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Optimal design of carbon and glass reinforced hybrid composite pipes under flexural loading

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ABSTRACT

This paper presents a study on the optimal design of carbon and glass reinforced hybrid composite pipes under flexural loading. The failure of composite pipes in three point bending was modelled numerically by Finite Element Analysis (FEA). Optimisation on hybrid composite pipes under flexural loading was conducted using non-dominated sorting GA-II (NSGA-II) with minimum cost and weight as the objective functions.

Introduction

Composite pipes are important structural members in various industries. Research has been done for the failure of composite pipes. Prabhakar et al. [1] presented an overview of burst, buckling, durability and corrosion analysis of lightweight fibre reinforced plastic (FRP) composite pipes and their applicability. Hastie et al. [2] investigated the failure of thermoplastic composite pipes (TCP) under combined pressure, tension and thermal gradient for an offshore riser application. Rafiee [3] reviewed the mechanical performance of glass-fibre-reinforced thermosetting-resin pipes. Most studies on the mechanical performance of composite pipes were focused on internal pressure [4–7], axial loading [6,7], and transverse loading [8]. Very limited have been seen on flexural loading [9–11]. Xia et al. [9] presented an exact solution for thick-walled filament wound composite pipes under pure bending using classical laminated-plate theory. Jonnalagadda et al. [10] presented an analytical model for composite tubes with bend-twist coupling.

Hybrid composite materials have been widely researched in order to take advantage of both virgin composite materials. A common hybrid composite is made by including both carbon and glass fibres in a common polymer matrix. When evaluating the properties of hybrid composites, the deviation from the Rule of Mixtures (RoM) [12] has been noticed by various researchers and is denoted hybrid effect. Positive hybrid effects, i.e. the flexural strength is higher than the RoM, have been notice in the previous research [13–16]. The main reason is that glass fibre has higher strain-to-failure than carbon fibre, the strain-to-failure is increased due to the inclusion of glass fibre [17]. The existence of hybrid effect can be potentially useful for achieving a balanced cost and weight optimal composite material.

Optimisation of composites has been extensively studied. However, limited studies have been done for the optimisation of composite pipes. Colombo and Vergani [18] conducted an optimisation study to minimise the wall thickness of a composite plain pipe under internal pressure and axial loads. It is shown the optimal fibre volume fraction is between 40% and 60% and the optimal winding angle is between $\pm 44.5^\circ$ and $\pm 52.5^\circ$. Harte et al. [19] presented an optimisation study for the design of high performance composite pipelines. The objective function was to minimise the weight of the pipeline. Pipeline to joint transition geometries, as well as overall pipe thickness were optimised. The maximum structural stresses were constraints. It was shown that a significant reduction in peak stresses at pipeline to joint transitions and a minimisation of pipeline mass were found. Häußler et al. [20] presented an optimisation approach which was aimed at providing design recommendations for multi-material composite piping with multiple fibre orientations.

When there are more than one objective function, e.g. cost and weight, the problem is referred to as a multi-objective optimisation problem. A solution to such problem can only be obtained through trade-off between objectives, i.e. one objective cannot be improved without compromising other objectives. Many classical multi-objective optimisation methods transform the multiple objectives into a single objective using *a priori* methods and preference-based strategies [21]. However, choosing a reliable and accurate preference of the objectives requires higher-level information which may not be available during the initial stages of the design process [22]. Thus, *a posteriori* methods generate a set of trade-off solutions, which is known as a Pareto set. When being plotted in the design space, the Pareto set is referred to as the Pareto front [22]. The Pareto set allows additional evaluation and comparison by the designer in order to make a final decision.

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Table 1
Selected properties of fibres and resin.

Material	Tensile modulus (GPa)	Tensile strength (MPa)	Density (kg/m^3)	Cost ($/l)[a]
High strength carbon fibre[b]	230	4900	1800	151.2
S-2 glass fibre[c]	86.9	4890	2460	103.3
E glass fibre[d]	72	3450	2580	10.8
High performance epoxy matrix[e]	3.1	69.6	1090	26.2

[a] All material prices were converted to US$.
[b] T700S® 12 K, Toray Industries, Inc., Tokyo, Japan.
[c] S-2 glass unidirectional Unitex plain weave UT-S500 fibre mat, SP System, Newport, Isle of Wight, UK.
[d] E glass SE 2350 single-end roving, Owens Corning, Toledo, OH, USA.
[e] Kinetix R240 high performance epoxy resin with H160 hardener at a ratio of 4:1 by weight, ATL Composites Pty Ltd., Australia.

Most of the research in the field of multi-objective optimisation of composites has used preference-based classical methods to convert the multi-objective optimisation problem into a single objective form [23–25]. For example, Hemmatian et al. applied a gravitational search algorithm [23] and elitist ant system [24] to solve the multi-objective optimisation of carbon/glass fibre hybrid composites in order to achieve designs with minimum weight and cost, with the first natural frequency being the constraint. The weighted sum method (WSM) was used to construct Pareto-optimal fronts. In contrast to this, Walker et al. [25] used a sequential optimisation procedure to minimise the weight and cost of symmetric carbon/glass/Kevlar hybrid laminated plates subject to a buckling load.

On the contrary, a multi-objective optimisation evolutionary algorithm (MOEA), which is classified as an *a posteriori* method, can be utilised to produce a set of Pareto optimal sets in a single simulation and hence improve the solutions in a number of evolutions without considering any preference of objectives. MOEAs achieve Pareto optimal sets in a single run and through evolution of a random initial population in a number of iterations called generations. Several MOEA methods are available, including strength Pareto evolutionary algorithm (SPEA-II) [26], Pareto archived evolutionary strategy (PAES) [27] and the non-dominated sorting GA (NSGA) [28]. A modified version of the NSGA, known as NSGA-II, is one of the most popular MOEAs due to its simplicity and efficiency [28].

In this paper, an optimisation study based on NSGA-II was conducted to achieve the optimal hybrid composite pipe under flexural loading with minimum cost and weight as the objective functions. The rest of this paper is organised as follows. First, the modelling approach for the hybrid composite pipe is presented. Next, the results are presented and discussion is made. Finally, conclusions are drawn.

Methodology

In this section, the modelling approach and optimisation are presented.

Materials

In this study, one high strength carbon fibre and two types of glass fibres, i.e. S-2 glass and E glass, were chosen to reinforce an epoxy matrix. Epoxy resins are widely used in composites because of their high strength (tensile, compressive and flexural), good chemical resistance, fatigue resistance, corrosion resistance and electrical resistance [29]. The properties of the fibres and epoxy resin are presented in Table 1 [13]. Hybrid composite pipes can be made by filament winding process.

Properties of composites

For each lamina, based on the constituent properties and its fibre volume fraction, the lamina properties, including the longitudinal modulus E_{11}, the transverse moduli E_{22} and E_{33}, and the shear moduli G_{12}, G_{13} and G_{23}, are derived by Hashin's model [30]. The strength components of composites were derived and stress based failure criteria were employed. When failure occurs in a ply, stiffness degradation factors [31] were used to reduce the stiffness. The stiffness degradation factor was chosen to be 0.9.

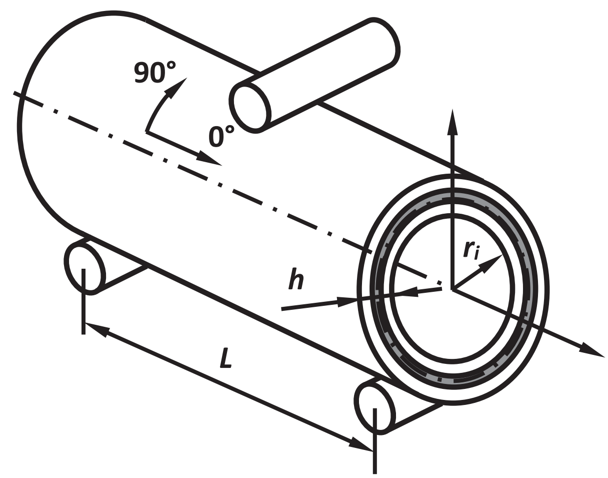

Fig. 1. A composite pipe in three point bending.

The weight of a composite material can be characterised by its density. The density of the hybrid composite reinforced by carbon and glass fibres, ρ_c, can be derived based on RoM as follows:

$$\rho_c = \rho_{fc}V_{fc} + \rho_{fg}V_{fg} + \rho_m V_m \quad (1)$$

where ρ_{fc}, ρ_{fg} and ρ_m are the densities of carbon fibre, glass fibre and the matrix, respectively, and V_{fc}, V_{fg} and V_m are the volume fractions of carbon fibre, glass fibre and the matrix, respectively.

The material cost of the hybrid composite, C_c, is given by

$$C_c = C_{fc}V_{fc} + C_{fg}V_{fg} + C_m V_m \quad (2)$$

where C_{fc}, C_{fg} and C_m are the costs of carbon fibre, glass fibre and the matrix, respectively.

Model development

The hybrid composite pipe in this study consists of eight laminas and the thickness of each lamina is 0.25 mm. A hybrid composite pipe in three point bending is shown in Fig. 1. The composite pipe is supported by two rollers at a span of L and loaded at its mid-span. The pipe length is 1000 mm. The inner radius is 50 mm. The span is 832 mm.

The hybrid composite pipe in three point bending was simulated by FEA using Ansys Workbench, as shown in Fig. 2. Shell elements are used to model the composite pipe and solid elements are used to model the supports and loading roller. Both supports are fixed and a prescribed displacement is applied to the loading roller. The contact between the

Table 2
Pipe designs for validation.

Winding design	Inside diameter (mm)	Thickness (mm)	Failure load (kN)		Difference (%)
			FEA	Theoretical	
$[90_2/60_5]$	100	6	24.845	20.109	23.55
$[90_2/10_3/90_2/30_4/60_2]$	100	10.5	87.448	79.332	10.23
$[90_2/10_2/90/10_2/90/30_4/60]$	100	10.5	85.446	87.683	−2.55

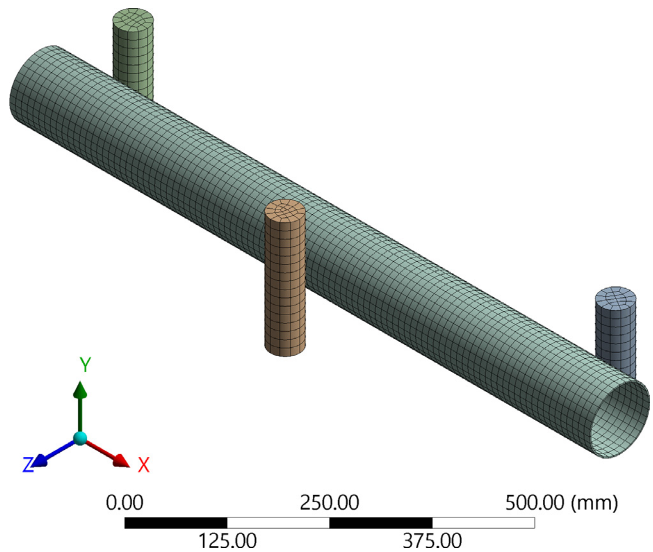

Fig. 2. FEA model of composite pipe.

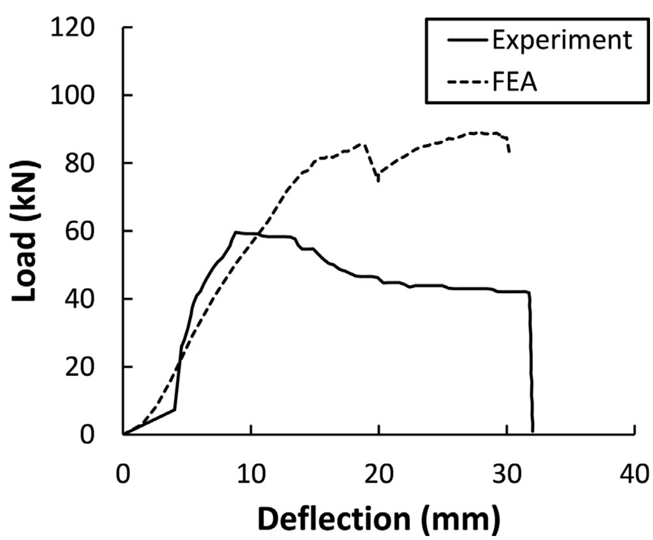

Fig. 3. Load-displacement curves of $[90_2/10_2/90/10_2/90/30_4/60]$.

composite pipe and the supports and loading roller is frictional contact. The force-displacement curved is obtained via nonlinear analysis.

Model validation

The developed FEA based model was validated against the results in [11]. Three winding designs were simulated, as shown in Table 2. For all winding designs, the innermost ply is 90° and the outermost ply is 60°. The load–displacement curves from FEA and experiment are shown in Fig. 3. It is shown at the initial stage, both curves show similar trends.

Table 3
Variables and their ranges of value in optimisation.

Variable	Range of value
V_{fc}	[0.3, 0.6]
V_{fg}	[0.3, 0.6]
Ply material	[Carbon/epoxy, glass/epoxy]
Ply angle	[−75°, −60°, ..., 75°, 90°]

However, the experimental failure load is significantly lower than the FEA. The failure loads were further compared with the theoretical solutions, as shown in Table 2, from which it is shown good agreement is found.

NSGA-II based optimisation

The developed FEA model was applied to conduct optimisation using NSGA-II. It is shown from previous research that the flexural strength of the composite can be improved via hybridisation. The present study aimed to minimise the density and cost of carbon/glass fibre reinforced epoxy hybrid composites subjected to a minimum failure load. The optimisation problem is formulated as:

$$Min \begin{cases} C_c \\ \rho_c \end{cases} \quad s.t.\ F_f \geq F_{f0} \tag{3}$$

The design variables are the fibre type, fibre orientation angle and fibre volume fraction of each lamina. The variables and their ranges of value are shown in Table 3.

The number of initial samples were 100 and the number of samples each iteration were 50. Up to 10 candidate points were found from optimisation.

Results and discussion

When carbon and E glass or S-2 glass fibres were used in the optimisation, the Pareto fronts are shown in Fig. 4. The optimal results are listed in Tables 4–9.

It is shown that for low failure loads e.g. 3 kN, carbon/E glass fibre reinforced hybrid composites offer significantly lower material cost but higher weight. For the middle failure loads e.g. 4 kN, carbon/E glass fibre reinforced hybrid composites offer lower material cost and slightly lower weight. For the high failure loads e.g. 5 kN, both glass fibre types offer similar cost and weight since the hybrid composite is dominantly reinforced by carbon fibre.

When carbon and E glass fibres were used in the optimisation, for minimum failure load 3000 N, it is shown from Table 4 that no obvious trends can be found. A wide range of optimal candidate points are found, as shown in Fig. 4. For minimum failure load 4000 N, it is shown from Table 5 that plies 1 and 8 are dominantly carbon/epoxy at 75°, ply 2 is dominantly carbon/epoxy at 90°, and E glass/epoxy is mostly in plies 4 and 6. For minimum failure load 5000 N, it is shown from Table 6 that most plies are carbon/epoxy. The inner surface (ply 8) is carbon/epoxy at 75° and the outer surface (ply 1) is carbon/epoxy at 10°.

Table 4
Optimal results for minimum failure load 3000 N, carbon and E glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m²)	Weight (mg/mm²)
			1	2	3	4	5	6	7	8			
1	0.3615	0.3484	60G	75G	75C	−15C	−60C	30C	−30C	−60C	3104	117.50	2.825
2	0.4053	0.3510	−15C	−45C	−75G	30G	−15G	45C	0C	−75C	3171	111.67	2.932
3	0.3655	0.4445	60G	75G	75C	−15C	−60C	30C	75C	75G	3232	104.37	3.001
4	0.3525	0.4609	45G	60G	75C	90G	−30C	10G	−75G	75G	3121	63.79	3.335
5	0.4045	0.4025	60C	75G	75C	−15C	−75G	45G	0C	−75C	3083	110.96	2.989
6	0.4045	0.4025	−15C	−30C	30C	−60G	−75G	45G	0C	−75C	3327	110.96	2.989
7	0.4045	0.4025	75C	−60C	15C	−60G	−75G	45G	0C	−75C	3152	110.96	2.989
8	0.4155	0.4187	−15C	−45C	−75G	30G	−15G	30C	−30C	90G	3097	97.89	3.099
9	0.4217	0.4187	−30C	−60C	−75G	45G	−15G	30C	−30C	90G	3230	98.67	3.103

Table 5
Optimal results for minimum failure load 4000 N, carbon and E glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m²)	Weight (mg/mm²)
			1	2	3	4	5	6	7	8			
1	0.5359	0.3095	7C5	90C	−15G	−60C	30C	−30C	−75G	90C	4092	150.49	2.981
2	0.5403	0.3132	75C	90C	15C	−45G	−45G	90C	−75C	75C	4179	151.30	2.989
3	0.5303	0.4083	75C	−75C	30C	−60G	−75G	45G	60C	−60C	4303	130.55	3.107
4	0.5307	0.3753	75C	90C	−15G	−60C	30C	90C	60G	−60C	4078	149.01	3.025

Table 6
Optimal results for minimum failure load 5000 N, carbon and E glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m²)	Weight (mg/mm²)
			1	2	3	4	5	6	7	8			
1	0.5657	0.5146	10C	60C	75C	−60C	30C	−30C	−75G	90C	5115	174.17	3.075
2	0.5649	0.5299	10C	60C	75C	−60C	−15G	−30C	30C	90C	5188	173.94	3.079
3	0.5649	0.5327	10C	60C	75C	−60C	90G	75C	30C	90C	5089	173.92	3.080
4	0.5649	0.5344	10C	60C	75C	−60C	90G	−45C	30C	90C	5252	173.92	3.081
5	0.5649	0.5344	10C	60C	75C	−60C	30C	−30C	30G	90C	5156	173.92	3.081

Table 7
Optimal results for minimum failure load 3000 N, carbon and S-2 glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m²)	Weight (mg/mm²)
			1	2	3	4	5	6	7	8			
1	0.3528	0.3115	−15C	−45C	−75G	30G	90G	−30C	45G	90C	3193	120.51	2.857
2	0.3528	0.3115	60G	75G	75C	90G	−30C	30G	90C	−75C	3009	120.51	2.857
3	0.3520	0.3089	60G	75G	75C	90G	30C	30C	−75C	90C	3465	125.27	2.810
4	0.3519	0.3111	60G	75G	75C	−15G	−60C	30C	−30C	−60C	3070	125.38	2.812
5	0.3610	0.3082	60G	60G	75C	−60C	−30C	0G	−75G	90C	3107	121.29	2.859
6	0.3558	0.3134	45G	75G	75C	−60C	−15C	0G	−75G	90C	3064	121.03	2.862
7	0.3558	0.3134	60G	60G	75C	−60C	−15C	0G	−75G	90C	3111	121.03	2.862

Table 8
Optimal results for minimum failure load 4000 N, carbon and S-2 glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m²)	Weight (mg/mm²)
			1	2	3	4	5	6	7	8			
1	0.5715	0.4070	75C	90C	−15G	−60G	−75G	45G	0C	−75C	4164	155.21	3.143
2	0.5660	0.4189	0C	45G	75C	−60C	60G	−45G	0G	−75C	4022	155.45	3.156
3	0.5662	0.4189	90C	−75C	30C	−60G	−75G	45G	0G	−75C	4279	155.48	3.156
4	0.5790	0.4070	45C	60G	75C	−30G	−75G	45G	0C	−75C	4071	156.15	3.149
5	0.5464	0.3972	75C	−75C	30C	60G	−30C	0G	60C	−60C	4216	170.16	3.034
6	0.5596	0.4253	−45G	45C	75C	90G	−30C	0G	−45C	60C	4149	164.43	3.114
7	0.5715	0.4070	90C	−75C	30C	−60G	−75G	45G	0C	−75C	4320	165.23	3.105
8	0.5715	0.4070	75C	−75C	30C	−60G	−75G	45G	0C	−75C	4391	165.23	3.105

When carbon and S-2 glass fibres were used in the optimisation, for minimum failure load 3000 N, it is shown from Table 7 that ply 8 is dominantly carbon/epoxy at 90°, and ply 1 is dominantly glass/epoxy at 60°. For minimum failure load 4000 N, it is shown from Table 8 that ply 8 is dominantly carbon/epoxy at −75°, and the results vary for other plies. For minimum failure load 5000 N, it is shown from Table 9 that ply 8 is dominantly carbon/epoxy at −75°, and ply 1 is dominantly carbon/epoxy at −15° When the required minimum failure load is high, the plies are mostly carbon/epoxy.

Table 9
Optimal results for minimum failure load 5000 N, carbon and S-2 glass fibres.

	V_{fc}	V_{fg}	Ply								Failure load (N)	Cost ($/m^2)	Weight (mg/mm^2)
			1	2	3	4	5	6	7	8			
1	0.5618	0.4410	−15C	−45C	−75G	−60C	30C	75C	0C	−75C	5015	183.79	3.029
2	0.5618	0.5487	−15C	−45C	−60C	75G	30C	−15C	0G	−75C	5018	178.90	3.154
3	0.5618	0.5487	−15C	−45C	−75G	−60C	30C	−15C	0G	−75C	5014	178.90	3.154

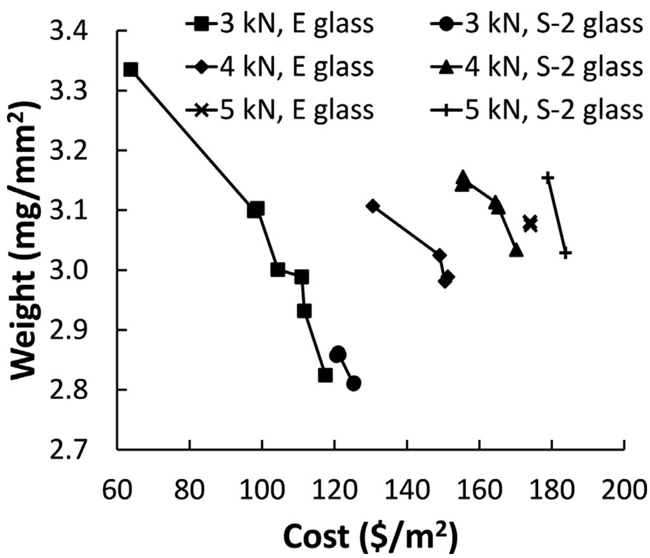

Fig. 4. Pareto fronts from NSGA-II optimisation.

Conclusions

In this paper, an optimisation study on hybrid composite pipes under flexural loading is presented in this paper. The optimal hybrid composite pipe was obtained using NSGA-II with minimum cost and weight as the objective functions. One high strength carbon fibre and two types of glass fibres, i.e. S-2 glass and E glass, were chosen to reinforce an epoxy matrix. It is shown that if the cost is priority, carbon and E glass fibres should be chosen to make the hybrid composite. If the required failure load is high, the hybrid composite is mostly reinforced by carbon fibre and the choice of E or S-2 glass fibre shows little difference. For the middle range failure loads, carbon/E glass fibre reinforced hybrid composites offer both lower cost and less weight, compared to carbon/S-2 glass fibre reinforced hybrid composites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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