Multi-objective design optimization of an innovative fibre composite sandwich panel for civil engineering applications

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ABSTRACT: Fibre reinforced polymer (FRP) composite materials have become an important target for providing innovative structures in civil engineering applications. FRP composite structures have been used as a replacement for old degrading traditional structures or building new structures. This paper describes a methodology and results for an optimal design of innovative structural fibre composite sandwich floor panel by using Finite Element (FE) and multi-objective design optimization methods. The materials cost and the structural panel weight minimizations are regarded as two objective functions for the design target. The multi-objective simulated annealing (MOSA) algorithm was used to find the optimum design variables. The optimization results show that the skin orientation of $\pm 45^o$ is the best design for two-way square floor panel design.

1 INTRODUCTION

Engineers have been developing different types of FRP sandwich panel for structural applications in civil, mechanical and aeronautical engineering. FRP sandwich panels have an acceptable structural behaviour due to their ability to carry a high flexural load and light weight. This type of construction could be used in different structural types such as FRP layered beam, floor panel and pedestrian bridge deck. LOC Composites Pty Ltd has fabricated a new structural FRP sandwich panel for applications; floors, pedestrian bridges and railways (Van-Erp and Rogers 2008). The sandwich panel is made from ECR-glass fibre skins and modified phenolic solid core as shown in Figure 1. Four plies glass fibre with $0/90^o$ were used in the top and bottom skin of the panel. The innovative FRP sandwich panel is expected to be used in the civil engineering applications instead of the traditional plywood panel. An experimental investigation of this type of sandwich structures was carried out by Manalo et al. (2010). The experimental work showed that this panel could be used in the structural applications as main loaded members.

Multi-objective design optimization has been applied to optimize the new FRP composite structures recently. Omaker et al. (2009) presented a new model for multi objective design optimization of laminate FRP composite structures. The new model depends on the basis of Quantum Particle Swarm Optimization (QPSO) and it is applied for finding the weight and cost minimization. Murthy et al.

(2006) presented an optimization of strength and stiffness for the honeycomb sandwich panel. It was concluded that the maximum bending stiffness occurred at the core to skin weight ratio equal to 2.04. Walker and Smith (2003) presented multi-objective design optimization of fibre composite structure by using FE and genetic algorithms (GA). It was found that the weight and deflection as a multi-objective could be optimized by the GA to suite the design engineers requirements. Park et al. (2009) optimized the FRP composite one-way plate made from carbon fibre and fibre glass. A GA was used to find the optimum design of plate in a single and multi-objective form. An orientation $0/90^o$ was used for the plies parametric study to find the effect of the plies number on the cost and weight objectives.

GFRP Skin
L1, 400 gsm, main disrection
L2, 300 gsm, transfers direction
L3, 400 gsm, main direction
L4, 300 gsm, transfers direction
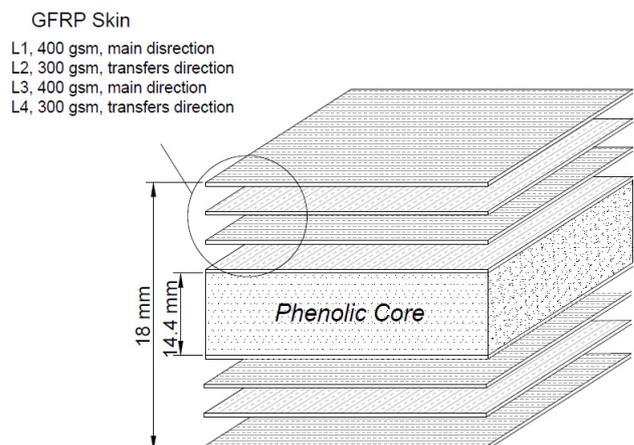
18 mm
14.4 mm

Phenolic Core

Figure 1. FRP Sandwich Panel Profile

However, the literature review revealed that there is a lack of optimization studies in the design of FRP domestic floor panel. The present study tries to find out the optimum design of two-way innovative FRP sandwich floor panel. The design variables are the plies orientation, plies thicknesses and core thickness. The objective of this study is to minimize the cost and the weight of the innovative panel. The multi- objective simulated Annealing (MOSA) method is used to find the optimum design variables.

2 FE SIMULATION OF SANDWICH PANEL

The FE simulation is formulated for the analysis of FRP composite sandwich panel by using ABAQUS commercial software. The experimental testing indicated that the behaviour of the FRP skin is approximately linear; the behaviour of core material is linear in tension and non-linear in compression. The full details of the FE model and materials model are described in Awad et al. (2009). The material specifications are shown in Table 1. The top and bottom skins are formulated by using shell element type S8R (8- node doubly curved shell element). The core is meshed by using 3D solid element type C3D20R. The interaction between skin and core is assumed to be full and there is no slip between them. The Hashin elastic failure model was used to find the failure part through the FRP skin plies. The damage of FRP materials is considered and it depends on Hashin failure theory. Hashin theory considers four types of failure: fibre tension, fibre compression, matrix tension and matrix compression (Hashin 1980).

Table 1. Material properties

Material Type	Density Kg/m^3	Elastic Modulus MPa	Poisson Ratio	Ultimate Tensile strain%	Tensile strength MPa
FRP Skin	1800	23,550	0.3	0.018	376.8
Core	850	1,154	0.2	0.0061	5.95

The damage initiation criteria (F) in the four cases are:

Fibre in tension:

$$F_f^t = \left(\frac{\sigma_{11}}{X^T} \right)^2 + n \left(\frac{\tau_{12}}{S^L} \right)^2 \qquad (1)$$

Fibre in compression:

$$F_f^c = \left(\frac{\sigma_{11}}{X^C} \right)^2 \qquad (2)$$

Matrix in tension:

$$F_m^t = \left(\frac{\sigma_{22}}{Y^T} \right)^2 + n \left(\frac{\tau_{12}}{S^L} \right)^2 \qquad (3)$$

Matrix in compression:

$$F_m^C = \left(\frac{\sigma_{22}}{Y^C} \right)^2 + \left[\left(\frac{Y^C}{2 S^T} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y^C} + \left(\frac{\tau_{12}}{S^L} \right)^2 \qquad (4)$$

Where X^T = tension and X^C = compression strength in longitudinal direction, Y^T = tension and Y^C = compression strength in transverse direction. S^L and S^T are shear in longitudinal and transverse directions. n = factor represents shear contribution in the tensile fibre initiation (0 or 1.0). σ_{11} and σ_{22} = normal stresses; τ_{12} = shear stress. Core material is considered relatively similar to concrete behaviour. Therefore, the plasticity of the concrete model was used to simulate the nonlinear behaviour of the core.

3 DESIGN OPTIMIZATION

Multi objective optimization is very essential in the real design of aerospace and civil engineering structures. The single objective simulated annealing was developed by Kirkpatrick et al. (1983). It is considered as the basis of the multi-objective optimization (Paya et al. 2008).The single objective optimization gives an optimum set of design variables with respect to single objective, while the same variables give an unacceptable design for other objectives. A reasonable design solution could be reached by using a combination of more than single objective by using multi-objective design optimization (Konak et al. 2006). Pareto optimal set procedure is preferred in the multi objective design optimization. In the movement from one Pareto solution to another solution, there is always an amount of loses in one objective to achieve some gain in the other objective. The multi-objective optimization method gives a set of solutions and the best solution measured regarding to all objective functions. Engineers are always like to get only one value from the set of solutions. Therefore, solving Multi-objective optimization problems can be conducted by both searching and decision making (Bui & Alam 2008). In the present research, MOSA is used to find the solution for the cost and weight minimization objectives of the FRL floor panel. The MOSA is a powerful method with high convergence rate in the solution of multi objective design optimization (Alrefaei and Diabat 2009; Nam and Park 2002).

In this work, simulated Annealing (SA) was implemented in modeFRONTIER. There are two external parameters to control the evolution system; the temperature (T) and the energy (E). When the initial configuration is introduced, the difference in the energy of the two states can be introduced:

$$\Delta E = E_{final} - E_{initial} \qquad (5)$$

If $\Delta E \leq 0.0$ a new configuration is accepted. Otherwise, a Boltzmann probability distribution is used to evaluate the new configuration (Rigoni 2003).

$$P(\Delta E) = -exp\left(-\frac{\Delta E}{T}\right) \qquad (6)$$

There are several points regard as an optimum solution in the multi-objective optimization design and there is no unique solution. These points or solutions are called Pareto solutions; the set of solutions can be called either "trade-off surface" or Pareto frontier. After finding a set of solution the decision making is essential to reduce the number of solutions to a preferred solution. The optimization layout is shown in Figure 2. The two-way FRP sandwich panel case study has dimensions 600mm x 600 mm and four edges simply supported as shown in Figure 3. The existing FRP sandwich panel has unequal fibre thicknesses in x and y directions as shown previously in Figure 1.
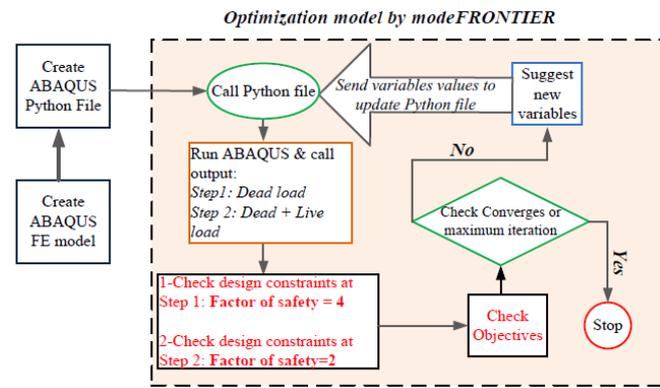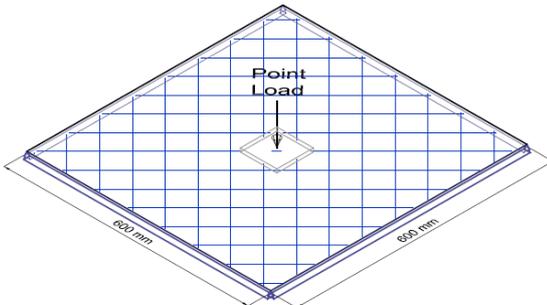

Figure 2. Optimization layout

Figure 3. Square FRP floor panel

3.1 Cost objective optimization

One of the disadvantages of fibre composite structures is a high initial fabrication cost. Developing an optimum design method of FRP composite structure is very important to avoid materials waste. Moreover, any form of FRP structure must be optimized in order to minimize the material cost (Hollaway & Head 1999). The cost of materials is required in the design of the FRP sandwich panel because the FRP sandwich has two materials with different costs. Core material is regarded as low cost compared to the skin material cost. The core part can have different material properties and few types of configurations such as: voided, solid and corrugated

core. In the present research, the cost of FRP skin is assumed five times the cost of phenolic core. The rate of skin to core cost affects the optimum design objective function and this will affect directly the skin to core thickness ratio as the FRP sandwich floor area same for both skin and core. The loading on the panel is based on AS/NZS 1170.1:2002 specifications for the serviceability requirements and it is explained in Table 2. The cost objective is:

Cost obj. = [(Thick.*cost)$_{skins}$ +(Thick. *cost)$_{core}$]

*Floor area $\qquad$ (7)

EUROCOMP constraints:

$$\sigma_{Tf} \leq \frac{\sigma_{Tfu}}{F.S} \qquad (8)$$

$$\sigma_{Cf} \leq \frac{\sigma_{Cfu}}{F.S} \qquad (9)$$

$$\sigma_{TC} \leq \frac{\sigma_{TCu}}{F.S} \qquad (10)$$

$$\sigma_{CC} \leq \frac{\sigma_{TCu}}{F.S} \qquad (11)$$

$$\delta \leq Span / 250mm \qquad (12)$$

Where, σ_{Tf}= allowable tensile, σ_{Cf}= allowable compressive stress of FRP skin material; σ_{TC}=allowable tensile and σ_{CC} = allowable compressive stresses of the core material; σ_{Tfu} = tension and σ_{Cfu} = compression strength of the FRP skin. σ_{TCu} = tension and σ_{CCu} = compression strength of the core materials; $F.S$ = design factor of safety, which is assumed equal to four in the step one of the dead load and it represents the long-term load factor. A factor of safety equal to two is assumed for all total load cases (live and dead load) as explained in Table 2; δ = the total vertical deflection.

The optimization design starts with initial design of the existing FRP sandwich panel as shown in Figure 1. The optimization results of the cost minimization is shown in Figure 4-a. The results show that the optimum skin plies orientation is $\pm45^\circ$ with total cost 0.00989 units. This cost is less than the initial design cost of the FRP sandwich panel, which it is equal to 0.01164 units. The design details are shown in Table 3. The deflection of the initial design panel under service load is equal to 0.00278 m, which is greater than the allowable deflection (span/250).

Table 2. Design Parameters

	Dead Load	Dead Load + Point Live Load
Load	4 kN/m²	4 kN/m² + 1.8 kN
Factor of safety	4	2
Allowable stress for skin	94 MPa	188 MPa

| Allowable stress for core	5.25 MPa	10.5MPa

3.2 Weight objective optimization

The weight benefit of a sandwich panel construction is relatively light weight, due to the core configuration with low density and voided style. There are a few types of FRP sandwich panels such as solid core, voided core and honeycomb panel. The objective of developing this new FRP sandwich panel is to replace the traditional wood panel. The disadvantage of traditional wood panel is the degradation under the effects of weather and termite. Therefore, the new FRP panel should have better resistance to the degradation effects and slightly higher self-weight than wood. In the present research, weigh minimization was considered as an objective of the optimum design of FRP floor panel. The design constraints are same as mentioned above in equations (7-11). The weight objective is:

$$Weight\ obj.\ =[(Thick.*dens.)_{skins}+(Thick.*dens.)_{core}]$$
$$*Floor\ area \qquad (13)$$

The optimization results for weight minimization are shown in Figure 4-b. The results show that the optimum skin plies orientation is ±45° with total weight equal to 7.6 kg.
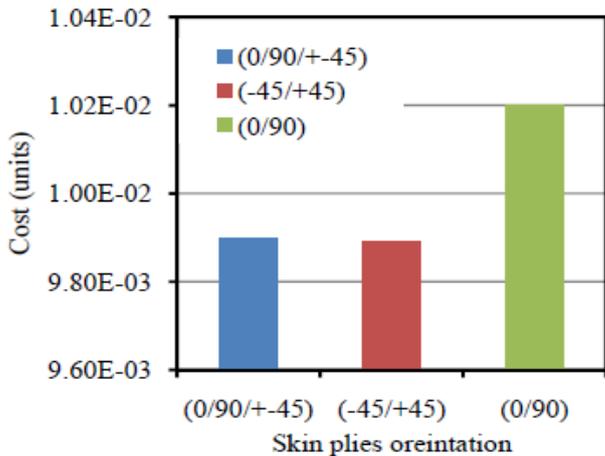
a-Cost
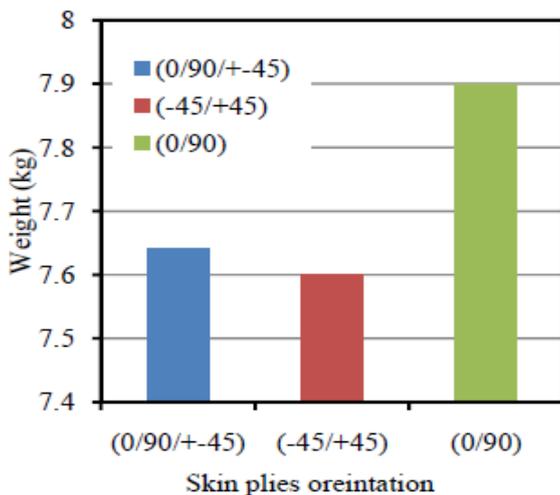
b-Weight

Figure 4. Cost and weight objectives

3.3 Cost and weight multi-objective optimization

The optimum design results for single objective are shown in Figure 4. The cost objective shows that the optimum configuration for the two-way FRP sandwich panel skin is ±45°. Also, the weight objective shows the same result for the skin orientation. The final decision is a skin orientation at ±45°, is the optimal with the results shown in Table 3. The optimum design challenge is to design the two objectives simultaneously in order to get an optimum design FRP sandwich panel for both cost and weight minimization. Three different plies orientations were studied and the results of the objectives are shown in Figure 5. It can be confirmed that the orientation ±45° is the optimum for multi-objective results. The objectives scatter chart for the solution of orientation ±45° is shown in Figure 6. There are two points in the scatter chart located in the optimal Pareto set, whereas one of them can be selected for further evaluation. The decision was made that the top point is selected as it has the minimum cost in the scatter chart. Design history for orientation ±45° of the two objectives is shown in Figure 7. The results of this optimum selected point are described in Table 3. The core to the skins thickness ratio is 8.28; this ratio is relatively higher than the initial design of 4.0 as mentioned previously in Figure 1.

Table 3. Optimum design results for orientation ±45°

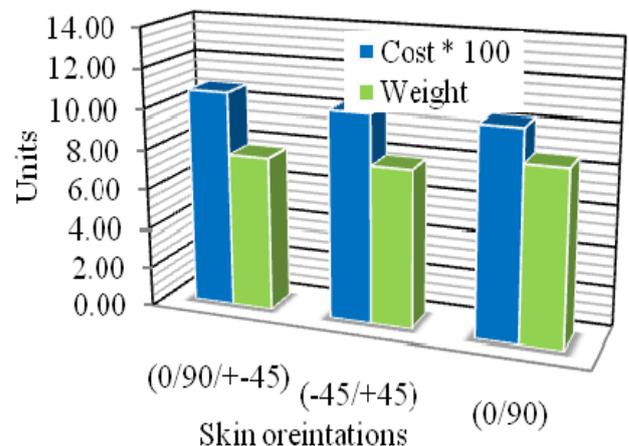| Objective minimization	Core th. mm	45/-45° th. mm	Cost unit	Weight kg	Defl. mm
Cost	20.15	0.367	0.0098	no	2.39
Weight	15.1	0.835	no	7.6	2.38
Cost and Weight	17.87	0.539	0.0103	7.83	2.36

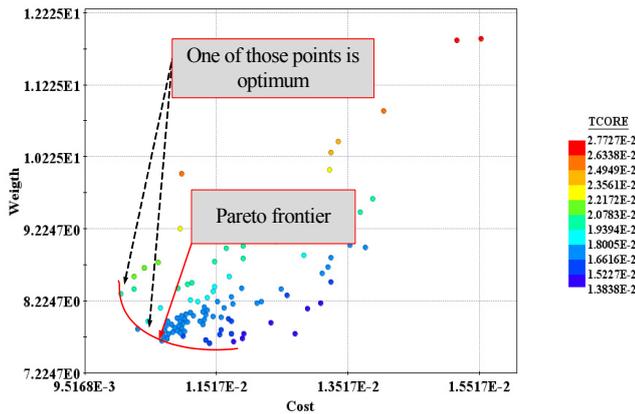Figure 5. Multi-objectives analysis for the three orientations
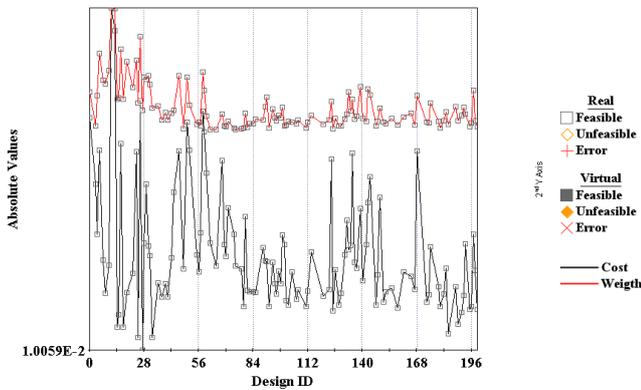

Figure 6. Scatter chart for cost and weight objectives

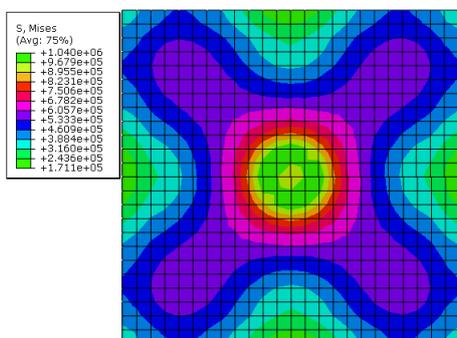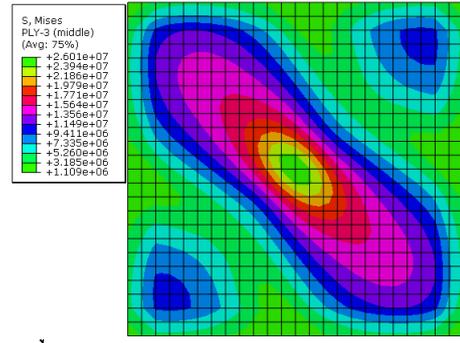Figure 7. Design history for Multi-Objective Optimization

a- Core

b- Ply -45°

c- Ply 45°

Figure 8. Von-Mises stress at service load
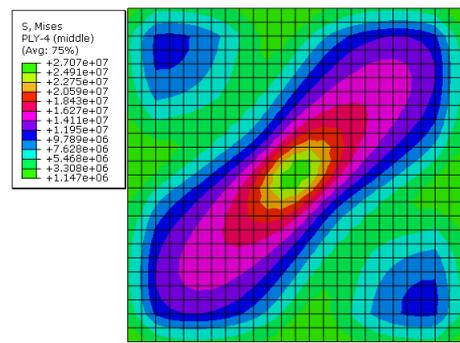
4 FE ANALYSIS AND FACTOR OF SAFETY ANALYSIS

An FEA is important to determine the behaviour of the optimized two-way FRP sandwich panel with 600 mm span (four edges supports). The FE model was developed with the nonlinear core material behaviour. The stress distribution in the service load level for both core and skins is shown in Figure 8. It was found that the behaviour of the FRP sandwich two-way panel is linear up to failure. The bottom skin fails before the top skin at load factor approximately equal to 6. As the load increase, failure starts to occur on the top skin as shown in Figure 9.
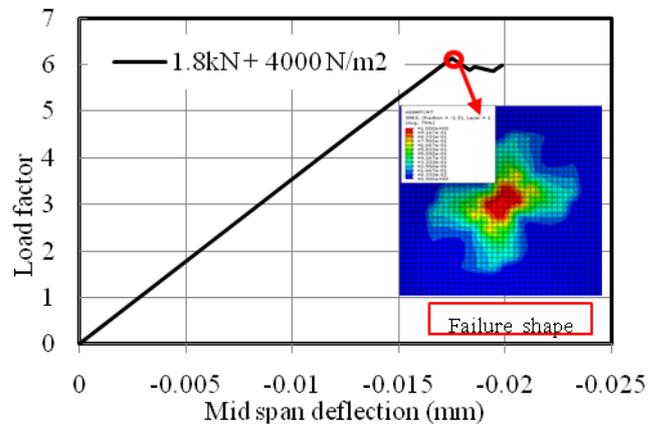

Figure 9. Load factor – deflection

5 CONCLUDING REMARKS

The optimization of two-way FRP sandwich floor panel showed that one layer of ±45° FRP skin is enough to design the FRP two-way sandwich panel. A multi-objective optimization analysis presented a Pareto set of optimal variables and the design point located between the single objective design of the cost and the weight. The optimization processes reduce the cost and the weight of the existing FRP sandwich panel. The optimized panel showed an ac-

ceptable factor of safety and service deflection within the allowable limit. Further work will focus on multi-objective robust/uncertainty design and comparing the results with experimental analysis.

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