METAMODELS FOR THE OPTIMIZATION OF DAMAGE-TOLERANT COMPOSITE STRUCTURES

Kaspars Kalnins[1,2], Chiara Bisagni[2], Rolands Rikards[1], Edgars Eglitis[1],
Potito Cordisco[2], Andris Chate[1]
[1]Institute of Material and Structures, Riga Technical University, Latvia, e-mail:
kasisk@latnet.lv, rikards@latnet.lv, exec@inbox.lv, and_chate@latnet.lv
[2]Department of Aerospace Engineering, Politecnico di Milano, Italy, e-mail:
chiara.bisagni@polimi.it, cordisco@aero.polimi.it

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Abstract

The research here presented regards the development of an optimization technique for the design of damage-tolerant stiffened composite structures subjected to combined axial compression and shear loading. Some techniques are already has been presented in literature regarding the optimization of composite stiffened panels [1-3]. The proposed methodology wants to satisfy a number of different performance requirements, such as buckling load and post-buckling stiffness for various states of damage. In particular, the design must be tolerant of predetermined degradation, due to disbonding between the skin and the stiffeners. The results from a comprehensive set of benchmark studies are summarized to establish the accuracy and validity of proposed material softening approach in order to simulate material degradation.

A metamodelling method has been introduced to optimize a composite stiffened box structure for maximum reliability, while accounting for predetermined degradation. This approach is based on the combined use of probabilistic structural analysis, sampling of computer experiments and approximations of the response functions. A set of numerical experiments has been complemented through experimental tests performed at Politecnico di Milano, using dedicated test equipment [4-5].

1 Introduction

Damage resistance and repair ability of thin-walled composite structures under the postbuckling loading regime has become a major issue in the new generation of aircraft design [6]. In order to improve cost efficiency of composite structures, allowable damage-toleration must be set at their maximum allowable size while still meeting regulatory ultimate load requirements [7]. To achieve this goal, test data and numerical methods encompassing the complete range of potential damage sizes and types are required to be investigated.

The design of stiffened structure components for buckling and post-buckling constraints requires global optimization in design space of design variables. In spite of outstanding advances in computer capacity and speed, the enormous computational cost of complex, high precision scientific simulations makes it impractical to rely exclusively on simulation codes for the purpose of design optimization. A more appropriate strategy is to utilize approximation models that are often referred to as metamodels, as they replace the extensive simulation model during the preliminary design [8] and optimization process.

Initially a study [1] applying metamodelling methodology for the optimal design of axially loaded stiffened composite panels where significant post-buckling deformations before the final collapse of the structure has been elaborated. From the validation procedure with experimental results [9] has been concluded [1,8] that metamodelling approach has sufficient for post-buckling prediction accuracy for axially compressed stiffened composite panels. The current research extends the use of metamodelling to in-torsion loaded structures. The proposed optimization approach for damage tolerant composite structures is based on the combined use of probabilistic structural analysis by sampling of computer experiments and approximating of the load shortening or torque versus rotation structural responses.

1.1 Numerical design of tested composite box structure

A numerical study by finite element analysis code ANSYS/LS-DYNA has been carried out in order to approximate the post-buckling responses of stiffened box structure as shown in Figure 1. The closed box structure has been made of carbon fibers reinforced plastics and subjected to torsion loading.

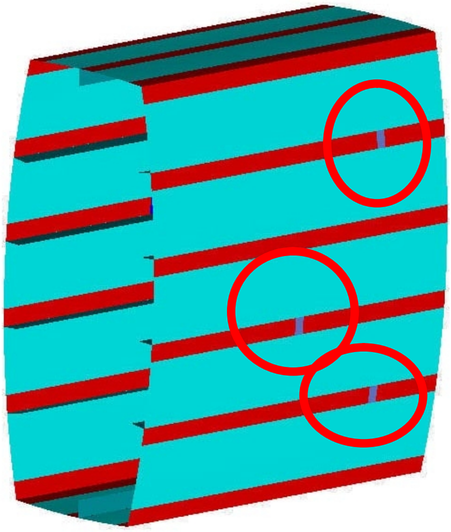

Figure 1. ANSYS/LS-DYNA model of the AGUSTA/WESTLAND Box.

The sample structure (AGUSTA/WESTLAND Box) has been tested at the Politecnico di Milano and manufactured by AGUSTA/WESTLAND within the EC FP-6 project COCOMAT [6] (www.cocomat.de). Geometrical dimensions of the box structure along with stacking orientation and composite material selection are given in Table 1.

Table 1. AGUSTA/WESTLAND box specification.

	AGUSTA/WESTLAND Box
Box length, *L*	700 mm
Free length, L_f	640 mm
Panel radius, *R*	1500 mm
Arc length, *a*	700 mm
Number of stiffeners, *n*	4
Distance between stringers, *d*	136 mm
Distance between stringers and longitudinal edge, e	132 mm
Material	T = 985-GT6-135UD F = 985-GF3-5H-100
Laminate lay-up of the skin	$[0_F, -45_F, 0_F]$
Laminate lay-up of the stiffener: Blade Flange	$[0_F, (0)_{2T}, 45_F, 0_T]_s$ $[0_F, (0)_{2T}, 45_F, 0_T]_s$
Ply thickness, *t*	$t_T = 0.15$ $t_F = 0.33$
Skin thickness, t_s	1.0 mm
Stringer thickness, t_h	2.2 mm
Stringer height, *h*	28.0 mm
Stringer flange width, *f*	28.0 mm

2 Physical tests of the box structure

The physical tests without predetermined damage have been performed on two box sample structures. With addition of two more boxes with the same geometrical design consisting of predetermined damage by Teflon inserts in-between the skin-stiffener in three regions (shown in Figure 1.) For tested specimens damage sites and size was decided by AGUSTA/WESTLAND corresponding to the current certification requirements. The combined torsion/compression load was introduced in counter-clockwise direction and keeping compression of the box constant and equal to zero during the entire test. In order to monitor the evolution of the post-buckling mode shape during the physical tests, the external surface of a panel has been automatically scanned by means of a laser sensor. During the tests, the torque versus rotation curves have been recorded by means of load cell, LVDT transducers and the strain gauge readings. Thus the data from physical experiments has been implemented in validation procedure of ANSYS/LS-DYNA numerical model. An optical image of compression/torsion postbuckling mode shape is shown in Figure 2.

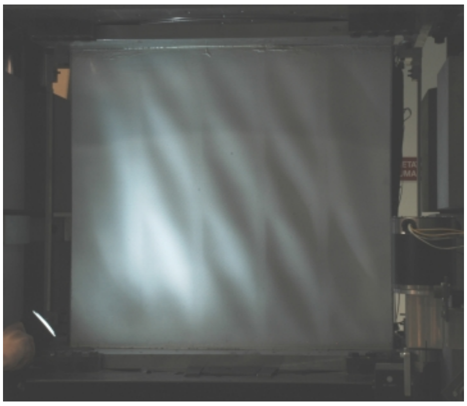

Figure 2. A photo of a composite panel in the post-buckling field.

2.1 Verification of numerical versus physical tests

Detailed numerical verification was required, as both torsion and combined biaxial loading application is not a strait forward procedure. In order to simulate torsion of the structure both box edges have been coupled with rigid elements. Clamped boundaries conditions have been applied for the simulation of the physical experiment. Pure torsion test versus numerical torsion rotation results and corresponding mode shapes are presented in Figures 3 and 4.

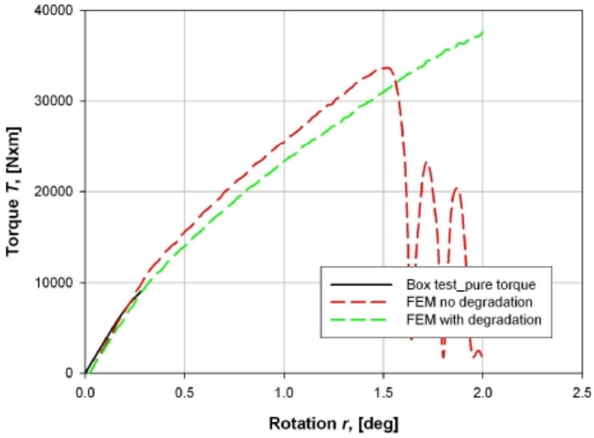

Figure 3. Verification of numerical versus physical torsion test.

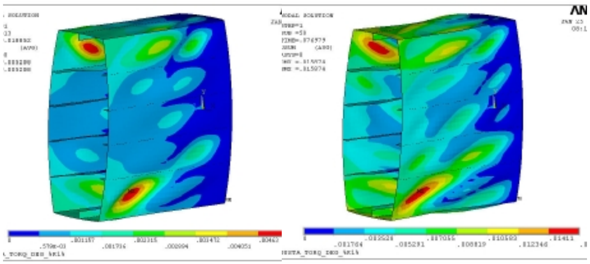

Figure 4. Numerical torsion postbuckling mode shapes.

Comparing torsion loading test data and the numerical results a overall good agreement can be observed. Furthermore combined torsion compression load has been introduced physically by keeping axial compression reaction constant meanwhile increasing the torque in the counter-clockwise direction until collapse of the box structure. This is particularly difficult for numerical simulation to keep the reaction constant, because applied torsion load unloads from initial compression pre-load. A methodology of linear increment of axial load during the torsion tests has been proposed, however more detailed elaboration has to be followed. Combined loading test versus numerical torsion rotation results with corresponding mode shapes are presented in Figures 5 and 6.

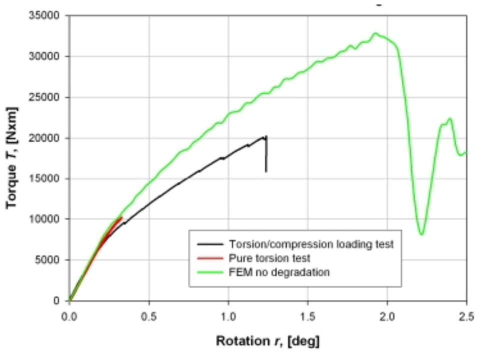

Figure 5. Verification of numerical versus physical combined load test.

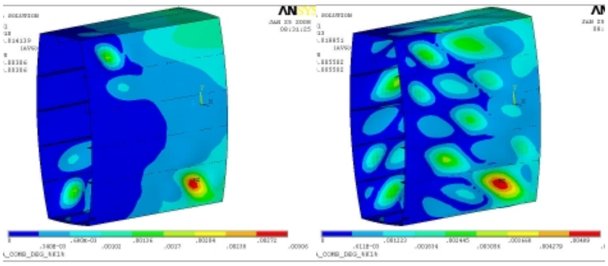

Figure 6. Numerical combined postbuckling mode shapes.

2.2 Validation of structural degradation scenarios

Considering the fact that damage tolerance of the structure is associated with considerable uncertainties in prediction of failure in buckling and postbuckling simulations. Validation benchmark studies over a wide range of damage sizes and sites were carried out to study the effects of material softening parameters over postbuckling behavior. In order to estimate material degradation reliability comparison has been performed assessing the level of required material softening in contrary to fully removed stiffener numerical designs. A various benchmark cases have been proposed as shown in Figure 8, where structural degradation has been incorporated in various damage sites. For each damage case the material properties were softened by ½ of the initial elastic properties. The resulting convergence shown in Figures 9 and 10 in acquired torsion-rotation curves outlined the phenomenon that by local decrease of panel stiffness can trigger different post-buckling mode shape evolvement.

Thus it can be concluded that box structure in general is robust and local degradation doesn't have explicit collapse tendency. It should be stressed that degradation has been applied to only one side of the panels as required by industry, thus assuming unsymmetrical structural behavior. Nevertheless for metamodeling procedure a benchmark case with three middle skin-stiffener degradation scenarios has been selected.

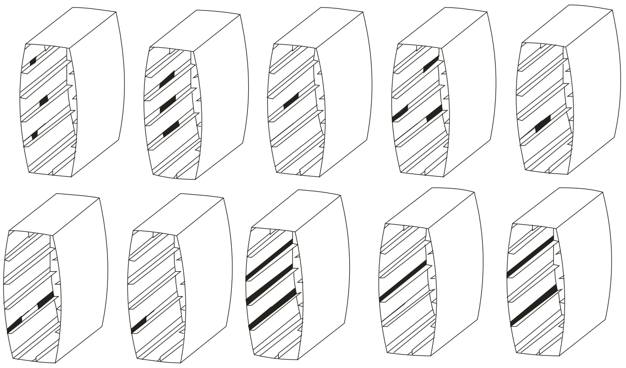

Figure 8. Validation of structural degradation scenarios.

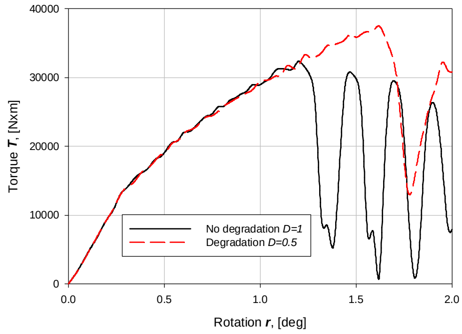

Figure 9. Validation of three stiffener structural degradation scenario.

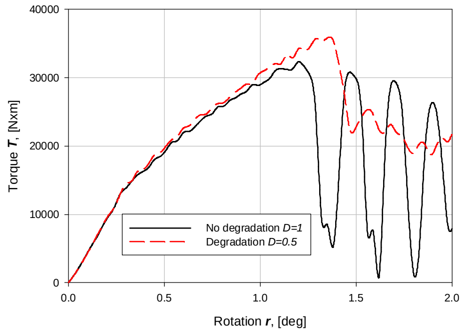

Figure 10. Validation of one stiffener degradation scenario.

3 Metamodels for the optimization of damage-tolerant composite structures

Experimentation and approximation are essential for efficiency and effectiveness in engineering analyses of complex systems. This could involve both multi-disciplinary and multi-objective analysis using very complicated and expensive-to-run computer analysis codes. Such process of model simplification has been referred as metamodelling, in which one should: choose an experimental design for sampling of data, to choose and to fit the mathematical model of response functions moreover to solve the constrained optimization problem. The datasets may include both computer experiments and natural experiments made under uncertainty. The most widely used techniques have been based on second order polynomial response surface approximation, using classical factorial or composite experimental designs.

A set of geometrical design variables (see Table 2.) as the length of the composite stiffened box structure, the curvature radius, the height of stiffeners and the stiffener spacing ratio were used to elaborate the metamodels. Furthermore damage criterion variables has been incorporated – degradation length and material degradation/softening ratio.

Table 2. Design space for parametrical variables.

Name	Notation	Lower bound	Upper bound
Box length	*L*	600	800
Box inner radius	*R*	800	1600
Stiffener spacing	*d*	120	200
Stiffener height	*h*	15	25
Stiffener flange width	*b*	15	25
Degradation region length proportion	*D*	0.1	1
Degradation ratio	*D%*	0.25	1

A space-filling design of computer experiments optimized according to the Mean Squared Error uniformity criteria was selected in order to achieve the best performance – minimal prediction error of metamodels [1]. The sampling procedures mostly involve a large amount of analyzed numerical samples that are unacceptably demanding in terms of solution time. Considering this, a more efficient strategy was used, by arranging and adding new sample points to an already existing design of experiments according to a selected space-filling criterion, thus achieving a good balance among the space filling quality in the whole design space and a quantitative improvement by added sample points [10-12]. An advantage of the proposed approach is the fine sampling quality even before all experiment runs are performed, which once elaborated could be made publicly available (www.rtu.lv/mmd/). All samples where analyzed in parallel exploring the BalticGrid (www.balticgrid.org) LatvianGrid (grid.lumii.lv) computing capabilities, therefore reducing the training time per sample point.

3.1 Torsion-rotation response simplification

One of the principal challenges of the present investigation was to develop metamodels based on torque versus rotation curves obtained from finite element analyses as shown in Figure 11. A piece-wise uniform approximation procedure [1] has been applied to extract main torsion rotation structural response characteristics, consisting of pre-buckling k_1, post-buckling k_2 and collapse regions stiffness k_3 as well as skin and stiffener buckling load values.

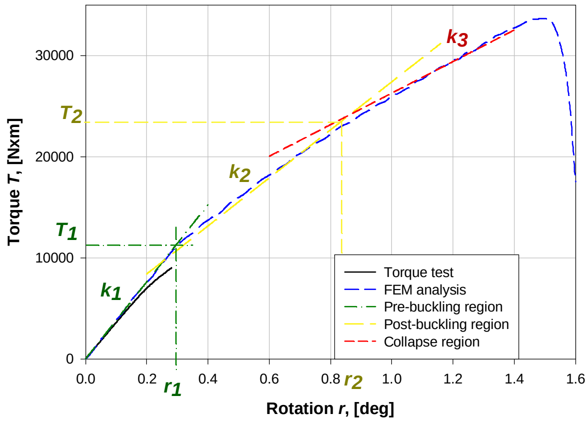

Figure 11. Graphical validation of elaborated torsion-rotation response simplification

3.2 Metamodelling results

Partial polynomial functions has been obtained by regression approximation from the data of numerical simulation. FEM simulations were performed in 50 sample points for data set with seven variables. The Cross-Validation (CV) technique has been used, where validation procedure has been applied to 40 training points and 10 validation points. The test sample accuracy measure used is the Relative Root Mean Square Error:

$$RRMSE\% = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{STD}} \qquad (1)$$

where y_i is i-th test point, $\hat{y}_i$ is predicted value of i-th test point, n is the number of test sample points, and STD is the standard deviation in test sample:

$$STD = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{n}} \qquad (2)$$

It should be noted that RRMSE% and STD are calculated using strictly only the test sample and averaged over the Cross-Validation runs.

When comparing the RRMSE% approximation errors shown in Table 3. for torsion responses, one could observe that the error distribution has been achieved within the 5% range for pre-buckling k_1 and post-buckling k_2 region stiffnesses, which is sufficiently accurate for preliminary design procedure. However stiffener buckling and collapse region boundaries could be doubtful. In particular there have been a set of sample runs where stiffener buckling has not been explicitly identified therefore deflating the collapse region identification procedure.

Table 3. Approximation prediction RRSM error.

Responses	RRSME%	Response	RRSME%
k_1	2.74	r_1	26.17
k_2	4.56	r_2	24.23
k_3	99.06	T_1	17.25
		T_2	118.49

Conclusions

To conclude, the metamodels extracted from torsion-rotation curve with different level of structural degradation can be used for furtherance of damage tolerant design scenario. Thus preselected damage locations have been validated by varying the degradation zone location, damage site length and the stiffness reduction ratio.

The resulting design procedure will be implemented in the optimal design tool for the preliminary study of damage tolerant composite stiffened structures.

The robustness of the design procedure ill be further assessed using different composite failure analysis criteria, determining the most vulnerable zones for structural degradation.

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