BUCKLING AND POST-BUCKLING OF ISOTROPIC AND COMPOSITE STIFFENED PANELS: A REVIEW ON OPTIMISATION (2000-2015)

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SUMMARY

Stiffened panels made out of isotropic or anisotropic materials are being extensively used as structural elements for aircraft, maritime, and other structures. In order to maintain stiffness and strength with light weight, new design techniques must be employed when utilising these materials. Their stability, ultimate strength and loading capacity are the key issues pertaining to these engineering structures which have attracted a number of investigators to undertake in-depth research, either in an academic or actual engineering context. This paper presents a review of the optimisation techniques applied to buckling and post-buckling of stiffened panels. Papers published in the period from 2000 to May 2015 have been taken into consideration. The topic is addressed by identifying the most significant objectives, targets and issues, as well as the optimisation formulations, optimisation algorithms and models available. Finally a critical discussion, giving some practical advice and pointing out the most common issues involved in optimisation of buckling and post-buckling of stiffened panels, is provided.

1. INTRODUCTION

New, fast, large, light, efficient and safe aerospace, marine, offshore and civil engineering structures, among others, require the adoption of new structural concepts and materials with superior mechanical performance. However, it is perhaps in the area of marine structures that the number of applications is greatest. Here, structures span the spectrum from offshore platforms to warships and submarines to ocean liners, tankers, LNG and bulk carriers, as well as to yachts, catamarans and small pleasure craft. These may variously be built from structural steels, aluminium alloys, graphite/epoxy, glass/epoxy or even boron/epoxy composites.

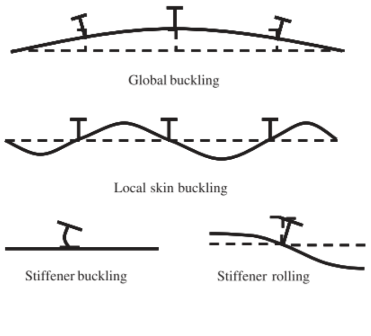

Figure 1: Different buckling modes of axially stiffened panel under compression load [1]. Reproduced under license from Wiley.

Shells are able to meet the requirements outlined above and have been widely used in these engineering fields. The use of stiffened panels made by alloy or composite materials with blade-, hat-, T-, J- or Z-shaped stiffeners, which offer considerable high strength-to-weight and stiffness-to-weight ratios, can bring a further substantial reduction in structural weight. In addition, the design of stiffened panels is able to overcome the buckling load and to work in the post-buckling field. More and more researchers have begun to understand the importance of buckling in the optimisation design of engineering structures. Therefore, stiffened panels are a structural typology extensively used in many fields mainly for their high efficiency, such as in aerospace: aircraft fuselages, helicopter tails, plus wing skin and rocket structures are but a few examples [2-5]. Stiffened panels exhibit a variety of failure modes, some global and some local in nature, and stability (buckling) failure is the most common failure mode. Global and overall buckling modes result in deformation of the shell and stiffeners together [1], see Figure 1. Therefore, an important consideration in the design of thin-walled stiffened structures is the stability (buckling) requirement.

However, owing to a lack of design standards, the majority of the existing applications of stiffened shell structures in various engineering fields have been designed based on experimental research, simulations and the designer's experience. This frequently leads to the over-design of final structures in order to ensure that these structures are safe and reliable. The emergence of various optimisation methods can contribute to the rationality of structural design, particularly for improving the buckling or post-buckling capacity of stiffened shell structures. However, there are at least two main difficulties to carry out these kinds of optimisations. The first one is related to the high computational efforts required to predict the post-buckling behaviour of each configuration analysed throughout the optimisation process. The second difficulty is due to the presence of discrete variables and continuous variables with various dimensions or various orders of magnitude and of nonlinear constraints, which significantly increase the total number of configurations to be analysed by the optimisation algorithm [6, 7]. In this sense, finding an optimal design scheme for stiffened panel structures under a set of design constraints and one or multiple specific targets (objectives) is a complex problem. For that reason, this paper aims to present an overview of the optimisation techniques that have been applied to buckling and post-buckling performance optimisation of stiffened metallic and composite structures.

The key objective of this paper is to present a broad perspective of the recent research (2000-2015) done on optimisation of the buckling and post-buckling behaviours of stiffened shells and panel structures. The present paper will concentrate on the optimal design of stiffened structures and the various optimisation methods that are typically used.

In order to undertake the design optimisation of stiffened plates or shells with buckling and post-buckling problems, there are several issues to initially consider. At the outset of this paper in Section 2, to further understand the progress of buckling optimisation problems of stiffened panels, many preceding reviews are examined. In Section 3, the buckling optimisation problem of stiffened panels is described and the optimisation problem definition, the design variables and constraints that are used are presented by an enumeration of design problems. Next, the most commonly used optimisation algorithms employed with stiffened plates and shells are described in Section 4, and a detailed discussion and argument about the challenges, issues, current trends and future developments are presented in Section 5. In fact, solving stiffened panel optimisation design problems often necessitates combining several different methods; therefore, many articles may be cited more than once in this paper.

2. LITERATURE REVIEW

In 2001, Ronagh [8] described and reviewed restricted distortional buckling (RDB), which occurs in places where part of a cross-section is restricted from free deformation during buckling (owing to the existence of external discrete or continuous restraints) while some other part(s) of the cross-section are slender and may deform in a mode that is dependent on the cross-section being flexible. In 2008, Wicks et al. [9] reviewed the horizontal cylinder–cylinder buckling under compression, torsion and gravitational loads, while in the same year Błachut and Magnucki [10] focussed their attention on the stability of cylinders under external pressure and the stability of end closures, their review comprising 287 references and 50 figures.

Sidharth [11] published a literature review concerning the effect of localised corrosion on buckling. His main attention was given to localised corrosion such as pitting, which causes the thickness to vary non-uniformly in the structural plate region, and its effect on the ultimate and buckling strength of thin plates. Xu et al. [12] described common buckling and post-buckling behaviours of composite structures and reviewed the capabilities of corresponding analysis techniques. Related articles concerning main buckling and post-buckling analysis methods for composite structures are referenced [13-15].

The global–local buckling and optimisation of cold-formed thin-walled channel beams with open and closed flanges have been reviewed [16]. The review includes simple analytical descriptions and calculations, numerical analysis, and the laboratory testing of selected beams. Randjbaran et al. [17] reviewed the nonlinear flutter and thermal buckling of a functionally graded material (FGM) panel under the combined effect of elevated temperature conditions and aerodynamic loading, finding that the temperature increase has an adverse effect on the FGM panel flutter characteristics through decreasing the critical dynamic pressure. Decreasing the volume fraction enhances flutter characteristics, but this is limited by the structural integrity aspect. Ni et al. [18] collated and categorised papers on two main research methods, namely: numerical analysis and experiment, used to study various buckling problems of various stiffened structures under various loading conditions. None of the aforementioned literature reviews set out to include the related optimisation of stiffened shell or panel structures with respect to buckling or post-buckling. However, from 2000 to present, various researchers have studied in depth the optimisation of stiffened panels or shells regarding buckling or post-buckling problems. They have proposed different objectives, methods of resolution, constraints, algorithms, tools and models in their quest to optimise the buckling performance of stiffened panel or shell structures. There is no doubt that optimisation algorithms and optimisation models are still the main research focus. Therefore, the purpose of this paper is to review the optimisation techniques applied to stiffened shell or panel structures. A summary of the research work on the buckling and/or post-buckling optimisation of alloy or composite stiffened panels or shells is given in Table 1 according to the different structure types and optimisation methods.

Table 1 shows that researchers have examined a variety of different stiffened shell or panel structures, including stiffened flat panels, laminated composite stiffened panels, cylindrical panels, as well as cylindrical shell and integrally stiffened panels. Most of the axially or orthogonally stiffened panels or grid-stiffened panels are made of alloy and/or composite materials. According to Table 1, numerous optimisations were carried out to find the minimum weight and/or maximum performance designs. The objective functions that were explored are divided into three main categories: minimisation of the structure weight; maximisation of the buckling load; and multi-disciplinary optimisations. Almost all optimisation strategies had a direct impact on the stiffener shape, the dimension of skins (including stacking sequences) and the number of layers when laminated composite materials were used; therefore, design variables are treated as continuous or discrete or mixed discrete–continuous values in various cases. The optimisation process based on the genetic algorithm (GA) has been used the most, but there are still many other different optimisation algorithms.

Table 1: Summary of research work on buckling/post-buckling optimisation of stiffened panels or shells

Structure Type	Design Variables (Continuous or Discrete)	Optimisation Algorithm	Objectives
Stiffened panels [2, 6, 19-27]	Number of layers of skin and stiffeners; Number of stiffeners; Side dimension of stiffeners; Dimension and stacking sequences	Based on genetic algorithms	Minimum weight; Maximum buckling load
Stiffened cylindrical shells [28-31]	Shell thickness; Numbers of rings and stringers; Dimensions of rings and stringers; Order of ring spacing distribution		
Composite advanced grid-stiffened (AGS) cylinder [32]	Number of stiffeners; Stiffener thickness; Stiffener height		
Grid-stiffened panel [3, 33]	Axial and transverse stiffener spacing; Stiffener height and thickness; Skin laminate; Stiffening configuration		
Stiffened liquid-filled steel conical tanks [34]	Shell thicknesses; Geometry of the steel vessel; Dimensions and number of stiffeners		
Stiffened model of a rectangular plate [4]	Dimension of plate (width, length and thickness)	Based on parametric optimisation	Maximum critical shear stress; Minimum weight
Stiffened cylindrical shell [35, 36]	Shell thickness; Skin thickness; Skin winding angle; Stiffener orientation angle and longitudinal modulus		Maximum critical load
Stiffened panel [37, 38]	Stacking sequences	Based on fractal branch and bound method	Maximum buckling load
Stiffened cylindrical shells [39-41]	Shell wall thickness; Stiffener section width; Stiffener section height	Based on linear programming optimisation	Maximum load-bearing capacity
Stiffened rectangular plate [42]	Thickness of rectangular plate; Width and height of stiffeners		
Ortho-grid stiffened shell [43]	Height of stringer; Number of stringers; Number of plies	Based on surrogate-based optimisation	Minimum weight or maximum load-carrying capability
Stiffened cylindrical shell [44-47]	Wall thickness; Ring spacing; Ring thickness and width; Each unique steered ply definition		
Hat-stiffened laminated composite panel [48]	Dimension	Based on response surface techniques	Minimum weight
Laminated composite stiffened panels (T-shape) [49]	Stacking sequence of panel skin; Stiffened laminate thickness; Height of the stiffeners	Based on an ant colony algorithm (ACA)	Maximum buckling load without weight penalty
Thin cylindrical shell with stiffened rings [50]	Number of rings; Configuration (inside or outside)	Chaos optimisation algorithm (COA)	Maximum buckling non-probabilistic reliability index η
Integrally stiffened panels [51-53]	Cross-section shape and dimensions	A hybrid differential evolution and particle swarm optimisation (HDEPSO)	Maximum buckling carrying load

The main contributions of this paper include the following:

- The analysis of buckling and post-buckling optimisation of stiffened shells and panels, plus the establishment of optimisation models with different design variables and under various constraints, including global and local constraint conditions.
- The description and comparison of several optimisation algorithms for stiffened shells or panels subjected to arbitrary boundary conditions.
- The application of optimisation tools to different stiffened shell or panel structures.

3. BUCKLING OPTIMISATION PROBLEM

3.1 OPTIMISATION PROBLEM DEFINITION

Structural optimisation problems are characterised by various objective and constraint functions that are generally nonlinear functions of the design variables. These functions are usually implicit, discontinuous and nonconvex. The mathematical formulation of structural optimisation problems with respect to the design variables, the objective, and the constraint functions depend on the type of the application [54].

For the buckling optimisation problem, once the structure is identified, it will have a variety of buckling modes and it will also have a number of corresponding critical forces. However, the critical force of the first order buckling mode is of most concern to designers. The buckling eigenvalue equation can be described as in Eq. (1) below:

$$(K + \lambda_j G)u_j = 0 \qquad (j = 1, \ldots, J) \tag{1}$$

where K is the elastic stiffness matrix of the structure; G is the geometric stiffness matrix of the structure; λ_j represents the eigenvalues for the equation, that is the buckling critical force of the structure; u_j is the vector of nodal displacements; j is the mode order number.

The relationship between the critical force and the external force can be expressed as in Eq. (2) below:

$$\lambda_j = \xi_j \times P \tag{2}$$

λ_j is the critical force of buckling; ξ_j is the factor of buckling; P is the external force.

If the minimum structure weight is the optimisation objective, the optimal model under multiple orders of buckling critical force can be described as in Eq. (3) which follows:

$$\begin{cases} find & \{X\} = (x_1, x_2, \ldots, x_n)^T \\ \min & W \\ s.t. & \lambda_{jl} \le \overline{\lambda}_{jl} \quad (j = 1, \ldots, J, l = 1, \ldots, L) \\ & X_i^L \le X_i \le X_i^U \quad (i = 1, 2 \ldots, K) \end{cases} \tag{3}$$

where X represents the design variables, X_i^L and X_i^U are the lower and upper bounds for the design variables, respectively; W is the weight of the structure; $\overline{\lambda}_{jl}$ is the upper limit of the jth critical force; J is the total number of buckling modes; N is the total number of elements; L is the number of work conditions.

Eq. (3) only describes the optimal mathematical model for the minimum mass under the buckling constraints. For complicated buckling optimisation design involving stiffened shell or panel structures, it is necessary to modify the optimisation objective, to determine different design variables and constraint functions (displacement, stress-strain limit, etc.).

3.2 DESIGN VARIABLES

Stiffened shells or panels are complex thin-walled structures. In their design, many parameters and interactions between parameters must be considered in order to obtain safe, economical, robust and reliable solutions [55]. Generally, the choice of design variables is determined based on the material and geometric form of the structure plus the complexity of optimisation.

For example, for integrally stiffened panels (ISP) [51] (see Figure 2), the design variables are the shape and the dimension of the cross-section. For a ring stiffened cylindrical shell (see Figure 3), if the ring stiffeners are constructed from different materials from one another and also from the parent shell material, then the shell thickness, the width and height of stiffeners, the number of stiffeners, the stiffeners eccentricity distribution order, and the stiffeners spacing distribution order are considered as design variables [29]. In that case, the design variables take on mixed discrete-continuous values. Similarly, the optimisation of an advanced grid-stiffened (AGS) composite conical shell (see Figure 4) has mixed discrete-continuous design parameters [32, 33].

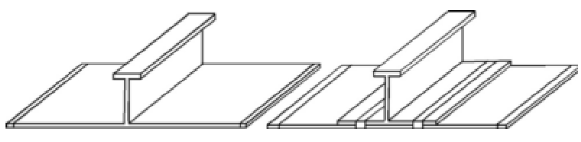

Figure 2: Integrally stiffened panel (left) and built-up panel (right) [51]. Reproduced under license from Elsevier.

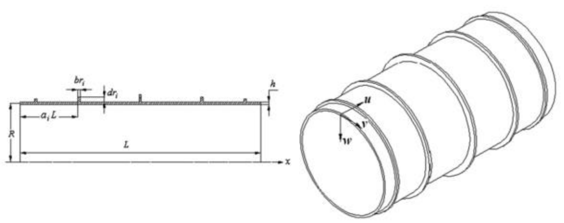

Figure 3: Ring stiffened cylindrical shell with a non-uniform stiffener distribution [29]. Reproduced under license from Elsevier.

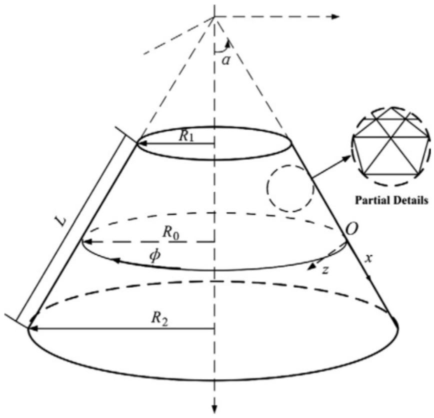

Figure 4: Typical AGS carbon-fibre conical shell [33]. Reproduced under license from Elsevier.

For stiffened laminated panels [19, 49], the design variables are the number of plies, the ply angle in each ply, as well as the size and the location of the stiffeners. For grid-stiffened panels (see Figure 5), design variables are the axial and transverse stiffener spacing, stiffener height and thickness, skin laminate, and stiffening configuration. The stiffening configuration indicates the combination of axial, transverse and diagonal stiffeners in a stiffened panel. In addition, the stacking sequences of the skin panel and stiffeners affect the buckling load of the stiffened panel; therefore the stacking sequence is considered as a design variable [22, 37]. Furthermore, for more complex structures, such as grid-stiffened cylinders, these are cylinders with stiffening structures either on the inner, outer or both sides of the shell (see Figure 6). Because shell thickness, shell winding angle, longitudinal modulus and stiffeners orientation angle together affect the buckling load, they are all taken as design variables in the optimal design process [36].

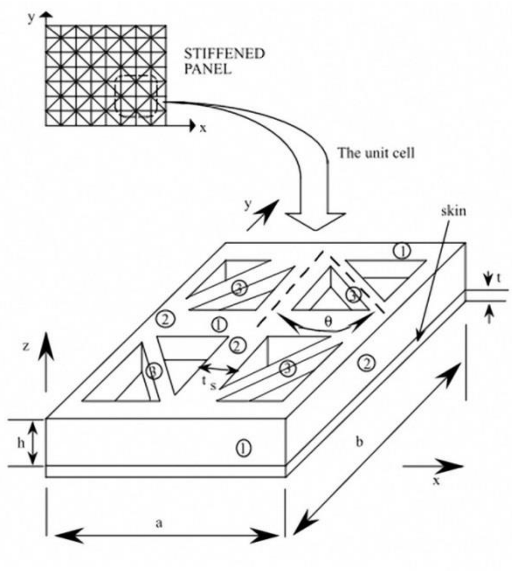

Figure 5: Unit cell of a grid-stiffened panel and design variables {(1) Axial Stiffener; (2) Transverse Stiffener; (3) Diagonal Stiffener} [3]. Reproduced under license from Elsevier.

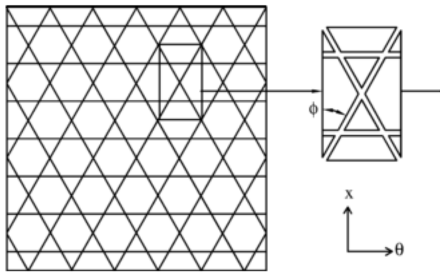

Figure 6: Unit cell of a grid-stiffened cylinder [36]. Reproduced under license from Elsevier.

3.3 CONSTRAINTS

Only by taking into account all kinds of constraints of the structure, can the structure optimisation be as close as possible to engineering practice and improve the performance of the structure. According to the characteristics of the constraints, these may be divided into global and local constraints. Global constraints include the displacement constraint, the frequency constraint, and the global stability constraint; local constraints include the stress constraint, the local stability constraint, and so on. Sometimes, the global and local constraints are dealt with simultaneously. Ambur and Jaunky [3] considered the global and local buckling constraints when they performed an optimal design of composite grid-stiffened structures with variable curvature. Similarly, Rikards et al. [44] developed an optimisation procedure for the design of composite stiffened shells subjected to buckling and post-buckling constraints. El Ansary et al. [34] also took the global and local buckling as constraint conditions when they studied an optimum design technique for stiffened liquid-filled steel conical tanks.

In the practical engineering application of stiffened shells or panels, to ensure that the stiffened shell or panel structure can work normally and safely, many kinds of constraints should be considered together. Bagheri et al. [29] carried out an optimisation for ring-stiffened cylindrical shells with four constraints, namely the fundamental frequency, the structural weight, the axial buckling load, and the radial buckling load. When Simões et al. [56] carried out an optimal design for a welded stringer-stiffened steel cylindrical shell under axial compression and bending, the local shell buckling, stringer panel buckling and horizontal displacement were taken as constraints. Herencia and his coworkers [20, 57-61] performed initial sizing optimisation of anisotropic composite panels with T-shaped stiffeners under strength, buckling, and practical design or manufacturing constraints. The strength constraints are introduced by limiting the laminate in-plane strains longitudinally, transversely and in shear, for both tension and compression. The practical design constraints are imposed on the skin, stiffener flange and web laminates, respectively. Vitali et al. [48] chose buckling and stress response surfaces as optimisation constraints to conduct a hat-stiffened laminated composite panel optimisation, while Xu and his colleagues [62] chose strength and buckling response surfaces as constraints, in order to complete a similar optimisation for a hat-stiffened composite plate.

3.4 SOLVING

During the past 15 years, many methods have been developed to meet the demands of structural design optimisation for stiffened shells or panels. According to the mathematical model of the problem, these methods can be classified into two general categories: deterministic and probabilistic [54].

For the deterministic category, such as mathematical programming methods (MP), this kind of method is mainly used to optimise the design variables or parameters as the amount of determined parameters; while for the probabilistic category, such as evolutionary algorithms (EA), this kind of method is mainly used to optimise the design variables or parameters as the amount of uncertainty, but the method is one of the most studied in recent years.

The selection of an optimisation algorithm was based on the experience of the authors as well as that of other researchers, regarding the relative superiority of one optimisation method over the rest of the methods in some specific problems. However, the superiority of these methods cannot be generalised.

4. OPTIMISATION ALGORITHMS

The selection of an optimisation algorithm is an important task in engineering optimisation which depends on the nature of the problem and the characteristics of its design space. The choice of the optimisation algorithm is central to the optimal design of stiffened shell or panel structures, because the final results depend on the specific algorithm in terms of accuracy and local minima sensitivity.

Most of the time, choosing what kind of algorithm is used is based on discrete variable optimisation or continuous variable optimisation. For continuous variable optimisation problems, the most important and popular methods include gradient-based methods, stochastic approximation methods, and response surface methodology. On the other hand, ranking and selection, multiple comparison procedures, ordinal optimisation, optimal computing budget allocation, and metaheuristics are often used to solve discrete variable optimisation problems [63]. Over the years, the algorithms used to solve buckling optimisation problems in stiffened shell or panel structures have developed and evolved.

The techniques that are most commonly used in this review can be categorised into genetic algorithm (GA), serial linear programming, surrogate model (SM), parametric optimisation, fractal branch-and-bound method (FBB), plus various other algorithms and optimisation tools.

4.1 GENETIC ALGORITHMS

Genetic algorithms (GA), a family of evolutionary algorithms, have been growing in popularity recently and represent the most commonly used technique in a wide variety of buckling or post-buckling capacity determinations for stiffened shell and panel structures. The original formulation of GAs is based on the concept of natural evolution: the survival of the fittest members, i.e., the better adapted members have more possibilities to transmit their characteristics to future generations. The ability of a GA to learn from the history and exploitation of the environment provides the basis for its effectiveness in optimisation. Therefore, the minimising of weight, optimal shape, stacking sequences, and ply angles has been sought for some composite structures by using GAs.

To minimise the weight per unit area of a grid-stiffened composite panel or shell (see Figure 5) with variable curvature given the design loading condition, Ambur and Jaunky [3] used a GA as the optimisation tool for evolving the design. For a curved panel with variable curvature, the grid-stiffened designs are more than 10% lighter than the existing optimised design. Chen [64] adopted a GA to optimise the robustness of a composite advanced grid-stiffened (AGS) cylinder (see Figure 4) under the constraint of buckling load, which is calculated based on a parametric smear model analysis. Results show that the reliability and robustness of structures are greatly improved, while the weight is heavier than the results generated by the conventional method. A GA using multi-parameter concatenated coding has been applied to the layout optimisation of the number and height of stiffeners, thickness of stiffeners and panel of composite stiffened plates [65].

Faggiani and Falzon [66, 67] optimised the stacking sequence of several areas of a panel and maximised damage resistance within the post-buckling regime of stiffened panels based on a GA. Iuspa and Ruocco [21] performed the optimum topological design of simply supported composite stiffened panels via GAs based on a specific bit-masking orientation, which handles in parallel different genetic operators, expressly conceived to process with proper metrics, both discrete and continuous design variables.

Another GA is called the micro-genetic algorithm, which was used to perform the optimal layer design of a composite stiffened panel up to post-buckling based on an analysis model. The optimised result showed a higher maximum failure load in the post-buckling region [68, 69].

A genetic algorithm is highly suited for use with a parallel computing scheme, because multiple design points should be evaluated in a single calculation step. To find minimum weights of structures for a given strength, Kang and Kim [19] used a modified GA with parallel computing to perform an optimisation for stiffened panels under constrained post-buckling strength. The objective function was defined as:

$$f = \begin{cases} \dfrac{W_{\max}}{W} \dfrac{11P_{fail}}{10N_{cr} + P_{fail,design}}, & P_{fail} \geq P_{fail,design} \\ \dfrac{P_{fail}}{P_{fail,design}}, & P_{fail} \leq P_{fail,design} \end{cases} \quad (4)$$

where $W_{\max}$ is the heaviest possible weight and W is the weight of the design point; $P_{fail,design}$ and P_{fail} are the design strength and the strength of the design point, respectively. The strength was defined as the load at the moment of the first fibre failure. The optimisation results showed that the optimal designs have better performance than conventional designs and that the modification to the algorithm was highly effective.

Genetic algorithms in combination with other approximation methods, such as neural networks, finite element (FE) analysis or an analytical formulation, have also been developed and applied in buckling and post-buckling optimisation of composite stiffened panels [2, 62, 70-78]. Bisagni and Lanzi [2] proposed a procedure based on a global approximation strategy, genetic algorithms and multilayer perceptron (MLP) neural networks to optimise a composite stiffened panel, where the critical buckling load and collapse load were approximated.

Zhang et al. [72] developed a new hybrid genetic algorithm by the conjunction of the genetic approach with a simplex algorithm to obtain the minimum weight of an AGS structure under the constraints of global buckling and strain. Results show that global buckling constraint is the key factor for identifying safety of an AGS structure. The optimisation procedure reduces considerably the total computational time, and can run different optimisations changing either constraints or objective function. An optimisation design model of a hat-stiffened composite plate was solved by using a GA. The optimisation model is based on the neural-network response surface as the objective function or the constraint conditions, combined with other conventional constraints [62, 73]. Under the global buckling constraint condition, Liang et al. [74] combined the improved parameterised smeared stiffened mathematical model and genetic algorithm to optimally design the configuration of grid-stiffened composite panels. The combination of micro-genetic algorithm and Grisham algorithm was used to analyse and optimise the design for the buckling of stiffened, thin-walled shear panels. Important reductions in weight were obtained within relatively few function evaluations [75]. To optimise the lay-up of the skin of an I-stiffened composite panel, in order to increase its damage resistance in the post-buckling regime, Falzon and Faggiani [76] developed an optimisation methodology by coupling GA and FE analyses. The objective function was chosen to be the sum of the damage variables of the interface elements in the local model, while the design variables were taken as the orientation of the plies in the panel skin. Vescovini and Bisagni [77] developed an optimisation approach, based on the use of an analytical formulation and genetic algorithms, to obtain optimal configurations in terms of skin and stiffener lay-ups, stiffener cross-section and geometry of composite stiffened panels loaded in compression and shear. A fast tool for buckling optimisation of stiffened panels based on a GA and an analytical formulation was presented [78], which takes into account buckling and post-buckling requirements with reduced computational times. Zhang et al. [7] proposed the updated Kriging approximate model for a metallic stiffened panel and obtained the optimal solution by GA and the trade-off method. An approximate model can effectively replace a finite element calculation. These procedures are highly efficient in terms of CPU time and are several times faster than an analogous finite element based approach.

Submersible pressure hulls with fibre-reinforced multilayer-sandwich constructions (see Figure 3) have been developed in recent years as substitutes for classical metallic ring-stiffened pressure hulls. The design of the former was optimised under hydrostatic pressure using the hybrid genetic algorithm (HGA) [79].

A two-step approach [20, 57-61, 80] to optimise anisotropic laminated fibre composite panels with T-shaped stiffeners under strength, buckling, and practical-design constraints has been provided. In the first step, composite optimisation is performed using MP (mathematics programming) to get near the optimum discrete design. In the second step, the actual skin and stiffener lay-ups are obtained using genetic algorithms, accounting for manufacturability and design practices.

António [81] proposed a multi-level genetic algorithm aimed at the identification of the global optimal solution of beam reinforced composite structures. The proposed genetic algorithm performs a sequence of optimisation stages at two levels, resulting from the decomposition of the original optimisation problem. It is an effective manner by which to reduce the search cost.

Hao et al. [32] developed an adaptive approximation-based optimisation (AABO) procedure for the optimum design of an AGS cylinder subject to post-buckling, with minimum weight as the objective. The multi-island genetic algorithm (MIGA) [43] was utilised for the global optimum search. The advantage of using the optimisation procedure is to save on computational cost.

The aforementioned published work all deals with single-objective optimisation based on GA. However, the single-objective formulation may be extended to consider multi-objective problems. Moreover, the use of multi-objective optimisations, capable of accounting for two or more objectives, one against the other, results in a successful strategy to identify the optimum solution. Lanzi and Giavotto [6] developed a multi-objective optimisation procedure based on GA and three different methods of global optimisation (neural networks, radial basis functions and Kriging approximation) to design composite stiffened panels for operating post-buckling. The optimisation results underline the significance of non-dominated solutions as the best panel configurations inside the domain of interest. In reference [82], a fast multi-objective optimisation procedure is based on neural networks and genetic algorithms for the geometric design of stiffened panels under mechanical and hygrothermal loads, which minimises the mass, the stresses between elements and the strain due to hygrothermal effects. The multi-objective genetic algorithm (MOGA) and Kriging approximation were also used to optimise a stiffened panel configuration to reduce the weight under buckling load constraint. Moreover, the method produced a feasible optimal structure at a low computational cost [37, 83].

The optimum design of a Y-stiffener plate combination was conducted by Badran et al. [25] as shown in Figure 7. Five independent variables (*hw*, *tf*, *tw*, *bp* and *L*), the others being dependent variables, were selected for use in optimising the Y-section. The objective functions are the ultimate buckling load and the volume per unit area of the Y-stiffener plate combination. The Pareto optimal sets were calculated using multi-objective optimisation with real-coded GA.

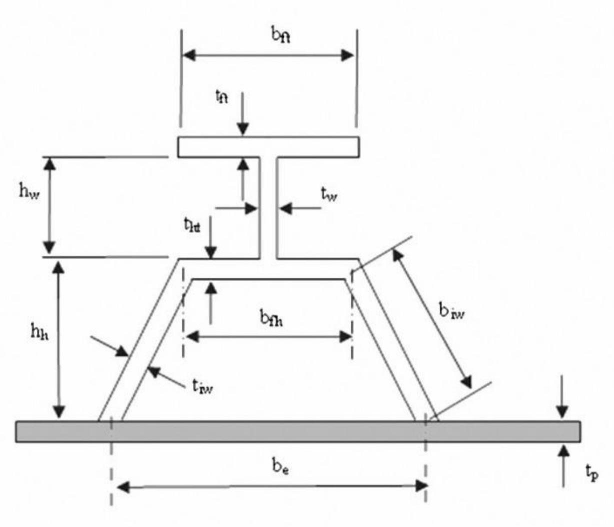

Figure 7: Single Y-stiffener plate combination with variables [25]. Reproduced under license from Elsevier.

Sadeghifar et al. [28] used GA to perform a multi-objective optimisation of an orthogonally-stiffened cylindrical shell for minimum weight and maximum axial buckling load. Bagheri et al. [29] took the maximum fundamental frequency and minimum structural weight as the objective function, and used the GA method to optimise ring-stiffened cylindrical shells subjected to four constraints including the fundamental frequency, the structural weight, the axial buckling load, and the radial buckling load. Based on the adoption of genetic algorithms, Corvino et al. [84] have presented a multi-objective optimisation procedure for impact damage resistant stiffened composite panels with minimum weight, as well as minimum cost and buckling constraints. Chen et al. [70] also adopted GA to optimise a composite AGS cylinder with multi-objectives, these being minimisation of the structure weight as well as minimisation of the sensitivity coefficient of the structure weight to uncertain parameters. The relation between the buckling load and the structure coefficient is simulated by an artificial neural network, while the neural network is trained by particle swarm optimisation (PSO).

4.2 SERIAL LINEAR PROGRAMMING

Aiming at the inflection of a stiffened cylindrical shell under uniform axial compression, the critical buckling load of the structure is the objective; to achieve this, a serial linear programming optimisation procedure is executed. The optimised thickness of the shell and the size of the stiffeners are obtained accordingly. The optimisation model can be described as follows:

$$\begin{cases} \max\left[f_0 + C_1(x_1 - x_{10}) + C_2(x_2 - x_{20}) + C_3(x_3 - x_{30})\right] \\ s.t. \quad \begin{array}{l} \pi D L x_1 + n_b \pi D x_2 x_3 + n_h L D x_2 x_3 \le V_0 \\ \underline{x_i} \le x_i \le \overline{x_i}, (i = 1,2,3) \end{array} \end{cases} \tag{5}$$

The total shell volume is not changeable; wall thickness x_1, stiffener section width x_2, section height x_3 are design variables to set up the optimisation model in the formula; buckling load $f(x_1, x_2, x_3)$ is the optimisation objective, which is approximately linearised. C_1, C_2, C_3 are undetermined coefficients that will be determined by data fitting. D is the shell diameter, L is the shell height, n_b is the quantity of ring stiffeners, n_h is the quantity of vertical stiffeners, V_0 is the shell volume before optimisation; the upper and lower limits of x_1, x_2, x_3 are confirmed by engineering practice [39-41]. The critical buckling load of the structure is obviously increased after optimisation. In 2014, in order to improve the buckling capacity of a stiffened rectangular plate under uniform normal compression, Fang and Cai [42] built an optimisation model based on APDL and ANSYS commands, and adapted the sequential linear programming method to optimise the thickness of plate and the sizes of stiffeners.

The results reveal that the shell loading capacity in axial compression is basically not improved when the stiffeners are too sparse or overcrowded. Nevertheless, in the condition of reasonable stiffener distribution, it can increase by approximately 50%. The feasibility of the serial linear programming optimisation procedure is validated due to the comparison with both numerical and theoretical results.

4.3 SURROGATE MODELS

When the optimisation variables and objective function do not have explicit relationships and the variables have the characters of being multi-parameter, high dimension and nonlinear, a surrogate model (SM) can estimate the function value of all sample points by finite sampling points accurately – so as to obtain the response relationship between the design variables and the objective function with sufficient accuracy requirements [85]. Therefore, SM can be used to overcome the problem of excessive calculation in engineering optimisation, and to filter out some numerical calculation noise from the original analysis model. SM has been used successfully in the optimisation of stiffened shell structures. The most frequently used surrogate models are the response surface model (RSM) [44, 47, 62, 73], Kriging model [7, 86] and radial basis function model (RBF) [43, 45, 85], and so on.

The response surface methodology (RSM) combined with experimental design is a powerful optimum design tool in many technical fields. To realise the minimum weight design for composite stiffened panels under buckling and post-buckling constraints, an SM can be built based on experimental design and response surface methodology.

The surrogate models used in design optimisation can be constructed in the form shown in Eq. (6), representing the load-shortening curve of the stiffened panel:

$$\begin{aligned} P_A(x;u) &= \hat{k}_1(x)u, \\ P_B(x;u) &= \hat{k}_2(x)u + \hat{P}_n(x)\left(1-\frac{\hat{k}_2(x)}{\hat{k}_1(x)}\right), \\ P_C(x;u) &= \hat{P}_2(x) \end{aligned} \tag{6}$$

where A is the surrogate model for the first linear part (pre-buckling stiffness); B is the surrogate model for the second linear part (post-buckling part of the curve); and C is the surrogate model for the collapse load. u is a parameter (axial displacement); x is the vector of optimisation parameters. These models are employed in design optimisation of stiffened panels, where design parameters are also discrete variables – number of stiffeners, discrete thickness of layers [44, 47].

The radial basis function (RBF) model, a type of approximation method, was developed for the interpolation of scattered multivariate data. The RBF model has proven to be the most dependable method in most situations for global optimisation in terms of accuracy and robustness, compared to the Kriging and polynomial regression methods. Hao et al. [43] constructed an RBF model based on sampling data and employed a multi-island genetic algorithm (MIGA) to perform a surrogate-based optimisation (SBO) in the inner optimisation; this was to find the maximum performance design subject to weight constraint for stiffened shells, where the variables involved included the amplitude of hyperbolic generatrix shape, skin thickness, stiffener width and height, plus the numbers of circumferential and axial stiffeners. This method enhances the significance of considering imperfection sensitivity in the optimisation of realistic stiffened shells.

Salehghaffari et al. [45] established surrogate models based on RBF to represent the relationships between the individual objective functions (SEA – the ratio of total energy absorption to maximum crush force) and the design variable vector over the entire design space. Both single- and multi-objective optimisation problems of external stiffening by multiple identical rings were solved, to find an optimal geometric design that results in maximum specific energy absorption and minimum peak crush force.

Blom et al. [46] optimised the buckling load of a fibre-reinforced composite cylinder in pure bending by using a multiple-segment constant curvature fibre angle variation in the circumferential direction, while taking into account manufacturing constraints. The optimisation was done using the surrogate model optimiser in Design Explorer, in order to minimise the number of FE analyses. However, only laminates with a constant thickness were optimised for a maximum buckling load under pure bending.

Zhao et al. [87] built a surrogate model for structure efficiency optimisation using the panel's macroscopic compression and bending stiffness parameters as variables. This model can not only avoid the appearance of a local optimal point, but also has a high efficiency. The following year, the same authors [88] constructed a neural network (NN) surrogate model to represent the relationship between structural stiffness and the buckle resistance of a composite skin. Based on that, a two-level layout optimisation strategy for large-scale composite wing structures was proposed. Compared with polynomial response surfaces, the neural network surrogate model provides a more accurate approximation for fitting this nonlinear relationship.

4.4 PARAMETRIC OPTIMISATION METHOD

The parametric optimisation method is also a method to achieve design objectives, which belongs to the category of direct optimisation methods. Alinia [4] adopted the parametric optimisation method to research the geometric properties of stiffener cross-section under different shear stresses. The results showed that the optimum geometric properties of the stiffeners correspond to the point when the buckling shape of a plate changes from the overall mode to local mode. Wodesenbet et al. [36] carried out parametric optimisation on an iso-grid stiffened composite cylinder, and drew general conclusions regarding optimum configurations of the different parameters of the grid-stiffened cylinder. In addition, the parametric optimisation method was used to obtain the optimum design for improving the buckling performance of some specific stiffened composite panels [89-91] and to research the effects of structural parameters upon the buckling loads and modes [35, 92].

4.5 FRACTAL BRANCH-AND-BOUND METHOD

The fractal branch-and-bound method (FBB) is the most commonly used algorithm for solving integer programming problems. The method was used to maximise the buckling load of a blade-stiffened panel [37] and hat-stiffened panel [38, 93-95] by optimising the multiple stacking sequence. However, in reference [95], the FBB combined with particle swarm optimisation (PSO) was applied to optimise the stacking sequence and stiffener configurations, while in reference [56] a branch-and-bound strategy coupled with an entropy-based algorithm was used to solve the reliability-based optimisation for a stiffened shell.

4.6 OTHER OPTIMISATION METHODS

There are several other optimisation methods and optimisation tools that have been used in the design of stiffened shell structures to obtain good buckling or post-buckling performance.

The ant colony optimisation (ACO) algorithm is one of the meta-heuristic algorithms and has been successfully used in the optimisation of laminated panels to maximise the critical buckling load. In addition, ACO and other meta-heuristic search algorithms are suitable for solving problems in which the objective function can be discontinuous, non-differentiable, stochastic, or highly nonlinear.

The search mechanism of the ACO algorithm is based on the ants' capability of finding the shortest path from a food source to their nest. To achieve the objective of finding a shortest route corresponding to an optimum laminate stacking sequence, the optimisation problem of the composite stiffened panel T-shape stringer was modelled as an MCLTSP (multi city-layer travelling salesman problem). A modified TSP and ACO algorithm has been used for optimum buckling design of laminated composite skin panels with different numbers of stiffeners [47]. The optimisation problem can be formulated so as to maximise the critical load F_{cr} of the stiffened panel, by finding the optimum thickness and laminate stacking sequence of the skin panel and stiffeners, as well as the blade height:

$$\textit{minimize} \qquad F_{obj} = \frac{1}{F_{cr}\left(T_s, T_b, T_f\right)} \tag{7}$$

$$\textit{subject to} \quad W_{total} = \text{constant} \quad \textit{and} \quad g\left(\theta\right) \le 4$$

where F_{obj} is the objective function; F_{cr} is the critical load of the stiffened panel depending upon the design variables, which is the critical buckling load; and $g\left(\theta\right)$ is the number of contiguous plies of the same orientation. T_s is the thickness of the skin panel, T_b is the stiffener blade thickness and T_f is the stiffener flange thickness. The results show that the buckling load increases dramatically with the number of stiffeners at first, and then has only a small improvement after the number of stiffeners reaches a certain value.

Using the panel weight as the objective function, with stress and buckling constraints, the response surface technique was adopted to optimise hat-stiffened structures for considerable weight savings [48, 62, 73].

The chaos optimisation algorithm (COA) is a new, global, optimisation algorithm which has arisen in recent years. It is very popular because COA has some advantages such as a simple calculating process, high efficiency and good global characteristics. COA is used to calculate buckling non-probabilistic reliability index (BNRI). The results show that BNRI increases with increase in number of rings, and their values are higher when rings are placed inside of the shell rather than outside of the shell [50].

A novel optimisation procedure algorithm called hybrid differential evolution and particle swarm optimisation (HDEPS) has been developed [51-53], which can be applied to minimise the cross-sectional area (and consequently the weight) of an upper wing integrally-stiffened panel (ISP) structure, when subjected to buckling deformation modes within the elasto-plastic range.

A multi-objective evolutionary algorithm (EA), combined with global approximation of the objective functions to limit the calculation costs, was used to optimise composite stiffened panels to improve the performance of an existing design, in terms of both its first buckling load and ultimate collapse or failure loads, by taking the stacking sequence and the stiffener of the panel as design variables [96, 97].

To overcome the difficulty of solving the structural layout optimisation of composite materials (flexible and complex problems) by using a traditional mathematical programming method, Wu and Yao [98] developed a method of two-level optimisation design to reduce the size of the problem and realise the optimisation design of size, layout and stacking sequence. This method decomposes the layout optimisation of a composite stiffened plate structure into two sub-problems, which are easy to solve. The advantage of this method is to reduce the number of design variables, reduce the structural analysis of the nonlinearity, and not to limit the flexibility of the optimisation design. Similarly, a concurrent subspace optimum design method [99, 100] was proposed for composite stiffened panels. The optimum design process is decomposed into three steps. Firstly, the shape, number and size of the ribs are set as variables to deal with layout optimisation through constructing three sub-optimisation systems in consideration of the static strength and stability requirements. Then the stacking sequence of the laminates is set as variable, to deal with ply stacking sequence optimisation of the skin and ribs in consideration of manufacturing and process constraints. The equivalent bending stiffness is set as an intermediate variable. Finally, to determine the optimal composite stiffened panel, two optimisation results are collaboratively optimised. The optimisation design of a composite stiffened panel under compressive and shear loading was conducted to demonstrate its effectiveness.

Liu et al. [101] carried out optimisation of composite stiffened panels subject to compression and lateral pressure using a bi-level approach. In this optimisation, the first level (panel level) is to get the geometric cross-section to minimise weight by calculating an equivalent orthotropic laminated plate; the second level (laminate level) is to get the stacking sequence under the buckling and strain constraints. After that, to aid the process of optimising the design of composite structures and layups, while ensuring a low mass, an integrated optimisation procedure using a bi-level programming scheme is carried out for minimisation of the weight of top-hat stiffened composite panels with probabilistic deflection constraints [5].

4.7 OPTIMISATION TOOLS

In addition to optimising the design of a stiffened shell or panel by various optimisation algorithms, there are some relevant optimisation tools which can be chosen, such as VICONOPT, PANDA2, etc.

Because optimisation ensures that the buckling stability of the panel includes an allowance for a post-buckling reserve of strength, the optimisation code VICONOPT, based on exact strip theory, was used to investigate the optimum design of stiffened panels with multiple stiffener sizes or sub-stiffeners [102, 103].

To reveal the interesting buckling and post-buckling behaviour of a stiffened panel under combined axial compression, in-plane shear, and normal pressure, and to demonstrate how a preliminary optimum design of such a panel can be obtained in the presence of the extremely nonlinear behaviour associated with local buckling and post-buckling, the PANDA2 computer program, based on a gradient optimisation algorithm, was used to find a minimum weight design of a flat panel with T-shaped stringers [104].

4.8 SUMMARY OF OPTIMISATION METHODS

The stacking sequence, fibre orientation angle, cross-section shape, as well as the number and configuration of stiffeners, are still the most important optimisation problems in the design of stiffened shell structures; meanwhile, weight minimisation and buckling performance maximisation are the basic optimisation objectives. Of course, the challenge of optimisation is to balance the largest structural ultimate strength with the minimum cost. According to the various optimisation methods used for buckling and/or post-buckling of stiffened shell structures discussed above, standard GA and the modified GA method were used widely. More often than not, for stiffened composite shells, coupling of GA and FE analysis, neural networks and other methods is adopted in order to improve the accuracy and efficiency. Moreover, for the multi-objective optimisation problem in buckling of stiffened shell structures, GAs show the biggest advantage, because they can handle integer, zero-one, discrete and continuous variables, plus are effective with nonlinear functions and nonconvex design spaces.

SM can be used to overcome the problem of excessive calculation in engineering optimisation and to filter out some numerical calculation noise from the original analysis model. However, there is a need to explore more effective methods of how to construct a high-precision SM based on less sample points.

ACO is suitable to solve problems in which the objective function can be discontinuous, non-differentiable, stochastic, or highly nonlinear. For example, for the sequence optimisation of a discrete laminated panel, compared with GA, ACO showed a good improvement in the solution quality and computational costs.

The FBB, parametric optimisation method and other optimisation algorithms generate considerable benefits for the design of stiffened shell structures.

Rapid increases in computer processing power, memory and storage space have not eliminated computational cost and time constraints on the use of structural optimisation for design. This is due to the constant increase in the required fidelity (and hence complexity) of analysis models. Venkataraman and Haftka [105] conclude that one can solve problems with the highest possible complexity in only two of the three components of analysis model: analysis procedure and optimisation.

5. CONCLUSIONS

Within the last 15 years, optimisation technology for buckling or post-buckling of stiffened shells and panels has reached maturity.

In fact, in this review it was apparent that very few buckling or post-buckling optimisation problems of stiffened shells or panels were solved using a multi-objective algorithm. From the reviewed papers, a growing number were found that tackled their performance optimisation problem using heuristic optimisation methods, especially genetic algorithms (GA) and a few other applied optimisation algorithms. GA is a promising approach for stiffened panel or shell structures, since it can treat two very important optimisation difficulties: one being discrete and continuous design variables; the other being non-linear and discontinuous domains less sensitive to the initial configuration.

In addition, GA can be combined with other optimisation technologies to become more efficient and more reliable. However, calculating the buckling load of stiffened shell structures requires high computational cost to solve the optimisation problem; a surrogate-based optimisation algorithm and the combination of various other optimisation algorithms can effectively improve the efficiency and accuracy of optimisation.

Many optimisation technologies, including their application and advantages, are discussed, and existing research on the topic is reviewed. It is worth mentioning that there are also some other useful methods that are not covered in this review paper, such as Levenberg–Marquardt [53], simulated annealing [106], etc.

Nevertheless, there are many issues in the optimisation for buckling performance of stiffened shell structures that have not yet been satisfactorily resolved:

- The optimisation design of stiffened shell structures under dynamic buckling is one such issue. As analysed in references [107, 108], dynamic buckling nonlinearity seems to be an important factor affecting the performance of stiffened shell structures. Most of the existing optimisation algorithms and optimisation tools search for good solutions for static buckling; however, the dynamic buckling problems in optimisation design of stiffened shell structures have not been involved. In addition, the phenomenon where the material of a stiffened shell structure is in the elastic-plastic stress state or fully plastic state, is also very common when buckling occurs. However, at present, most optimisation design seldom involves this kind of stress state.
- Generally, for stiffened shell or panel structures, when the critical load for local buckling equals that for global buckling, the design based on the optimisation study governs the best design condition. However, initial imperfections exist in an actual structure; therefore, the relationship between the overall buckling and local buckling needs to be clearly defined. It is very important to research the relationship between local buckling and global buckling in optimisation design if initial imperfection is to be considered.
- In the literature, many techniques and algorithms have been proposed. However, there is not enough research on the comparisons between them. So it is very important to build and maintain a testbed for the optimisation problems, including benchmark problems, optimisation solution, optimisation accuracy and optimisation efficiency to evaluate the performances of different techniques, which can help researchers to compare their algorithms.

6. REFERENCES

1. LAMBERTI, L., VENKATARAMAN, S., HAFTKA, R.T. and JOHNSON, T.F., ‘Preliminary design optimization of stiffened panels using approximate analysis models’, *International Journal for Numerical Methods in Engineering, Volume 57(10), pp 1351-1380*, 2003.
2. BISAGNI, C. and LANZI, L., ‘Post-buckling optimisation of composite stiffened panels using neural networks’, *Composite Structures, Volume 58(2), pp 237-247*, 2002.
3. AMBUR, D.R. and JAUNKY, N., ‘Optimal design of grid-stiffened panels and shells with variable curvature’, *Composite Structures, Volume 52(2), pp 173-180*, 2001.
4. ALINIA, M.M., ‘A study into optimization of stiffeners in plates subjected to shear loading’, *Thin-Walled Structures, Volume 43(5), pp 845-860*, 2005.
5. XUE, X., LI, G., SOBEY, A.J. and SHENOI, R.A., ‘The application of reliability based optimization of tophat stiffened composite panels subject to bi-directional buckling loads’, *Journal of Materials Science and Engineering B, Volume 3 (11), pp 721-733*, 2013.
6. LANZI, L. and GIAVOTTO, V., ‘Post-buckling optimization of composite stiffened panels: Computations and experiments’, *Composite Structures, Volume 73(2), pp 208-220*, 2006.
7. ZHANG, Z.-G., YAO, W.-X. and LIU, K.-L., ‘Configuration optimization method for metallic stiffened panel structure based on updated Kriging model (in Chinese)’, *Journal of Nanjing*

University of Aeronautics & Astronautics, Volume 40(4), pp 497-500, 2008.

8. RONAGH, H.R., 'Progress in the methods of analysis of restricted distortional buckling of composite bridge girders', *Progress in Structural Engineering and Materials, Volume 3(2), pp 141-148*, 2001.
9. WICKS, N., WARDLE, B.L. and PAFITIS, D., 'Horizontal cylinder-in-cylinder buckling under compression and torsion: Review and application to composite drill pipe', *International Journal of Mechanical Sciences, Volume 50(3), pp 538-549*, 2008.
10. BŁACHUT, J. and MAGNUCKI, K., 'Strength, stability, and optimization of pressure vessels: Review of selected problems', *Applied Mechanics Reviews, Volume 61(6), pp 060801-1 - 060801-33*, 2008.
11. SIDHARTH, A.A.P., 'Effect of pitting corrosion on ultimate strength and buckling strength of plates – A review', *Digest Journal of Nanomaterials and Biostructures, Volume 4(4), pp 783-788*, 2009.
12. XU, J., ZHAO, Q. and QIAO, P., 'A critical review on buckling and post-buckling analysis of composite structures', *Frontiers in Aerospace Engineering, Volume 2(3), pp 157-168*, 2013.
13. ZHANG, Y. and WANG, S., 'Buckling, post-buckling and delamination propagation in debonded composite laminates: Part 1: Theoretical development', *Composite Structures, Volume 88(1), pp 121-130*, 2009.
14. WANG, S. and ZHANG, Y., 'Buckling, post-buckling and delamination propagation in debonded composite laminates Part 2: Numerical applications', *Composite Structures, Volume 88(1), pp 131-146*, 2009.
15. STAMATELOS, D.G., LABEAS, G.N. and TSERPES, K.I., 'Analytical calculation of local buckling and post-buckling behavior of isotropic and orthotropic stiffened panels', *Thin-Walled Structures, Volume 49(3), pp 422-430*, 2011.
16. MAGNUCKA-BLANDZI, E. and MAGNUCKI, K., 'Buckling and optimal design of cold-formed thin-walled beams: Review of selected problems', *Thin-Walled Structures, Volume 49(5), pp 554-561*, 2011.
17. RANDJBARAN, E., ZAHARI, R. and VAGHEI, R., 'Computing of post-buckling simulation in functionally graded materials - A review paper', *TELKOMNIKA Indonesian Journal of Electrical Engineering, Volume 12(12), pp 8344-8348*, 2014.
18. NI, X.-Y., PRUSTY, B.G. and HELLIER, A.K., 'Buckling and post-buckling of isotropic and composite stiffened panels: A review on analysis and experiment (2000-2012)', *Transactions of the Royal Institution of Naval Architects, Part A1: International Journal of Maritime Engineering, Volume 157, pp A-9 - A-29*, 2015.
19. KANG, J.-H. and KIM, C.-G., 'Minimum-weight design of compressively loaded composite plates and stiffened panels for postbuckling strength by Genetic Algorithm', *Composite Structures, Volume 69(2), pp 239-246*, 2005.
20. HERENCIA, J.E., WEAVER, P.M. and FRISWELL, M.I., 'Initial sizing optimisation of anisotropic composite panels with T-shaped stiffeners', *Thin-Walled Structures, Volume 46(4), pp 399-412*, 2008.
21. IUSPA, L. and RUOCCO, E., 'Optimum topological design of simply supported composite stiffened panels via genetic algorithms', *Computers & Structures, Volume 86(17-18), pp 1718-1737*, 2008.
22. TODOROKI, A. and SEKISHIRO, M., 'Optimization of blade stiffened composite panel under buckling and strength constraints', *Journal of Computational Science and Technology, Volume 2(1), pp 234-245*, 2008.
23. VESCOVINI, R. and BISAGNI, C., 'Buckling analysis and optimization of stiffened composite flat and curved panels', *AIAA Journal, Volume 50(4), pp 904-915*, 2012.
24. SHAW, A.D., DAYYANI, I. and FRISWELL, M.I., 'Optimisation of composite corrugated skins for buckling in morphing aircraft', *Composite Structures, Volume 119, pp 227-237*, 2015.
25. BADRAN, S.F., NASSEF, A.O. and METWALLI, S.M., 'Y-stiffened panel multi-objective optimization using genetic algorithm', *Thin-Walled Structures, Volume 47(11), pp 1331-1342*, 2009.
26. BADALLÓ, P., TRIAS, D., MARÍN, L. and MAYUGO, J.A., 'A comparative study of genetic algorithms for the multi-objective optimization of composite stringers under compression loads', *Composites Part B: Engineering, Volume 47, pp 130-136*, 2013.
27. VESCOVINI, R. and BISAGNI, C., 'Buckling optimization of stiffened composite flat and curved panels', in: *Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado, USA, Volume 8, pp 5961-5976*, 4-7 April, 2011.
28. SADEGHIFAR, M., BAGHERI, M. and JAFARI, A.A., 'Multiobjective optimization of orthogonally stiffened cylindrical shells for minimum weight and maximum axial buckling load', *Thin-Walled Structures, Volume 48(12), pp 979-988*, 2010.
29. BAGHERI, M., JAFARI, A.A. and SADEGHIFAR, M., 'Multi-objective optimization of ring stiffened cylindrical shells using a genetic algorithm', *Journal of Sound*

and Vibration, Volume 330(3), pp 374-384, 2011.

30. LONG, L.-C., ZHAO, B. and CHEN, X.-H., 'Buckling analysis and optimization of thin-walled stiffened cylindrical shell (in Chinese)', *Journal of Beijing University of Technology, Volume 38(7), pp 997-1003*, 2012.

31. BAGHERI, M., JAFARI, A.A. and SADEGHIFAR, M., 'A genetic algorithm optimization of ring-stiffened cylindrical shells for axial and radial buckling loads', *Archive of Applied Mechanics, Volume 81(11), pp 1639-1649*, 2011.

32. HAO, W., YING, Y., WEI, Y. and BAOHUA, L., 'Adaptive approximation-based optimization of composite advanced grid-stiffened cylinder', *Chinese Journal of Aeronautics, Volume 23(4), pp 423-429*, 2010.

33. SHI, S., SUN, Z., REN, M., CHEN, H. and HU, X., 'Buckling resistance of grid-stiffened carbon-fiber thin-shell structures', *Composites Part B: Engineering, Volume 45(1), pp 888-896*, 2013.

34. EL ANSARY, A.M., EL DAMATTY, A.A. and NASSEF, A.O., 'A coupled finite element genetic algorithm for optimum design of stiffened liquid-filled steel conical tanks', *Thin-Walled Structures, Volume 49(4), pp 482-493*, 2011.

35. YUAN, Z., GENG, X.-L. and WANG, F.-S., 'Stability analysis and optimal design of stiffened composite cylindrical shells (in Chinese)', in: *Proceedings of the 17th National Conference on Composite Materials (Composite Structure Design and Characterizatio*n*), Beijing, China, pp 117-121*, 12-15 October, 2012.

36. WODESENBET, E., KIDANE, S. and PANG, S.-S., 'Optimization for buckling loads of grid stiffened composite panels', *Composite Structures, Volume 60(2), pp 159-169*, 2003.

37. TODOROKI, A. and SEKISHIRO, M., 'Stacking sequence optimization to maximize the buckling load of blade-stiffened panels with strength constraints using the iterative fractal branch and bound method', *Composites Part B: Engineering, Volume 39(5), pp 842-850*, 2008.

38. SEKISHIRO, M. and TODOROKI, A., 'Extended fractal branch and bound method for optimization of multiple stacking sequences of stiffened composite panel', *Advanced Composite Materials, Volume 15(3), pp 341-356*, 2006.

39. LONG, L.C., CHEN, X.H., FU, X.R. and JU, J.S., 'Buckling capacity optimization of cylindrical shell with rectangle stiffeners under uniform axial compression (in Chinese)', *Journal of China Agricultural University, Volume 14, pp 124-130*, 2009.

40. FANG, H.-F., GE, S.-R. and CAI, L.-H., 'Buckling capacity optimization of coal mine refuge chamber's shell under uniform axial compression' in: *Proceedings of the 3rd International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), Shanghai, China, Volume 165, pp 649-653*, 6-7 January, 2011.

41. CHEN, X.H. and LONG, L.C., 'Buckling analysis and optimization of stiffened cylindrical shells under uniform axial compression', *Key Engineering Materials, Fracture and Strength of Solids VII, Volumes 462-463, pp 88-93*, 2011.

42. FANG, H.F. and CAI, L.H., 'Buckling capacity optimization of stiffened rectangular plate under uniform normal compression', *Journal of Computers, Volume 9(3), pp 581-585*, 2014.

43. HAO, P., WANG, B., LI, G., TIAN, K., DU, K., WANG, X. and TANG, X., 'Surrogate-based optimization of stiffened shells including load-carrying capacity and imperfection sensitivity', *Thin-Walled Structures, Volume 72, pp 164-174*, 2013.

44. RIKARDS, R., ABRAMOVICH, H., AUZINS, J., KORJAKINS, A., OZOLINSH, O., KALNINS, K. and GREEN, T., 'Surrogate models for optimum design of stiffened composite shells', *Composite Structures, Volume 63(2), pp 243-251*, 2004.

45. SALEHGHAFFARI, S., RAIS-ROHANI, M. and NAJAFI, A., 'Analysis and optimization of externally stiffened crush tubes', *Thin-Walled Structures, Volume 49(3), pp 397-408*, 2011.

46. BLOM, A.W., STICKLER, P.B. and GÜRDAL, Z., 'Optimization of a composite cylinder under bending by tailoring stiffness properties in circumferential direction', *Composites Part B: Engineering, Volume 41(2), pp 157-165*, 2010.

47. RIKARDS, R., ABRAMOVICH, H., KALNINS, K. and AUZINS, J., 'Surrogate modeling in design optimization of stiffened composite shells', *Composite Structures, Volume 73(2), pp 244-251*, 2006.

48. VITALI, R., PARK, O., HAFTKA, R.T. and SANKAR, B.V., 'Structural optimization of a hat-stiffened panel using response surfaces', *Journal of Aircraft, AIAA, Volume 39(1), pp 158-166*, 2002.

49. WANG, W., GUO, S., CHANG, N. and YANG, W., 'Optimum buckling design of composite stiffened panels using ant colony algorithm', *Composite Structures, Volume 92(3), pp 712-719*, 2010.

50. ZHOU, L., AN, W.G. and AN, H., 'Structure buckling non-probabilistic reliability index calculation of ventilated supercavitating vehicles', *Advanced Materials Research, Volumes 97-101, pp 4447-4450*, 2010.

51. CASEIRO, J.F., VALENTE, R.A.F., ANDRADE-CAMPOS, A. and YOON, J.W., 'On the elasto-plastic buckling of Integrally Stiffened Panels (ISP) joined by Friction Stir Welding (FSW): Numerical simulation and optimization algorithms', *International Journal of Mechanical Sciences, Volume 76, pp 49-59*, 2013.
52. CASEIRO, J.F., VALENTE, R.A.F., ANDRADE-CAMPOS, A. and YOON, J.W., 'On an innovative optimization approach for the design of cross-section profiles of integrally stiffened panels subjected to elasto-plastic buckling deformation modes', *International Journal of Material Forming, Volume 3(1), pp 49-52*, 2010.
53. CASEIRO, J.F., VALENTE, R.A.F., ANDRADE-CAMPOS, A. and YOON, J.W., 'Elasto-plastic buckling of integrally stiffended panels (ISP): An optimization approach for the design of cross-section profiles', *Thin-Walled Structures, Volume 49(7), pp 864-873*, 2011.
54. LAGAROS, N.D., FRAGIADAKIS, M. and PAPADRAKAKIS, M., 'Optimum design of shell structures with stiffening beams', *AIAA Journal, Volume 42(1), pp 175-184*, 2004.
55. TAYŞI, N., 'Determination of thickness and stiffener locations for optimization of critical buckling load of stiffened plates', *Scientific Research and Essays, Volume 5, pp 897-910*, 2010.
56. SIMÕES, L.M.C, FARKAS, J. and JÁRMAI, K., 'Reliability-based optimum design of a welded stringer-stiffened steel cylindrical shell subject to axial compression and bending', *Structural and Multidisciplinary Optimization, Volume 31(2), pp 147-155*, 2006.
57. HERENCIA, J.E., WEAVER, P.M. and FRISWELL, M.I., 'Local optimisation of long anisotropic laminated fibre composite panels with T shape stiffeners', in: *Proceedings of the 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Newport, Rhode Island, USA, Paper AIAA 2006-2171*, 1-4 May, 2006.
58. HERENCIA, J.E., WEAVER, P.M. and FRISWELL, M.I., 'Local optimisation of anisotropic composite panels with T shape stiffeners', in: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA, Paper AIAA 2007-2217*, 23-26 April, 2007.
59. HERENCIA, J.E., WEAVER, P.M. and FRISWELL, M.I., 'Optimization of long anisotropic laminated fiber composite panels with T-shaped stiffeners', *AIAA Journal, Volume 45(10), pp 2497-2509*, 2007.
60. HERENCIA, J.E., HAFTKA, R.T., WEAVER, P.M. and FRISWELL, M.I., 'Optimization of anisotropic composite panels with T-shaped stiffeners using linear approximations of the design constraints to identify their stacking sequences', in: *Proceedings of the 7th ASMO UK/ISSMO Conference on Engineering Design Optimization, Bath, UK*, 7-8 July, 2008.
61. HERENCIA, J.E., HAFTKA, R.T., WEAVER, P.M. and FRISWELL, M.I., 'Lay-up optimization of composite stiffened panels using linear approximations in lamination space', *AIAA Journal, Volume 46(9), pp 2387-2391*, 2008.
62. XU, Y.-M., LI, S. and RONG, X.-M., 'Composite structural optimization by genetic algorithm and neural network response surface modeling', *Chinese Journal of Aeronautics, Volume 18(4), pp 310-316*, 2005.
63. WANG, L.-F. and SHI, L.-Y., 'Simulation optimization: A review on theory and applications', *Acta Automatica Sinica, Volume 39(11), pp 1957-1968*, 2013.
64. CHEN, L., 'Robust optimum design of composite grid stiffened structure (in Chinese)', *Aircraft Design, Volume 31(4), pp 17-23*, 2011.
65. MU, P.-P., XIAO, X.-P. and ZHAO, M.-Y., 'Optimal design of composite stiffened plates (in Chinese)', *Fiberglass Reinforced Plastic/Composite Material, Volume 5, pp 57-60*, 2009.
66. FAGGIANI, A. and FALZON, B.G., 'Optimization strategy for minimizing damage in postbuckling stiffened panels', *AIAA Journal, Volume 45(10), pp 2520-2528*, 2007.
67. FAGGIANI, A. and FALZON, B.G., 'Minimizing damage in postbuckling stiffened composite panels: An optimization strategy using high performance computing', in: *Proceedings of the 17th International Conference on Composite Materials (ICCM-17), The Institute of Materials, Minerals and Mining, Edinburgh, UK, pp 1-15*, 27-31 July, 2009.
68. KIM, S.H. and KIM, C.G., 'Optimal design of composite stiffened panel with cohesive elements using micro-genetic algorithm', *Journal of Composite Materials, Volume 42(21), pp 2259-2273*, 2008.
69. KIM, J.S., KWEON, J.H. and CHOI, J.H., 'Optimization of a stiffened composite cylinder under external hydrostatic pressure for underwater vehicles', in: *Proceedings of the 18th International Conference on Composite Materials (ICCM-18), The Korean Society of Composite Materials, Jeju Island, South Korea*, 21-26 August, 2011.
70. CHEN, L., ZHAO, L.-L. and LIANG, D.-P., 'Robust optimum design of composite grid stiffened structure based on the intelligent alogrithm (in Chinese)', *Aircraft Design, Volume 32(1), pp 1-14/34*, 2012.

71. RONG, X.-M., XU, Y.-M. and WU, D.-C., 'Application of evolutionary neural networks to grid-stiffened composite structure design (in Chinese)', *Journal of Solid Rocket Technology, Volume 29(4), pp 305-309*, 2008.
72. ZHANG, Z.-F., CHEN, H.-R., LI, X. and JIANG, Y.-X., 'Hybrid genetic alogrithm for optimum design of advanced grid composite circular cylinders (in Chinese)', *Acta Materiae Compositae Sinica, Volume 22(2), pp 166-171*, 2005.
73. LI, S., XU, Y.-M. and ZHANG, J., 'Composite structural optimization design based on neural network response surfaces (in Chinese)', *Acta Materiae Compositae Sinica, Volume 22(5), pp 134-140*, 2005.
74. LIANG, D.-P., XU, Y.-M. and PENG, X.-L., 'Configuration optimum design of grid-stiffened composite panels (in Chinese)', *Journal of Solid Rocket Technology, Volume 31(5), pp 527-530*, 2008.
75. VILJOEN, A., VISSER, A.G. and GROENWOLD, A.A., 'Computationally efficient analysis and optimization of stiffened thin-walled panels in shear', *Journal of Aircraft, AIAA, Volume 42(3), pp 743-747*, 2005.
76. FALZON, B.G. and FAGGIANI, A., 'The use of a genetic algorithm to improve the postbuckling strength of stiffened composite panels susceptible to secondary instabilities', *Composite Structures, Volume 94(3), pp 883-895*, 2012.
77. VESCOVINI, R. and BISAGNI, C., 'Buckling optimization of stiffened composite flat and curved panels', in: *Proceedings of the 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, Colorado, USA, Paper AIAA 2011-2124, Volume 8, pp 5961-5976*, 4-7 April, 2011.
78. BISAGNI, C. and VESCOVINI, R., 'Fast tool for buckling analysis and optimization of stiffened panels', *Journal of Aircraft, AIAA, Volume 46(6), pp 2041-2053*, 2009.
79. LIANG, C.C., CHEN, H.W. and JEN, C.Y., 'Optimum design of filament-wound multilayer-sandwich submersible pressure hulls', *Ocean Engineering, Volume 30(15), pp 1941-1967*, 2003.
80. ZHANG, T.-L. and DING, Y.-L., 'Structural layout optimization of composite stiffened panel (in Chinese)', *Journal of Nanjing University of Aeronautics & Astronautics, Volume 42(1), pp 8-12*, 2010.
81. ANTÓNIO, C.A.C., 'A multilevel genetic algorithm for optimization of geometrically nonlinear stiffened composite structures', *Structural and Multidisciplinary Optimization, Volume 24(5), pp 372-386*, 2002.
82. MARIN, L., TRIAS, D., BADALLÓ, P., RUS, G. and MAYUGO, J.A., 'Optimization of composite stiffened panels under mechanical and hygrothermal loads using neural networks and genetic algorithms', *Composite Structures, Vol 94(11), pp 3321-3326*, 2012.
83. TODOROKI, A., 'Optimization of dimensions and laminates of stiffened composite structures with buckling load constraint using MOGA', in: *Neittaanmäki, P., Périaux, J. and Tuovinen, T. (Editors), Evolutionary and Deterministic Methods for Design, Optimization and Control with Applications to Industrial and Societal Problems, Proceedings of EUROGEN 2007, International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain*, 2007.
84. CORVINO, M., IUSPA, L., RICCIO, A. and SCARAMUZZINO, F., 'Weight and cost oriented multi-objective optimisation of impact damage resistant stiffened composite panels', *Computers & Structures, Volume 87(15-16), pp 1033-1042*, 2009.
85. FAN, Z.-R., YANG, S.-W., JIN, D.-F. and LIU, Z., 'Optimum buckling design of stiffened composite panel based on hierarchy optimization (in Chinese)', *Acta Materiae Compositae Sinica, Volume 32(3), pp 797-804*, 2014.
86. HAO, P., WANG, B., LI, G. and WANG, X.-J., 'Hybrid optimization of grid-stiffened cylinder based on surrogate model and smear stiffener model (in Chinese)', *Chinese Journal of Computational Mechanics, Volume 29(4), pp 481-486*, 2012.
87. ZHAO, Q., DING, Y.-L. and JIN, H.-B., 'Buckling optimization method based on structure efficiency of composite stiffened panels (in Chinese)', *Acta Materiae Compositae Sinica, Volume 27(3), pp 169-176*, 2010.
88. ZHAO, Q., DING, Y. and JIN, H., 'A layout optimization method of composite wing structures based on carrying efficiency criterion', *Chinese Journal of Aeronautics, Volume 24(4), pp 425-433*, 2011.
89. JADHAV, P. and MANTENA, P.R., 'Parametric optimization of grid-stiffened composite panels for maximizing their performance under transverse loading', *Composite Structures, Volume 77(3), pp 353-363*, 2007.
90. HOSSEINI-TOUDESHKY, H., LOUGHLAN, J. and KHARAZI, M., 'The buckling characteristics of some integrally formed bead stiffened composite panels', *Thin-Walled Structures, Volume 43(4), pp 629-645*, 2005.
91. ZHAO, Z., LIU, C.-S., CHEN, B. and ZHANG, Y., 'Parameterization study of orthogrid stiffened cylinder shells (in Chinese)', *Mechanics and Practice, Volume 26, pp 17-21*, 2004.
92. MAO, J., JIANG, Z.Y., CHEN, G.N. and ZHANG, W.H., 'Design and optimization

research on rib-stiffened thin cylindrical shell under axial loading (in Chinese)', *Engineering Mechanics, Volume 28(8), pp 183-191*, 2011.
93. TODOROKI, A. and SEKISHIRO, M., 'New iteration fractal branch and bound method for stacking sequence optimizations of multiple laminates', *Composite Structures, Volume 81(3), pp 419-426*, 2007.
94. TODOROKI, A. and TERADA, Y., 'Improved fractal branch and bound method for stacking-sequence optimizations of laminates', *AIAA Journal, Volume 42(1), pp 141-148*, 2004.
95. TODOROKI, A. and SEKISHIRO, M., 'Two-level optimization of dimensions and stacking sequences for hat-stiffened composite panel', *Journal of Computational Science and Technology, Volume 1(1), pp 22-33*, 2007.
96. IRISARRI, F.-X., LAURIN, F., LEROY, F.-H. and MAIRE, J.-F., 'Computational strategy for multiobjective optimization of composite stiffened panels', *Composite Structures, Volume 93(3), pp 1158-1167*, 2011.
97. IRISARRI, F.-X., BASSIR, D.H., CARRERE, N. and MAIRE, J.-F., 'Multiobjective stacking sequence optimization for laminated composite structures', *Composites Science and Technology, Volume 69(7-8), pp 983-990*, 2009.
98. WU, L.-L. and YAO, W.-X., 'Two-level collaborative optimum design method for composite stiffened panel (in Chinese)', *Journal of Nanjing University of Aeronautics & Astronautics, Volume 43(5), pp 645-649*, 2011.
99. CHENG, J.-L., FENG, Y.-L. and YAO, W.-X., 'Concurrent subspace optimum design method for composite stiffened panel (in Chinese)', *Advances In Aeronautical Science and Engineering, Volume 4(3), pp 292-305*, 2013.
100. FENG, Y.-L., CHENG, J.-L. and YAO, W.-X., 'Concurrent subspace optimum design method for composite stiffened panel (in Chinese)', *Journal of Nanjing University of Aeronautics & Astronautics, Volume 45(3), pp 360-366*, 2013.
101. LIU, W., BUTLER, R. and KIM, H.A., 'Optimization of composite stiffened panels subject to compression and lateral pressure using a bi-level approach', *Structural and Multidisciplinary Optimization, Volume 36(3), pp 235-245*, 2008.
102. WATSON, A., FEATHERSTON, C.A. and KENNEDY, D., 'Optimization of postbuckled stiffened panels with multiple stiffener sizes', in: *Proceedings of the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, USA, Volume AIAA-2, pp 1-8*, 23-26 April, 2007.
103. LIU, W., BUTLER, R. and MILEHAM, A., 'Optimum design, experimental testing and post-buckling analysis of thick composite stiffened panels', in: *AIAA-05-1826-CP, American Institute of Aeronautics and Astronautics, Reston, Virginia, USA*, 2005.
104. BUSHNELL, D., 'Optimization of a tee-stiffened panel under axial compression, in-plane shear, and normal pressure', in: *Proceedings of the 32nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Baltimore, Maryland, USA, Paper AIAA-91-1207-CP, pp 588-611*, 8-10 April, 1991.
105. VENKATARAMAN, S. and HAFTKA, R.T., 'Structural optimization complexity: what has Moore's law done for us?', *Structural and Multidisciplinary Optimization, Volume 28(6), pp 375-387*, 2004.
106. ERDAL, O. and SONMEZ, F.O., 'Optimum design of composite laminates for maximum buckling load capacity using simulated annealing', *Composite Structures, Volume 71(1), pp 45-52*, 2005.
107. ZHANG, T., LIU, T.-G., ZHAO, Y. and LUO, J.-Z., 'Nonlinear dynamic buckling of stiffened plates under in-plane impact load', *Journal of Zhejiang University SCIENCE, Volume 5(5), pp 609-617*, 2004.
108. YAFFE, R. and ABRAMOVICH, H., 'Dynamic buckling of cylindrical stringer stiffened shells', *Computers & Structures, Volume 81(8-11), pp 1031-1039*, 2003.