Multi-scale mechanical analysis and design optimization of threedimensional textile composite stiffened structures

Fu, Xinwei; Wang, Hao; Ricci, Sergio; Bisagni, Chiara

Publication date
2017

Document Version
Final published version

Published in
21th International Conference on Composite Materials

MULTI-SCALE MECHANICAL ANALYSIS AND DESIGN OPTIMIZATION OF THREE-DIMENSIONAL TEXTILE COMPOSITE STIFFENED STRUCTURES

Xinwei Fu[1], Hao Wang[2]

[1] Youyi Road 102, Beijing 100094, China, Institute of Manned Spacecraft System Engineering CAST, xinwei.fu@polimi.it
[2] Youyi Road 102, Beijing 100094, China, Institute of Manned Spacecraft System Engineering CAST, maugham0902@163.com

Keywords: Textile composite, Multi-scale analysis, Design optimization, Finite elements

ABSTRACT

The work proposes an optimization strategy applicable for the design of stiffened panels made of three Dimensional Woven Orthogonal Composites (3DWOC). Three-dimensional textile composite materials are distinctly heterogeneous, anisotropic and periodic, a multi-scale modelling strategy proposed here combines Representative Volume Elements (RVE) with Periodic Boundary Condition techniques to determine mechanical properties of different scales. A representative volume element enclosing the characteristic periodically repeated pattern in the fabric weave was isolated and modelled to homogenize the effective mechanical stiffness. The RVE includes all the important weaving parameters that influence the mechanical behaviours of the final stiffened structure such as the thickness of the lamina, loop yarn width, warp width, weft width and yarn spacing. The total modelling process includes defining the weaving architecture, creating geometry, generating meshes, applying the appropriate boundary conditions and implementing non-linear buckling simulation, it is computationally expensive.

The optimization procedure proposed here is composed by constructing the approximation models and implementing GA optimization. The approximated structural response of composite stiffened panels is obtained by neural networks system using the results automatic parameterizing modelling FE analysis. The automating parameterization modelling and FE analysis process is achieved by means of Python scripts to combine TexGen and ABAQUS software as well as ad hoc developed scripts written in Matlab language for the optimization. Through an optimization design example of 3-D weaving composite stiffened panels, it is proved that the proposed optimization strategy integrating the approximated models with genetic algorithms allows for yielding the optimal stiffened panels design without compromising the computational efficiency and applicability.

1 INTRODUCTION

Nowadays, advanced textile structural composites made from woven and reinforced braided fabric have found increasing use in the aeronautics, space, automobile, marine, sporting goods etc. This is because they possess light weight, high mechanical properties, excellent chemical resistance and design versatility. Textile composites have lower fabrication costs and are easier to handle in production environments than traditional tape laminates. Stiffened panels are widely used in aerospace structures due to their high efficiency, such as wings and fuselages.

Textile composites are characterized by the distinct hierarchical structure. The complexity of the structure and the presence of a hierarchy of structural and multi scale levels (10^{-5}m fibres, 10^{-3} yarns/tows, 10^{-1}m fabrics, 10^{0} composite structures) lead to a high complexity of the predictive models. A multi-level hierarchical approach has been utilized and is capable of predicting the properties and mechanical behaviour of the textile composite structure. The homogenization techniques provide the response of the response of a structure (global level) given the properties or response of the structure's constituents (local level). Various forms of homogenization methods aimed at bridging material and structural scales have been employed by papers [1-4]. A primary factor in materials design is the development, characterization, and validation of predictive models on a hierarchy of length scales so as to establish a multi-scale modelling framework.

Structural designers always seek the best possible design and use the least amount of resources, especially for aeronautical and space structures. The measure of the fitness for purpose of a design depends on the application, and is typically related to strength or stiffness while composite materials are measured in terms of weight or cost. Textile composite structures offer unmatched design potential since material properties can be tailored almost continuously throughout the structure. However, this increased design freedom also brings new challenges for the analysis and design process. The optimum design problems are often extremely tedious and require a large number of iterations. Rodolphe and Rapheal [5] implemented optimization design of laminate stacking sequences for critical load maximization through adding permutation operator to Genetic algorithm. Soremekun [6] suggests a generalized elitist genetic algorithm as an alternative to the standard genetic algorithm. Paper [7] adapts special operators and variables codification in a genetic algorithm for the specific case of optimising composite laminated structures. Kang and Kim [8] developed a parallel computing scheme for GA, considered buckling and post-buckling behaviours of stiffened panels, to obtain minimum-weight design. Bisagni and Lanzi put forward a global approximation post-buckling optimization procedure for laminated composite stiffened panel through combining neural networks and GA to reduce the cost and computational time [9]. Rikards et al. [10] developed an optimization frame work based on building surrogate models employing the design and response surface methodology. Lanzi and Giavottovo's work [11] considers three different methods of global approximation: Neural Networks, Radial Basis Functions and Kriging approximation, as well as performing multi-objective genetic searches. However, these studies have focused on optimization design of laminated composite stiffened panels, scarcely considering 3-D textile composite stiffened panels. 3-D woven composite materials reinforce with 3-D yarns are obviously distinguishing from traditional laminated material. Nevertheless, weaving parameters and routes of 3-D textile composites can significantly influence the mechanical performance of fabric composites, as well as affect the stiffness and strength of composite structures. Despite the current applications and many demonstrations of the potential use of 3-D woven composites, the lack of a large data base has also made it difficult to determine the optimum weave architecture required to provide the desired mechanical properties for a specific structural design.

A significant amount of research have been done on predicting mechanical properties of 3-D textile composite via experimental [12, 13], numerical [12, 14, 15] and analytical approaches [13, 15]. Although the experimental method is the most natural approach, it has some obvious drawbacks in the area of performing optimizations. The limited analytical solutions for composite structures, especially for complex topological and geometrical textile composites, preclude themselves as applications for design optimization. The numerical approach is a good choice for optimizing existing fabrics and creating new textile models. The author Fu [16] had proposed an optimization framework for 3-D orthogonal woven stiffened panels' minimum-weight design using neural networks and Genetic algorithms. Fu, Ricci and Bisagni [17] put forwards an optimisation strategy for the design of structures made of three-dimensional woven composites. The approach proposed consists of a multi-scale parameterization analysis strategy and an optimisation framework based on the response surface technique generated by neural networks and genetic algorithms.

The aim of this paper is to develop a strategy for the design optimization of textile composite structures. The structural analysis presented in this work is based on Multi-scale FE model of textile fabric composite structures, starting with the fiber and matric, through to the models of yarn and textile and finishing with the total model of the structure. A dedicated Python script able to automatically adjust weaving variables and to create all the requested models for the successive analysis and optimization phases is used to implement the design parameterization of the woven composite stiffened panels. A surrogate model of structural responses is obtained using neural networks' method to increase the computational efficiency and the applicability of the optimization method. Finally, the strategy integrated with Multi-scale homogenization, neural networks model and Genetic algorithm is developed to investigate weaving parameters.

2 MULTI-SCALE MODELLING STRATEGETY OF WOVEN COMPOSITES

2.1 Micro-level unidirectional yarns homogenization

A clear description of textile structure at each scale is necessary to better predict the composite material behaviour. Composite materials are generally used to fabricate large structures. Yet the behaviour of these structures depends on the composite microstructure. Analysing large structures on a Microstructural level, however, is clearly an intractable problem. Analysis method have therefore sought to approximate composite structural mechanics by analysing a representative element of the composite microstructure, commonly called a Representative a Volume Element (RVE). RVE based methods decouple analysis of a composite material into analysis at the local and global levels. The local level analysis models the microstructural details to determine effective elastic properties and stress fields. The global revel analysis calculates the effective or average stress and strain within the equivalent homogeneous structure. The process of the calculating effective properties has been called "homogenization" by Suquet [18].

The heterogeneous microstructures of woven composites is also approximated as periodic, where the RVE is the volume of the material that repeats itself to generate the overall woven composite [19, 20]. Periodical conditions are applied to the RVE boundaries to simulate the repeating nature of the RVE. The RVE response is very sensitive to periodic boundary conditions and one of the main tasks of the designer focuses on automating the creation of models of RVE using fast meshing whilst applying appropriate boundary conditions.

The ladder of textile composite multi-scale modelling starts with the micro-mechanical computation of fibres and matrix. The homogenization procedure of basic unidirectional yarns is illustrated in Fig. 1.

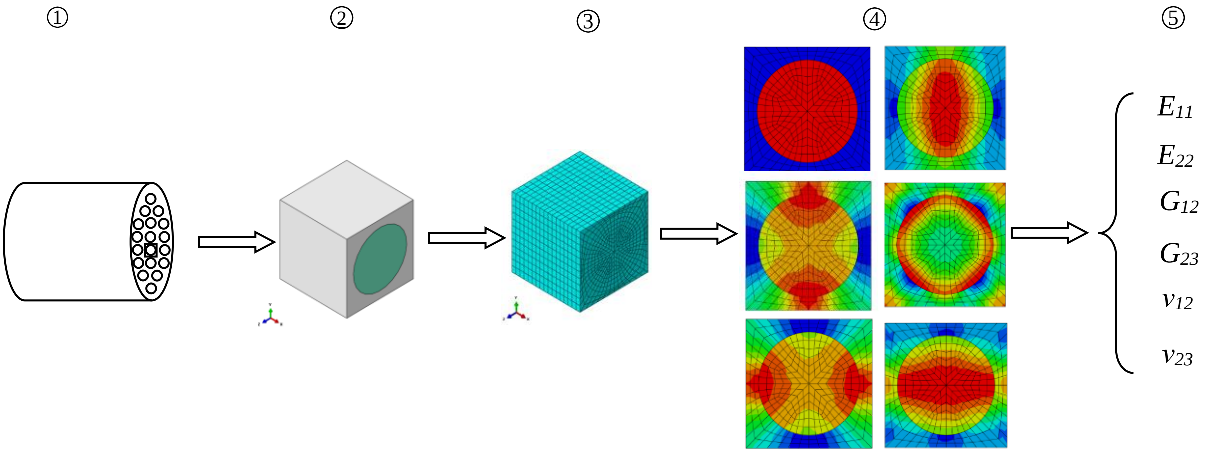


Figure 1: homogenizing process of micro-level unidirectional yarns

① Thousands of mono-filaments and matrix are visible in the fiber bundle at micro scale; the yarns and matrix constitute the basic fabric in mascot scale.

② As shown in Fig. 1, a square-arrangement unite cell is used to represent the Unite directional material behavior of the fiber yarns.

③ The square RVE has been meshed in order to use finite elements methods. The fiber and matrix properties are added to FE models.

④ Appropriate boundary conditions are applied on the six independent FE cases. Six independent boundary-value problems are solved through FE analysis

⑤ The effective engineering elastic constants of the composite yarns can be extract from FE analysis results.

The research developed in this paper concerns the application of MAPICC3D textile composites for aerospace structures. This novel textile has been developed within the European project MAPICC 3-D and is produced by the Institute of Textile Machinery and high performance material technology (ITM) at the Technische Uiversit ät Dresden (TUD). The MAPICC 3-D textile composite is produced by using commingled hybrid yarns. Commingled yarns are made of reinforcement and matrix filaments. The thermoplastic matrix is used to ensure good adhesion between fibres and fixes the reinforcement components in a defined order; indeed the matrix assures that the final product maintains the designed shape. The OCV Twintex®1398 R PP is used for reinforcement yarns, while loop yarns are made of a 68 Tex GF and 66 Tex PP commingled filament. The material elastic properties of fibre and matrix are given in

Table 1, while Fibre Volume fraction and other basic data of Twintex®1398 and of loop yarns are reported in

Table 2.

Material	GF	PP
Young modulus[MPa]	72000	1350
ν	0.22	0.36
ρ[Kg/m3]	2580	900

Table 1: Material property of E-Glass and Polypropylene (PP).

TW TR PP82 NUTURAL 1398		Loop Yarn	
GF[% by weight]	82	GF[%by weight]	50
PP[%by weight]	18	PP[%by weight]	50
Linear density[ypp]	345.83	Linear density[ypp]	3701
Linear density[kg/m]	0.001398	Linear density[kg/m]	0.00134
Fibre area[mm^2]	0.4443	Fibre area[mm^2]	0.0264
Matrix area[mm^2]	0.2796	Matrix area[mm^2]	0.0733
Total area[mm^2]	0.7239	Total area[mm^2]	0.0997
Fibre Volume fraction[%]	61.4	Fibre Volume fraction[%]	26.4

Table 2: Properties of Twintex®1398 and loop yarn.

2.2 Meso-level woven textile fabric homogenization

The Meso-level textile analysis tends to define the interactions between warp and weft yarns at the crossover points. The meso-scale modelling is based on the concept of homogenization and evaluates the mechanical properties of a fabric Representative Volume Element (RVE), which is typically used to determine the effective stiffness of textile fabrics. Meso-scale finite element (FE) modelling of textile composites is a powerful tool for homogenization of mechanical properties and aids the study of stress-strain fields inside the unit cell [21].

The internal architecture of textile fabric is significantly complex as shown in Fig. 2. Modelling and meshing of the weaving architecture and the application of the appropriate of boundary condition and extracting the effective elastic data are time-consuming. In the present work, TexGen [22] software, an open source software used for modelling the geometry of textile structures and developed at Nottingham University, is utilized to implement to model the RVE and to generate the input file for ABAQUS simulation. The TexGen program was written to give maximum flexibility to the fabric geometric modelling, thus allowing accurate modelling of a wide range of textiles. It permits realistic fabric geometric modelling of any weave or knit or non-woven architecture automatically as it uses a general vector path description of yarns using both a centreline and superimposed cross-sections. The yarn centre line in a 3-D space depicts the yarn path which further can be described by specifying a number of points (master nodes) along the length of yarn. The detailed modelling process is illustrated in Fig. 2. The yarn cross-section is defined as a function of distance along the yarn. The detail concept of modelling of 3-D commercial fabric along with the algorithms is reviewed in the literature [23].

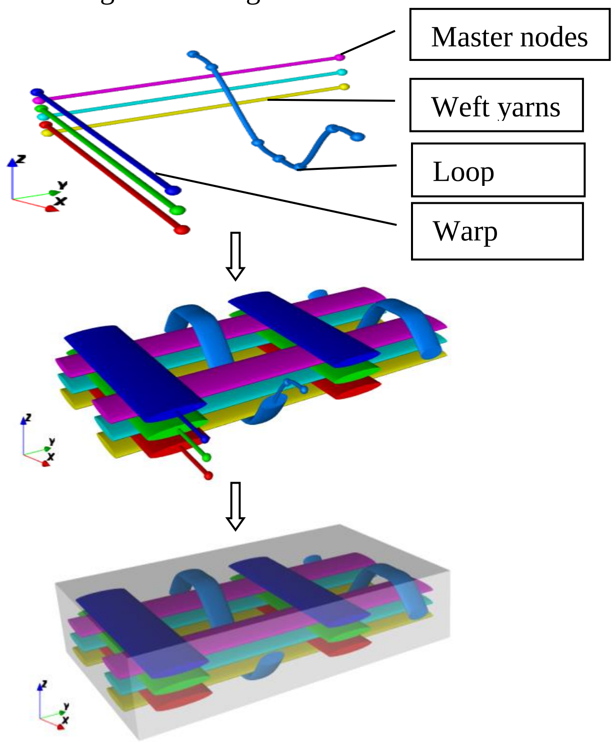


Figure 2: Modelling process of textile fabric.

Once the effective elastic properties of weaving fabric RVE are extracted from the finite element analysis, in the next step, the macro structural analysis could be implemented in general way.

2.3 Macro-level buckling analysis of composite stiffened panels

Stiffened panels are typically used in aerospace structures, such as fuselages and wings, mainly because of their high efficiency in terms of stiffness to weight and strength to weight ratios. The buckling responses of 3-D orthogonal woven composite stiffened panels are investigated in this research. Because composite stiffened panels tend to be relatively thin, buckling prior to the desired failure mode is a concern when specimens are loaded in compression. Abaqus package was applied to analyse the buckling and post-buckling behaviour of the structure. Buckling analysis will provide the eigenvalue value and buckling model of the stiffened panel, while the nonlinear analysis will generate detailed deformation information in the post-buckling region.

The critical buckling load point P_{cr} was determined from the intersection of two tangents drawn from the pre-buckling and post-buckling regions. The load-displacement curve can be divided into two relevant regions. The first one is the linear part where the load is lower than the buckling load P_{cr}. The corresponding displacement is identified by u_{cr}. The second part corresponds to the post-buckling region. The pre- and post-buckling stiffness can be linearized piecewise with two slopes. Before performing the design optimisation, the minimum allowable design value P_{cr}, K_{pre}, K_{post} have to be defined according to the design structural requirements.

The macro-level buckling analysis is scripted by Python codes and implemented in ABAQUS package. Meanwhile, the analysis results are extracted and calculated, the full analysis process is completed by Python codes in automatic way. It supply a fast and feasible approach to multi-scale parametric model textile composite without any manual intervention, which is the first step to implement weaving parameters optimization.

3 DEFINITION OF OPTIMIZATION PROBLEM

3.1 Model of 3DWOC stiffened panel

In the current case, the stiffened panel here considered to be analysed and optimized is a T-shape stiffened panel made of 3-D woven glass fibre composite. It has dimensions 840×700mm and is subjected to axial compression displacement. The upper and lower edges of the stiffened panels are simply supported while the longitudinal edges are free. The model of the stiffened panel with four equally spaced T-type stiffeners is illustrated in Fig. 3. Stiffeners are placed on external edges to avoid edge buckling. The width of the web and the height of the flange are both fixed at 20 mm. The thickness of the skin, web and flange varied according to weaving patterns. The architectures of the skin and stringers are shown in Fig. 4. There are 4 weft layers yarns in the skin and 12 yarns in the stiffeners.

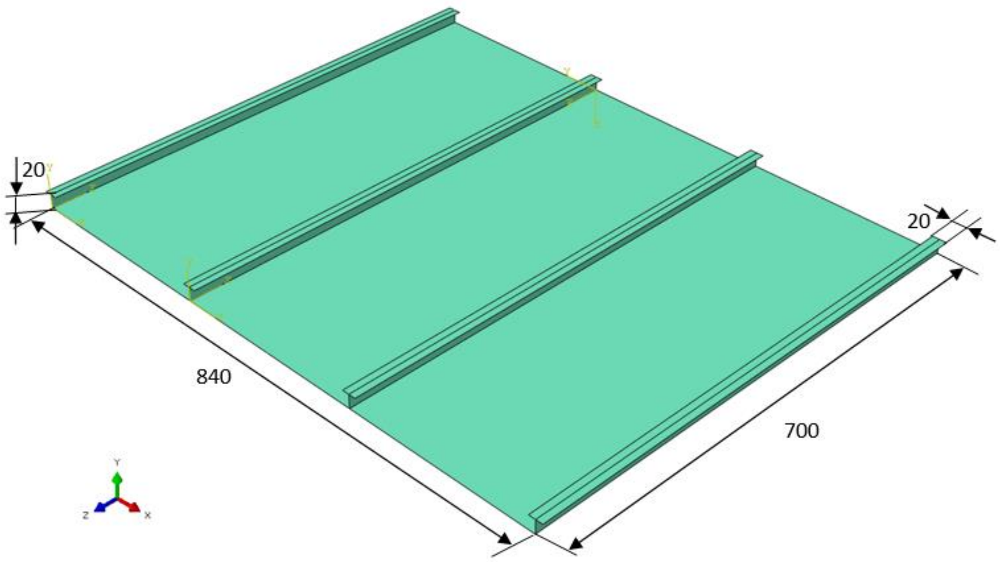
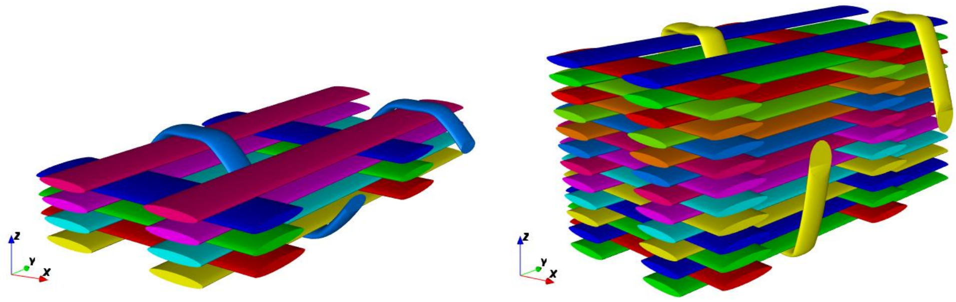


Figure 3: Geometry of 3DWOC stiffened panel.



(a) Skin weaving pattern. (b) Stringer weaving pattern.

Figure 4: Architecture of 3D weaving pattern.

3.2 Design Parameters and optimization objective

The aim of the present case is to minimise the mass of the considered stiffened panel subjected to the minimum allowable design values P_{cr}, K_{pre} and K_{post}. The mass of the stiffened panel is a function of the design variables, and can be expressed in function of the density and the geometric dimensions of the representative volume elements.

The weaving parameters are introduced as design variables of the optimisation problem, shown in Fig. 5. X_1 denotes the spacing between weft and loop yarns; X_2, the spacing between close warp and loop yarns; X_3, the thickness of all yarns; X_4, the width of weft yarn; X_5, the width of warp yarns; and X_6, the widths of loop yarns. The domain of the design variables is summarized in Table 3.

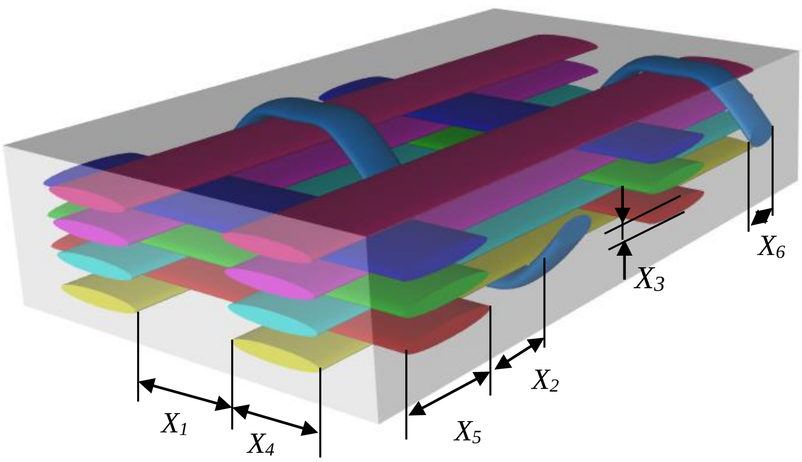


Figure 5: Geometrical parameters of weaving composite.

Design parameters		Domain
Spacing between weft and loop yarns [mm]	X_1	0-1
Spacing between warp and loop yarns [mm]	X_2	0-1
Yarns thickness [mm]	X_3	0.1-0.5
Weft yarn width [mm]	X_4	0.4-2
Warp yarn width [mm]	X_5	0.4-2
Loop yarn width [mm]	X_6	0-2

Table 3: Domain of the design variables for the optimization.

4 DETERMINATION OF APPROXIMATION MODELS

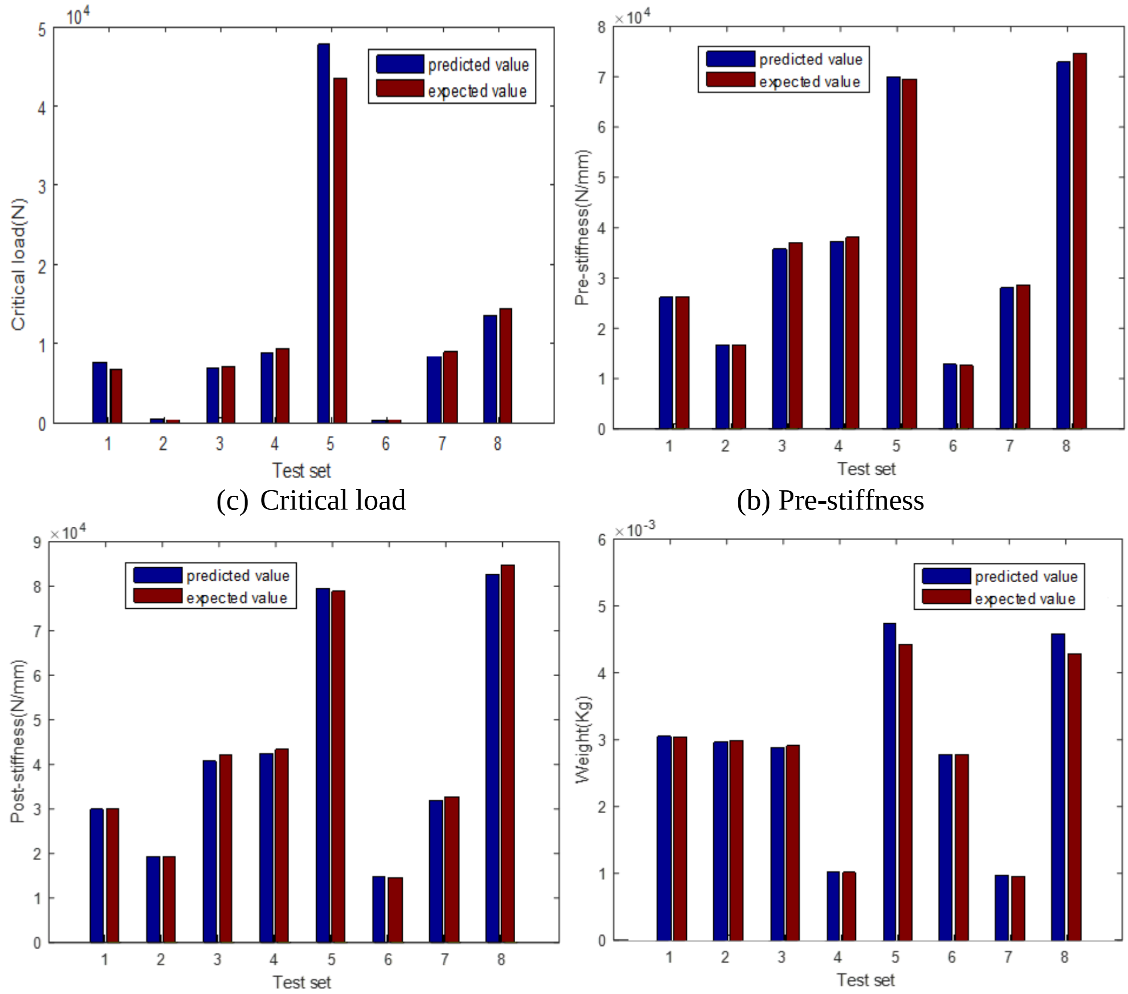
In order to address large scale optimization design problem, surrogate models are defined to be able to approximate the selected structural response. In this investigation, The Back Propagation Neural Network algorithm (BPNN) is used to create global approximation model that imitate the buckling behaviour of the composite stiffened panels as closely as possible while being computationally cheaper to evaluate. Neural networks system is capable of acquiring knowledge and resolve situations that cannot expressed mathematically by experience. The neural network needs a learning process and a training set, composed of input-output patterns. The back propagation neural network algorithm, in particular, is a multi-layer feed forward network trained according to error back propagation algorithm and is one of the most widely applied neural network models.

Four critical parameters (P_{cr}, Critical load; K_{pre}, pre-buckling stiffness; K_{post}, post-buckling stiffness; *W*, weight of the model), used to descript stiffened panels' buckling behaviours, are predicted by BPNN approximation models. The adopted BPNN architectures for each design parameters are summarized in

Table 4. The total sample points were 54, 46 points were used to train the neural network, and the other 8 testing sample points were in test set. Fig. 6 given the comparisons between expected and predicted value of stiffened panels' weight, critical load, pre-stiffness and post-stiffness, respectively. The smaller the errors are, the more accurate the evolutions are.

Output parameters	Nodes	Transfer functions	
		Hidden layers	Output layer
P_{cr}	12,12,6,1	logsig,tansig,purelin	purelin
K_{pre}	12,10,6,1	logsig,tansig,purelin	purelin
K_{post}	10,12,7,1	tansig,logsig,purelin	purelin
W	12,12,6,1	Tansig,tansig,purelin	purelin

Table 4: BPNN architecture.



(c) Critical load (b) Pre-stiffness

(d) Post-stiffness (d) Weight

Figure 6: Comparison predicted by NNs and expected values.

P_{cr} denotes the system that receives as input the scaled vector of the design variables and returns the buckling load values. The BPNNs' architecture of P_{cr} includes three hidden layer and one output layer, the nodes of hidden layers is 12, 12 and 6; the functions of the layers are logsig, tansig and purelin. The output layer has one node and the transfer function is purlin. According to the NNs predicted result for P_{cr} is good agreement with the expected one obtained the finite element analysis, the maximum predicted percentage errors is least than 16%.

K_{post} is pre-buckling stiffness of composite stiffened panels; K_{post} is post-buckling stiffness of composite stiffened panels; W is weight of composite panels. The architectures of BPNNs for $K_{pre,}$, K_{post} and W are illustrated in

Table 4. The data predicted by BPNNs compared with the ones obtained by the finite element analysis are shown in Fig. 7. The maximum predicted percentage errors of K_{pre}, K_{post} and W are 4%, 3% and 7%, respectively.

After constructing the BPNN architectures and checking the accuracy of the NN, the BPNN system is able to surrogate the detailed finite element analysis of composite stiffened panels.

5 STRUCTURAL OPTIMISATION RESULTS AND MODEL VERIFICATION

Once the approximation models of composite stiffened panels' buckling behaviours are defined using BPNN, the optimal design of 3-D weaving panels is discussed using proposed design procedure. Genetic algorithms (GA) are adopted to optimise the weaving parameters of the composite panels under the buckling constraints. GA are a stochastic global search and optimisation method that mimics natural biological evolution [44]. GA are robust and more straightforward to apply in situations where there is little or no a-priori knowledge about the problem being solved. MATLAB Genetic Algorithm toolbox implements a wide range of genetic algorithms to solve large and complex real-world design problems, and is here used to perform parameters optimisation for textile composite weaving designs.

In this investigation, it is exploited to solve the global optimisation problem aiming at the minimization of the total mass for the stiffened panel. As usually happens when Genetic Algorithms are adopted, the optimization problem must be formulated as an unconstrained minimization problem where the fitness function is a combination of the real objective function, the structural mass in our case, plus the constrains used as penalty functions. These last ones are not computed directly but estimated using the surrogate models created by the BPNN to reduce the computational effort.

5.1 Optimization

The optimization aims to improve the stiffened composite panels' buckling response with respect to the minimum possible mass. The constraints are formulated as:

$$P_{critical}(x) \geqslant 8000,\ K_{pre}(x) \geqslant 20000 \text{ and } K_{post}(x) \geqslant 7500 \quad (1)$$

The population of genetic algorithm is initialized with 100 individuals, randomly generated in the given design domain. Crossover is applied with a probability of 0.85. The probability of mutation is chosen equal to 0.01 for all the operators. The initial penalty of the constraint parameters is set equal to 1 and the penalty factor equal to 10. The stopping criterion is based on the maximum number of generations without improvements, here the maximum number of generations is 100.

5.2 Optimization results

The optimization results obtained for the optimization are here discussed. The best fitness was obtained after the evolution of 100 generations. The fitness of the best individual of each generation, until convergence, is illustrated Fig.7. The best fitness value was 2.3kg as shown in Fig. 7, when the design variablesX_1, X_2, X_3, X_4, X_5 *and* X_6 were 0.88, 1.00, 0.28, 0.65, 0.67 and 0 mm, respectively.

The optimized data are compared with those ones of the baseline design in Table 5. Comparing the mass of the optimal design with the Ref. design, 53% of the total mass of the composite stiffened panel is saved but must be pointed out that the Ref. design was not optimized yet.

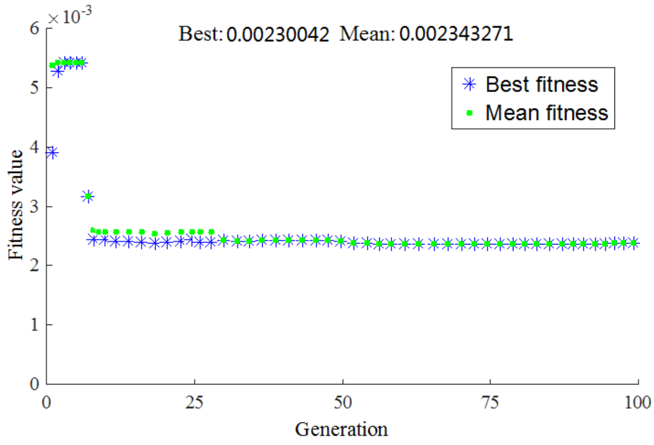


Figure 7: Optimisation results: fitness function versus generations.

	Constraint	Ref. design	Design by NNs
X_1 [mm]	0-1	0	0.88
X_2 [mm]	0-1	0	1
X_3 [mm]	0.1-0.5	0.1	0.28
X_4 [mm]	0.4-2	2	0.65
X_5 [mm]	0.4-2	2	0.67
X_6 [mm]	0-2	2	0
Critical load [N]	≥ 8000	41369	8000
Pre-buckling stiffness [N/mm]	≥ 20000	78321	20000
Post-buckling stiffness [N/mm]	≥ 7500	12675	14500
Mass [kg]		4.9	2.3

Table 5: Comparison between initial design and optimum design.

5.3 Model verification

In order to guarantee that the optimisation procedure is reliable, a detailed Multi-scale FE analysis of the optimal panel configuration is carried out to verify that the buckling behaviour meets the design requirements. The buckling mode obtained by the eigenvalue analysis and load-shortening curve extracted by the non-linear buckling analysis are shown in Fig. 8 and Fig. 9, respectively. Four out-of-plane deformed shapes of the optimised panel at different shortened displacements are illustrated in Fig. 10.

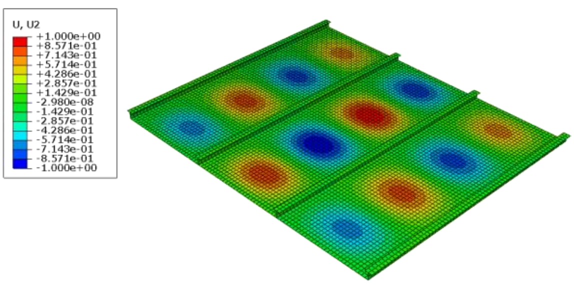


Figure 8: Eigenvalue analysis result.

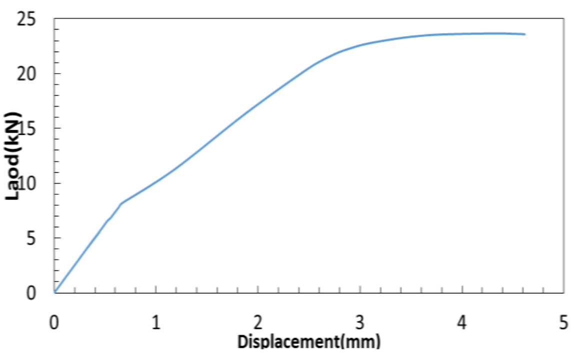


Figure 9: Load-shortening curve of optimised stiffened panel.

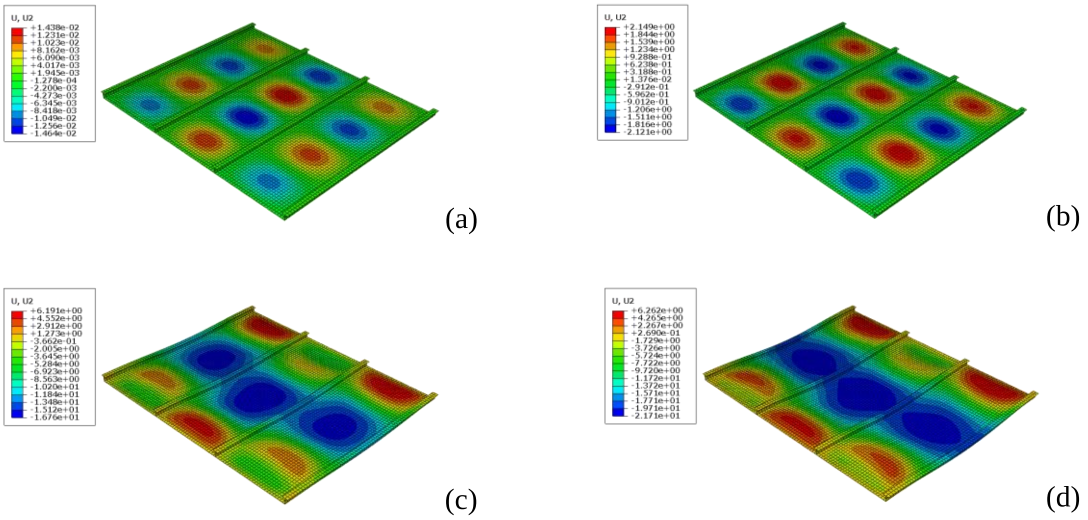


Figure 10: Deformed shapes of optimised stiffened panel: (a) Shortening = 0.05mm; (b) Shortening = 0.43 mm; (c) Shortening = 2.5 mm; (d) Shortening = 4.6 mm.

6 CONCLUSIONS

This paper developed a sufficient and reliable optimisation strategy for the design of stiffened panels made of MAPICC 3-D textile composite subjected to buckling and post-buckling constraints. The procedure is based on the combination of multi-scale FE model, neural network and genetic algorithms resulted in a minimum weight design of stiffened panel under axial compression.

A parameterization multi-scale modelling approach proposed here to determine buckling behaviour of 3-D woven composite stiffened panels. A representative volume element presenting the periodically repeated pattern in the fabric weave is isolated and modelled to homogenize the effective mechanical stiffness of yarns and woven fabric.

The surrogate and approximated modelling technique BPNN is defined and used to construct the response surface of composite stiffened pane due to time-consuming. The maximum percentage error predicted by BPNN modelling is least than 16%. The optimization strategy is based on combining neural networks system with genetic algorithm, and implemented in commercial software Matlab.

The developed optimisation procedure is validated considering a stiffened panel design case. The optimal weaving parameters of the composite stiffened panel with specific buckling constraints are obtained with a significant mass reduction. The optimal weaving parameters are obtained using optimisation procedure.

The optimal configuration of the stiffened panel is verified using a detailed multi-scale FE analysis. The critical load and the load-displacement curve are accurately predicted by the proposed multi-scale FE analysis method. It was proved that the proposed optimization strategy is efficient and reasonable for optimizing lightweight 3-D weaving composite structures in primary design stages.

REFERENCES

1. W.J. Shanahan, D.W. Lloyd and J.W.S. Hearle, Characterizing the elastic behavior of textile fabrics in complex deformations. *Textile Research Journal*, **48(9)**, 1978, pp. 495-505 (doi: 10.1177/004051757804800901).
2. S. Ghosh, K. Lee, and P. Raghavan, A multi-level computational model for multi-scale damage analysis in composite and porous materials. *International Journal of Solids and Structures*, **38(14)**, 2001, pp. 2335-2385 (doi: 10.1016/S0020-7683(00)00167-0).
3. J. Fish and K. Shek, Multiscale analysis of composite materials and structures. *Composites Science and Technology*, **60(12)**, 2000, pp. 2547-2556 (doi: 0.1016/S0266-3538(00)00048-8).

4. T.Y.Hou and X.H. Wu, A multiscale finite element method for elliptic problems in composite materials and porous media. *Journal of computational physics*, **134(1)**, 1997, pp. 169-189 (doi: 10.1006/jcph.1997.5682).
5. R. Le Riche and R.T. Haftka, Optimization of laminate stacking sequence for buckling load maximization by genetic algorithm. *AIAA Journal*, **31(5)**, 1993, pp. 951-956 (doi: 10.2514/3.11710).
6. G. Soremekun, Composite laminate design optimization by genetic algorithm with generalized elitist selection. *Computers & Structures*, **79(2)**, 2001, pp. 131-143 (doi: 10.1016/S0045-7949(00)00125-5).
7. F.S. Almeida and A.M. Awruch, Design optimization of composite laminated structures using genetic algorithms and finite element analysis. *Composite Structures*, **88(3)**, 2009, pp. 443-454 (doi: 10.1016/j.compstruct.2008.05.004).
8. J.H. Kang and C.G. Kim, Minimum-weight design of compressively loaded composite plates and stiffened panels for postbuckling strength by Genetic Algorithm. *Composite Structures*, **69(2)**, 2005, pp. 239-246 (doi: 10.1016/j.compstruct.2004.07.001).
9. C. Bisagni and L. Lanzi, Post-buckling optimisation of composite stiffened panels using neural networks. *Composite Structures*, **58(2)**, 2002, pp. 237-247 (doi: 10.1016/S0263-8223(02)00053-3).
10. R. Rikards et al., Surrogate models for optimum design of stiffened composite shells. *Composite Structures*, **63(2)**, 2004, pp. 243-251 (doi: 10.1016/S0263-8223(03)00171-5).
11. L. Lanzi and V. Giavotto, Post-buckling optimization of composite stiffened panels, computations and experiments. *Composite Structures*, **73(2)**, 2006, pp. 208-220 (doi: 1 10.1016/j.compstruct.2005.11.047).
12. M.J. King P. Jearanaisilawong and S. Socrate, A continuum constitutive model for the mechanical behavior of woven fabrics. *International Journal of Solids and Structures*, **42(13)**, 2005, pp. 3867-3896 (doi: 10.1016/j.ijsolstr.2004.10.030).
13. X.Q. Peng and J. Cao, A continuum mechanics-based non-orthogonal constitutive model for woven composite fabrics. *Composites Part A: Applied Science and Manufacturing*, **36(6)**, 2005,pp. 859-874 (doi: 10.1016/j.compositesa.2004.08.008).
14. G. Hivet and P. Boisse, Consistent 3D geometrical model of fabric elementary cell. Application to a meshing preprocessor for 3D finite element analysis. *Finite Elements in Analysis and Design*, **42(1)**, 2005, pp. 25-49 (doi: 10.1016/j.finel.2005.05.001).
15. X. Peng and J. Cao, A dual homogenization and finite element approach for material characterization of textile composites. *Composites Part B: Engineering*, **33(1)**, 2002, pp. 45-56 (doi: 10.1016/S1359-8368(01)00052-X).
16. X. Fu S. Ricci and C. Bisagni, Minimum-weight design for three dimensional woven composite stiffened panels using neural networks and genetic algorithms. *Composite Structures*, **134**, 2015, pp. 708-715 (doi: 10.1016/j.compstruct.2015.08.077).
17. X. Fu S. Ricci and C. Bisagni, Multi-scale analysis and optimisation of three-dimensional woven composite structures combining response surface method and genetic algorithms. *CEAS Aeronautical Journal*, **8(1)**, 2017, pp. 129-141 (doi: 10.1007/s13272-016-0227-y).
18. P. Suquet, Elements of homogenization theory for inelastic solid mechanics. *Homogenization Techniques for Composite Media*, 1987, pp. 194-275.
19. S. Jacques I. De Baere and W. Van Paepegem, Application of periodic boundary conditions on multiple part finite element meshes for the meso-scale homogenization of textile fabric composites. *Composites Science and Technology*, **92**, 2014, pp. 41-54 (doi: 10.1016/j.compscitech.2013.11.023).

20. S.C. Quek et al., Analysis of 2D triaxial flat braided textile composites. *International Journal of Mechanical Sciences*, **45(6-7)**, 2003, pp. 1077-1096 (doi: 10.1016/j.ijmecsci.2003.09.003).
21. S.V. Lomov et al., Meso-FE modelling of textile composites: Road map, data flow and algorithms. *Composites Science and Technology*, **67(9)**, 2007, pp. 1870-1891 (doi: 10.1016/j.compscitech.2006.10.017).
22. M. Sherburn and A. Long, TexGen open source project. 2010.
23. M. Sherburn, Geometric and mechanical modelling of textiles. 2007, *University of Nottingham*.