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Weight optimisation of damage resistant composite panels with a posteriori cost evaluation

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ABSTRACT

In the present paper, we attempt a novel optimisation strategy for damage resistant composite stiffened panels based on genetic algorithms and oriented towards the satisfaction of minimum weight criteria. In order to accomplish this task, first, minimum weight solutions for panel configurations with T and I stringers, satisfying the buckling resistance constraint are examined. Some minimum weight solutions are imposed to be *buckling resistant only*, that is, capable to sustain a given minimum admissible buckling load, while other solutions are imposed to be *buckling and damage resistant*, in other words, capable to sustain a given admissible buckling load being at the same time able to resist to a given impact energy without developing significant damage.
Then a-posteriori evaluation of costs is performed for the best minimum weight solutions. Such an evaluation takes, at the same time, into account the manufacturing costs, which depend on the selected manufacturing process and on the geometrical configuration, and the maintenance costs which are related to impact events and consequent repairing actions. Finally, the influence of the impact damage and buckling resistance constraints on the stiffened composite panel's costs is critically discussed providing useful considerations oriented to a cost effective composites design.

1. Introduction

Safety requirements are mandatory for aerospace structures; however, modern design approaches should properly consider also weight and cost reduction as fundamental targets. In particular, the reduction of costs, apart from being a mere consequence of the weight reduction (increase in payload), should pass through an effective optimisation of the global aerospace component structural costs which are related to manufacturing and maintenance (including repair) aspects.

A consistent weight reduction can be achieved by adopting composite materials which allow to build very light structures, compared to those made of classical metal-based materials [1]: moreover, owing to the fact that composite materials can be tailored to give specific properties, the weight savings can be in principle accompanied by a consistent increase in strength and stiffness. In other words, high values of strength-to-weight and stiffness-to-weight ratio can be achieved by using composite materials.

However, the successful application of composite materials to aircraft structures is somewhat limited by

– high manufacturing costs, due mainly to the high costs of the entire production process,
– high maintenance and repair costs due respectively to the complexity of monitoring and repair techniques,
– poor knowledge of damage mechanisms occurring in composite materials and lack of affordable procedures for damage tolerant design.

Generally speaking [2], composites are poorly tolerant to overload and are susceptible to local damages which may grow under the action of *in-service loads*.

Damage in composites may be introduced by accidental impact loads, even though flaws or defect may exist due to the manufacture process. When damage is detected, repair actions are usually characterised by relevant costs.

Thus, when designing composite structures, the optimisation of structural costs becomes of main concern and even mandatory in order to provide affordable solutions especially with respect to damage management aspects. In particular, damage resistant [3–5] and damage tolerant [6–8] design approaches should be adopted in order to lower the maintenance costs during the in-service life, providing respectively, composite structures able not to develop relevant damages under certain loading condition and once damaged, able to sustain the in-service loads without an increase of damage size.

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Among the several composite components normally adopted in aerospace, the wing and the fuselage stiffened panels can mainly benefit from a structural cost optimisation because they are susceptible to impact damage and to the consequent damage growth under compressive loading conditions.

The literature lacks of papers dealing with the optimisation procedures for composite structures. Some examples can be found which respect structural criteria *only* and concern un-stiffened panels [9–11] with some attention paid to weight saving [12].

The present paper, introduces a novel optimisation strategy for composite stiffened panels based on genetic algorithms [13,14] and oriented towards the satisfaction of the *minimum weight goal with buckling and damage resistance constraints*. This optimisation strategy will be proven to provide also cost effective structural solutions, by minimising the repair costs as a consequence of the damage resistance constraint.

The numerical applications are carried out by adopting an in-house genetic algorithm based optimisation tool [13] able to interact with the ANSYS FEM code to run the analyses needed for the optimisation process. The optimisation procedure is applied to stiffened composite panels.

First, minimum weighted stiffened composite panels, characterised by a given buckling threshold are identified; then, the search is focused on panels being both *buckling and damage resistant*. Damage resistance is here considered as the ability to not develop relevant damage as a consequence of an impact characterised by a limit energy.

In Section 2, the methodologies employed for the optimisation procedure, including the cost evaluation, are described. In the same section, a schematic overview of the adopted genetic algorithm is given, with emphasis on its suitability and affordability for the problems under consideration. In Section 3, the geometrical description of the composite panels adopted for numerical applications and their modelling are presented. Furthermore, in Section 4, the results of the optimisation of the stiffened composite panels fulfilling the specified constraints are given. Finally conclusions and possible perspectives for future research are presented.

2. Methods and FEM implementation

2.1. Genetic algorithm based optimisation procedure with buckling/damage resistance constraints

A schematic representation of the problem under investigation together with the approaches and methodologies adopted in this paper is presented in Fig. 1.

The problem consists in carrying out a weight-performance optimisation having, as an input, a certain number of design variables. In particular, the optimisation is focused on minimum weight configurations satisfying specified constraints on buckling and damage resistance.

The in-house genetic algorithm based software described in detail in [13] represents the core of the optimisation procedure. This software is able to interact with the ANSYS environment by running linearised buckling FEM analyses for the evaluation of the buckling load of the geometrical configurations under consideration. The genetic algorithm based software adopts special ANSYS macros in order to determine the damage resistance of composite structural component by applying the delamination threshold force method introduced in [15] and extended to stiffened composite panels in [16,17].

The linearized buckling FEM analysis is finalised to searching those values of the applied load/displacement for which the global stiffness $\underline{K}$ of the mechanical system becomes singular:

$$\det(\underline{K}) = 0 \tag{1}$$

relation (1), if the stiffness $\underline{K}$ is assumed to be a linear function of the applied load, reduces to a classical eigenvalue/eigenvector (buckling loads/buckling modes) problem which can be easily solved by adopting the linearised buckling ANSYS solution tool.

The ANSYS macro, written by using the ANSYS Parametric Design Language (APDL) [18], used for the evaluation of the damage resistance is based on the theory by Zhang and Davies [15], which is applicable to impact induced delaminations in laminated plates. This theory assumes that a critical impact force, P_c is able to cause delaminations in composite laminate plates. This force is given by

$$P_c = \sqrt{\frac{8\pi^2 E_r t^3 G_{IIC}}{9(1-\nu^2)}} \tag{2}$$

where E_r is the mean flexural modulus of the laminated plate, G_{IIC} is the critical energy release rate pertinent to fracture mode II, t is the laminate thickness and ν is the Poisson ratio. As a first approximation, it is possible to apply the impact load statically and to consider the material as linearly elastic. With these hypotheses, the impact induced delamination onset energy, W_{on}, can be calculated as follows [15]:

$$W_{on} = \frac{k}{n-1}\left[\frac{P_c}{k}\right]^{\frac{n+1}{n}} + \int_0^{\delta_{MAX}} P \cdot d\delta \tag{3}$$

The first member on the right side of Eq. (3) is the impact energy fraction absorbed by indentation: k is a contact stiffness and n is a constant equal to 1.5. The second member is the impact energy fraction absorbed by global deformation of the structure: it can be found by applying *statically* P_c to the structure and by finding the elastic energy/work due to this value of force. Being P_c a threshold force depending on geometry and material properties, it is possible to determine, by linear static analyses, the maximum W_{on} which keeps the impact load below P_c. This value of W_{on}, is representative of the damage resistance [17].

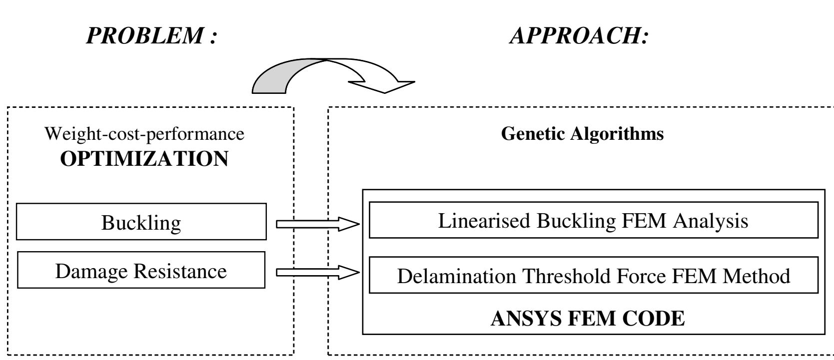

Fig. 1. Schematic representation of the adopted approaches and methods.

As already mentioned, the linearised buckling and the damage resistance analyses are managed as constraints within an optimisation procedure based on genetic algorithms and aimed to find the configurations with minimum weight.

The genetic algorithm drives, through an opportune interface, the optimisation process. In the following, some generalities about the optimisation by genetic algorithms are given in order to better understand the developed optimisation procedure.

Generally speaking, an optimisation process can be considered as the problem of finding a maximum (minimum) of a function, within a given set of parameters and under specified constraints. The problem can be formulated as follows:

$$\text{find} \quad \max \quad f(X); \quad X = (x_1, x_2, \ldots, x_N) \tag{4}$$

with

$$\underline{x}_i \leqslant x \leqslant \bar{x}_i \tag{5}$$

$$\underline{g}_j \leqslant g_i(x_1, x_2, \ldots, x_N) \leqslant \bar{g}_j \tag{6}$$

where $i = 1,\ldots,N$ and $j = 1,\ldots,M$. $f(X)$ is the target function, X is the vector of the design parameters (variables) $\underline{x}_i$ and $\bar{x}_i$ are, respectively, lower and upper bounds of the interval to which the ith variable x_i belongs and, finally, $\underline{g}_j$ and $\bar{g}_j$ are, respectively, lower and upper bounds of the jth function $g_j(X)$ which represents a given functional constraint for the problem under study.

Analytical methods, when applicable, make use of the *method of Lagrange multipliers*, which is a classical method of explicit optimisation under constraint.

However, by increasing the number of involved parameters, analytical (explicit) solutions become unpractical thus they have to be replaced by numerical based optimisation methods.

Traditional numerical based optimisation methods can be roughly divided into [12]:

- calculus-based methods,
- enumerative methods,
- random methods.

Calculus-based methods try to follow the same strategies of the traditional calculus, in other words, for an unconstrained problem, try to find a possible peak by searching for those points whose slopes are zero in all directions or, alternatively, climb the function along the steepest permissible direction.

Two main drawbacks can be singled out for such methods:

- they are local, i.e., the optima are searched in the neighbourhood of the current point,
- they depend upon the notion of smooth (regular) function, i.e., the existence of a derivative.

Thus they are not suitable for problems with many optima or when the objective functions present some discontinuities.

Enumerative methods look at objective function values at every point of a finite (or discretized) search space – one at a time. Each current value is compared with its previous and is saved if bigger (smaller). Obviously these methods are extremely inefficient, since they explore the whole search space without adopting any rational criterion.

Random search algorithms try to overcome the inefficiency related to enumerative schemes, however both are based on the same principles thus, in the long run, they do not behave much differently.

Genetic algorithms (GAs) can be defined as search algorithms which simulate the evolution of individual structures via processes of selection, mutation and crossover. In practice, they use the principle of survival of the fittest: they code a parameter set, start from a population of points and make it evolve according to a single objective selective function.

Schematically, the mechanism of GAs is as follows: starting from a initial population, the individuals climb towards an optimum which best fits a fixed requirement. The worst individuals die, the best individuals are subjected to crossover and mutation. Both crossover and mutation are driven by stochastic rules and mutation adds additional variability to the population.

Ref. [19] presents in a clear way the differences between traditional and genetic based algorithms. In fact the main advantages of GAs over the traditional optimisation procedures can be summarised as follows:

- GAs work with a coding of the parameter set, not the parameters themselves,
- GAs search from a population of points, not a single point,
- GAs use objective functions and do not employ derivatives,
- GAs use probabilistic rules, not deterministic rules.

The way the in-house genetic algorithms based procedure, adopted in the present work, interacts with the ANSYS FEM model is schematically represented in Fig. 2.

First, in the pre-processor phase, the set of design parameters (basically geometry and materials) of the selected component is coded for implementation into the optimisation algorithm; further details about parameter coding are given in the next section.

The solution phase comprises, in the more general case, linear static and linearised buckling analyses, which allow for the determination of the buckling load and the damage resistance (W_{on}). Since all the analyses are linear elastic, the computational cost of each run is low.

In the post-processing phase the buckling load and the impact energy threshold for delamination onset are saved as parameters and serve as state functions for the genetic algorithm [19].

The genetic algorithm allows for the estimation of an optimal configuration through a cyclical process of selection, crossover and mutation of initially selected configurations.

2.2. Cost evaluation

The damage resistance constraint is expected to give benefits from the economical point of view lowering the repair costs. This is the reason why the cost of optimised configurations has been roughly estimated according to a military experimental/historical database [20].

The life cycle costs (LCC) can be split into manufacturing and repairing costs:

$$\text{LCC} = \text{MC} + \sum_{i=1}^{n} (\Pr R_i)(\text{RC}_i) \tag{7}$$

where MC are the manufacturing costs (material, labour, non recursive), $\Pr R_i$ indicates the probability of repair at the ith location (over n total locations) and RC_i is the related cost.

The probability of repair at a given location is a function of the probability of impact and of the damage resistance at that location. In the present paper the probability of repair at the ith location is considered equal to the probability of impact, $\Pr I_i$, when the structure is no damage resistant at that location. On the other hand, $\Pr R_i$ is set equal to zero when the structure is damage resistant at the ith location.

For a stiffened composite panel, the probability of impact can be different cording to the ith location. In particular, for skin locations, the probability of impact is expected to be greater than for stiffener location because the actual area covered by the skin is much greater than the one covered by the stiffeners.

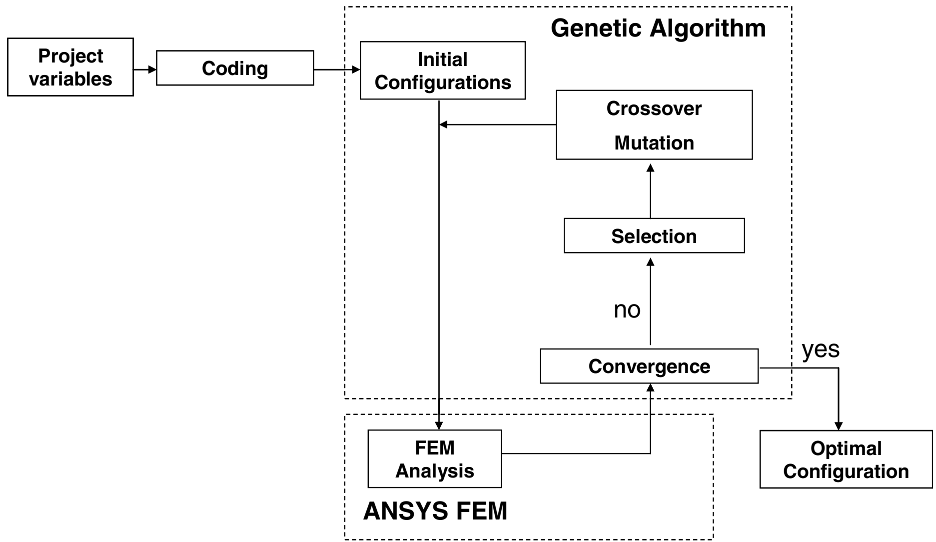

Fig. 2. Schematic representation of the optimisation procedure.

In the present paper, for the sake of easiness, it is assumed that there is only one possible impact location at the centre of the skin and that the probability of impact at this location is PrI = 1. Considering an impact energy of 15 J, at this location, two situations, depending on the damage resistance of the panel, may occur

(1) if the damage resistance of the panel at the centre of the skin is W_{on} < 15 J, PrR = PrI = 1 and the costs are given by

$$LCC = MC + RC_{Skin} \tag{8}$$

(2) if the damage resistance of the panel at the centre of the skin is $W_{on} \geqslant 15$ J, PrR = 0 and the costs are given by

$$LCC = MC \tag{9}$$

In the second situation of course no skin repair cost is needed, hence repair costs are eliminated from the life cycle costs.

3. Panel geometry and FEM model

Two different panel typologies have been included in the optimisation: they are characterised respectively by T and I stiffeners, as schematically indicated in Fig. 3.

The internal arrangement of a repetitive section of the stiffened panels in terms of lay-up and geometry is presented in Fig. 4. Some geometrical parameters, such as the panel length, the width, the ply thickness, the stiffener height and the cap width (for the I-stiffened panels only) have been considered fixed and the relevant values are indicated in Table 1.

As shown in Fig. 4 each part of the panel is such that the stacking sequence is symmetrical and balanced. This choice is made in order to avoid coupling and distortions as a consequence of the manufacturing process.

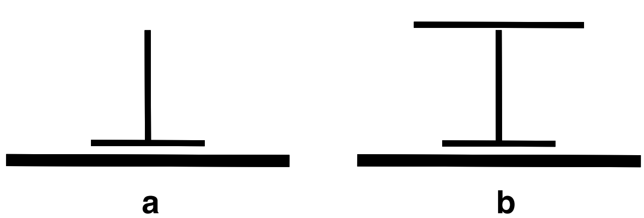

Fig. 3. Schematic representation of (a) T-stiffened and (b) I-stiffened panels.

It is important to underline that, although manufacturing induced distortions can be eliminated by such strategy, *residual curing stresses* are not eliminated: they can be released only at a temperature which is approximately equal to the cure temperature.

Stiffeners are "embedded" into the skin and each section of the panel is constituted by a "superficial laminated quartet" composed by eight plies (four plies + four symmetrical plies) and a "laminated core", whose number of plies vary between 4 and 32. The laminated core is composed by couples of plies which are considered together with the symmetrical counterparts in order to make the core globally symmetrical. Actually three parameters resume the total number of plies:

- $n_{ply\ skin} \in [1;8]$ which indicates the number of possible ply couples inside the skin core,
- $n_{ply\ web} \in [1;2]$ which indicates the number of possible ply couples inside the web core,
- $n_{ply\ cap} \in [1;2]$ which indicates the number of possible ply couples inside the cap core.

Thus, for instance, the total number of plies in the skin is given by $4 \cdot n_{ply\ skin} + 16$, the first term indicates the total number of plies in the core, while the second indicates the number of plies of the superficial quartets.

In summary, the design/optimisation parameters are

- $n_{stiff} \in [1;4]$, number of stiffeners in the half-width,
- $n_{ply\ skin}$, $n_{ply\ web}$, $n_{ply\ cap}$,
- the laminate stacking sequences of the superficial quartets,
- the laminate stacking sequences of the cores (skin, web and cap).

The stacking sequences of the superficial quartets are chosen in such a way that the quartets are almost quasi-isotropic and the core ply couples are composed by 0°, 90° or 45° plies. Fig. 5 resumes schematically the possible combinations for the superficial quartets (SLQ) and the ply core couples (SC).

As an example let us consider a T-stiffened panel with the following set of parameters:

- SLQ = 2 ($[0; 90; +45; -45]_s$),
- $n_{ply\ skin}$ = 4 and the skin core couples given by the couples [0; 90], [+45; −45], [90; 90], [0; 0],

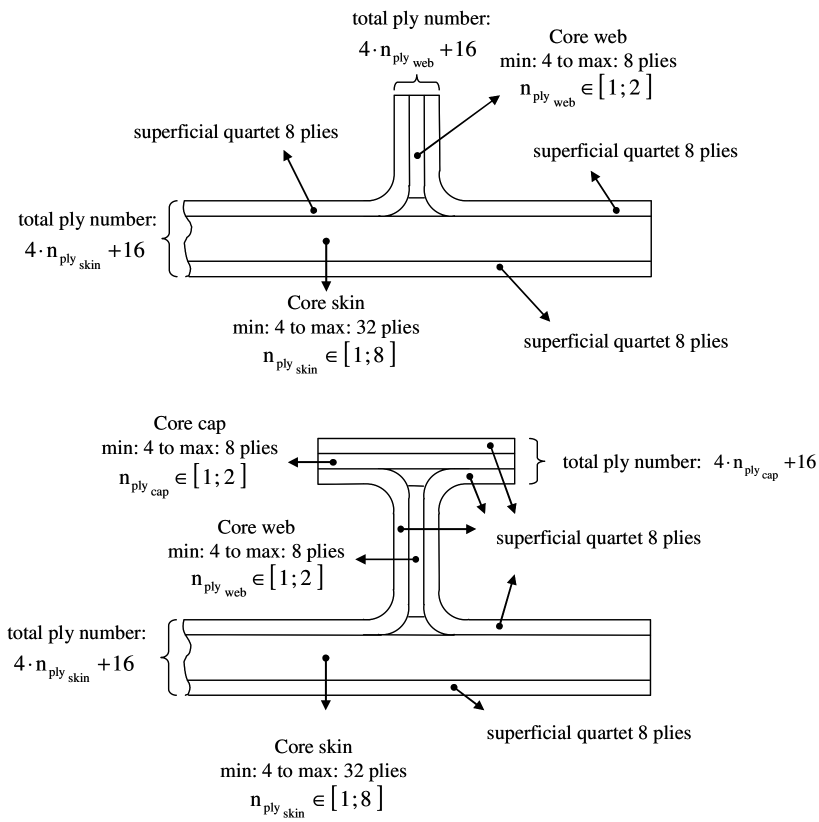

Fig. 4. Detailed arrangement of the stiffened panel repetitive section.

Table 1
Fixed geometrical parameters

Panel length $L_{x\ \mathrm{skin}}$ (mm)	Panel width $L_{y\ \mathrm{skin}}$ (mm)	Ply thickness t_{ply} (mm)	Stiffener height h_{stiff} (mm)	Cap width $l_{y\ \mathrm{stiff}}$ (mm)
533	800	0.25	30	20

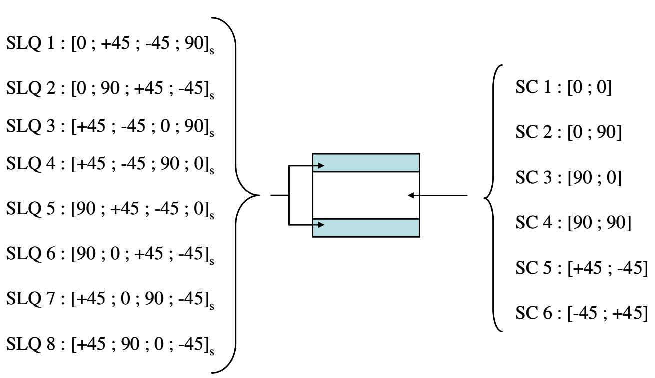

Fig. 5. Possible ply combinations for the superficial quartets (SLQ) and the ply core couples (SC).

– $n_{\mathrm{ply\ web}} = 2$ and the web core couples given by the couples [−45; +45], [90; 0].

The panel appears as in Fig. 6, the skin and the web are composed, respectively by 32 and 24 total plies.

Both T and I-stiffened panels have been modelled in ANSYS by using the ANSYS Parametric Design Language (APDL) to take into account the design parameters variability during the optimisation process. 8-node shell99 layered shell elements have been adopted. These elements can represent laminated structures and are based on the first order shear lamination theory [18].

The panels are constrained as shown in Fig. 7, which gives also some details about the employed discretization; one side of the panel is subjected to displacement controlled compression and the impact is simulated by the static application of a vertical force at the centre of the central bay.

The material properties used for simulations are summarised in Table 2.

4. Results and discussion

For both T and I-stiffened panels configurations the two optimisation processes have been formulated as follows:

– find the *minimum weight* stiffened panel subjected to the constraint: $N_{\mathrm{cr}} > 1500$ N/mm,
– find the *minimum weight* stiffened panel subjected to both constraints: $N_{\mathrm{cr}} > 1500$ N/mm, $W_{\mathrm{on}} > 15$ J.

N_{cr} and W_{on} are, respectively, the first buckling load (per unit width) and the energy needed for the onset of impact damage.

In other words the first optimisation cycle gives a *bucking-no-damage-resistant* minimum weight panel, the second one gives a *buckling-damage-resistant* minimum weight panel. For both panels it is also verified, *a posteriori*, that no ply failure is produced by

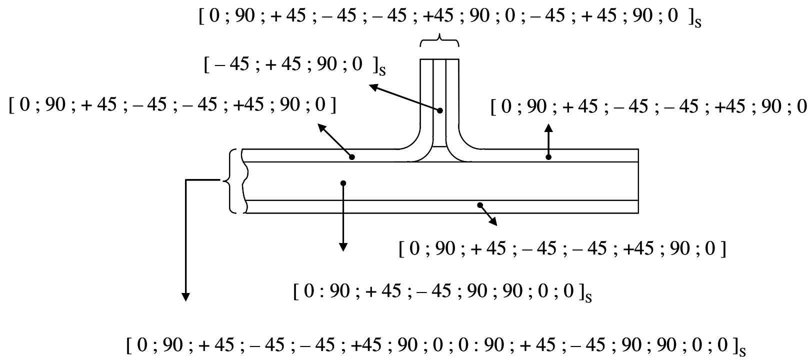

Fig. 6. Example of T-stiffened panel.

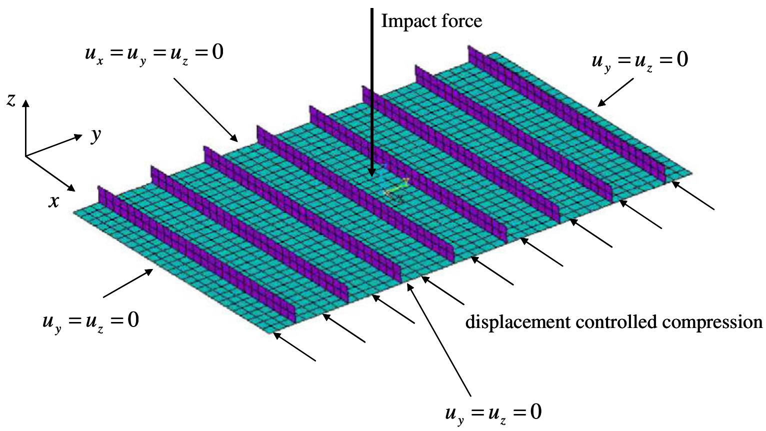

Fig. 7. Boundary and load conditions on a T-stiffened panel.

Table 2
Material properties employed for simulations

E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}	ρ (Kg/m^3)	G_{IIC} (J/m^2)
92600	7730	3820	0.36	1431	570

compression loads below the buckling threshold by adopting the maximum stress criterion available in the ANSYS FEM code [18].

The genetic algorithm employs 50 generations with a population of 50 individuals: thus, for each optimisation analysed, 2550 panels are screened. The population size and the number of generations have been considered adequate considering the nature of the problem, and the very short length of binary sub-strings related to high-sensitivity discrete design variables.

A five-point envelope control for main GA parameters has been defined. In particular, a variable mutation rate [0.02, 0.02, 0.02, 0.04, 0.06], 25 couples per generation, a roulette-wheel selection operator with fitness pre-scale and a classical one-cut crossover have been adopted.

4.1. Buckling resistant T-stiffened panel

The *minimum weight* buckling resistant T-stiffened panel is characterised by the following set of parameters:

– $n_{stiff} = 8$ (8 stiffeners),
– SLQ = 4 (the superficial quartet sequence is [+45; −45; 90; 0]$_s$),
– $n_{ply\ skin} = 2$ (2 ply couples + their symmetrical ones for the skin with total stacking sequence [90; 90; 0; 0]$_s$),
– $n_{ply\ web} = 2$ (2 ply couples + their symmetrical ones for web with total stacking sequence [90; 0; 0; 0]$_s$).

The optimal configuration is schematically shown in Fig. 8, together with the first buckling mode of the best design panel.

The minimum weight buckling resistant T-stiffened panel configuration is characterised by

– weight: $W = 46.68$ N,
– buckling load: $N_{cr} = 1500.042$ N/mm,
– impact energy onset: $W_{on} = 8.31$ J.

This configuration has been obtained at the 19th generation. It can be noticed that the panel satisfies the buckling requirement but, due to the lack of constraints on the damage resistance, the energy onset is below the specified threshold of 15 J.

Fig. 9 presents the evolution of the panel weight vs. the generation. The hollow symbols represent non admissible configurations, i.e., configurations that do not respect the buckling requirement. It should be noticed that unfeasible configurations switch to feasible ones at the same level of weight: this is due to the fact that buckling load values update from inadmissible to admissible at constant weight. In this case, the transition from unfeasible to feasible configurations takes place by changing the stacking sequence only.

4.2. Buckling and damage resistant T-stiffened panel

The *minimum weight* buckling and damage resistant T-stiffened panel presents the following set of parameters:

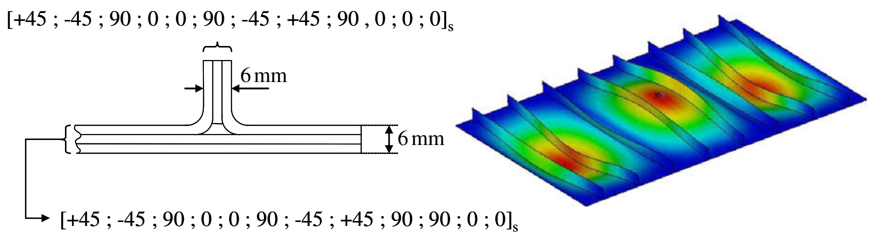

Fig. 8. Configuration and first buckling mode of the best buckling resistant T-stiffened panel.

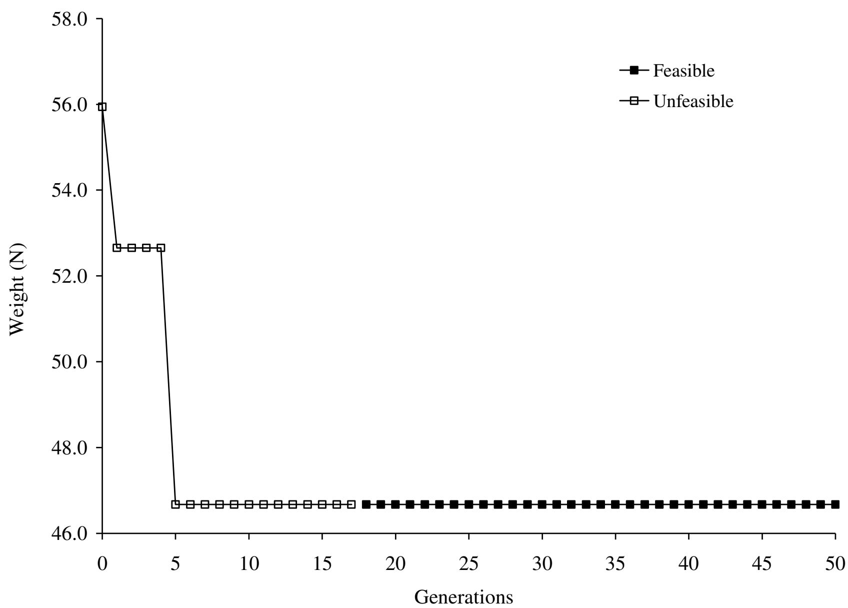

Fig. 9. Panel weight vs. generation (buckling resistant T-stiffened panel).

- $n_{stiff} = 6$ (6 stiffeners),
- SLQ = 3 (the superficial quartet sequence [+45; −45; 0; 90]$_s$),
- $n_{ply\ skin} = 4$ (4 ply couples + their symmetrical ones for the skin with total stacking sequence [0; 0; 0; 90; 90; 90 ; 0; 90]$_s$),
- $n_{ply\ web} = 2$ (2 ply couples + their symmetrical ones for the web with total stacking sequence [−45; +45; 0; 0]$_s$).

The optimal configuration is schematically reported in Fig. 10. This figure also gives an idea of the first buckling mode of the optimal panel, which is characterised by a different number of waves (two waves) with respect to the buckling mode found for the buckling resistant T-stiffened panel (three waves).

The optimal panel, obtained at the 50th generation, has the following characteristics:

- weight: $W = 55.99$ N,
- buckling load: $N_{cr} = 1504.693$ N/mm,
- impact energy onset: $W_{on} = 17.80$ J.

The panel satisfies both the buckling and the damage resistance requirements, since the energy onset is above the specified threshold of 15 J. It should be pointed out that the damage resistant T-stiffened panel is heavier than the no damage resistant one by about 16%. As expected, the damage resistance condition tends to be quite penalising in terms of weight.

Fig. 11 presents the evolution of the panel weight vs. the generation. The hollow symbols represent non admissible configurations, that is, configurations that do not respect the damage resistance and/or the buckling requirements.

4.3. Buckling resistant I-stiffened panels

The *minimum weight* buckling resistant I-stiffened panel presents the following set of design variables:

- $n_{stiff} = 8$ (8 stiffeners),
- SLQ = 5 (the superficial quartet sequence [90; +45; −45; 0]$_s$),

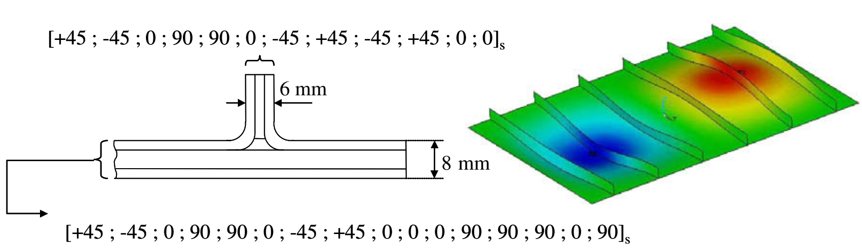

Fig. 10. Configuration and first buckling mode of the best buckling and damage resistant T-stiffened panel.

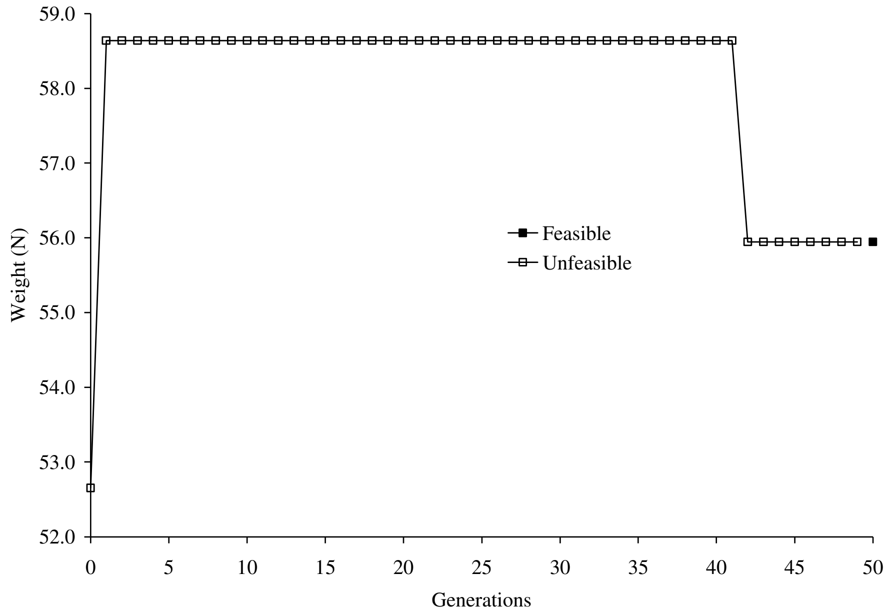

Fig. 11. Panel weight vs. generation (buckling and damage resistant T-stiffened panel).

– $n_{ply\ skin} = 1$ (1 ply couple + its symmetrical one for the skin with total stacking sequence $[0; 0]_s$),
– $n_{ply\ web} = 1$ (1 ply couple + its symmetrical one for the web with total stacking sequence $[+45; -45]_s$),
– $n_{ply\ cap} = 1$ (1 ply couple + its symmetrical one for the cap with total stacking sequence $[0; 0]_s$).

The optimal configuration layout is shown in Fig. 12, where also the first buckling mode of the best design panel is introduced.

The optimal buckling resistant I-stiffened panel configuration, obtained at the 34th generation, is characterised by

– weight: $W = 44.91$ N,
– buckling load: $N_{cr} = 1502.28$ N/mm,
– impact energy onset: $W_{on} = 5.28$ J.

Fig. 13 presents the evolution of the panel weight vs. the generation. Also for this configuration, the low value of the impact energy onset can be attributed to the absence of the damage resistant constraint in the optimisation procedure. As expected, the buckling resistant I-stiffened optimal configuration results lighter than the buckling resistant T-stiffened optimal configuration due to the higher moment of inertia of the I section with respect to the T section. However the difference in terms of weight between these two optimal configurations is negligible (3%).

4.4. Buckling and damage resistant I-stiffened panel

The *minimum weight* buckling and damage resistant I-stiffened panel is characterised by the following set of parameters:

– $n_{stiff} = 4$ (4 stiffeners),
– SLQ = 2 (the superficial quartet sequence $[0; 90; +45; -45]_s$),
– $n_{ply\ skin} = 4$ (4 ply couples + their symmetrical ones for the skin with total stacking sequence $[90; 0; 90; 0; 0; 90; 0; 0]_s$),
– $n_{ply\ web} = 1$ (1 ply couple + its symmetrical one for the web with total stacking sequence $[90; 0]_s$),
– $n_{ply\ cap} = 1$ (1 ply couple + its symmetrical one for the cap with total stacking sequence $[90; 0]_s$).

The optimal configuration scheme and the first calculated buckling mode are presented in Fig. 14.

The optimal panel has been obtained at the 26th generation and it is characterised by

– weight: $W = 55.30$ N,
– buckling load: $N_{cr} = 1503.04$ N/mm,
– impact energy onset: $W_{on} = 21.23$ J.

Fig. 15 presents the evolution of the panel weight vs. the generation. According to the constraints imposed during the optimisa-

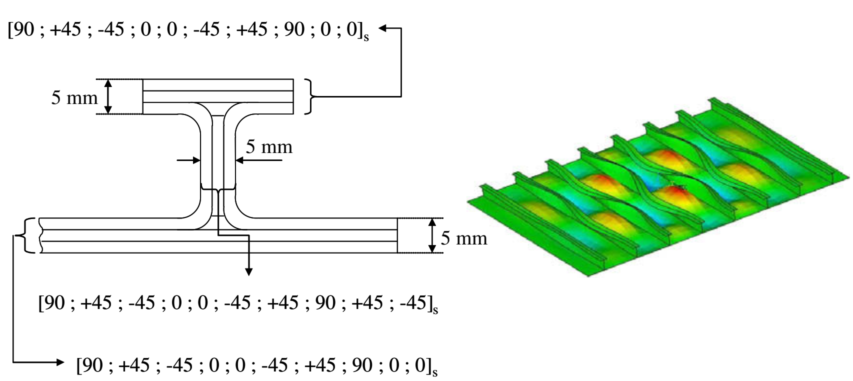

Fig. 12. Configuration and first buckling mode of the best buckling resistant I-stiffened panel.

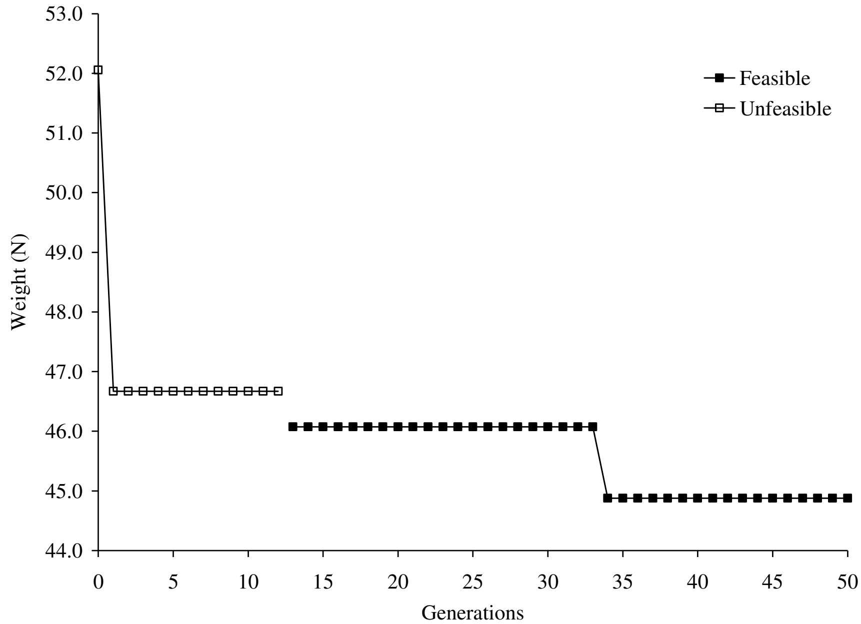

Fig. 13. Panel weight vs. generation (buckling resistant I-stiffened panel).

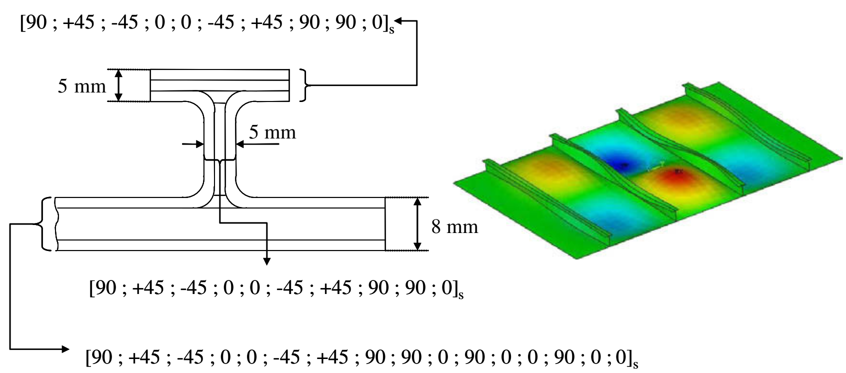

Fig. 14. Configuration and first buckling mode of the best buckling and damage resistant I-stiffened panel.

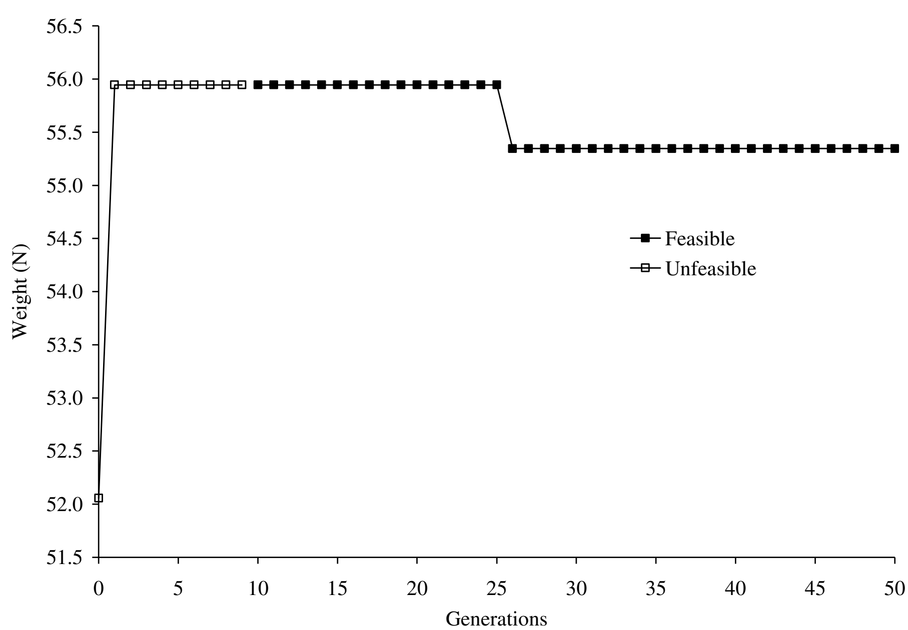

Fig. 15. Panel weight vs. the generation (buckling and damage resistant I-stiffened panel).

tion process, the impact onset energy is above 15 J. Also for the I-stiffened panels, the damage resistant optimal configuration is heavier that the no damage resistant one (18% difference in weight). Again the difference in terms of section moment of inertia causes the I-stiffened damage resistant optimal configuration to be slightly lighter than the T-stiffened damage resistant optimal configuration (4% difference in weight).

4.5. Estimation of the life cycle costs of the optimal configurations

As a matter of fact, for both T and I-stiffened panels configurations, the damage resistance constraint has induced relevant increase in weight (16–18%), however, as already mentioned in Section 3, an influence of this constraint on the life cycle cost of the composite components is expected. By adopting relations (8)

	Weight (N)	Buckling Load (N/mm)	W_{onset} (J)	Manufacturing costs		Repair	Total
				Material	Labour		
No Damage Resistant	47.14	1500.04	8.31 J	690.94 €	628.36 €	900 €	2219.30 €
Damage Resistant	56.55	1504.69	17.80 J	833.81 €	751.26 €	0 €	1585.06 €

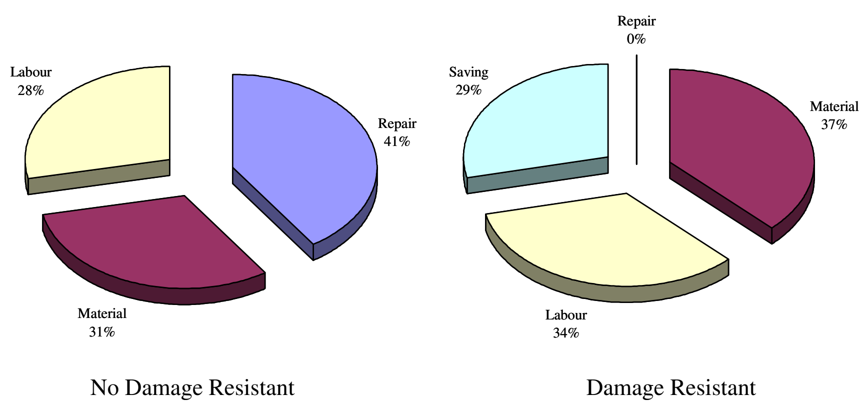

Fig. 16. Cost evaluation of T-stiffened panels.

	Weight (N)	Buckling Load (N/mm)	W_{onset} (J)	Manufacturing costs		Repair	Total
				Material	Labour		
No Damage Resistant	45.28	1502.28	5.28 J	659.05 €	618.28 €	900 €	2177.34 €
Damage Resistant	55.86	1503.04	21.23 J	825.48 €	749.12 €	0 €	1574.60 €

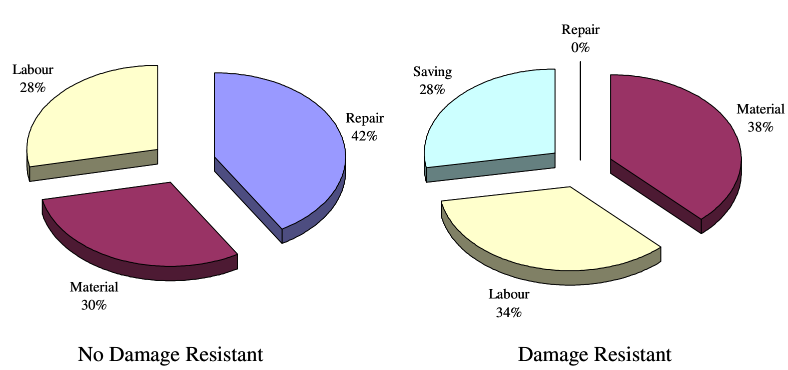

Fig. 17. Cost evaluation of I-stiffened panels.

and (9) the LCC, respectively for the no damage and the damage resistant configurations have been calculated and reported in Figs. 16 and 17. The costs, according to the military database adopted in the frame of the Euclid JP 3.29 DAMOCLES II project are evaluated on a base of 600 pieces production. Figs. 16 and 17, which present the cost estimation for the two panel typologies (respectively T and I-stiffened panels) give us an idea of the influence of the damage resistance constraint on the total LCC of the composite components.

It should be noted that, although buckling resistant panels are heavier than the buckling and damage resistant ones, the latter are less expensive, thus are "optimal" from the point of view of costs.

In particular, for the T-stiffened panel configuration a percentage of the total LCC of about 29% can be saved adopting the damage resistance approach. This is due to the lack of repair costs which are usually dominant over the increase of manufacturing costs depending on the increase of weight. The same considerations can be repeated for the optimal I-stiffened panel configuration; for this configuration a 28% of the total LCC can be saved by introducing the damage resistance constraint.

These differences in costs, even if calculated considering only one impact point with a probability of impact set to 1, can be considered quite representative of the real influence of damage resistance constraints in terms of costs on the design of composite stiffened panels.

5. Conclusions

Buckling and damage resistant composite stiffened panels have been designed by adopting the introduced optimisation procedure, based on genetic algorithms and oriented to the satisfaction of the minimum weight criterion with additional constraints on performances. Some T and I-stiffened panels minimum weight solutions have been asked to sustain a given admissible buckling load, while other minimum weight solutions have been imposed to be capable to sustain also a given impact load.

In general, damage resistant configurations have been found heavier (16–18% difference in weight) than the no damage resistance ones. A slight difference in terms of weight have been observed between the T and I-stiffened panels configurations; as expected, the I-stiffened panel configurations have been found lighter (3–4% difference in weight) due to the higher moment of inertia.

Costs have been roughly evaluated for all the analysed configurations. In terms of life cycle costs, the damage resistant configurations have been found more effective being around 30% less expensive than the no damage resistant ones. In fact the increasing in manufacturing costs due to the increase in weight is overtaken by the cost saving due to the absence of repair costs.

These results about the influence of the damage resistance on the performance and costs of composite components are representative of the contrasting trends which should be taken into account when designing with composite materials.

Even if it is able to provide very interesting solutions, the developed optimisation procedure could be further improved by removing the hypotheses on impact locations and probability and by considering the costs as an additional target function.

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