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Corresponding Author: Mr Ziad K Awad, M.D.

Corresponding Author's Institution: University of Southern Queensland

First Author: Ziad K Awad, MSc, BSc

Order of Authors: Ziad K Awad, MSc, BSc; Thiru Aravinthan, PhD, MEng, BScEng; Yan Zhuge, PhD; Felipe Gonzalez, PhD

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RESEARCH PAPER

A review of optimization techniques used in the design of fibre composite structures for civil engineering applications

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By

Ziad K. Awad [a], Thiru Aravinthan [a], Yan Zhuge [a] & Felipe Gonzalez [b]
[a] Centre of Excellence in Engineered Fibre Composites (CEEFC),
Faculty of Engineering and Surveying, University of Southern Queensland,
Toowoomba, Queensland 4350, Australia

[b] Faculty of Built Environment & Engineering,
Queensland University of Technology (QUT),
Brisbane, Australia

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Corresponding Author:

Ziad K. Awad
PhD Student
Centre of Excellence in Engineered Fibre Composites (CEEFC),
Faculty of Engineering and Surveying, University of Southern Queensland,
Toowoomba, Queensland 4350, Australia
Tel: +61 7 4631 2633
E-mail: awad@usq.edu.au

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A review of optimization techniques used in the design of fibre composite structures for civil engineering applications

Ziad K. Awad [1a], Thiru Aravinthan [a], Yan Zhuge [a] & Felipe Gonzalez [b]

[a] Centre of Excellence in Engineering Fibre Composite (CEEFC), University of Southern Queensland (USQ), Toowoomba QLD 4350, Australia
[b] Faculty of Built Environment & Engineering, Queensland University of Technology (QUT), Brisbane, Australia

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[1] Corresponding author, tel. +61 7 4631 2633 , +61 7 4631 1385
E-mail addresses: awad@usq.edu.au (Z.K. Awad), aravinthant@usq.edu.au (T. Aravinthan).

1. Introduction

In the last 60 years since the Second World War, fibre reinforced polymer FRP has been used in many structural applications due to their excellent strength and weight characteristics as well as the ability for their properties to be tailored to the requirements of several applications with complex [1]. There are many benefits of FRP, which encourage engineers to use these materials in many structural forms. The benefits could be summarized as; weight saving (high strength to weight ratio), able to add to the old structures in the form of strengthening or repairing, low maintenance requirement, resistance to the environment effects, and ability to be formed into a complex shape [2].

FRP is increasingly used in the last decades in civil engineering constructions. The fibre composite members have been used in many countries to construct large-scale fibre composite structures such as traffic bridges and pedestrian bridges. Pedestrian bridges in rural areas are the most famous application of the fibre composites, but there are limited design guidelines for such applications. The designers are likely to combine between two standards; the specification for pedestrian crossing bridge and the specifications for highway bridge [3, 4]. Most of the available fibre composite design structures depend on the coupon level experimental test and submit the result into the FEA model to get the analysis results for the real structure [5, 6]. The re-analysis and hand design variables change might be unable to go to the right design point. The efficiency of the re-analysis process depends on the experience of the designer as a prediction factor.

The Centre of Excellence in Engineered Fibre Composite (CEEFC) at the University of Southern Queensland (USQ) participated in the research, development and installation of the first fibre composite bridge in Australia in 2002 [7]. The Structure and Materials Research Laboratory at Virginia Technology developed a fibre composite bridge design in 1997 [8]. This new bridge was installed instead of the Tom's Creek timber bridge. The Tom's Creek composite bridge was designed according to the EXTREN DWB design guide [9]. In 1997, Potntresina pedestrian Bridge was built in Switzerland. The bridge was designed to carry a load of 500 kg/m^2 [10]. In addition, fibre composite has also been used in the constructions of other types of structures such as railway sleepers [11], floating walk way and piles [12]. Generally, the design of the fibre composite structures depends on the principle of allowable deflection limit under the external service load. The EUROCOMP design code recommends a deflection limit for the fibre composite structure under the serviceability conditions which is between span/150 to span/400 [13].

The attention in USA has been increased towards the fibre composite bridge deck to get a non-corrosive and light weight decking system and over 117 bridges have been built or rehabilitated until 2008 [14]. In the absence of the beneficial design standards for the fibre composite structures in civil engineering applications, the optimization methods and Finite Element Analysis (FEA) represent the important solution to get an acceptable structure design with regard to the limits of the serviceability. Therefore, this paper attempts to review the importance of the optimization techniques and its application for the design of fibre composite structures of civil engineering applications.

2. Challenges in the design of fibre composite structures

Many researchers have accepted that the traditional materials such as wood, steel and concrete lose the battle against corrosion. New construction technologies have been trialled using FRP materials as an alternative to the traditional steel, concrete, and wood materials [15]. In addition, its use has been increasing for the repairing, strengthening and replacement of old structures. Therefore, the evaluation of the fibre composites in civil engineering applications is important to justify whether this material is reliable enough to be used as a construction material. Steel is a homogenous material with constant stiffness in all directions, while the FRP composite material has different stiffness in different directions. The fibre composite member designed for tension cannot be loaded with torsion forces [16]. Therefore, fibre composites are generally anisotropic, brittle, low modulus, and are highly dependent on the properties of its components matrix and fibre. The design of fibre composite structure is not only a shape or geometry design, the material itself should be included in the design process. Any design method for fibre composite structure has to consider the fibre plies design level and the overall geometry level of the structure. Optimization methods have the advantages of offering the solution of geometry and materials design at the same stage.

3. Analytical methods of fibre composite structure

The analysis of fibre composite structure is different to the analysis of isotropic materials such as steel and concrete. It is recommended to go for multi-layers analysis called meso-level approach. The perfect analysis of fibre composite structures represents the key of the optimum structural design, which is controlled by the design constraints. The design of composite materials is complicated by its anisotropic nature and multi-orientation plies. Governing equations were used to analyse the laminated beam by assuming zero in-plane forces. The simplest and most popular model for the simulation of composite layer is the Equivalent Single Layer (ESL) and the first order shear theory to obtain a reliable solution. The fibre composite structure could accumulate damage before the final failure. Therefore, it is essential to use the non-linear behaviour of quasi-brittle material to calculate the damage tolerance of the structure [17].

Several analysis methods have been combined with the optimization methods to design FRP composite structures. The bending theory was used with some assumptions to optimize the FRP sandwich beam [18]. The FE method is the most popular analytical method in the optimization of the composite structures, and it is appropriate to deal with different objective functions [19, 20]. Shell element and 3D brick element are used in the analysis of the fibre composite structures. The shell element allows considering the fibre layers in the model within the element thickness [21, 22]. While, the 3D brick element allows the use of the incompatible mode and the layered solid section in the calculation of the flexural response of the element [23].

4. Experimental optimization of fibre composite structures

Fibre composite girders have been used by civil engineers in the replacement of a traditional old wood girder bridges. There are about 27,000 timber bridges in Australia. Most of them are 50 years old, and are degraded under environmental conditions [24]. The Queensland Department of Transport and Main Roads recommended the replacement of these degraded bridge girders by new girders with the same stiffness. The design requirements are related to the stiffness and strength of the new girders. The new girders are developed by two Queensland based manufacturers are made of glass fibre composites (GFRP) as shown in Figures 1 and 2 [25]. The experimental tests conducted at CEEFC showed that the fibre composite girders satisfy the strength and stiffness requirements. [25]. Those two different beams were developed in 4-stages of the design process based on the full structures experimental tests and designer experience. These types of fibre composite girders require substantial research and development to satisfy the design requirements, including effects such as environmental impact, long-term durability, load variation, cost, and dynamic consideration.

The conventional concrete, steel, and wood decks showed degradation under the effects of cyclic loading and the environment [14]. Gan et al. [26] evaluated seven applicable FRP composite deck sections as shown in Figure 3. It was shown that the optimum section was a triangular section. The triangular section enhanced the global and local stiffness, and improved buckling. Jeong et al. [27] on the other hand, tried to find the safety factor of fibre composite pultruded deck by static and fatigue tests under load equivalent to DB-24 truck load. The test showed that the ultimate factor of safety was 3.5 with a service deflection of

1.74 mm less than span/800, and the strain is 13% of the ultimate strain. Kumar et al. [28] conducted an experimental study to investigate the behaviour of a composite bridge. The deck was made of small square pultruded glass and carbon fibre tubes as shown in Figure 4. The first version of this deck has been 8-layers. The experimental test was indicated that the 7-layers I-beam could carry the external load with factor of safety equal to 4. Roy et al. [29] started to develop a new GFRP bridge deck using manual optimization, and it showed that the optimum size of the new deck was 3.1 m long, 1.2 m wide, and 0.215 m thickness as shown in Figure 5. The voids of the deck were filled with structural foam. The deck test revealed that the deck can carry twice the design load but the deflection was higher than the allowable limit. A new FRP bridge deck was developed at CEEFC as shown in Figure 6. The experimental verification indicated that the deflection exceed the allowable limit [30].

Experimental investigations are good in that they investigate the real behaviour of full scale structures. The real-life fibre composite structures have many aspects that cannot be covered by numerical simulation such as; the differences in fabrication quality, the effect of gluing of different parts of the structure, boundary conditions, and contact surfaces. In contrast, there are few disadvantages of using experimental investigation such as high cost, longer time taken for testing, and the need of experimental test facilities, which tends to limit the number of iterations to one or two, thus not achieving an optimum design. In addition, it can be noted from the literature review that in some experimental investigations the structural design constraints for deflection criteria could not be met, resulting in non-compliance structure.

5 Optimization methods in fibre composite structural design

This section will review the most popular optimization methods used in the design of fibre composite structures for civil engineering applications. The design optimization of civil engineering structures has specific design requirements or constraints regarding to the serviceability of the structure during its long life.

5.1 Design Sensitivity Analysis (DSA)

Design sensitivity method has been used in the last two decades in automotive optimization due to the increase of hardware capability. Design sensitivity method requires the calculation of the gradient of the objective and the constraints with respect to the design variables. There are two methods used to find the variation of the objective function and the constraints: the finite difference method and the response surface method (RSM). The simple form of the finite difference for function *f(x)* and *x* variable is [31]:

$$\frac{df}{dx} \approx \frac{\Delta f}{\Delta x} = \frac{[f(x+\Delta x) - f(x)]}{\Delta x} \qquad (1)$$

The RSM is a statistical method and it depends on an approximation function to simulate the response of the variables. The relation between variables *x* and the real response ξ is:

$$\xi = f(x) \qquad (2)$$

$$E(\xi) = f(x) + \boldsymbol{\varepsilon} \qquad (3)$$

Where, E(ξ) is an estimate of the real response and **ε** is the error.

Optimum design of FRP composite shell has been studied by using DSA method. Analytical, semi-analytical, and finite difference methods were used in the analysis. The conclusion was made that different optimization objectives could be used with DSA method. In addition, using a higher order discrete model could enhance the accuracy [32, 33]. Wu and Burgueño [34] studied the optimum shape and stacking sequence design of FRP composite shells using FE and DSA. Lindgaard and Lund [35] studied the non-linear buckling optimization of fibre composite shells. The bucking behaviour was improved by using DSA method.

FRP composite box beam was studied to minimize the weight of the structure. The design constraints were stress, displacement, critical load, and natural frequency. The optimization variables were layer thicknesses and layer orientations of the rectangular beam section [36]. The geometrical non-linearity was included in the design and optimization of composite beam dome and the optimum size of the dome was 42.23 m in span and 6.1 m height [37].

5.2 Genetic Algorithm (GA)

In the last few decades, GA has been used in the structural design optimization due to its capability to deal with complicated and large variable problems. The fundamental theorem of the genetic algorithm was developed by Holland [38]. GA was used to optimize the FRP composite plate as shown in Figure 7, and the objective was minimizing the weight and the cost of FRP plate. Two types of external loads were applied; impact load [23] and static load [39]. It was found that the optimization of composite structure using parallel GA gives relatively a good convergence and low process time. In addition, it was found that the quality of the results depends on the problem size. He and Aref [40] used GA to find the optimum selection of design parameters; the number of stiffeners, thicknesses, and the orientations of outer skin layers of the fibre composite bridge deck, as shown in Figure 8. They concluded that the weight was decreased by 25% from the initial design, and the GA algorithm might be the suitable method to deal with this type of problems because it can accommodate both discrete and continuous design variables.

Kim et al. [41] studied the optimum shape of hollow pultrusion fibre composite deck bridge under the truck load DB-24. The objective function was the cost minimization, and the conclusion was made that the trapezoidal shape was the optimum shape for hollow bridge deck as shown in Figure 9. It showed that the sensitivity of deflection and buckling to the deck dimensions was higher than the material variables. However, the estimated cost of the optimized GFRP deck is twice compared to the conventional concrete deck. In addition, the same authors [42] presented an optimization design for a temporary FRP bridge deck. The optimum deck shape is shown in Figure 10.

5.3 Simulating Annealing Method (SA)

In structural design, SA method was used to find the optimum design of fibre composite structures as an efficient method to solve the problems with multiple-global optima [43].

Erdal and Sonmez [44] discussed the optimum design of composite layer orientations in order to maximize the buckling load capacity of the laminated plate by using the direct SA algorithm. The optimum design enhanced the buckling load factor from 3973.01 to 4123.28 for the plate aspect ratio equal to one. Rao et al. [45] presented an optimization of composite plate in order to maximize the natural frequency as a dynamic consideration by using SA method. It was concluded that the SA is a less expensive method to deal with the complicated design optimization, especially when the design considers the layup optimization as well as the ply orientations. Ertas and Sonmez [46] used SA method to design fibre composite structure for maximum fatigue life. The conclusion was made that increasing the number of fibre angles has a positive impact to the fatigue life.

5.4 Reliability based design optimization (RBDO)

Reliability-based design optimization (RBDO) method is different to the normal optimization method and it is called non-deterministic method or probabilistic method. The objective function is limited by probabilistic constraints instead of conventional deterministic constraints. It considers the uncertainty of the optimization design in fibre composite structural problem. The mathematical form of the RBDO is described below [47] :

find x

minimizing $f(x)$ (4)

subject to constraints $P(g_i(x) \leq 0 - \Phi(-\beta_i) \leq 0 \; (i = 1,2, \dots., k)$ (5)

$x_{lower} \leq x \leq x_{upper}$ (6)

Where, x is any design variable, $P(g_i(d)\text{- } 0)$ is the probability, Φ is the integral of the (0,1) standardized normal distribution and $\boldsymbol{\beta}_i$ is the so-called safety - index.

Since the application of FRP composite structures are new, the ultimate load and risk assessment in the optimum design of FRP composite structure have become a critical consideration for engineers. Furthermore, there is a limitation in a full-scale testing due to the cost issue, and there is a lack of the result for construction of probability distributions. The probability design methods have a target for the research to fill the design gap in the new technology. Thompson et al. [48] used the RBDO to design FRP composite bridge deck panel. The objective function was to minimize the weight of the panel. Two types of constraints are used in the design; deterministic stress constraints and two probabilistic deflection constrains. The design optimization was achieved 55% weight saving compared to the initial design. António [49] carried out a research on the optimization of FRP composite shallow shell reinforced with a composite beam including a geometrical non-linearity. The objective function was a weight minimization. The RDBO included the probabilistic stress, deflection, and buckling constraints.

5.5 Particle Swarm Optimization Algorithm (PSOA)

Particle swarm optimization algorithm (PSOA) is an optimization algorithm, which is based on swarm intelligence. PSOA comes from a research on the bird and fish flock movement behaviour. PSOA consists of group of particles and the position of each particle is affected by the surrounding most optimal position during its movement. The speed and position of each particle change according to this equation for one-dimensional [50]:

$$v_{k+1} = a \, . \, v_k + b_1 \, . \, r_1(p_1 - x_k) + b_2 \, . \, r_2(p_2 - x_k) \tag{7}$$

$$x_{k+1} = c \, . \, x_k + d \, . \, v_{k+1} \tag{8}$$

where, v is the velocity, a is the momentum, k is the iteration, b is the strength of attraction coefficient, x is the particle position, and c and d are the position factor at velocity v_{k+1}.

Optimum design of a new sandwich panel structure was conducted by Kovács et al. [51] as shown in Figure 11. This structure is made of carbon fibre reinforced plastic polymer (CFRP) plate and aluminium section. The PSOA was used to find the minimum cost and maximum stiffness of the structure. The CFRP was optimized by finding the layers' orientation angles. The aluminium section was optimized with respect to the wall thickness, and the edges length.

Design constraints were the maximum allowable deflection, buckling of CFRP plate and aluminium stiffeners and stresses in the CFRP and aluminium were included. The major finding was the CFRP plates increased the damping capacity of the aluminium section and the optimum design with plies oreintation 0/90^o. FRP composite box beam was studied by using PSOA method under single objective optimization function [52] and multi-objective optimization function [53]. The conclusion was made that the box beam walls with different orientations had a better strength than the box walls with the same fibre orientations. Naik et al. [54] used a vector evaluated particle swarm optimization (VEPSO) to find the minimum weight of the composite structure under different failure criteria such as a Tsai-Wu, maximum stress and failure mechanism based. The comparison between those criteria showed that the failure mechanism produced better results. The objective was achieving specific stiffness and maximum elastic coupling. The optimization solution was compared with GA, and it showed a less computational time than GA.

5.6 Ant colony optimization (ACO)

In each social insect colony, there is a system or plan to follow by the individuals and the overall groups seem to be well organized. The basic algorithm depends on the swarm intelligence to solve the complicated problems. In the solution, the real ants try to find the shortest path from the nest to reach food. The procedure of the ACO is different to the GA, where in the ACO the ant tries to construct the solution step by step. Whereas, GA method builds the coded solution candidate, and then does the evaluation. In ACO, each ant should decide the direction of the next step. The state transition rule in ACO can be described as [55]:

$$l_{k+1} = \begin{cases} \arg max\{[\tau(l_k, l_i][l_k, l_i]^{\beta}\} \; if \; q \le q_o \\ p\left(\frac{[\tau(l_k,l_i][l_k,l_i]^{\beta}}{\sum[\tau(l_k,l_i][l_k,l_i]^{\beta}}\right) \quad if \; q > q_o \end{cases} \tag{9}$$

where, τ is the pheromone, η is the heuristic, l_k is the latest chosen element, l_i belong to the list L of all possible candidature, $\boldsymbol{\beta}$ is a parameter, P is the probability, q is randomly generated number in the domain [0,1] and q_o is a constant parameter.

ACO has been used successfully in the optimization of the fibre composite structure. Abachizadeh and Tahani [56] used the ACO to maximize the fundamental frequency and minimize the cost of the symmetric hybrid laminate. The sample was made of two graphite/epoxy stiff skins and glass/epoxy core. Omkar et al. [57] optimized the FRP composite plate by using multi-objective ACO. The target was to achieve certain strength with minimizing the weight and the cost of the plate. The variables were plies number, stacking sequence and thicknesses. The ACO performance was compared with the GA, PSO and Artificial Immune System (AIS) and showed a good improvement. Wang et al. [58] presented an optimal design of composite stiffened panel with a T-shape stiffeners. ACO and finite strip method were used in the study to maximize panel buckling.

5.7 Multi-objective Robust Design optimization (MRDO)

Li et al. [59] presented a new robust multi-objective genetic algorithm (RMOGA). The advantages of this method are: i) it measures the optimum solution performances and ii) measures the robustness index. Messac and Yahaya [60] developed a MRDO method under the consideration of physical meaningful term. The design showed that the MRDO allowed considering parameters which was not a part of the normal optimization. The MRDO is different from the traditional optimization method. The traditional optimization methods provide a poor off-design solution and it becomes very critical to insure the design requirements. The designer has to consider the MRDO as an efficient tool to consider the variation of the input parameters in the range of circumstances. The simplest form of MRDO problem is [61]:

$$min_x \; f_v \; (f_2, f_2, \dots \dots, f_m \,, g_1, \dots, g_G) \tag{10}$$

$$max_x \ \eta = \frac{R}{R_E} \tag{11}$$

$$x^{lower} \leq x \leq x^{upper} \tag{12}$$

The f_v is the fitness value and is a function of the design objectives *(f_1, …, f_m)* and constraints *(g1,…., g_G)*. $\boldsymbol{\eta}$ is the robust index, R is the optimum solution and R_E is the radius of the exterior radius of the normalized tolerance.

Application of the MRDO is very important in the design of fibre composite structures because it considers the uncertainty due to material properties and manufacturing process. The uncertainty of the design variables and constraints could be included. The MRDO enhances the design results by reducing the standard deviation of the design objectives. Choi et al. [62] used the MRDO to minimize the residual stresses in the FRP composite plate. These stresses are the major cause of the bond failure. The robust optimization showed a reduction in the mean and standard deviation of the residual stresses to enhance the FRP plate production. Doltsinis et al. [63] studied the design of non-linear structure by using MRDO. The designer expected to have design uncertainty or fluctuation of the material, fabrication, and load, which affected the design result. The optimization of the structure using deterministic structural optimization might become unreliable due to the deviation between the actual structure and the nominal one. The conclusion was made that the MRDO helped reducing the structural performance sensitivity with respect to the design variables and noise parameters.

5.8 Other optimization methods

There are several other optimization methods have been used in the design of fibre composite structures. Farkas and Jarmai [18] presented an optimization study to select a sandwich beam by using Rosenbrock's Hillclimb method. The expected beam should have a good damping capacity and low deflection. The optimum composite sandwich beam consists of five layers: double box beam, rubber layer and two layers of FRP as shown in Figure 12. The objective of adding FRP layer was to increase the stiffness of the beam and to reduce the deflection. The optimization design was made to minimize the cost of the three sandwich beams. It was concluded that the five layers composite beam was the best one due to its high stiffness and damping ratio. Fam and Son [20] presented a parametric study in the design of concrete-filled fibre composite poles and the problem was shown in Figure 13. Lund [21] used Discrete Material Optimization to design multi-layers fibre composite shell. The conclusion was made that the middle layers required only ±45^{o} fibre in the corners to carry the shear forces and the top and bottom layers have fibre in different directions as shown in Figure 14. Ghiasi et al. [64, 65] presented a comparison study for the optimization methods used in the constant and variable stiffness design of fibre composite structures. This work indicated that the Gradient - based methods are the best for the constant stiffness design. Furthermore, the optimality criterion and topology methods are the best for the variable stiffness design.

5.9 Summary of optimization outcomes

From the previous review of literature, it can be summarised some benefits of using optimization in the design of FRP composite structures as shown in Table 1. This table contains different examples of the optimization and parametric studies with the results as a benefit for the fibre composite structures design.

6 A comparison of optimization methods

Various optimization methods have been discussed in the previous sections. There are many benefits achieved by using different design methods and procedures. The optimization formulation of composite structures leads to non-linear functions of the design variables; number of plies, lamina thickness, and fibre orientations. DSA method relies on the gradient derivative to formulate the optimization process, and it can optimize both discrete and continuous variables problem. The DSA was applied to the design of problems for geometry and lamina design. The DSA methods cannot solve the multi-objective optimization problem, but it can be used in the decision making of multi-objective optimization as mentioned by Avila et al. [72]. Recently, engineering applications show more interest in solving optimization problems with multi-objectives due to the multiple conflicting objectives. SA was used on the fibre composite structures for multi-objective optimization. The SA method showed a high ability to deal with non-linear optimization problems. SA is regarded as a general solution method, and it can be applied to large number of problems. However, SA results are not able to produce the same results with another run and it might go for another solution. It is effective in local optimum result and this result depends on the initial configuration. On the other hand, researchers have used GA in several applications in FRP composite structural optimization including multi-objective. GA is a global optimization method, and it can work in a wide range of problems. In addition, it does not need to find the derivatives, and it is easy to parallelize. GA can store and use the information from previous steps. The disadvantage of GA is that it is very slow and cannot always find the exact solution, but it can find the best solution among populations.

The RBDO is regarded as an expensive method in computational work, because it needs more function evaluations than corresponding deterministic optimization methods. Using RBDO gives a reliable optimization result due to considering a randomness of the problem variables and constraints. RBDO has the probabilistic distribution and this may lead to substantial errors in the reliability analysis. In this sense, RBDO might be less useful on the practical side, if the information about the random uncertainty is not available or not sufficient to authorize a reliability analysis of the problem.

PSOA is an evolutionary global algorithm, and it has been used recently in the optimization of fibre composite structures. PSOA can solve the continuous global optimization problem with a non-linear objective function. PSOA is quite similar to GA with a randomly generated population but GA is more popular due to its simplicity. The difference between PSOA and

GA is PSOA does not need complicated encoding and decoding and can work directly with real numbers. Moreover, both PSOA and GA start with a randomly generated population, evaluate the population for fitness values, update the population and use random methods to search for the optimal. The main disadvantage of this method is that the particles may follow wider cycles and may not converge when the individual best performance of the particles group is far from the local particles in the same swarm. In addition, when the inertia weight is decreased, the ability of swarm to search new areas becomes low because it is unable to create exploration mode.

ACO regards as a constructive search algorithm to deal with some complicated problem such as Travelling Salesman problem. In addition, ACO has advantages of giving positive and rapid feedback for the food solution. Furthermore, ACO can be used in dynamic applications. In contrast, there are some disadvantages of using ACO such as; the probability distribution is changing by iteration, in spite of convergence is guaranteed, the time of convergence is uncertain and finally, the theoretical analysis is difficult.

MRDO has been developed to optimize the products by reducing the effects of uncontrollable variation on the design parts. These uncontrollable variations can significantly reduce the design quality. Therefore, the robust solution is very important to avoid the small deviation of the uncontrolled parameters. There is a trade-off between accuracy and efficiency; MRDO provides a good balance between accuracy and efficiency. The disadvantage of robust design is the problem size become large quickly, and it needs long time to find the solution. Since MRDO optimization can provide an efficient design procedure for complicated multi-objectives problems by considering the types of variables control and uncontrolled variable. The MRDO relies on the probabilities to improve the design robustness and provide an attractive design framework of robustness. In the design of fibre composite structures, there are many variables eligible to be included in the design process. These variables come from the natural anisotropic of the fibre composite, different martials could be used, the fibre volume ratio is important, fibre orientations, geometry variable, sequence of layers, load position, load percentage at the service state, manufacturing quality and environmental effects. All these variables might affect the design of fibre composite structures. Under the consideration of multi-objective optimization and the controlled and uncontrolled design variables of fibre composite structures, the MRDO method might represent an appropriate choice to design a complicated non linear optimization problem. Finally, a comparison of the reviewed optimization methods is shown in Table 2. This table compares the differences among each optimization method according to its ability to solve the optimization problems. The methods ranking is classified according to four categories such as; multi-objective, probability, uncontrolled parameter, and free derivative. As indicated in Table 2, all the reviewed methods are able to solve the multi-objective optimization except DSA method. In addition, the GA, SA, PSOA, ACO and MRDO methods do not require the derivative of the objective function. While the DSA and RBDO required the derivative of the objective function. Overall, MRDO method offers a good ability to consider all aspects in the design optimization.

7 Proposed optimization approach for civil infrastructures

The previous sections reviewed various optimization methods and the design objectives associated with. The design optimization methods might be the right choice to find an economic, light weight, and serviceable fibre composite structures. In some of the optimization studies the designer did not adopt the guidelines in their actual case study in the form of the dimensions, external applied load, and the serviceability requirements. Civil engineering structural design requires special constraints and limitations in the design compared to other structures such as automobile and aircraft. These requirements focus on the service load level of the structure. In addition, the literature review showed that there is no limitation for the stresses at the service load level. Several structural design standards give some recommendations for the external applied service load and the allowable deflection. These recommendations depend on the type of structural materials. For fibre composite structure, the only available guideline is the EUROCOMP which recommends the allowable deflection, the allowable stresses and the factor of safety for some structural applications [13]. The design optimization of fibre composite structure is important to get an economical and a safe structure. In order to achieve this objective, the authors of this paper suggested an optimization procedure to link different design aspects to achieve an optimum design. These aspects are; experimental material test, FE analysis, design codes and standards, and optimization methods. Figure 15 shows the proposed optimization methodology addressing the shortcomings of the currently available optimization techniques. The suggested methodology focuses on different parts of the structure design process. Initially, experimental investigation was carried out on the available FRP material to find the basic design data such as; strength, strain, modulus of elasticity, density, and failure mode. Then, the behaviour of the structural elements made from this material was investigated, such as beam and plate. Thirdly, FE method was employed to simulate the tested FRP composite element. The major part of the simulation is to select the most appropriate material model and element type. A reviewing of the available design standards, design guides, and previous structural data was followed. This will help to identify the most suitable and critical design constraints. Moreover, the design process should satisfy the standards' recommendation with regard to dimensions, loads, allowable stresses and deflections. Once the design simulation satisfies all the requirements, the results produced from the design optimization will be more realistic and useful to the practicing engineers. Considering the available optimization methods, the MRDO method seems to be a good option to cover any manufacturing or fabrication uncertainty in the design variables.

This methodology was applied on the design of the FRP sandwich floor panel as a preliminary study. A simply supported square FRP sandwich floor panel was designed for multi-objective optimization by using MRDO method as shown in Figure 16. The objectives were minimizing the weight and maximizing the first natural frequency of the FRP sandwich panel. The core thickness was selected as a robust design variable. The development of the optimization model involved three stages; experimental data collection, FE modelling and design constrains. The magnitude of the load was determined according to the AS/NZS 1170.1:2002 and the design constraints were based on EUROCOMP. It was found out from this study that there was a trade-off between the two objectives as shown in Figure 17 and the relationship between them was a direct correlation. In addition, the MRDO assists in the decision making of selecting the optimum design point from the Pareto frontier. Further details of this investigation have been published by the authors elsewhere [73].

8 Conclusions

The advantages of the fibre composite structures make them attractive to be used in the building and construction industries recently. Many full-scale fibre composite structures have been built through the last two decades which are significantly lighter compared to the traditional structures. The challenge is to optimize the fibre composite structures to achieve both the structural performance and the minimum cost. The application of optimization methods offers many benefits in the design of fibre composite civil structures. The literature review showed that the DSA method was used with single objective function. The GA, PSOA, ACO, RBDO, and MRDO methods could be applied for multi-objective optimization. These methods have been applied successfully to different fibre composite structures such as; plate, beam, box beam, sandwich panel, bridge girder, and bridge deck. In the multi-objective optimization MRDO method was found to be more suitable for the design optimization of FRP composite structures because it allows to consider the variables and constraints uncertainty in the design. Considering the limitations of the existing optimization methods, the authors proposed a methodology for the optimization of civil infrastructure. Preliminary results of applying this methodology showed an enhancement in the final structural design, considering multi objective optimization. Finally, it is important that the designers consider several objectives to find the optimum solution in the civil engineering applications. These solutions are not simply achievable by hand calculations or simplified assumptions. However, further investigation is needed on the proposed methodology applied to different case studies to investigate its validity and limitations.

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Table 1 Benefits of optimum design to different fibre composite structures

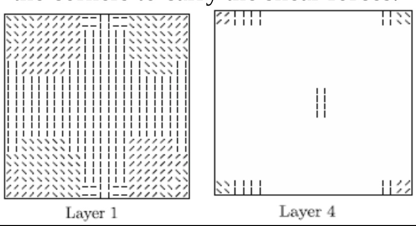
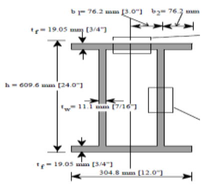
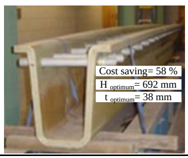
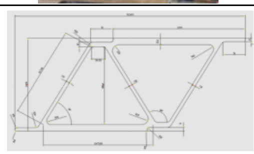
FRP Structure Type	Reference	Optimization method	Objective	Main benefit and conclusion
Sandwich beam	[18]	Rosenbrock's Hillclimb method	Cost	Five layer sandwich beam should be used
Laminate composite beam	[36]	Design sensitivity	Weight minimization	Design open and closed box section
Column	[66]	Genetic algorithm	Maximum buckling	Column with variation sections is the optimum
FRP poles	[20]	Parametric study	Length of filling part, Figure (14)	$X_{opt} = Length * (1 - \frac{Moment_{hollow}}{Moment_{full}})$ - *Diameter*
Impact plate design	[23]	Genetic algorithm	Cost and weight	*Impact Velocity m/s* | *Optimum thickness (mm)* 6 | 0.00288 9 | 0.0034 12 | 0.00558
Shell	[21]	Discrete Material Optimization	Maximize buckling	The middle layers required only ±45 fibre in the corners to carry the shear forces. 
Bridge deck	[40]	Genetic algorithm	Weight minimization	Total weight decreased by 25%.
Bridge deck	[41, 67]	Genetic algorithm	Cost minimization	• The optimum cross section is trapezoidal • The cross section dimensions have higher impact on the deflection and buckling than the materials variables.
CFRP sandwich panel	[68]	Particle swarm	Cost	Orientation of $0^0/90^0$ is the optimum.
Beam Girder	[69]	commercial program IDESIGN	Minimization beam cross section area	
Beam Girder	[70]	Graphical method	Weight minimization	
Bridge deck unit	[71]	Genetic algorithm	Volume minimization	

Table 2 C`omparison of the optimization methods

Method	Objective	Probability	Uncontrolled parameters	Free derivative	Solution cost	Optimum solution remark	Overall ranking
DSA	Single	x	x	x	Moderate	Discrete and continuous variables	Low
GA	Multi-objective	√	x	√	Low in parallel optimization	Global	High
SA	Multi-objective	√	x	√	Low	Multiple global optimum	Moderate
RBDO	Multi-objective	√	x	x	High	Convergence difficulties	Moderate
PSOA	Multi-objective	x	x	√	Less than GA for single objective	-Global -Convergence difficulties	High
ACO	Multi-objective	√	x	√	Moderate	Good performance	Moderate
MRDO	Multi-objective	√	√	√	High	Enhance the design objectives	High

Figure

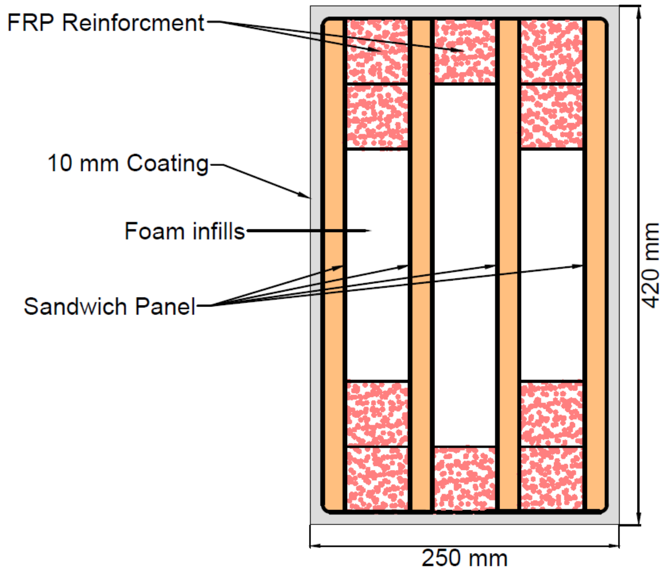


Figure (1) Beam girder section for span (9700mm) [25]

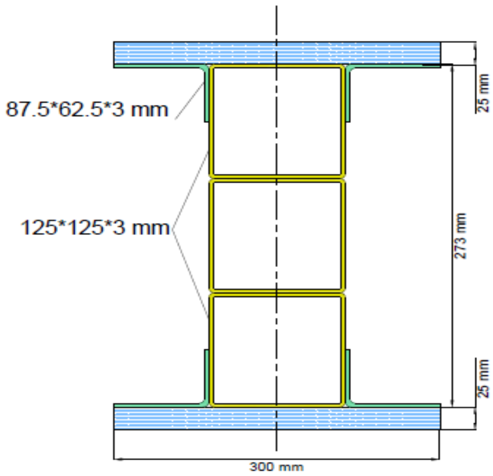


Figure (2) GFRP beam girder cross-section [25]

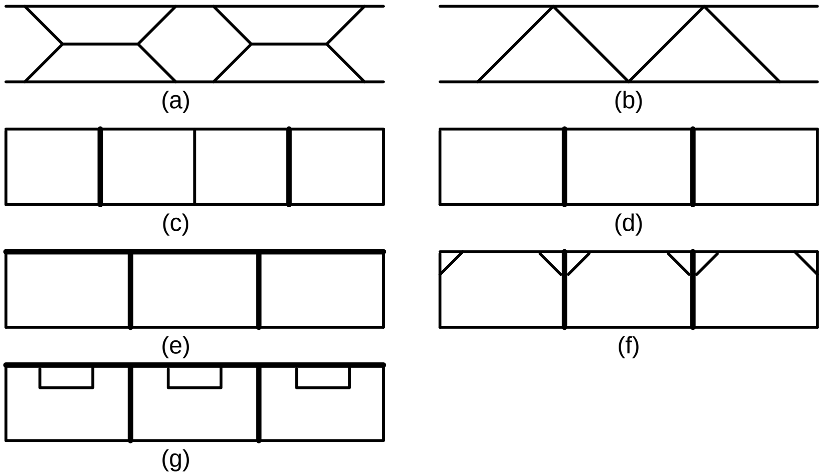


Figure (3) FRP deck sections [26]

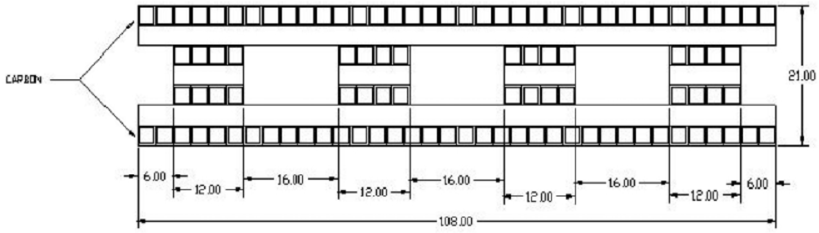


Figure (4) Assembly bridge deck [28]

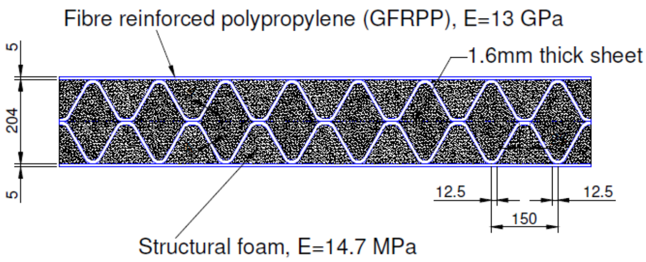


Figure (5) Bridge deck [29]

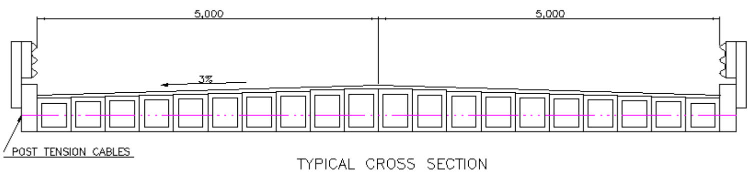


Figure (6) Bridge deck [30]

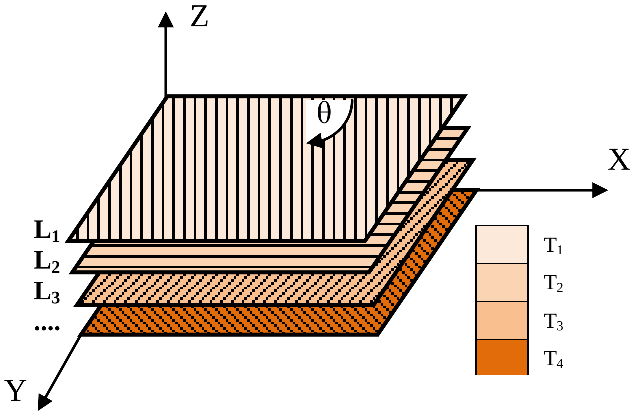


Figure (7) Composite laminate orientations

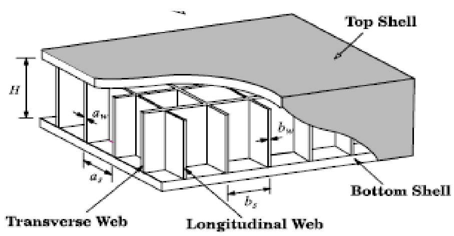


Figure (8) Sandwich bridge deck [40]

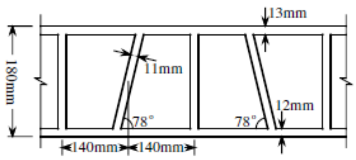


Figure (9) FRP deck [41]

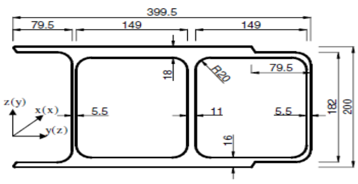


Figure (10) FRP deck [42]

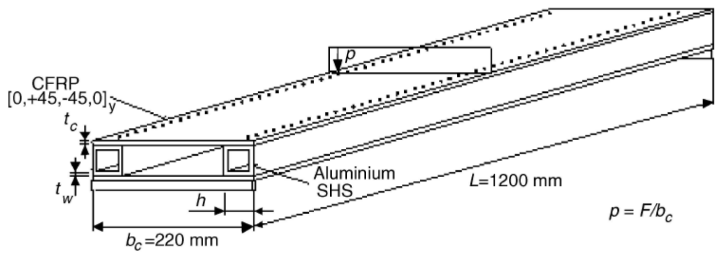
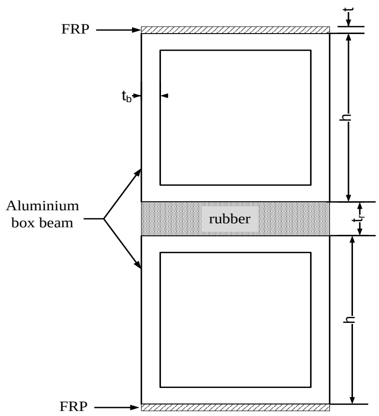
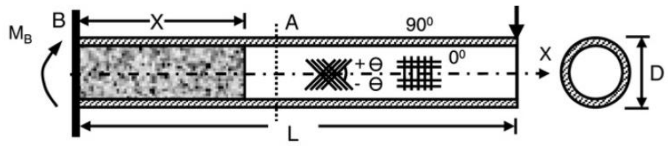


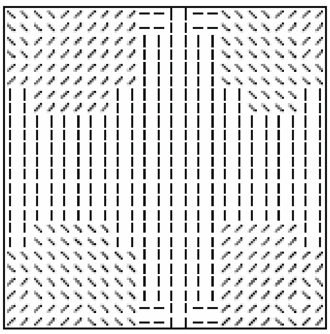
Figure (11) Panel Details [51]



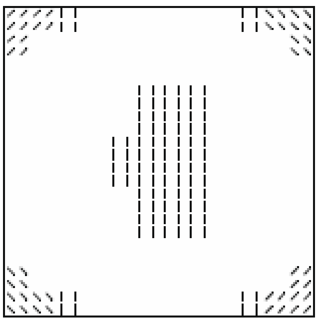
Figure(12) Five layers beam [18]



Figure(13) FRP poles [20]



a- Top layer



b-Middle layer

Figure (14) Fibre distribution [21]

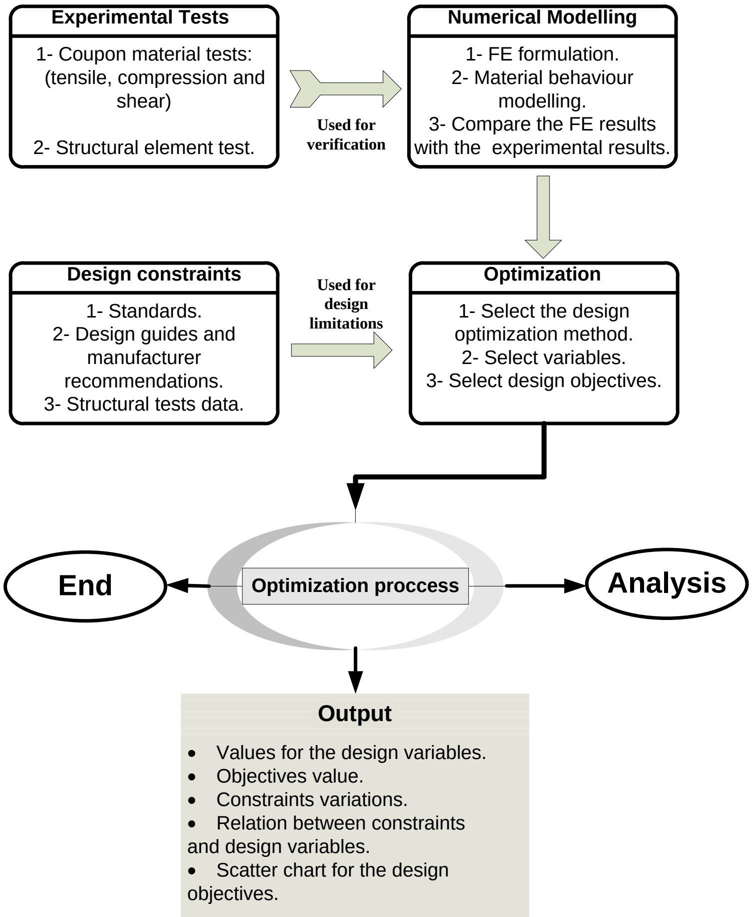


Figure (15) Proposed design optimization methodology of FRP structures

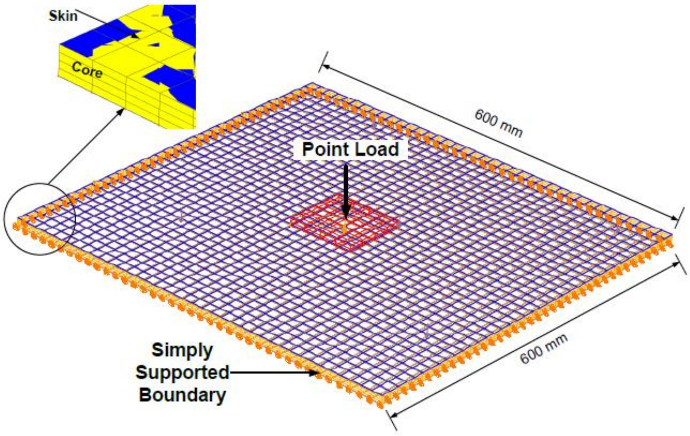


Figure (16) FRP sandwich panel model [73]

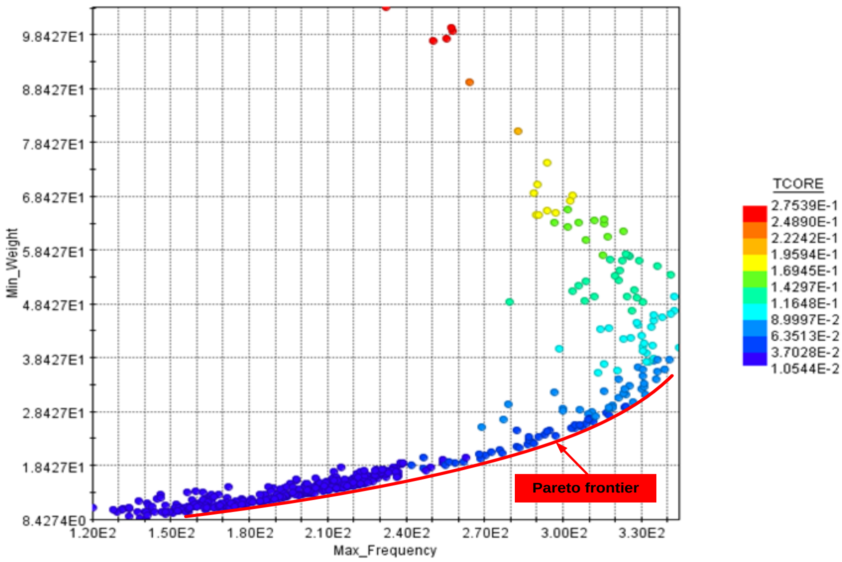


Figure (17) Scatter chart for the design objectives [73]