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# Multi-scale analysis and optimisation of three-dimensional woven composite structures combining response surface method and genetic algorithms

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## Abstract

The paper proposes an optimisation strategy for the design of structures made of three-dimensional woven composites. The knowledge of the weaving architecture is essential to properly optimise the design of the structural components subjected to specific load conditions. Owing to the hierarchy and periodicity of the textile composite materials, a multi-scale parameterization modelling strategy combining the adoption of a representative volume element and periodic boundary conditions is employed in order to estimate the behaviour of stiffened panels. In order to minimize the expensive computational cost, response surface method techniques are used to generate the approximated structural responses in an efficient and applicable way. The approach here proposed consists of a multi-scale parameterization analysis strategy and an optimisation framework based on the response surface technique and genetic algorithms. The optimal design results are verified by finite element analysis proving that the response surface method integrated with genetic algorithms allows to easily investigating the influence of the fabrics constitutive parameters on the structural behaviour.

**Keywords:** Three-dimensional composite; multi-scale analysis; representative volume element; genetic algorithms; optimal design.

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## 1. Introduction

Advanced textile structural composites made from woven and reinforced braided fabric have found increasing use in many high performance and light-weight applications in the aerospace, automobile, and marine industries over the last two decades. This is mainly due to the fact that they possess more balanced properties in the out-of-plane direction, and at the same time high stiffness, strength and resilience. They usually also have lower fabrication costs and are easier to handle in production environments than traditional tape laminates.

The composite stiffened panels are widely used in aeronautical industry. For this type of panels, usually the buckling load does not represent the maximum load that the structure can carry, and failure may not actually occur until the applied load is several times the buckling load [1]. Consequently, the post-buckling strength capacity offers significant potential for further weight saving. In the three-dimensional (3D) woven stiffened panels the through-thickness binder yarns are able to decrease the growth of delamination cracks and so 3D woven stiffened panels can resent increased delamination resistance [2]. This combination of factors has caused the increasing interest of woven stiffened panels in load-bearing structures.

Several authors have written on the subject of the optimisation of composite stiffened panels, aiming at creating the lowest possible weight based on geometric [3-4] and stacking sequence optimal design [5-8]. However, most of the studies focus on the optimal design of laminated composite stiffened panels, without considering 3D woven composite stiffened panels. This is an unfortunate oversight as weaving parameters and paths of 3D woven composites can significantly influence the mechanical performance of fabric composites [9-14], as well as positively affect the stiffness and overall strength of composite structures. Despite the current applications and many demonstrations of the potential use of 3D woven composites, the lack of a significant data base has also made difficult to determine the optimum weaving architecture required to provide the desired mechanical properties for a specific structural design [15].

In terms of modeling approach, due to the highly heterogeneous internal structure of 3D textile materials, with a variety of configurations more extended than traditional composites, numerous multi-scale modelling strategies [16-19] were developed to predict their mechanical behaviour. Concerning the optimization strategies, the solution to the optimisation problem of composite stiffened panels is generally obtained using genetic algorithms [20-24]. In particular, most of the researchers make use of meta or surrogate models to approximate the response of the stiffened panels in order to reduce the computational resources needed for the optimisation [1, 3, 22, 25-27].

The objective of this work is to define a fast and reliable optimisation procedure for the design of 3D woven stiffened panels with buckling and post-buckling constraints. The structural analysis presented in this paper is based on a multi-scale finite element (FE) model of woven composite stiffened panels, starting with the fibre, through to the models of yarn and textile and finishing with the complete 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 optimisation phases is used to implement the design parameterization of the woven composite stiffened panels. An approximated approach is obtained using Design of Experiments and Response Surface techniques. Response surface method techniques are used to generate the approximated structural responses of 3D woven composite to increase the computational efficiency and the applicability of the optimization process here proposed. Finally, the response surface method integrated with genetic algorithms is used to optimise the weaving parameters of a typical textile composite material, investigated during the Europen project MAPICC 3D [28].

## 2. Multi-scale model of 3D woven composites

The mechanical properties of panels made of 3D woven composites are dependent on the multi-scale internal architecture of the material. A three-scale strategy is developed inside the MAPICC 3D project [28-29] to model the effect of the lower scale inhomogeneity on the macro-scale behaviour of woven textile materials. A three-level hierarchy on micro, meso and macro scale is proposed as shown in Figure 1. Micro and meso mechanical models of woven composites are utilised to homogenise the effective elastic properties.

Then, the macro mechanical behaviour of the investigated stiffened panel under complex deformation states is obtained assuming the fabric to be a continuous medium.

A representative volume element (RVE) is used on the micro- and meso-scale to describe the textile architecture of the fibre yarns and of the textile fabrics. In particular, the constant parameters of the fibre yarns in the material are discretised in the meso-mechanical RVE and computed with a micro-mechanical RVE that determines the behaviour of the fibre bundles in the material. When the effective elastic properties of woven fabric are obtained, the textile structural analysis can be implemented based on the material data. The objective of this section is to illustrate the modelling method and the periodic boundary conditions technique of the RVE, which serve as basis of later design optimisation. The approach here adopted is applied to a specific material, i.e. Twintex 1398 used inside MAPICC 3D project, but can be fully generalized.

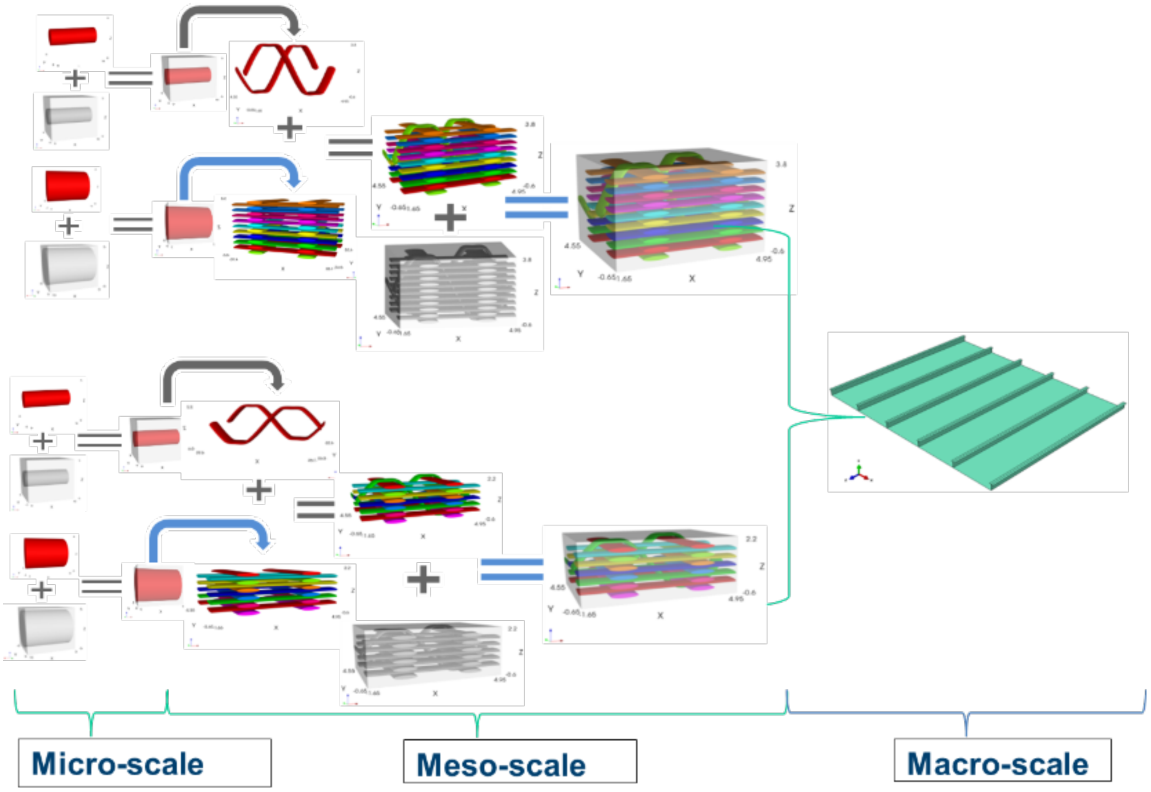


Figure 1. Multi-scale models of 3D woven stiffened panel. (qualita’ bassa)

### *2.1. Micro-level yarns homogenization*

The ladder of the 3D textile composite multi-scale modelling starts with the micro-mechanical computation. A square-arrangement unit cell is used to represent the material behaviour of matrix and loop yarn. Fibre within the yarn cross-section can be packed into a rectangular packing array, and the circular shape is used to describe the fibre cross-section of the yarn, as shown in Figure 2. It is assumed that the fibres are arranged in an even distribution with the measured volume fraction and same-average-filament diameter. Therefore, each yarn is represented by a unit cube with a single fibre having the same volume fraction. The fibres packing arrangements is illustrated in Figure 3. The material elastic properties of the fibre and the matrix are given in Table 1, while the fibre volume fraction and other basic data of Twintex 1398 and of loop yarns are reported in Table 2. Stochastic fibre arrangements for yarn irregularities are neglected. Based on the hypothesis of square packing array, fibre and matrix are assumed to be in a perfect bonding condition.

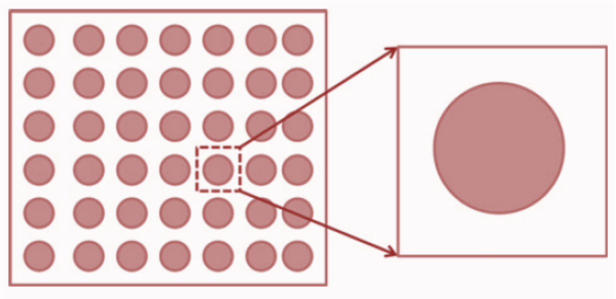
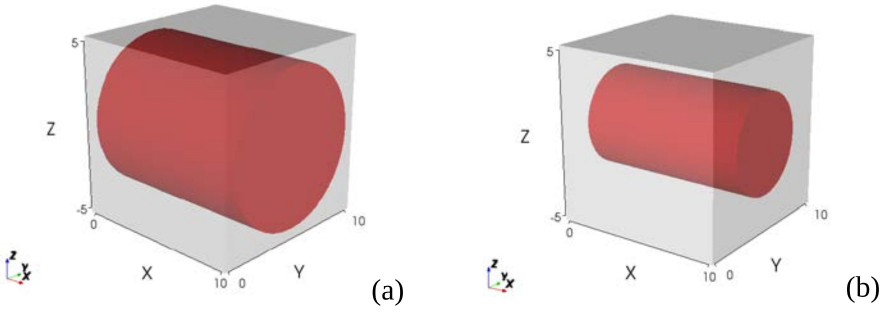


Figure 2. Square arrangement of the micro-scale unit cell.



(a) (b)

Figure 3. Fibres packing arrangements: (a) Model of yarn 1398, (b) Model of loop.

| Material | GF | PP |
|---|---|---|
| Young modulus E [MPa] | 72000 | 1350 |
| Poisson coefficient ν | 0.22 | 0.36 |
| Density ρ [kg/m$^3$] | 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

The elastic properties of Twintex 1398 and loop yarn are calculated through homogenizing RVE of the yarns, using the material data supplied by the manufacturer. The detailed homogenization process are coded in Python and implemented in the finite element commercial code ABAQUS [30], following the approach described in [31-32]. After the analysis, the effective material properties of yarn are extracted as presented in Figure 4. The obtained elastic properties of Twintex 1398 and of loop yarns are reported in Table 3.

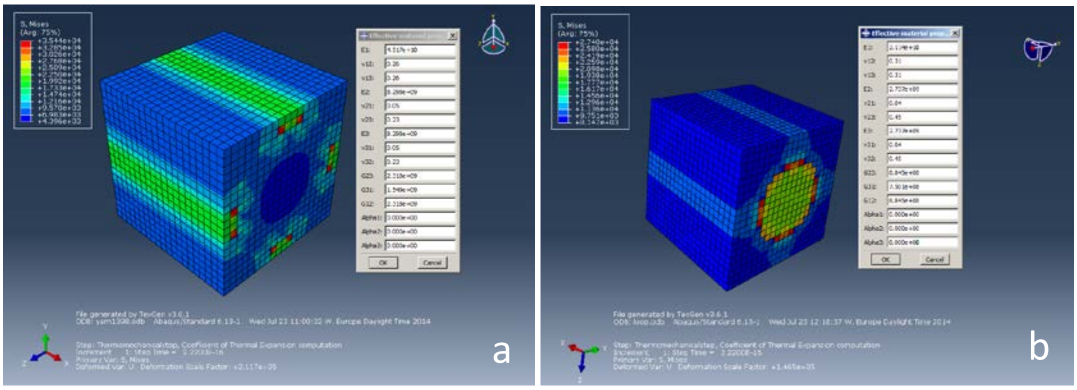


Figure 4. Material properties obtained by ABAQUS: (a) Twintex 1398 yarn; (b) Loop yarn

| | Twintex 1398 | Loop yarn |
|---|---|---|
| Volume fraction of fibre | 61.4% | 26.4% |
| Density ρ [kg/mm$^3$] | 1.93E-6 | 1.35E-6 |
| $E_{11}$ [MPa] | 45170 | 21140 |
| $E_{22}$ [MPa] | 8298 | 2737 |
| $G_{12}$ [MPa] | 2318 | 886 |
| $G_{23}$ [MPa] | 1549 | 750 |
| $v_{12}$ | 0.26 | 0.31 |
| $v_{23}$ | 0.23 | 0.45 |

Table 3. Elastic constant of Twintex 1938 and loop yarns.

### *2.2. Meso-level woven composite homogenization*

The meso-scale modelling is based on the concept of homogenization and evaluates the mechanical properties of a fabric RVE, which is typically used to determine the effective stiffness of the woven. The internal architecture of the woven fabric is significantly complex as shown in Figure 5. It is difficult and time consuming to model and mesh the weaving architecture, apply the appropriate boundary condition and extract the effective elastic data. In the present case, TexGen [33] software, an open source software used for modelling the geometry of textile structures and developed at Nottingham University, is used to model the RVE and to generate the input file for ABAQUS simulations. The

TexGen program was written to give maximum flexibility to the textile model, 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 with a centreline and superimposed cross-sections.

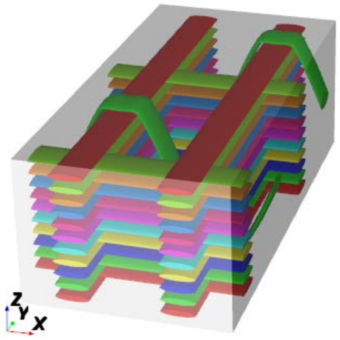


Figure 5. Model of woven composite.

The 3D FE approach towards the modelling of woven composite at multi-scale levels emerges as a powerful tool which permits the construction and representation of the fabrics, the types of contact and the geometry between weft and warp yarns [34]. The meshes of the representative volume element obtained using TexGen software are represented in Figure 6.

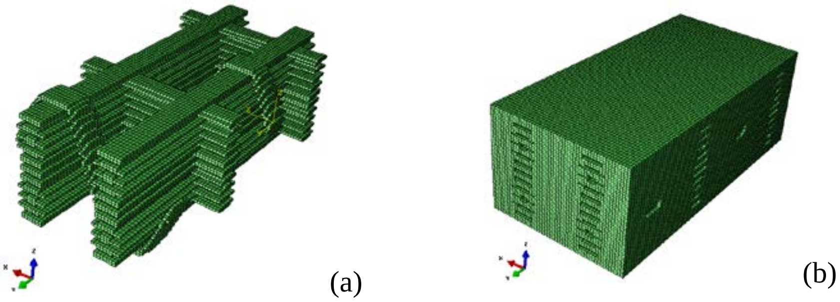


Figure 6. Mesh for woven composite: (a) for yarns; (b) for matrix.

Once the effective elastic properties of the weaving fabric RVE are extracted from the finite element analysis, the macro structural analysis can be then implemented.

## 2.3. *Macro-level buckling analysis of stiffened panel*

In analysing the buckling behaviour of stiffened panels under axial compression, the numerical process can be divided into two steps; eigenvalue analysis and nonlinear analysis. Eigenvalue analysis provides the buckling load $P_{cr}$ and the buckling mode of the stiffened panel, while the nonlinear analysis allows obtaining the data of the post-buckling region.

To simplify the optimization problem, the load-shortening curve of the stiffened panel can be linearized piecewise, as shown in Figure XX. The first two lines, of slope $K_{pre}$ and $K_{post}$ , characterize the pre- and post-buckling stiffness, respectively, that will be used as design constraints in the optimization process, together with the buckling load $P_{cr}$. Before performing the design optimisation, the minimum allowable design values $\overline{P}_{cr}, \overline{K}_{pre}$ and $\overline{K}_{post}$ are defined according to the design structural requirements.

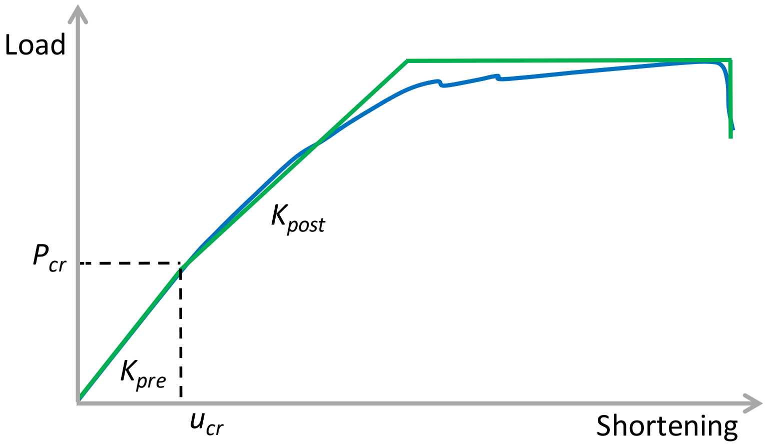


Figure XX: Typical load-shortening curve of a stiffened panel.

## 2.4. *Automatic parameterization of modelling strategy*

The development of an automated parameterization solid model and finite element meshing capability, that can link the textile microstructures to the mechanical response of the structure, is a fundamental step towards a methodology for the analysis and optimization of woven composites [35]. The strategy proposed herein aims at integrating different modelling steps and simulation tools into a holistic system that can help materials development and transform the engineering design optimisation process. The multi-scale modelling strategy begins with the identification of the matrix and interface mechanical properties to build up a ladder of the numerical simulation, which takes into account the mechanical properties at different length scales. The main feature of this strategy is the ability to carry out accurate simulations of the mechanical behaviour of composite structures without any manual intervention.

Python scripts allow the creation and modification of the shape and properties of the ABAQUS model, the submission of ABAQUS analysis tasks as well as the reading from output databases. The open source software TexGen, using its internal application programming interface (API) accessible through the Python language, is used as pre-processor of input files for ABAQUS/CAE. The combination of these two software elements is ideal for dealing with textile composite modelling and mechanical analysis problems. The application of Python script provides a clear methodology for linking the two codes. For these reasons the present approach integrated the available modelling tools TexGen and commercial finite element software ABAQUS into a multi-scale strategy capable of simulating properties and performance of different multi-scale modelling simulations.

In the present study the Python scripts are run within the ABAQUS/CAE interface, which is able to call TexGen library functions, scripted in Python, without intervention from the user. A standardised procedure can be defined to complete the whole task to create the geometry, generate the mesh, define the weaving architecture, apply the appropriate boundary conditions, and extract the finite element analysis results to be exported to the next scale analysis process. The Python code not only integrates multi-scale analysis, data extraction and transmission but also automatically repeats this analysis process according to the required optimisation needs. This point is of significant importance for the implementation of the optimisation using Genetic Algorithms (GA).

## 3. Definition of optimization problem

### *3.1. Geometry of stiffened panel*

The stiffened panel here considered to be analysed and optimized is a T-shape stiffened panel made of woven glass fibre composite subjected to axial compression loads. The model of the composite panel with four equally spaced T-type stiffeners is presented in Figure 7. The panel presents a width of 840 mm and length of 700 mm. Stiffeners are placed on external edges to avoid edge buckling. The length 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 Figure 8. There are 4 weft layers yarns in the skin and 12 in the stiffeners.

The upper and lower edges of the stiffened panels are simply supported while the longitudinal edges are free. The load condition is axial compression.

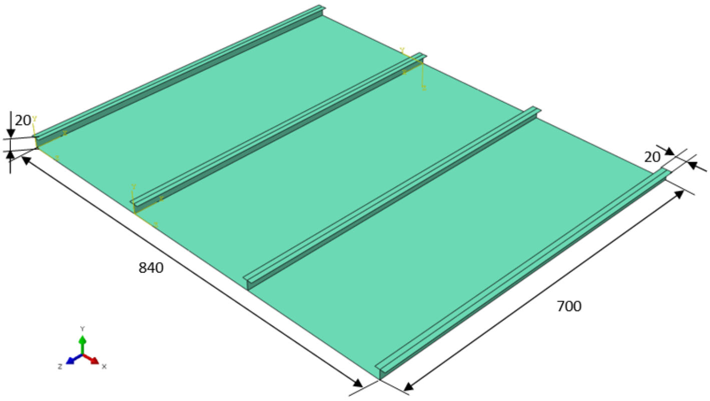


Figure 7. Dimensions of the woven composite stiffened panel.

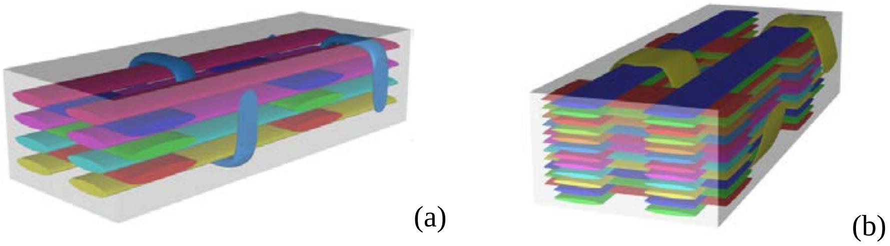


Figure 8. Architecture of 3D weaving pattern:

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

### 3.2. Design variables and optimization objective

The objective of the present investigation is to minimise the mass of a considered stiffened panel subjected to buckling constraints [36]. The weaving parameters are introduced as design variables of the optimisation problem. They are shown in Figure 9, and are: $X_1$, 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; $X_6$, and the widths of loop yarns. The domain of the design variables is reported in Table 4.

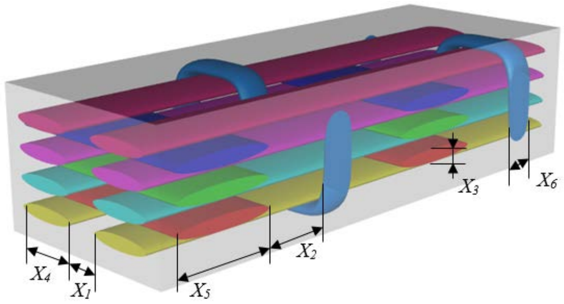


Figure 9. Geometrical parameters of weaving composite.

| 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 4. Domain of the design variables for the optimisation.

The mass of the stiffened panel is a function of the design variables, and can be expressed in function of the density and the thickness of the representative volume elements.

The objective of the optimization is to minimize the mass of the stiffened panel, respecting the minimum allowable design values $\overline{P}_{cr}, \overline{K}_{pre}$ and $\overline{K}_{post}$.

## 4. Approximation models

Despite rapid increases in computer processing, the structural optimisation still faces high computational costs and time constraints. This is due to the significant increase in the required fidelity and complexity of the analysis models. In the current investigation, the optimisation design of woven composite stiffened panels depends on multi-scale analysis models and genetic algorithms, which are both time-consuming and request several iterations in order to obtain the optimal design. The Response Surface Methodology (RSM) is used in this work to approximate the behaviour of the composite stiffened panel.

Response surface methodology (RSM) involves the Design of Experiments (DOE) strategy to achieve adequate and reliable measurement of the response of interest [37]. It consists of a collection of mathematical and statistical techniques useful for the modelling and analysis of problems in which a solution is influenced by several variables and the objective is to optimise this solution. Through careful design of experiments, the objective is to optimise an output variable which is influenced by several independent input variables. An experiment is a series of tests in which changes are made to the input variables in order to identify the reasons for changes in the output response. It was originally developed by Box and Wilson in 1951 [38]. RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces. If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, x_3, \cdots \cdots, x_k) \tag{1}$$

where $y$ is the solution of the system, and $x_k$ is the design variable. The goal is to create the response variable $\hat{y}$. An important assumption is that the independent variables are continuous and controllable by experiments with negligible errors. The task is then to find a suitable approximation for the functional relationship between the independent variables and the response surface.

Box-Behnken designs (BBD) [39] are a class of rotatable or nearly rotatable second-order designs based on three-level incomplete factorial designs. Box-Behnken Design is almost uniform in its precision of estimates, but usually fewer runs are required than for the central composites design approach. It is for this reason that BBD is used in the present study to design the experiments.

The experimental design is evaluated for the 6-dimensional space of the design variables using second order polynomial functions for approximation. In particular, 54 sample points of design are defined using SAS_JMP software for Box-Behnken designs [39].

The regression process involved in generating an approximation model yields unique insight into the design parameters. At each sample point, the real responses of composite stiffened panel are calculated using the developed multiscale finite element analysis models. The response surface approximations are constructed by employing all the data. Assuming that all variables ($k = 6$) are continuous, the approximations $\hat{y}$ (here Pcr, Kpre, Kpost) are performed by second order polynomial functions:

$$\hat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

The second-order model contains L= (k+1)(k+2)/2 coefficients. For six variables, the total number of coefficients is 28. However, some quadratic items are omitted in order to improve the prediction accuracy of the response surface according to the significance of the estimated parameters.

Because of the cost of non-linear buckling analysis, a response surface is built for the critical load of the stiffened panels. Surrogate models for pre-buckling and post-buckling stiffness are also created. The fit of the used coefficients, evaluated using the standard and adjusted correlation coefficient ($R^2$, adjusted $R^2$) is satisfactory, as shown in the parameters estimates of Table 6.

| | $R^2$ | Adj $R^2$ |
|---|---|---|
| Fit of pre-buckling stiffness | 0.986 | 0.983 |
| Fit of post-buckling stiffness | 0.968 | 0.962 |

Table 5. Fit of post-buckling stiffness.

## 5. Structural optimisation results and model verification

Once the accurate surrogate models of composite stiffened panel are obtained by the response surface method, genetic algorithms (GA) [40] are adopted to optimise the weaving parameters of the composite laminate under the buckling constraints. GA are a stochastic global search and optimisation method that mimics natural biological evolution. 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 and evolutionary algorithms to solve large and complex real-world design problems, and is here used to perform parameters optimisation for textile composite designs [41]. In the current 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 response surface method to minimise the computational effort.

### 5.1. *Optimisation*

The objective of the optimisation problem is to find the minimum possible mass of the stiffened composite panel. The constraints are:

$P_{critial}(x) > 8000, K_{pre}(x) > 20000 \text{ and } K_{post}(x) > 7500$

The population is initialized with 100 individuals, randomly generated in the 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 stop criterion is defined by allowing a maximum number of 40 generations without improvement.

### 5.2. *Optimisation results*

The best fitness is obtained after the evolution of 30 generations. The mass results equal to 2.60 kg as shown in Figure 10. The optimized data are compared to those ones of the initial design in Table 6. Comparing the mass of the optimum design and the initial design, 47% of the total mass of the composite stiffened panel is saved but is must be pointed out that the initial design was not optimized yet.

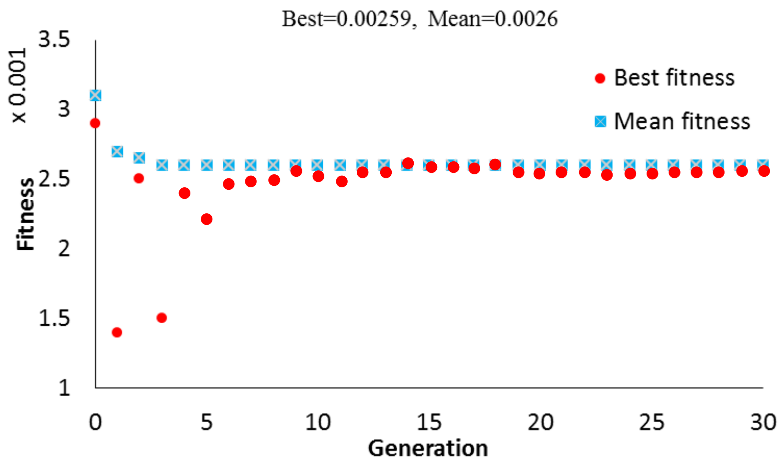


Figure 10. Optimisation results: fitness function versus generations.

| | Constraint | Initial design | Design by RSM |
|---|---|---|---|
| $x_1$ [mm] | 0-1 | 0 | 1 |
| $x_2$ [mm] | 0-1 | 0 | 0.38 |
| $x_3$ [mm] | 0.1-0.5 | 0.1 | 0.27 |
| $x_4$ [mm] | 0.4-2 | 2 | 2 |
| $x_5$ [mm] | 0.4-2 | 2 | 1.4 |
| $x_6$ [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 | 16500 |
| Mass [kg] | | 4.9 | 2.6 |

Table 6. Comparison between initial design and optimum design.

### *5.3. Model verification*

In order to guarantee that the optimisation procedure is reliable, a finite element analysis of the optimal panel configuration is carried out to verify that the behaviour meets the design requirements. At the optimal design point, the critical buckling parameters obtained by response surface based on Box-Behnken strategy are compared with the ones obtained by the multi-scale analysis in Table 7. The differences for what concerns the critical load and the pre-buckling stiffness are limited to 4%, while the one of the post-buckling stiffness is equal 19.6%. This is mainly due to the highly non-linear behaviour that strongly depends on the evolution of load-shortening path in the deep non-linear region. The buckling mode obtained by the eigenvalue analysis and load-shortening curve obtained by the non-linear analysis are shown in Figure 11 and 12, respectively. Four out-of-plane deformed shapes of the optimised panel at different shortened displacements are illustrated in Figure 13.

| | Box-Behnken designs | Multi-scale FE validation | Difference |
|---|---|---|---|
| Critical load [N] | 8000 | 8335 | 4% |
| Pre-buckling stiffness [N/mm] | 20000 | 20562 | 2.7% |
| Post-buckling stiffness [N/mm] | 16500 | 13799 | 19.6% |

Table 7. Comparison between Box-Behnken design and multi-scale FE validation.

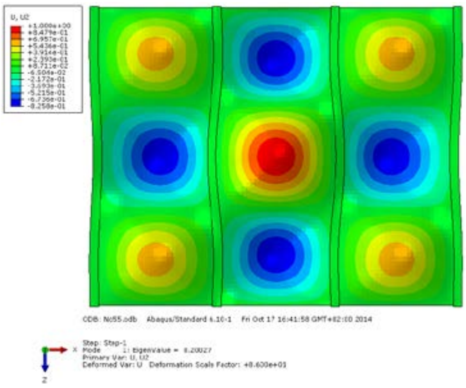


Figure 11. Eigenvalue analysis result: first buckling mode.

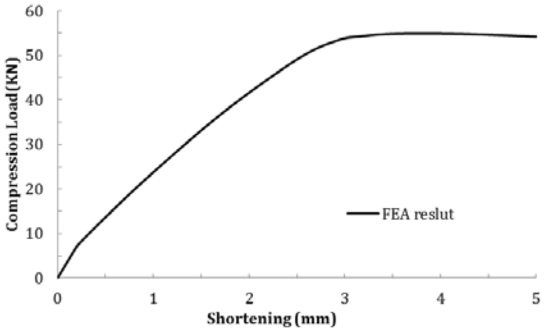


Figure 12. Load-shortening curve of optimised stiffened panel.

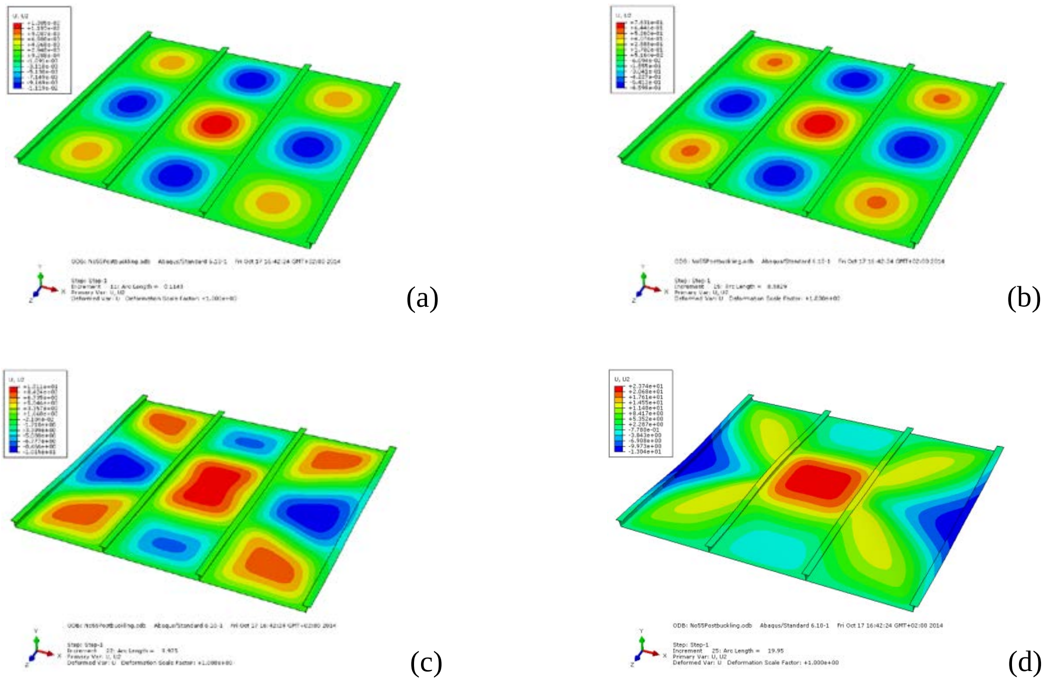

(a)
(b)
(c)
(d)

Figure 13. Deformed shapes of optimised stiffened panel: (a) Shortening = 0.1mm; (b) Shortening = 0.2 mm; (c) Shortening = 2.5 mm; (d) Shortening = 4 mm.

## 6. Conclusions

This paper presents a fast and reliable optimisation procedure for the design of stiffened panels made of 3D woven composite subjected to buckling and post-buckling constraints. The procedure is based on the combination of multi-scale finite element analysis, design of experiment, response surface approximation and genetic algorithms.

A three-level hierarchical modelling strategy is proposed to predict the mechanical behaviour of 3D woven composite stiffened panels, including micro level (fibres-yarns), meso level (yarns-fabric), and macro level (fabric-panels). A representative volume element presenting the characteristics periodically repeated pattern in the fabric weave is isolated and modelled to homogenize the effective mechanical stiffness of yarns and woven fabric.

To limit the total number of detailed finite element analyses an approximated problem used design of experiments and response surface techniques. Design of experiments are implemented to definite the sample points for six design factors problem. Box-Behnken designs are performed to construct the response surfaces of the critical load, as well as the pre- and post-buckling stiffness of the stiffened panel.

A modelling strategy is here proposed covering all the necessary phases, i.e. finite element modelling, multi-scale analysis and optimisation. The automatic parameterisation modelling and the analysis process is achieved by means of Python scripts interface TexGen and ABAQUS software, as well as ad hoc developed scripts written in Matlab language for the optimisation. The optimizing procedure is implemented using genetic algorithms based on the approximation models obtained from the Box-Behnken designs.

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

The optimal configuration of the stiffened panel is verified using finite element analysis. The critical load and the load-displacement curve are accurately predicted by the proposed multi-scale finite element analysis method. The proposed optimisation strategy results to be an efficient and reliable method for the optimisation of 3D woven composite structures in the preliminary design stages.

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