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Advanced robust design optimization of FRP sandwich floor panels

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Abstract: FRP composite is now being used in the construction of main structural elements, such as the FRP sandwich panel for flooring system and bridges. The objective of this research is to use multi-objective optimization and robust design techniques to minimize the weight of the FRP sandwich floor panel design as well as maximizing the natural frequency. An Australian manufactures has invented a new FRP composite panel suitable for civil engineering constructions. This research work aims to develop an optimal design of structural fibre composite sandwich floor panel by coupling a Finite Element FE and robust design optimization method. The design variables are the skin plies thickness and the core thickness as a robust variable. Results indicate that there is a trade-off between the objectives. The robust design technique is used then to select a set of candidate geometry, which has a high natural frequency, low weight and low standard deviation. The design simulation was formulated by depending on the EUROCOMP standard design constraints.

1. Introduction

Sandwich structures build up the advantages of using different layers with different properties in the structure. Sandwich structures are used by engineers due to their ability to carry a high flexural load, less weight and good thermal insulation. This type of construction could be applied to different structural types such as layered beam and sandwich plate and shell. Murthy et al. [1] 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 [2] presented multi-objective design optimization of fibre composite structure by using FE and genetic algorithms (GAs). It was found that the weight and deflection as a multi-objective could be optimized by the GA to suite the design engineers requirements. The LOC Composites Pty Ltd has fabricated a new structural sandwich panel for the applications such as pedestrian bridges and railways [3]. The sandwich panel is made from ECR-glass fibre for the skin materials and modified phenolic solid core as shown in figure 1. The FRP sandwich panel is expected to be used in the civil engineering applications instead of the traditional ply-wood panel. The experimental investigation of this type of sandwich structures was carried out by Manalo et al. [4]. The research showed that the failure of the flat-wise sandwich beam is a delamination and rankling in the top skin under compression.

The Robust Design Optimization method is being considered as it is a relatively useful method for optimization of possible uncontrolled variation parameters during manufacturing [5,6]. These

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uncontrolled parameters are called noise factors and the robust design method tries to reduce the effect of noise factors without eliminate them [7]. Also a real structure always has a deviation from the design code state. Li *et al.* [8] presented a new Robust Multi- Objective Genetic Algorithm (RMOGA) the advantages of this method were that it gives an ability to measure the optimum solution performances as well as measuring the robustness index. Chen *et al.* [9] proposed the robust design a proach to design a complex fibre composite thick laminated structure and used it to design a laminated composite femoral component for a hip joint arthroplasty. Standards specification and codes for FRP in civil engineering are not available yet except British standard code for the design of composite BS4994 [10] and the EUROCOMP design code [11]. Optimization of FRP plate represents a good practice for the designer to find the configuration of plies thicknesses and core thickness. This paper discusses the optimum design of the FRP sandwich panel for the domestic floor system.

The rest of the paper is organised as follows, section 2 discusses the material specifications and the FE simulation model, section 3 explains the robust design method, section 4 contains the case study on the design of the FRP sandwich floor panel, section 5 discuss the optimization solution and the FEA of the optimum design and finally, the conclusions are presented in section 6.



Figure 1. FRP Sandwich Panel Profile

2. Materials and FE Model Simulation

The finite element simulation is formulated for the analysis FRP composite sandwich panel and it is conducted using ABAQUS commercial software [12]. The behaviour of this panel is complicated due to the linear behaviour of the FRP skin until failure. While, the behaviour of core material is nonlinear in compression and approximately linear in tension. The experimental tests were done in CEEFC to find the core behaviour in compression and tension as shown in figure 2. The first part of both tension and compression behaviour curve was found by the experimental work, while the softening part is assumed for the analysis model. The behaviour of the elastic skin is assumed linear up to failure at stress 336 MPa. It was noticed that the behaviour of the panel is approximately linear up to the failure. It was realized from the analysis that the first failure happens in the top layer of the top skin under compression [13]. The materials specifications are shown in table 1. The top and bottom skin is formulated by using a shell element type S8R (8- node doubly curved shell element). While, the core is meshed by using 3D solid element type C3D20R. The interaction is assumed to be full between skin and core, figure 3 shows the FE model. The damage of FRP materials is considered, and it depends on Hashin failure theory [14]. Hashin theory considers four failure types: fibre tension, fibre compression, matrix tension and matrix compression [14]. This behaviour of core material is relatively similar to concrete behaviour [13]. Concrete plasticity model provides a general capability to simulate any quasi brittle materials and this model was used to simulate the non linear behaviour of the core [12], as shown in figure 3. The stress strain relations under uniaxial tension and compression loading are, respectively:

$$\sigma_t = (1 - d_t) E_0(\epsilon_t - \epsilon_t^{pl}) \tag{1}$$

$$\sigma_c = (1 - d_c) E_0 (\epsilon_c - \epsilon_c^{pl}) \tag{2}$$

Where, the subscripts t and c refer to the tension and compression respectively. σ is the stress. d is the damage variables. E_0 is the initial elastic modulus. ϵ is the strains. Subscript pl refers to the equivalent plastic strain.

Table 1. Materials properties					
	Density Kg/m ³	Elastic Modulus MPa	Poisson Ratio	Ultimate Tensile strain%	Tensile strength MPa
FRP Skin	1800	24000	0.3	0.018	336
Core	850	1000	0.2	0.006	6.2







Figure 3. Concrete plasticity model [12]

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Figure 4. The FRP panel mesh and dimensions

3. Multi-Objective Robust Design Method

Messac and Yahaya [15] developed a multi-objective robust design optimization (RDO) method under the consideration of a physical meaningful term. The physical meaning or physical programming means that it addresses two issues a qualitative and quantitative physical description of the designer's preferences. The design showed that the RDO allowed considering parameters which it are not a part of the normal optimization such as the noise and vibration caused by the variation of dynamic loads. Multi objective robust design optimization (MORDO) is different to the traditional optimization method such as Six Sigma [7]. The Traditional optimization methods provided good solutions at design point but poor off-design solution. For the manufacturing purposes, the designer has to regards the RDO as an efficient tool that considers the variation of the input parameters in a range of circumstances [16].

The simple form of the robust multi objective design optimization problem is [8]:

$$min_x f_v (f_2, f_2, \dots, f_i, g_1, \dots, g_G)$$
 (3)

$$max_{\chi} \eta = \frac{R}{R_{F}} \tag{4}$$

$$x^{lower} \le x \le x^{upper} \tag{5}$$

The f_v is the fitness value and it is a function of the design objectives $(f_1, ..., f_i)$ and constraints $(g_1, ..., g_G)$. η is the robust index, R is the optimum solution and RE is the radius of the exterior radius of the normalized tolerance. i is the total number of objectives and G is the total number of constraints.

4. FRP Domestic Floor Panel Design

The research work aims to develop an optimum design for simply supported square FRP floor panel as shown in figure 4. EUROCOMP specifies the allowable deflection in the service load conditions to be equal to span/250. The serviceability limit of the civil engineering structure might include few considerations such as the deformation of the structure should not cause any damage for the finishing and non- structural elements. Also, the structure under service load should not have any form of uncomfortable vibration [11].

The analysis of a 300 mm simply supported flat-wise FRP sandwich beam, for example showed that maximum allowable working load of sandwich panel approximately 520 N. In comparison, the failure load of the sandwich panel is around 4855 N. The failure load is about nine times the allowable working load [13]. Ultimate load to working load ratio represents the safety factor of the structure.

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Gay *et al.* [17] explain the design factors for the composite structure design which is between 2 for short term loading and 4 for long term loading as shown in table 2.

Structural applications are considering light weight constructions by using FRP composite material instead of traditional materials. Therefore, the structure has to become lighter with a higher natural frequency. Engineering design experience has indicated that the minimum stiffness equal to 1kN/mm is required for the office and residential occupancies [18].

Table 2. Design Parameters [17]			
	Dead Load	Dead Load + Point Live Load	
Load	4 kN/m^2	$4 \text{ kN/m}^2 + 1.8 \text{ kN}$	
Factor of safety	4	2	
Allowable stress for skin	84 MPa	168 MPa	
Allowable stress for core	5.25 MPa	10.5 MPa	

5. Optimization

In this research, we use a multi-objective robust design optimization method for the design of the FRP sandwich floor panel and the core thickness is regarded as a robust parameter. Weight minimization and frequency maximization are two design objectives. Design methods need to be sophisticated to avoid material waste and it is also recommended to optimize any form of the composite structure to reduce the FRP material in the structures [10]. The design variables are the thicknesses of the four layers skin at top and bottom and the thickness of the phenolic core. The initial design was made on the simply supported two-way sandwich panel with orientations 0/90/45/-45°. The design variables are the thickness of the skin plies (TT) and thickness of the core (Tcore). The objective function and design constraints are shown below:

$$Objective^{l} = Minimize (f_{l})$$
(6)

$$Objective^{2} = Maximize (f_{2})$$
⁽⁷⁾

$$Variables = \begin{cases} TT \\ Tcore \end{cases}$$
(8)

EUROCOMP constraints:

$$\sigma_{tf} \le \frac{\sigma_{tfu}}{FS} \tag{9}$$

$$\sigma_{tf} \leq \frac{\sigma_{cfu}}{FS} \tag{10}$$

$$\sigma_{tC} \le \frac{\sigma_{tCu}}{F_{s,c}} \tag{11}$$

$$\sigma_{cC} \le \frac{\sigma_{cCu}}{F.S} \tag{12}$$

$$\delta \le Span/250 \, mm \tag{13}$$

Where, f_1 is weight objective and f_2 frequency objective. σ_{tf} and σ_{tf} are the allowable tensile and compressive stresses of FRP skin. σ_{tC} and σ_{cC} are the allowable stresses in tension and compression for core material. σ_{tfu} and σ_{cfu} are the ultimate strength in tension and compression of FRP skin. σ_{tCu} and

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 σ_{cCu} are the ultimate strength in tension and compression of core materials. F.S is the design factor of safety, which it is assumed equal to four in the step one of the dead load as a long term load factor. The factor of safety equal to two is assumed for the total load cases (live and dead load) as explained in table 2. δ is the total vertical deflection.

5.10ptimization results

The Robust design optimization is applied using modeFRONTIER 4.2 software. The applied load describes in table 2 and the initial geometry is same as in figure 1. The design optimization history of the two objectives is shown in figure 5. It can be noticed that the optimization tries to increase the frequency and minimize the weight. The scatter results of the two objective functions are shown in figure 6 and it describes the relation between the two objectives. The Pareto frontier represents the optimum design points. This means, any point on the curve (Pareto frontier) can be considered a good candidate for the final design. The choice of an optimum point will depend on the designer decision making. All design points at the bottom left part of the "frontier" are good designs with low weight, while those at the top right of the curve have high frequency and weight. The probability density is shown in figure 7. It can be noticed that the robust optimization focuses on meeting the target of a good grade production by reducing the standard deviation of the objectives. The investigation of a parallel chart in figure 8 shows that the selected point 210 has a lower core thickness standard deviation compare to the starting design point and other points. The design results for the design point 210 are illustrated in a table 3.

Point	Core th. mm	0/90 ⁰ th. mm	$45/-45^{0}$ th. mm	Weight kg	Frequency Hz	Deflection mm
210	12.1	1.38	0.9	10.2	128	2.09

Table 3 Design results



Figure 5. Design history of two objectives

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Figure 6. Scatter chart for the design objectives



Figure 7. Probability density for objectives



Figure 8. Parallel chart for core thickness and objectives

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Figure 9. Load deflection curve for the design FRP floor panel

5.2 FE analysis results

A design optimization process was imported to minimize the weight and maximizing the natural frequency of a two-way FRP sandwich panel with 600 mm span (four edges supports). The optimum design was considered for four layers orientations $0/90^{\circ}$ and $\pm 45^{\circ}$. The optimization shows that the $0/90^{\circ}$ configuration has greater fibre than $\pm 45^{\circ}$ as described in table 3. The core to the skins thickness ratio is 2.65; this ratio is relatively lower than the original production of 4.0 as mentioned previously in figure 1. The reason for this is that the design optimization considers the weight objective without any production cost consideration. A FE element analysis was conducted to find the behaviour of the designed sandwich panel. It was found that the behaviour of the sandwich two-way panel is non-linear up to failure. The top skin is failed at a load factor approximately 5. The complete failure of the FRP panel at a load factor 7 as shown in figure 9. The non-linear analysis shows that the safety factor is more than the expected factor of safety, the design uses a factor of safety between 2 and 4 for material allowable stresses.

6. Conclusions

The robust design optimization helps to find the most appropriate design point for both the objective functions. The optimization results indicate that there is a trade-off between the objectives. The best selected design point from the robust design Pareto shows the low core to skins thickness ratio, two stages for the failure of the FRP floor panel and a global factor of safety, which is higher than the expected factor of safety. Current work focuses on two different objectives weight minimization and frequency maximization and the relation between them is a direct correlation.

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