in peak stress between the static and dynamic methods. It is considered that the differences between these two analysis methods (nonlinear static and dynamic) may be due to dynamic effects allowing the transient models to better evolve modes with lower energy states.
- Nonlinear dynamic implicit[1] and explicit[2] analyses gave similar peak buckling values to the nonlinear static solution. For explicit analysis single precision is generally considered acceptable however under slow loading rates where an accumulated global error is evident, double precision should be considered.

COCOMAT PANEL ANAYSIS

Using LS-OPT a sensitivity check on the peak compressive capacity of the COCOMAT panel was carried out using a stochastic analysis. The aim of this analysis was to improve the robustness of the panel such that manufacturing and material variance are minimised insuring better repeatability of the panel during manufacturing and testing.

SECTION CONSIDERED

The panel under consideration was a curved stiffened panel with plan dimension 720 x 680 mm, a radius of 938 mm and five stiffeners of height 15.5 mm as per figure 6. The panel was constructed from a laminated carbon/epoxy composite with thicknesses ranging from 1 to 3 mm. The panel was supported on all for sides with a compressive strain produced in the Z direction. Initial perturbations were produced using the *PERTURBATION_NODE keyword command and the analysis method was single precision explicit using the 4 node Belytschko-Tsay shell elements.

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[1] The shell available for composite implicit analysis is limited to the 8 node thick shell element; also double precision is recommended by [3].

[2] The shells available for composite explicit analysis are the 4 node shell and the 8 node thick shell elements [3].

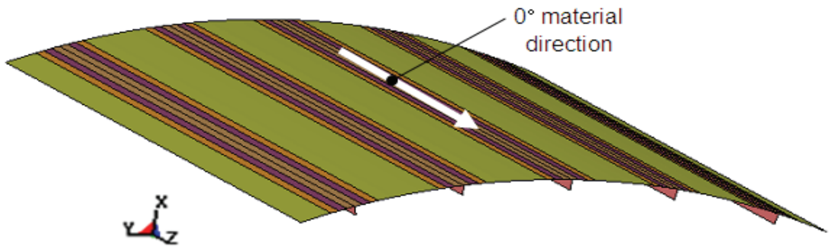

Figure 6: Isometric view of curved stiffened composite panel

The load capacity comparison (without variable variance) between the experimental and LS-Dyna simulation is shown in figure 7 and the associated mode shapes in figure 8. The experimental test specimen and the LS-DYNA simulation experienced no material degradation.

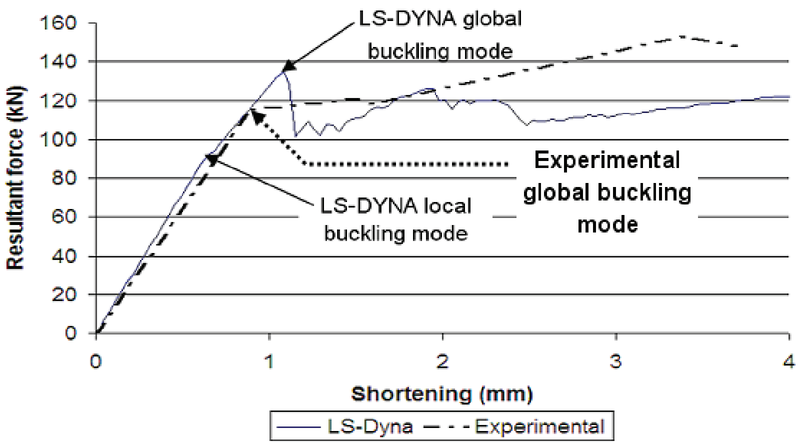

Figure 7: Axial compression force verses shortening for experimental & LS-DYNA

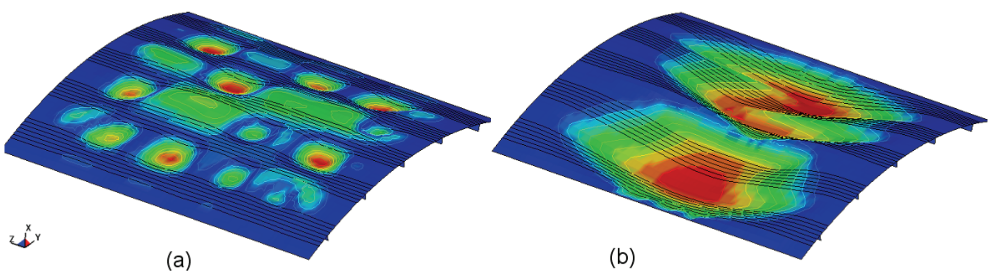

Figure 8: Predicted local buckling mode at 90 kN and (b) global collapse load at 137 kN

VARIABLES CONSIDERED

A total of 11 variables were considered, four ply orientations, four E_{11} moduli, skin thickness, perturbation magnitude and perturbation wave length as per table 1.

Table 1: Variable mean and standard deviations adopted for the panel from [5]

Variable	LS-OPT symbol	Distribution	Mean	Standard deviation
Ply angles (0°, 45°, 90° & -45°)	p0, p45 p90, p135	Normal	Mean	3°
Elastic 11 ply modulus (0°, 45°, 90° & -45°)	e0, e45 e90, e135	Normal	Mean	0.05x Mean
Skin thickness (1 mm)	thick	LogNormal	1 mm	0.045 mm
Perturbation	pert	Normal	0.75 mm	0.4 mm
Perturbation wave length	wave_l	Normal	75 mm	25 mm

STOCHASTIC ANALYSIS RESULTS

This section of the paper reviews the stochastic results from the LS-OPT/LS-DYNA simulations and discusses their significance. The LS-OPT model adopted was a linear Metamodel based Monte Carlo simulation derived from a D-Optimal point selection. Using this basis; 19 LS-DYNA experiments were conducted, with the results further extended to include 10,000 Monte Carlo experiments. The aims of this section were achieved by using the LS-OPT statistical tools and its visualisation capabilities of response probability distributions, stochastic contributions of variables and correlation coefficient.

Probability Distribution of Buckling Response

LS-OPT visualises the shape of the probability distribution of the resultant load as per figure 9. This information allows the further statistical data to be developed by:

- The user identifying the form of the distribution and carrying out additional computations to determine the probability verses the buckling load.
- LS-OPT assumes that the distribution is normal and determines the resultant mean and variance. In this example LS-OPT predicts a mean of 114 kN and standard deviation of 6.07 kN, allowing a probability verses bucking load relationship to be developed by the user as per table 2.

Table 2: Buckling load verses probability of collapse

Load	130 kN	120 kN	110 kN	100 kN	90 kN
Probability of collapse	99.6%	84%	26%	1%	0.004 %

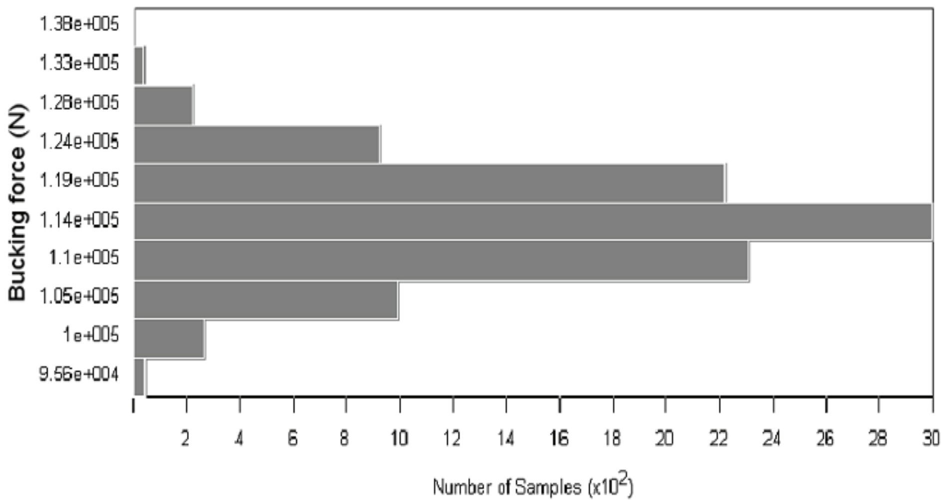

Figure 9: Probability distribution for the buckling force

Stochastic Contribution of the Variables

LS-OPT visualises the stochastic contribution of each variable by plotting its contribution to the panels buckling load capacity as per figure 10. The graph shows that the most significant uncertainty is associated with the accumulative effect of ply placement for the three plies 0° (p0), 45° (p45) and -45° (p135) which together represent 47% of the total variation (refer table 1 for variable nomenclature).

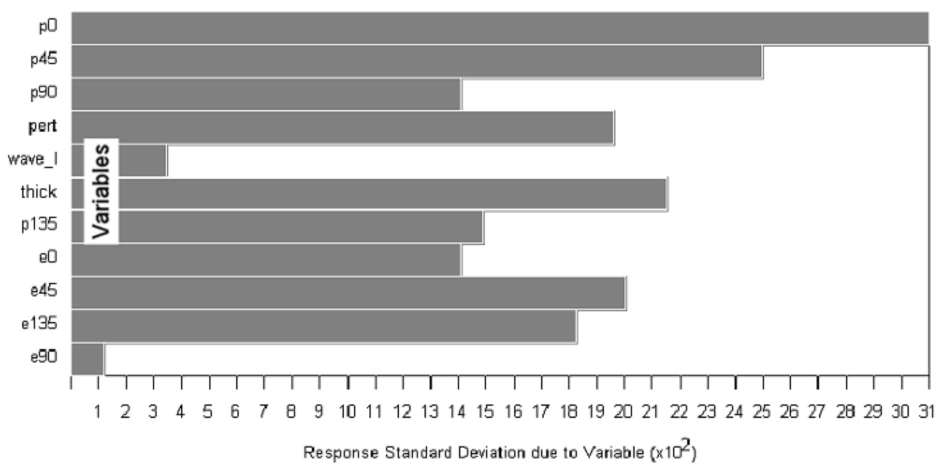

Figure 10: Stochastic contribution of variables to the buckling capacity

Coefficient of Correlation

The correlation coefficient provides a measure of the linear relationship between a variable and the response. The coefficient range is bound by the limits of -1 to 1. At 1 or -1 an exact linear relationship exists between the variable and the response. For positive values, as the variable increases so does the response, while the opposite is true negative values. For a correlation coefficient of 0 no relationship exists and a value of 0.3 is deemed as significant correlation [6].

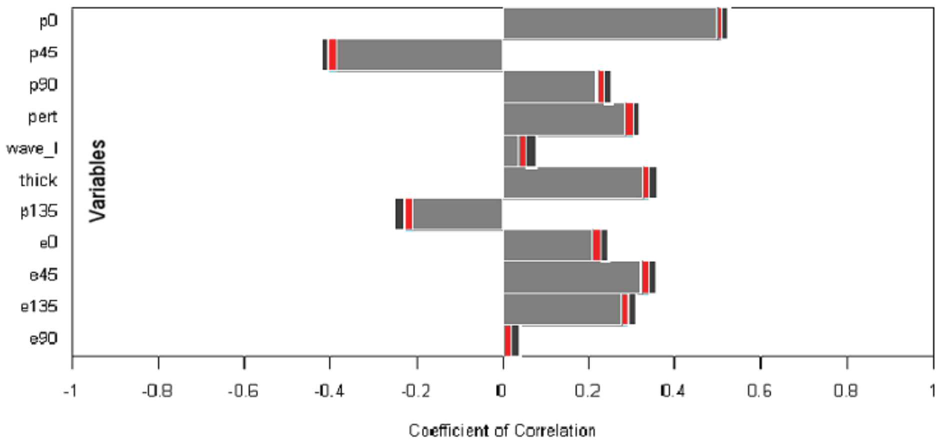

Figure 11: Coefficient of correlation for each variable

The two ply variables with a negative coefficient 45° (p45) and -45° (p135) indicates that by reducing their magnitude this will increase the buckling force.

SUMMARY AND CONCLUSIONS

The study of analysis methods with respect to buckling concluded that consistent peak buckling capacities for quasi-static loading scenarios that are typically experienced during panel testing can be accurately achieved through either nonlinear static or nonlinear dynamic analyses. For dynamic analysis suitable loading rates and out of plane damping magnitudes are required to produce convergence in the peak buckling capacity. However in the prediction of peak elastic stresses, the nonlinear static method produced significantly higher axial shortening magnitudes and correspondingly larger peak stress when no initial perturbations were included. The inclusion of a full wave length perturbation with a magnitude of 0.1 mm in the nonlinear static model reduced the buckled shortening length to that of approximately 50% of the non perturbed model. In comparison the dynamic model experienced no reduction in the shortening length with the same perturbation. It is considered that the differences between these two analysis methods may be due to dynamic effects allowing the transient models to better evolve modes that mimic critical initial perturbations with lower energy states.

The COCOMAT panel (without variable variance) gave a reasonable estimate of the peak buckling load of 137 kN compared to the test peak of approximately 117 kN. The panel stochastically analysed predicted a mean buckling load at collapse of 114 kN, this compares well with the test of 117 kN.

The stochastic analysis of the panel using LS-OPT considered the theoretical variance of 11 variables with respect to the peak buckling load and concluded that while nine of the variables had significant effect on the axial capacity the three variables that represented 47% of the total variability were easily controlled in the manufacturing process. These variables were three of the four ply orientation angles (0°, 45° and -45°).

Further work expected on this topic is to determine the effects of higher order Metamodels on the stochastic results and progress the understanding on the differences between nonlinear static and dynamic analysis methods for quasi-static loadings.

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