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Optimised laminated composite ship-structures against wave impact for enhanced dynamic stiffness

Lee, Chanhui[1]
Imperial College London / Hyundai Heavy Industries Co., Ltd.

Greenhalgh, Emile S.[2]
Panesar, Ajit[3]
Imperial College London
The Composite Centre, Department of Aeronautics, Imperial College London, SW7 2AZ, UK

ABSTRACT

Fibre-reinforced laminated composites are increasingly being utilised in marine and offshore structures due to their superior stiffness and strength to weight ratios, such as resistance to corrosion and enhanced toughness over conventional materials like steel and aluminium. A potential application of composites is in the design of wave-breakers on ship structures. These structures absorb the impact energies from a wave slam to ensure vessel serviceability and safety. The inherent anisotropy of composites and the associated dynamic loading characteristics, make the design process for such a structure very challenging. There are limited studies looking at the design optimisation of composite structures under wave impact loads. In particular, dynamic optimisation based on modal vibration characteristics has not been sufficiently studied. In this study, we have optimised a composite wave-breaker to improve the specific dynamic stiffness based on modal vibration characteristics. To tackle this problem, a multi-level optimisation procedure has been adopted; firstly, the minimum thickness of the composite plate has been determined to avoid delamination; subsequently, the stacking sequence has been identified using lamination parameters along with local thickness variation. Importantly, the optimal arrangement of damping materials (sandwiched between plies) has also been investigated to further enhance the dynamic energy dissipation performance.

Keywords: Laminated composites, Layup optimisation, Lamination parameters, Wave impact, Dynamic stiffness

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[1] c.lee17@imperial.ac.uk
[2] e.greenhalgh@imperial.ac.uk
[3] a.panesar@imperial.ac.uk

1. INTRODUCTION

Fibre-reinforced laminated composites are now widely used throughout the marine and offshore industries due to their superior stiffness and strength to weight ratios, such as resistance to corrosion and enhanced toughness over conventional materials like steel and aluminium [1]. Moreover, material properties of laminated composites can be adjusted or tailored to meet the design requirements by simply varying the stacking sequence and percentage of layers. Over the last four decades, the lay-up optimisation of laminated composites has attracted great attention [2–4]; some previous studies utilised fibre orientation angles as continuous design variables to maximise structural stiffness. Although these studies showed a substantial increase in stiffness, the optimisation process required a repeated transformation of material properties [5]. Moreover, the optimal solutions were often trapped in local optima due to the non-convex region of design variable when using fibre orientation angles. Some researchers adopted lamination parameters (LPs) to express the stiffness of a laminate in a compact form. LPs are the compact representation of a stacking sequence and allow to reduce the number of design variables such as fibre orientation angles and thickness with just 12 LPs based on the classical laminate theory (CLT) [6].

A two-level method has been widely utilised in the optimisation of laminated composites with LPs. Specifically, LPs were used as design variables for the gradient-based layup optimisation at the first level. Subsequently, the second level searches the exact stacking sequence which matches the requirement between optimal LPs and fibre orientation angles. At this second level, GAs have been widely used as a heuristic optimisation method in previous studies [7]. Although there was a good improvement in the second level optimisation, GAs inherently required high computation cost with the increased number of design variables.

A water impact is a significant threat to marine and offshore structures because these structures experience a complicated dynamic stress state due to randomly generated water impact loads. Hence, a number of numerical and experimental studies [8] have been performed to understand and estimate the wave impact load. To date, previous studies have not yet considered the effect of the dynamic behaviour of structures. Hence, in this study, we considered the dynamic modal behaviour of structures in the design stage to consider the complex stress states induced by randomly generated wave load.

Delamination of laminate composites occurs at the interface between adjacent layers due to inter-laminar shear stress. Although there are many parameters defining the dynamic relation between impact event and composite structures, the laminate composites are generally known to be very susceptible to impact load. Hence, a number of studies have been conducted to evaluate the impact strength and to derive accurate formulae for delamination onset load [9].

Damping is an important design factor to predict accurate dynamic response of machinery and structures. Based on the energy dissipation capacity (i.e. damping) of materials, it is possible to suppress the vibration and noise radiation of composite structures. Hence, structural design for the dynamic system should consider the effect of damping to further improve its dynamic behaviour beyond anti-resonance design [10].

Wave-breakers or break-waters are shielding structures installed on the bow of a ship or offshore platforms, used to protect important facilities and cargos from harsh wave impacts. To fulfil their function, wave-breakers are generally designed higher than the wave height on the deck, and the supporting structures should be strong enough to deal with the dynamic load induced by the wave impacts [8]. Although great research effort has been paid for accurate prediction and evaluation of wave impact load on laminate composites, it has not yet been fully clarified due to the complex relationship between impact events and composite materials.

In this study, we have optimised a composite wave-breaker to improve the specific dynamic stiffness based on modal vibration characteristics. Due to the stated complex nature of the objective, this optimisation based endeavour is very challenging. To tackle this problem, a multi-level optimisation procedure has been adopted; firstly, the minimum thickness of the composite plate has been determined to avoid delamination; subsequently, the stacking sequence has been identified using lamination parameters along with local thickness variation. Importantly, the optimal arrangement of damping materials (sandwiched between plies) has also been investigated to further enhance the dynamic energy dissipation performance.

2. Methodology for design optimisation

The aim of this study is to maximise the dynamic stiffness of composite wave-breakers against wave impact loads. The optimisation process was divided into three levels. The minimum thickness of a composite plate for wave-breakers was determined to avoid delamination by evaluating the maximum through-thickness shear stress of wave-breakers at the first level. Subsequently, the optimised stacking sequence, which maximises the dynamic stiffness of wave-breakers, was obtained from LPs-based layup optimisation. Next, the local thickness of the optimised laminated composite was varied to improve specific dynamic stiffness. Finally, the optimal arrangement of damping materials (i.e. sandwiched between plies) has also been investigated to further enhance the dynamic energy dissipation performance of wave-breakers. It should be noted that the optimisation of this work utilised finite element analysis (FEA) to obtain the dynamic modal information. Specifically, ABAQUS was used as a pre-and post-processor for FEA of composite structures as shown in Figure 1. The design specification of a target wave-breaker is presented in Table 1. In this work, the carbon/epoxy (IM7-8552) was used as the composite material of interest, and its material properties are presented in Table 2.

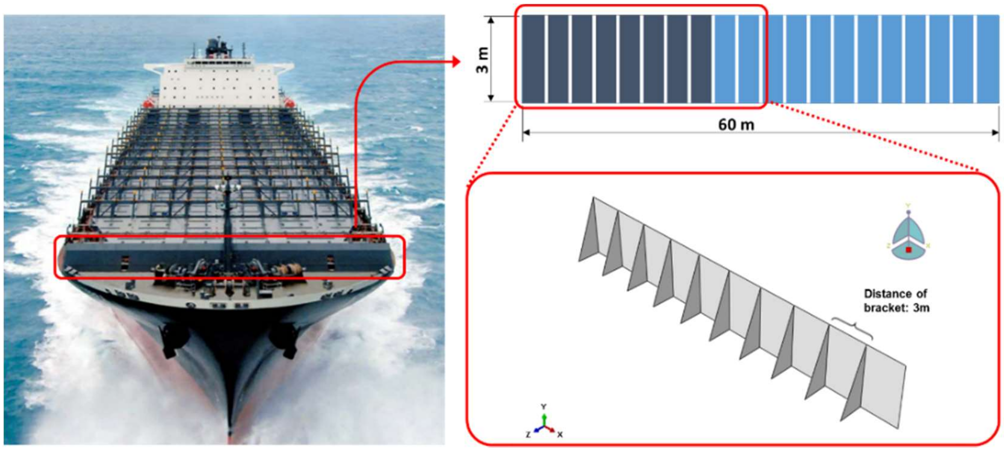


Figure 1. Numerical models of wave-breakers (a half-side model)

Table 1. Design specification of the target wave-breaker

Width [m]	Height [m]	Thickness [mm]	Remarks
60.0	3.0	20.0	- The thickness has been determined from the minimum thickness.

Table 2. Material properties of the carbon/epoxy (IM7-8552) [11]

Density [kg/m^3]	Young's Moduli [GPa]			Shear moduli [GPa]			Poisson's ratio		
	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
1590	171.4	9.08	9.08	5.29	5.29	3.97	0.32	0.32	0.5

2.1 Minimum thickness of a composite plate for wave-breakers

The minimum thickness of a laminated composite plate for wave-breakers was determined to avoid delamination by evaluating the maximum through-thickness shear stress of wave-breakers. The structural optimisation of this study used this minimum thickness as the initial thickness of composite plates for wave-breakers, however, the local thickness of composite plates was adjusted at the following optimisation stage to maximise the specific dynamic stiffness. To be conservative, the minimum thickness was selected when the maximum through-thickness shear stresses were still lower than the shear strength of the polymer matrix with the safety factor of three.

2.2 Layup optimisation of laminated composite wave-breakers

The two-level method was adopted to obtain the optimised stacking sequence which matches the requirement between optimal LPs. We proposed a gradient-based optimiser based on SQP with multiple starting points to improve the computation efficiency. As a benchmark case, GAs were used to compare the efficiency of optimisation. In this work, symmetric and balanced laminates with a stacking sequence of $[(\pm\theta_1)_{P_1}/(\pm\theta_2)_{P_2}/,\cdots,/(\pm\theta_n)_{P_n}]_s$ were considered to neglect the coupling effect between in-plan and out-of-plane stresses.

2.3 Optimal arrangement of damping materials

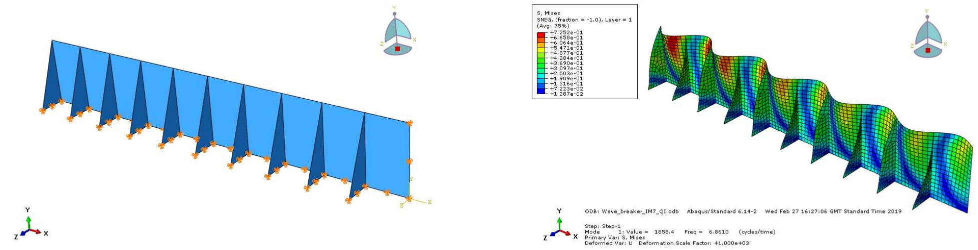
Damping is an important design factor to suppress the vibration and noise radiation of composite structures. Based on the energy dissipation capacity (i.e. damping) of materials, it is possible to further enhance the dynamic behaviour beyond anti-resonance design. Although this part not yet fully prepared in this stage, it will be explored and investigated in our future research.

3. Results and discussion

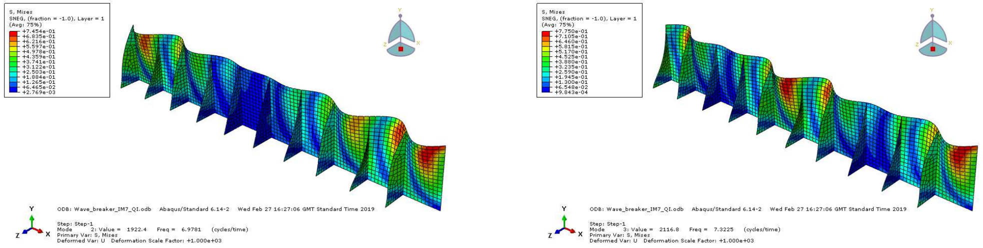
To validate the proposed multi-level optimisation strategy, the numerical study was conducted using the finite element model of laminated composite wave-breakers. Particularly, the LPs-based layup optimisation was applied to achieve the optimised laminated composite main panel of wave-breakers. Firstly, the layup of composite main panel was optimised to maximise the fundamental natural frequency and dynamic modal stiffness. Subsequently, the local thickness of the main panel was adjusted to improve specific dynamic stiffness of the optimised composite main panel. Then, the through-thickness shear stress of the optimised laminated composite main panel was re-assessed to avoid any possibility of delamination. Lastly, the optimal arrangement of damping materials was discussed for future work.

3.1 Vibration modes and modal strain energy of the wave-breaker

Figure 2 presents the lowest three vibration mode shapes of a laminated composite wave-breaker. In this study, the quasi-isotropic (QI) stacking sequence of $[\pm 45/90/0]_s$ was considered as the reference case of the optimised composite wave-breaker. As you can see from the modal strain energy (modal compliance) distribution of the first vibration mode of the wave-breaker (see Figure 3), the maximum stresses and straines were concentrated close to the top centre of main panels, which indicates that the modal strain energy (i.e. modal compliance) of these region was relatively high compared to that of other regions. In other word, the region of high modal strain energy are very vulnerable to the corresponding vibration mode. Hence, in this work, the layup optimisation by using LPs was applied to the main panel of wave-breakers to enhance the dynamic stiffness (i.e. minimisation of modal compliance). For the subsequent optimisation and numerical analysis, a laminated composite main panel with da imension of 3000 × 3000 mm^2 and total thickness 20 mm was used.



(a) Wave-breaker model (half) (b) First vibration mode: 6.86Hz



(c) Second vibration mode: 6.98Hz (d) Thrid vibration mode: 7.32Hz

Figure 2 Vibration mode shapes and the stress distribution (Mises stress) of the composite wave-breaker with $[\pm 45/90/0]_s$

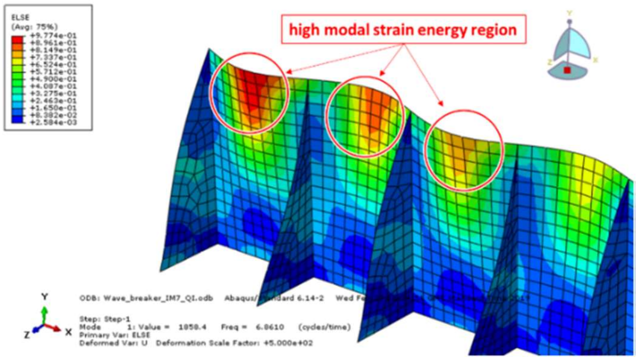


Figure 3 Modal strain energy distribution of the first vibration mode

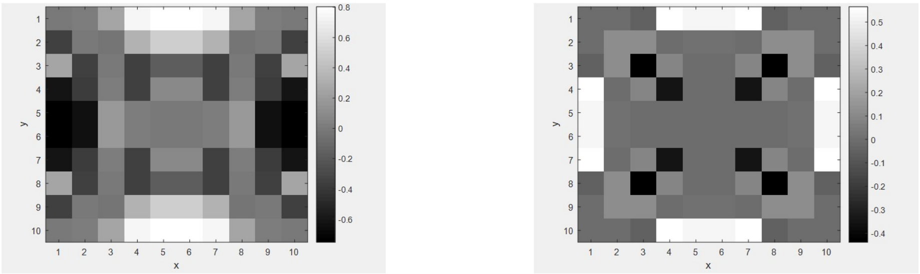
3.2 Maximisation of the fundamental natural frequency

The maximisation of the fundamental natural frequency of the laminated composite main panel was considered. By adopting the LPs approach, we can define the optimisation problem as [12] :

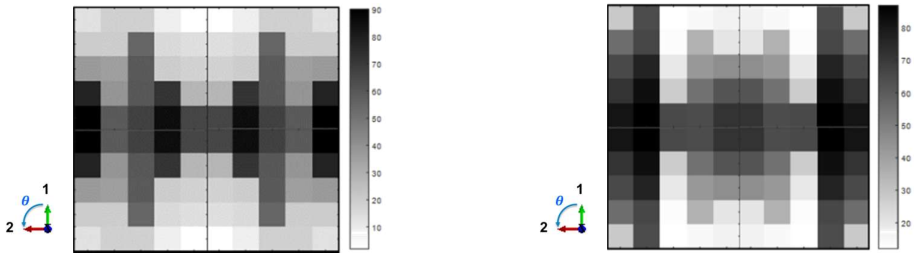
$$\begin{aligned} &Maximise\ \omega\left(V_{1\{A\}}, V_{1\{D\}}, V_{3\{A\}}, V_{3\{D\}}\right) \\ &\text{subject to } 2\left(V_{1\{A\}}\right)^2 \leq V_{3\{A\}} \leq 1, \\ &\qquad\qquad 2\left(V_{1\{D\}}\right)^2 \leq V_{3\{D\}} \leq 1 \end{aligned} \quad (1)$$

When the optimal LPs were obtained, the corresponding stacking sequence was determined from the materials invariants introduced by Tsai and Hahn (1980) [13]. Figure 4 (a) presents the optimal LPs obtained from the optimisation problem in Equation (1). The two optimal solutions of the gradient-based optimisation (SQP) and GAs were presented in Figure 4 (b), (c). The result of SQP presented better convergence to optimal LPs compared to that of GAs (N.B. the smaller sum of squared errors (SSE) represents better convergence). To understand the physical meaning of the optimal LPs, the popular Miki's lamination diagram [14] were adopted as shown in Figure 5(a).

As desired, the fibre orientation angles from optimal LPs presented that they were arranged to the optimal fibre orientation arrangement, which maximises the flexural stiffness [15] and fundamental natural frequency [12] (See Figure 5(b)). These results were in line with those of previous studies. The fundamental vibration mode shapes and the modal strain energy density distribution of the main panel for QI case and optimised orientation angles are presented and compared in Figure 6. The fundamental natural frequency of the optimised layup presented approximately 1.2 greater value than that of the QI case, which represents that the optimised layup obtained more than 1.4 times greater dynamic stiffness than that of the QI case.

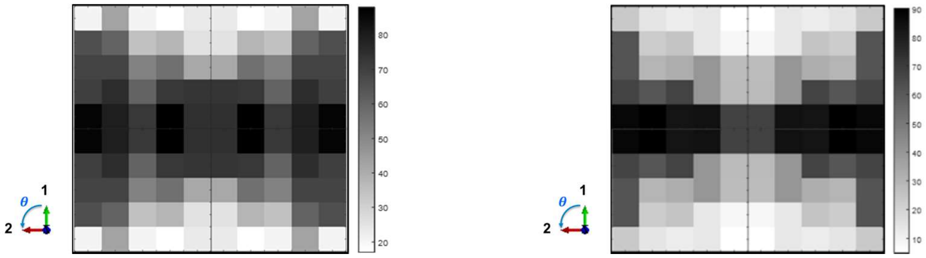


(a) Optimal LP $V_{1\{\boldsymbol{A}\}}$ (left) and $V_{3\{\boldsymbol{A}\}}$ (right)



[θ1] [θ2]

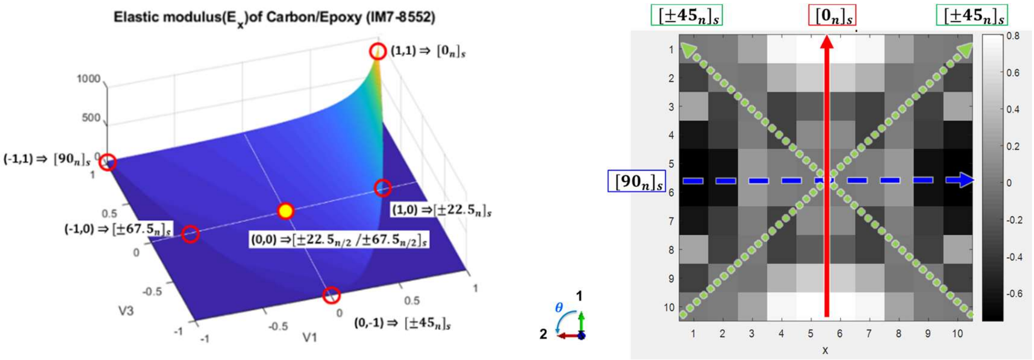
(b) Optimal stacking sequence $[\pm\theta_1/\pm\theta_2]_s$ from the proposed method (SQP);
multiple starting points:100 / SSE: 0.481



[θ1] [θ2]

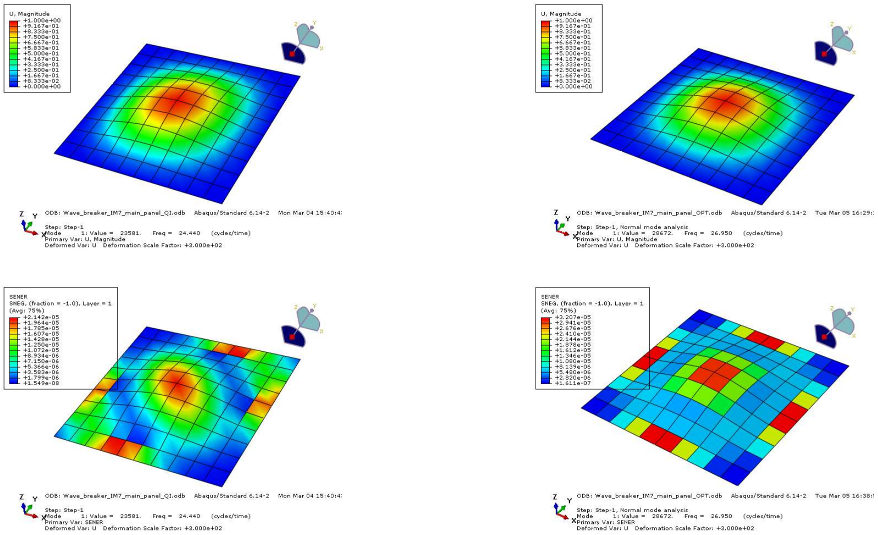
(c) Optimal stacking sequence $[\pm\theta_1/\pm\theta_2]_s$ from GAs;
population size:100, max generation number:100 / SSE: 0.762

Figure 4 Optimal lamination parameters of fundamental frequency maximisation (Design domain: 10×10 elements)



(a) Miki's lamination diagram (b) The fibre orientation angles

Figure 5 Miki's lamination diagram and the fibre orientation angles of the optimised laminated composite main panel

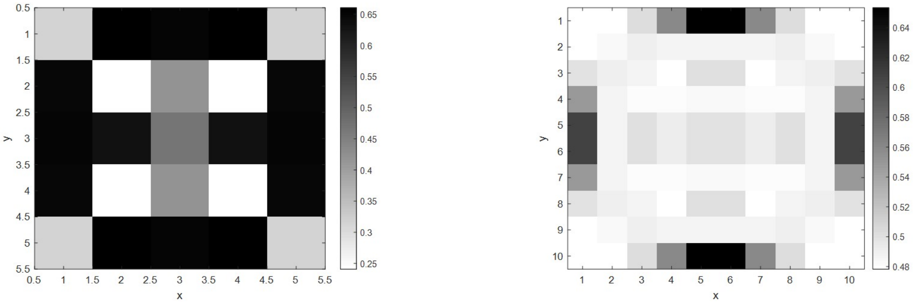


(a) QI : 24.4 Hz (b) Optimal LPs: 29.1Hz

Figure 6 Fundamental vibration mode shapes (top) and modal strain energy density distribution (bottom) of the optimised laminated composite main panel

3.3 Variation of local thickness of laminated composite wave-breakers

After obtaining the optimal LPs, the local thickness optimisation was followed to improve specific dynamic stiffness. Figure 7 presents the optimised local thickness distribution of the main panel. By varying the local thickness, the constraint of 50% weight saving (i.e. on average, the half of an initial thickness) was utilised in the previous optimisation problem in Equation (1). As can be seen from Figure 7, the thickness of a region occupying the central crossing area of the main panel (i.e. [0] and [90] orientation angles region) was converged to relatively thick, while the thickness of the region located diagonal area (i.e. [±45] orientation angle region) converted to thin. Although it was difficult to find previous optimisation results under the same conditions of these results, it was able to be validated by the optimisation results of a previous study using isotropic materials [16].



(a) Design domain: 5×5 elements (b) Design domain: 10×10 elements

Figure 7 Optimised local thickness distribution of the main panel with 50% weight saving

4. Conclusions and future works

This study presents a novel multi-level optimisation strategy to obtain the optimised laminated composite wave-breaker. The fundamental frequency and dynamic modal compliance have been used to optimise the layup of the laminated composite main panel. Lamination parameters (LPs) have been utilised as the design variables of layup optimisation to solve the limitation of fibre orientation angles (non-convex design region). To save the computation expense, a gradient-based optimisation with m multiple starting points has been introduced by replacing conventional GAs-based approach. After obtaining the optimal LPs, the local thickness optimisation has been followed to improve the specific dynamic stiffness based on modal vibration characteristics.

Importantly, the through-thickness shear stress of the minimum thickness and the optimised local thickness of the composite main panel has been identified to avoid delamination. The numerical results of this work have demonstrated that the proposed multi-level optimisation strategy was successful in obtaining optimised laminated composite main panel for wave-breakers. The fundamental natural frequency of the optimised layup presented approximately 1.2 times greater value than that of the QI case, which represents that the optimised layup obtained more than 1.4 times greater dynamic stiffness than that of the QI case.

Future studies will explore the experimental validation of the proposed optimisation strategy, and further extended study such as modal transient behaviours, fluid-structure interaction (FSI) and the optimal arrangement of damping materials to further enhance the dynamic energy dissipation performance of laminated composite wave-breakers.

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