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DESIGN OF A LAMINATED COMPOSITE MULTI-CELL STRUCTURE SUBJECTED TO TORSION

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Abstract

Laminate composite multi-cell structures have to support both axial and shear stresses when sustaining variable twist. Thus the properties and design of the laminate may not be the most adequate at all cross-sections to support the torsion imposed on the cells. In this work, the effect of some material and geometric parameters on the optimal mechanical behaviour of a multi-cell composite laminate structure is studied when torsion is present.
A particle swarm optimization technique is used to maximize the multi-cell structure torsion constant that can be used to obtain the angle of twist of the composite laminate profile.

1 Introduction

Laminated composite multi-cell structures are widely used in the construction of aircraft wings. This type of structure is often a thin-walled structure which provides a good mechanical performance with a low weight, which is very desirable and also very important for this type of applications. As such, the study of these structures requires not only the use of thin-walled theory but also of multi-cellular structures and of laminated composites analysis.

Analysis of thin-walled multi-cell structures can be found in several publications. Among other authors, Oden and Ripperger [1] refer that when subjected to torsion these structures develop an additional shear flow associated with the multi-cell effect that cannot be obtained by statics. This means that a statically undetermined problem of $n+1$ degree needs to be solved, considering a structure with n cells. Thus not only equilibrium issues have to be ensured, but also strain compatibility among the cells has to be considered assuming deformation consistence. According to this, besides the geometrical configuration of the section, the section material distribution is also determinant, namely the laminated elements constitution [2,3]. Another issue introduced by the number of cells in section is the determination of the shear stress in the boundary of a closed-section. This problem was considered by Yoo et al. [4] and these authors concluded that if a wider multi-cell cross-section is considered, the classical method may underestimate the maximum shearing stress developing in the cross-section.

Adding a laminated composite to the complexity of the analysis of thin-walled multi-cell structures introduces an even greater complexity to the problem. The material properties, and consequently the behaviour, along the cross-section of the structure are not constant, for instance, the stiffness of the section is dependent on the geometry of the section and also on the individual cell's stiffness [2]. The coupling problem when bending and torsion loads are applied to this type of structures is studied by Lee et al. [5]. A general analytical model was developed based on the classical lamination theory and several stacking sequences on the webs and the flanges of an I-beam subjected to torsion are studied. It is inferred that the stacking sequence has considerable influence in the behaviour of the beam. This study was extended to closed-section thin-walled composite box beams [6] and similar results are obtained.

Considering their layup, laminate composite multi-cell structures have to support both axial and shear stresses when sustaining variable twist. This is a problem with some complexity, as the properties and design of the laminate may not be the most adequate at all cross-sections to support the torsion imposed on the cells. Optimization approaches have long been used to study complex structures and behaviours. However, from the literature review carried out, as far as to the author's knowledge, there are no optimization studies specifically oriented to the maximization of the torsional rigidity. Therefore in this work we will consider Particle Swarm Optimization (PSO) to this purpose. This approach was proposed and developed by Kennedy and Eberhart [7] and it is inspired by swarm intelligence, where the behaviour of the individuals, or particles, affects the collective behaviour of the population. The global optimum solution is reached through the position and velocity of the individuals that move iteratively in the search space according to a cognitive knowledge of the individual and a social interaction between individuals of the swarm. This technique has continued to evolve with new versions and new applications and theoretical studies [8,9]. Fourie and Groenwold [10] presented a study on the application of PSO technique to the optimal size and shape design problem. These authors showed that, in terms of performance, the PSO technique compares better than that of a Genetic Algorithm, with the same kind of computational effort of a gradient based recursive quadratic programming algorithm. Therefore, it is considered suitable for structural optimization problems. The PSO technique has been further improved by authors such as Venter and Haftka [11] that introduced an approach for dealing with constrained PSO where the constrained, single objective problem is converted into an unconstrained, bi-objective problem and it is solved by implementing a multi-objective PSO algorithm. Chang et al. [12] proposed a permutation discrete particle swarm optimization that was used to optimize the stacking sequence of a composite laminate and showed improved computational efficiency. In the work by Kathiravan and Ganguli [13], the PSO technique is used to obtain the optimum design of a composite box-beam structure subject to strength constraints. The results obtained by the PSO technique are compared with gradient based results and it was demonstrated that PSO provides globally better designs. Suresh et al. [14] use the same application to compare PSO results with genetic algorithm results in a multi-objective optimization problem. The PSO technique not only provides better results but also uses less computational time than the genetic algorithm approach in agreement with the work by Fourie and Groenwold [10].

The objective of this work is to characterize the effect of some material and geometric parameters on the optimal mechanical behaviour of a multi-cell composite laminate structure when torsion is present. This study will be done by applying a particle swarm optimization technique to maximize the multi-cell structure torsion constant which can be further used to obtain the angle of twist of the composite laminate profile. The optimal solution profile will be discussed.

2 Laminated composite multi-cell beam

The effects of the application of a torsional load to laminated composite beam structures with thin-walled multi-cell section are studied in this work. To accomplish this, the preliminary formulation of the equivalent shear stiffness or shear compliance is required because the torsional rigidity of a thin walled closed section is dependent not only on the geometric characteristics but also on the lamination of the composites used on different locations of the section studied.

The materials considered for the plies were assumed to be orthotropic. However, due to the nature of the problem, a simplified plane stress constitutive relation was used.

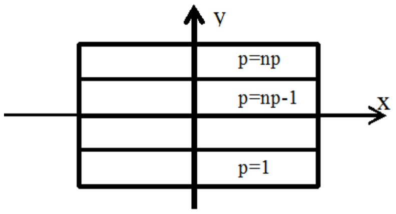

Fig. 1. Layout of a general composite laminate (p – ply; np – number of plies)

Additionally, it was considered that the laminates (Fig. 1) would be symmetric about their mid-planes thus being possible to neglect coupling effects. Therefore the reduced laminate constitutive equations [2] can be written as:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{12} & A_{22} & A_{23} \\ A_{13} & A_{23} & A_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{12} & D_{22} & D_{23} \\ D_{13} & D_{23} & D_{33} \end{bmatrix} \begin{bmatrix} \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{bmatrix} \quad (2)$$

where the stiffness coefficients A_{ij} and D_{ij} are:

$$A_{ij} = \sum_{p=1}^{n} t_p \left(\bar{Q}_{ij}\right)_p \quad (3)$$

$$D_{ij} = \sum_{p=1}^{n} \left\{ t_p \bar{z}_p^2 + \frac{t_p^3}{12} \right\} \left(\bar{Q}_{ij}\right)_p \quad (4)$$

By inverting these relations, the compliance relationships are obtained:

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} \\ d_{12} & d_{22} & d_{23} \\ d_{13} & d_{23} & d_{33} \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} \quad (6)$$

with a_{ij} and d_{ij}, the membrane and bending compliance coefficients, respectively. In the present work, where only closed cells sections submitted to torsion moments are considered, there is typically a membrane-type answer at the wall's thickness level. So the required equivalent properties must correspond to this specific situation, no matter the number of cells within the cross-section. According to this, the equivalent elastic constants [2] will be obtained as:

$$\begin{aligned} &E_x = (t\, a_{11})^{-1}; E_y = (t\, a_{22})^{-1}; \\ &G_{xy} = (t\, a_{33})^{-1} \\ &\nu_{xy} = -(a_{12})(a_{12})^{-1} \end{aligned} \quad (7)$$

where t represents the thickness of the laminate and E_x, E_y, G_{xy} and ν_{xy} have the usual physical meaning. The solution of an unconstrained twist of a multi-cell section is obtained through Bredt's relations. So, in a static equilibrium situation, when the section is subjected to a moment of torsion M_t, it is given by:

$$M_t = 2 \sum_{i=1}^{nc} \Omega_i q_i \quad (8)$$

where M_t is the moment of torsion, nc is the number of cells in the cross-section, Ω_i is the area within the midline of cell i, and q_i is the shear flow in cell i. The twist rate for each cell in a multi-cell section can be written as:

$$\frac{\partial\theta}{\partial z} = \frac{1}{2\Omega_i} \left\{ q_i \oint_{Si} \frac{ds}{G_{xy}^S t_S} - \sum_{j=1}^{mc} q_j \oint_{Sij} \frac{ds}{G_{xy}^S t_S} \right\} \quad (9)$$

where mc is the number of common elements among adjacent *i-th* and *j-th* cells, t_s is the thickness of an element of length s. According to the deformation consistence principle, the rate of twist of each cell within a section, is the same and equal for all the cells, as:

$$\frac{\partial\theta_1}{\partial z} = \frac{\partial\theta_2}{\partial z} = \cdots = \frac{\partial\theta_{nc}}{\partial z} = \frac{\partial\theta}{\partial z} \quad (10)$$

Equation (10) constitutes a system of nc compatibility equations. Knowing that torque is given by:

$$M_t = G_{xy} J \frac{\partial\theta}{\partial z} \quad (11)$$

where G_{xy} is the shear modulus and J is the torsion geometric constant of the section, the torsional rigidity of the section, $G_{xy}J$, may now be written as:

$$G_{xy} J = 2 \sum_{i=1}^{nc} \Omega_i q_i \left(\frac{\partial\theta}{\partial z}\right)^{-1} \quad (12)$$

The objective of the present work is to optimize the torsional rigidity to ensure that the maximum angle of twist will not exceed an admissible value.

3 Optimization procedure

A Particle Swarm Optimization procedure is used in this work to design a laminated composite multi-cell thin-walled section. This procedure, that has been used to successfully solve a wide variety of problems in different fields [15-20], was developed by James Kennedy and Russell Eberhart [7] and it uses the idea of swarm intelligence to solve the optimization problem. The idea behind this optimization technique is that the behaviour of the individuals, or particles, of a population affects the collective behaviour of the population. This is considered a characteristic of the system, known as swarm intelligence. A detailed description of this optimization technique and an enhanced approach of it, considering a re-initialization strategy and a "keep the best" particle strategy, can be consulted in Loja [20].
In the present study, the objective is to maximize the torsional rigidity when a defined twist angle in the section is verified subjected to the variable constraints. These variables are the stacking sequence of the laminate and the width of the cells in the cross-section of the beam.

4 Application

The work presented in this paper is a preliminary study on the design of a laminated multi-cell thin-walled section subjected to unconstrained torsion.

This study intends to analyse the influence of the layers fibre orientation, stacking, as well as the influence of different number of layers in different elements (webs and flanges), on the torsion rigidity of the section which is to be maximized. Also, the symmetry of the section will be studied in terms of its influence on the section behaviour.

4.1 Validation Case

The procedure used in this work is validated using an example from Murray [3]. In this example, a beam with a rectangular three cell cross-section, shown in Fig. 2, is subjected to a torsion moment of 1000 N.mm.

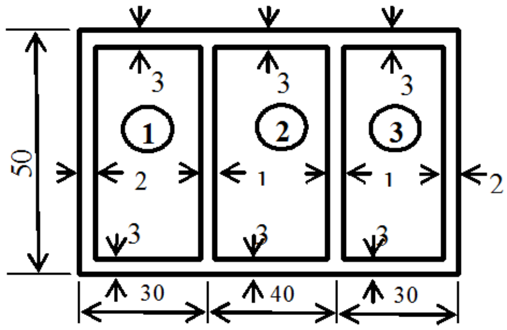

Fig. 2. Cross-section of the beam of the validation case

The beam is made of an isotropic material and for this case it was intended to obtain the shear modulus G_s of the cross-section as well as the torsion geometric constant *J*. The dimensions are expressed in mm (as well as in further figures) and the material properties are presented in Table 1.

E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
140	10	80	0.3

Tab. 1. Material properties of the beam used for the validation case

As can be seen in Tab. 2, the same values for the shear modulus and for the torsion geometric constant of the section were obtained when compared with the reference solution.

	Murray	Present
G_s [MPa]	80000	80000
J [mm^4]	881516.6	881516.6

Tab. 2. Shear modulus and torsion geometric constant of the section for the validation case

4.2 Application Case

The study performed for this work used a multi-cell section that has a rectangular configuration with three rectangular cells, as shown in Fig. 3. This section is loaded so that a twist angle θ=1° occurs. The material properties of the composite used are presented in Tab. 3.

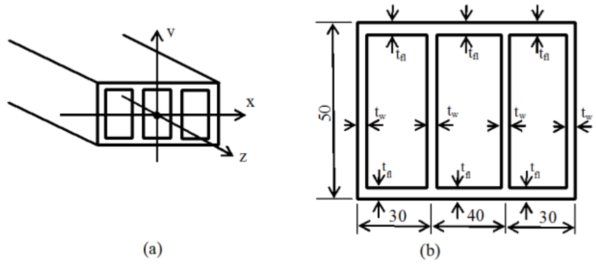

Fig. 3. Rectangular three-cell section. (a) Global axis orientation; (b) Cross-sectional area

Tab. 4 presents the optimization parameters used, namely the population size, the number of iterations carried out and the number of re-initializations considered. The cognitive and social factors (c1, c2) as well as the inertia weight (w) and the constriction factor (K) are fixed.

E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12}
140	10	5	0.3

Tab. 3. Material properties of the composite in the application case.

Population	Iterations	Reinitialize	c1	c2	w	K
50	100	50	2	2.5	0.7	1

Tab. 4. Optimization parameters used in the application case.

In the first study performed, the objective is to understand the influence of the number of plies in the laminate considering that all the walls would have the same number of plies. The laminates are symmetric and the thickness of each ply is equal to 0.125 mm. Tab. 5 presents a summary of the results obtained. It should be noted that in the column "Nb. Eval.", we denote the number of the objective function evaluations, required to achieve the best solution.

The case where only 4 plies are considered in the laminate is the one that yielded the best optimal value for the objective function of the problem. However, this may be only an indication that for higher number of plies in a laminate, thus for a higher number of design variables, we will need more iterations to find better solutions. For the 8- and 12-ply laminates, the optimization procedure had to be re-initialized to obtain better results and that was not case for the 4-ply laminate thus reinforcing the previous idea.

Lami-nate	Nb. Eval.	Optimum [N.m^2]	Best solution	
			Web [(°)$_S$]	Flange [(°)$_S$]
4-ply	16289	3869.646	-49.6/48.9	90/31.6
8-ply	11839	2913.315	90/-31.0/ -44.4/37.8	-90/90/ 24.4/90
12-ply	9760	2574.654	90/-50.7/ -51.6/ -18.3/ 90/37.9	-78.5/-90/ 90/90/ 43.9/90

Tab. 5. Optimal results for N-ply laminates with same number of layers on flanges and webs.

Concerning the stacking sequences obtained for the best solution, it is noted that different combinations are obtained for the laminates in the webs and in the flanges. This is a consequence of the response of the different elements in the section to the loading case.

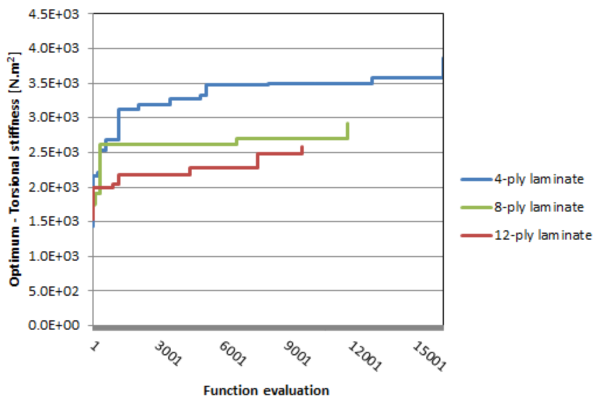

Fig. 4. Evolution of the optimum value (Identical number of plies in all section)

The profiles associated to the different cases studied in the optimization process evolution for this first study are shown in Fig. 4. As expected, the simpler problem is the fastest to converge while the others are slower and do not obtain such a good optimum. The 12-ply laminate problem gets an optimum value similar to the one obtained by the 8-ply laminate problem with a faster convergence.

In the second optimization case considered, different number of plies in the flanges and in the web laminates were permitted. Again, the orientations of the fibres were taken as design variables and the same material properties and optimization parameters (shown in Tables 3 and 4) were used. The results obtained are presented in Tab. 6 and it may be observed that, when the flanges and the webs do not have the same number of plies, the convergence is faster than when compared to a case where the webs and the flanges have the same number of plies (see Tab. 5), for the reasons already mentioned, as shown by the number of function evaluations needed to obtain the best solution (column "Nb.Eval.").

Design Var.	Nb. plies		Nb. Eval.	Optimum [Nm^2]	Best solution	
	Webs	Flanges			Web [(°)s]	Flange [(°)s]
6	8	4	8025	3501.223	32.9/ -44.1 /-90/ -57.2	90/ -40.6
6	4	8	6310	3123.076	-52.8 /62.1	48.3/ -36.2/ 90/90

Tab. 6. Optimal results for beams with different number of plies in laminates on flanges and webs

It may also be noted that between the cases studied with different laminates in the webs and flanges of the section, the case where the flanges have a higher number of plies, thus also a higher thickness, resulted in an improved solution and a faster convergence to the solution.

Starting width	cell 1	0.0300	0.0300	0.0280	0.0200	0.0200
	cell 2	0.0400	0.0400	0.0430	0.0350	0.0350
	cell 3	0.0300	0.0300	0.0290	0.0450	0.0450
Range		-0.1*W … +0.1*W	-0.2*W … +0.2*W	-0.1*W … +0.1*W	-0.1*W … +0.1*W	-0.2*W … +0.2*W
Nb. Eval.		6413	5312	103	4713	3615
Optimum		6741.27	6817.92	6813.23	6767.94	7441.8
Best solution	Webs [(°)s]	51.9/ -46.5	36.3/ -33.9	-51.1/ 48.1	-43.4/ 51.1	45.5/-41
	Flanges [(°)s]	-90/90	-44/-90	-90/-90	90/90	-50/90
	cell 1	0.0330	0.0360	0.0308	0.0220	0.0240
	cell 2	0.0340	0.0280	0.0384	0.0285	0.0220
	cell 3	0.0330	0.0360	0.0308	0.0495	0.0540

Tab. 7. Optimal results for beams with different starting sections

The stiffness of the section also depends on the section itself. An optimization study was performed to the section considering the orientations of the fibers in the webs and flanges and the width of the cells as design variables. The webs and flanges of the section have 4 plies but different orientation is allowed. However, considering the results from the previous study, the thickness of the plies was increased to 0.250 mm in order to improve the stiffness of the section while guaranteeing a faster response. As expected the optimization procedure yields a symmetric section with a narrower middle cell, as shown in Tab. 7. When the initial configuration is non symmetric, the procedure is not able to achieve symmetry because of the restriction on the allowable movement of the internal flanges (Tab. 7 – see range, a percentage of the width of the cell) but the final configuration shows that the outer cells are wider than the middle one thus increasing the torsional rigidity of the section. If the initial configuration is almost symmetric, the optimization procedure converges rapidly to the symmetric configuration. It can also be observed in Tab. 7 that, for the same starting section, if the range is larger, a better solution is attained and it is faster.

Starting section	cell 1	0.03
	cell 2	0.04
	cell 3	0.03
Nb. Evaluations		206
Optimum [Nm2]		19003.7
Best solution	Web [(°)s]	47.7/-51.9
	Flange [(°)s]	-56.2/90
	cell 1	0.033
	cell 2	0.034
	cell 3	0.033

Tab. 8. Optimal results for beams with different thicknesses of the plies on flanges and webs

If the initial section is symmetric but the inner flanges have different thickness from the outer flanges, then a better solution is obtained as can be seen in Tab. 8. For this study it was considered that the inner flanges were thinner than the outer ones which in turn were thinner that the webs. The solution was restricted to

10% of the initial width of the cells, resulting in a symmetric section with a torsional rigidity much higher than the previous studies. This indicates that this type of section will be better suited for resisting torsion.

5 Conclusions

The design of a laminated composite multi-cell section with thin walls submitted to torsion using an optimization scheme by means of the Particle Swarm technique was presented. The objective function to be maximized is the torsional rigidity of the cross-section.

A preliminary study was presented showing the influence of the number of plies in the laminate configuration on the torsional rigidity of the section. As expected, a smaller number of plies in a laminate provide a faster convergence of the optimal solution. The maximum torsional rigidity of the section diminishes when increasing the number of plies in the laminate.

Considering different number of layers in the laminates associated to the flanges or the webs of the section results in a better result for the section stiffness when a higher number of constant thickness' plies is used in the flanges. A better convergence is also obtained on those conditions.

When looking at the influence of the section, the optimization procedure produces a symmetric section with the middle cell narrower than the outer cells. Also, the thickness of the flanges has a great impact on the torsional rigidity of the section, thus allowing for better results. It seems to be the right direction to improve the design of a section subjected to torsion.

This study is a preliminary study that will be improved to consider the influence of other section parameters. However the results obtained, qualitatively agree with the expected behaviour of this type of sections.

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