

Vibration behaviours of single/multi-debonded composite sandwich structures with nanoparticle-modified matrices

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Abstract

Sandwich structures with carbon fibre reinforced plastic (CFRP) facesheets are widely used in aerospace and marine structures because they have high strength, stiffness and light weight. However, debonds between the facesheets and the core can reduce greatly the stiffness and the strength of the structures, whilst affecting the vibration behaviours. Hammer impact tests and finite element simulations were conducted to analyse the vibration behaviours of sandwich structures with single and double debonded regions, different matrix modifiers and facesheet stacking orientations. The debonded regions reduced the natural frequencies of sandwich structures, an 80 mm debonded region reduced the natural frequency by 57 %. The natural frequencies in bending modes of the structures with $[0^\circ]_4$ facesheets were more sensitive to debonds; while structures with $[+45^\circ/-45^\circ]_s$ facesheets were more sensitive in torsion modes. When the debonds were present in the same location for both upper and lower facesheets, there was a greater reduction in the natural frequencies of the bending modes than for other debond arrangements. Reductions in the natural frequency can cause a structure to vibrate at resonance and cause structural failure, therefore understanding of how debonded regions affect the vibration of sandwich structures is critical.

Keywords: Sandwich structures, Debonded region, Vibration, Silica nanoparticles, Graphene, CFRP

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1. Introduction

Sandwich structures, which are light but have good mechanical properties such as high stiffness and high durability to flexural loading, have been widely used in many areas, for example in the aerospace, automotive, marine and energy industries, and even in construction. A sandwich structure is manufactured by adhering a core between two thin but strong facesheets. High stiffness materials such as fibre reinforced plastic (FRP) or metal panels are commonly used as the facesheets; light materials such as honeycomb panels or polymers are usually chosen as the core. To reduce the weight of sandwich structures, if the sandwich structure is subjected to lower loads, typical materials of sandwich structures such as polymer foam can be used as the core and glass fibre reinforced plastic (GFRP) can be used as the facesheets; while if the sandwich structure is subjected to higher load, carbon fibre reinforced plastic (CFRP) facesheets and steel square honeycomb core is idea for taking the load and reducing the weight of the structure [1].

The mechanical properties of sandwich structures can be significantly affected by the materials used as the cores and facesheets. Thermoset polymers such as epoxy are widely used as the matrices of the FRPs which are common materials for the facesheets of sandwich structures. Adding modifiers such as carbon nanotubes (CNTs) [2–5], graphene [6, 7] or silica nanoparticles [5, 8] into the polymers can improve their thermal and mechanical properties. For example, the fracture toughness and fracture energy of the epoxy were increased by 49 % and 53 % with an hybrid addition of both 6.0 wt% silica nanoparticles and 0.18 wt% multiwalled carbon nanotubes (MWCNTs) [5].

The modifiers used to modify polymers can also be used to modify FRPs only if the particles are small enough to flow between the fibres [9]. The modifiers mentioned above have been researched to modify the matrices of FRPs [9–12]. For example, adding 4 wt% graphene into the resin can improve the tensile modulus and thermal conductivity of the CFRP by 11 % and 45 % respectively [10]. Fatigue is an important issue for the use of materials since it affects the service lives of the manufactured parts. By adding 10 wt% silica nanoparticles into the matrix, the fatigue life of glass fibre reinforced plastic (GFRP) can be

52 extended by 3 to 4 times because of the reduction of crack growth rate which results from the
53 particle debonding and subsequent plastic void growth [11].

54 For practical applications, vibration is an important issue since resonance can cause se-
55 vere vibration and damage of structures. The vibration behaviours of sandwich structures
56 have been widely studied, and different approaches have also been developed to predict the
57 natural frequencies and deformation modes of sandwich structures [13–15]. For example,
58 the spline finite strip method was developed and the results showed a good agreement with
59 other literature [15]. The geometry and the materials of the core and facesheets can affect the
60 vibration of sandwich structures significantly [2]: if the thickness of the core is increased,
61 the damping properties can be increased since the loss factor is increased; while changing
62 the facesheet stacking orientations can have a significant influence on the natural frequencies
63 since the stiffness of the structure is changed.

64 For sandwich structures, it is critical to bond the core and facesheets firmly to prevent
65 debonding, crack propagation and failure in-service. However, due to defects in the man-
66 ufacturing process or in-service damage (e.g. impact from stones or vehicles), debonding
67 may occur between the core and facesheets, which can decrease significantly the stiffness
68 and strength of the structures, thus leading to failure. The delamination of the adhesive layer
69 between the core and facesheets has been indicated to be a critical problem in sandwich
70 structures [16]. By four-point bending tests, it was reported that stiffness and the strength of
71 sandwich structures decreases more when there is a longer debonded region [17].

72 Debonding can also affect the vibration of sandwich structures significantly. The in-
73 fluence of debonded regions on structures are not only affected by the size and location of
74 debonded region but also by the shape of the structure, the boundary conditions and the modes
75 of vibration [18, 19]. It was indicated that the natural frequencies of sandwich structures de-
76 crease more when the debonded region becomes longer [20, 21], and significantly drop when
77 the debonded region is longer than a critical length (e.g. a critical debond length of 50 mm
78 for a 270-mm-long cantilever beam) [20]. For a CFRP laminate beam, if there are multiple
79 debonded regions which are located at the same place, the natural frequencies of the beam
80 can further decrease [21]. Lower natural frequencies are undesired since they can be excited

more easily in service and result in resonance, which can lead to failure of structures. It is also noted that the reduction in stiffness caused by debonds can be identified by the reduction in natural frequencies.

In the present work, both finite element simulation and vibration tests were conducted, and the results are compared. According to the principles of vibration mechanics, the natural frequencies of a structure are positively correlated to the structure's stiffness, which can be affected by different factors. This work investigates the vibration behaviours of debonded sandwich structures with single or double debonded regions of different lengths. The effects of the materials chosen for modifying the epoxy polymer used for the core and the matrix of the facesheets, and of the stacking orientations of the facesheet CFRP are also discussed. The effects of these factors when combined have not previously been considered in the literature. The natural frequencies affected by these factors are presented and discussed. The aim is to identify the effects of these factors on the vibration response of sandwich structures.

2. Materials and Specimen Manufacturing

The core materials of the sandwich structures used in this study were bulk epoxy polymer. The resin was a diglycidyl ether of bis-phenol A (DGEBA) epoxy, Araldite LY 556 [22] from Huntsman, UK, having an epoxy equivalent weight (EEW) of 185 g/eq; the hardener used to cure the epoxy was an accelerated methylhexahydrophthalic acid anhydride, Albidur HE 600 [23] from Evonik, Germany, having an anhydride equivalent weight (AEW) of 170 g/eq. The facesheets of the sandwich structures were carbon fibre reinforced plastic (CFRP). The carbon fibre UT-C300 [24] used was an unidirectional (UD) carbon fibre fabric manufactured by Gurit. The areal density of the fibre was 300 g/m².

Two types of nanoparticles were used to modify the epoxy, silica nanoparticles (SNPs) and graphene. The silica nanoparticles were supplied as a masterbatch, dispersed in DGEBA epoxy resin, as Nanopox F400 [25] from Evonik, Germany. The EEW was 195 g/eq and the concentration of SNPs was 40 wt%; the average diameter of the SNPs was 20 nm [25]. The graphene was xGnP M-25 [26] from XG Sciences, USA. The carbon content was higher than 99.5 % and the average thickness of the graphene particles was 6 to 8 nm with an average

diameter of 25 μm [26]. The formulations of modifiers used in this research are listed in Table 1.

To manufacture the core, the required amount of epoxy resin, hardener and modifiers were weighed and mixed. The SNPs were mixed with epoxy using an overhead stirrer; the graphene can increase the viscosity of the resin significantly so was mixed with the epoxy using an Exakt 80E 3-roll mill from Germany, USA, to achieve a better degree of dispersion. The mixture was then poured into the moulds, then cured at 90 °C for one hour and post-cured at 160 °C for two hours. The facesheet CFRP was manufactured by resin infusion under flexible tooling (RIFT). The materials of the matrices were epoxy resins which had the same formulations as the core. The curing cycle of the RIFT was the same as for curing the core materials since the same epoxy system was used. After the core epoxy and facesheet CFRP were manufactured, they were cut to the desired sizes, see Table 2. A two-component adhesive, Araldite 2014-1 [27] from Huntsman, Switzerland, was used to bond the facesheets to the cores. The resulting sandwich structures were heated in an oven at 50 °C for 2 hours to cure the adhesive.

To form artificial face/core debonded regions, non-adhesive polytetrafluoroethylene (PTFE) insert films with a thickness of about 20 μm were inserted between the facesheets and the cores when bonding them. Figure 1 illustrates the sandwich structure and shows the positions of the debonded regions in this work.

3. Experimental

Tensile tests were conducted on both the bulk epoxy and CFRP according to the relevant standards [28–31] to measure the tensile moduli and Poisson’s ratios of the materials. An Instron 5584 universal test machine fitted with a 5 kN (for testing epoxy) or 150 kN (for testing CFRP) load cell was used to carry out the tests. A displacement rate of 1 mm/min (for bulk epoxy) or 0.5 mm/min (for CFRP) was used, and the strain in the gauge length was measured using a video extensometer Video Gauge MT-Pro System from iMETRUM, UK. The densities of the materials were also measured using the pycnometer method according to the standards [32, 33]. At least five specimens of each formulation were used for the

137 tensile and density tests. The resultant mechanical properties are listed in Table 1. These
 138 values were used in the finite element (FE) simulations. The bending stiffness matrices of
 139 the intact sandwich structures using unmodified epoxy resin were also calculated according
 140 to the mechanics of composite materials. The bending stiffness matrix, D , when using $[0^\circ]_4$
 141 facesheets is:

$$D_0 = \begin{bmatrix} 4373.14 & 97.56 & 0 \\ 97.56 & 292.20 & 0 \\ 0 & 0 & 175.22 \end{bmatrix} \text{ (GPa-mm}^3\text{)} \quad (1)$$

142 where the subscript “0” means using $[0^\circ]_4$ facesheets. The bending stiffness matrices when
 143 using $[90^\circ]_4$ or $[+45^\circ/-45^\circ]_s$ facesheets are as follows:

$$D_{90} = \begin{bmatrix} 292.20 & 97.56 & 0 \\ 97.56 & 4373.14 & 0 \\ 0 & 0 & 175.22 \end{bmatrix} \text{ (GPa-mm}^3\text{)} \quad (2)$$

$$D_{\pm 45} = \begin{bmatrix} 1390.33 & 1039.89 & 8.00 \\ 1039.89 & 1390.33 & 8.00 \\ 8.00 & 8.00 & 1117.56 \end{bmatrix} \text{ (GPa-mm}^3\text{)} \quad (3)$$

144
 145 Hammer impact tests were conducted on the sandwich structures to measure the response
 146 frequencies and mode shapes. The specimen size is listed in Table 2. The boundary condi-
 147 tions of the sandwich structures were free-free, which means the specimens were only hung
 148 by two strings and had no other constraint. The hammer and the accelerometer were from
 149 PCB Piezotronics, USA, and had standard sensitivities of 22.5 mV/N [34] and 1.02 mV/m/s²
 150 [35] (calibrated at 0.981 mV/m/s² for the one used). The original hard hammer tip was capped
 151 with a soft tip to reduce the noise level. The signal acquisition device SignalCalc Ace and the
 152 analysis software SignalCalc 240 used were from Data Physics Corporation, UK. Fast Fourier
 153 transform (FFT) analysis was used to transfer the time-domain signals to frequency-domain
 154 signals, to obtain the amplitude and phase corresponding to the frequencies.

155 During the hammer tests, the hammer was tapped at different points and the accelerometer
 156 was adhered at a fixed position depending on the mode. To measure the bending and torsion

157 modes, the accelerometer was adhered using wax at the corner of one face and the hammer
158 was tapped at six different points on the opposite face to excite the structure. To measure
159 lateral modes, the accelerometer was adhered at the end of one long side, and the hammer
160 was tapped at the diagonal point on the opposite side. Each point was struck at least twice and
161 the results were recorded only if the coherence was good. The resultant magnitude and phase
162 responses were recorded and analysed. Matlab [36] codes were used to plot and analyse the
163 frequency responses.

164 **4. Finite Element Simulation**

165 Finite element simulation was used to model the vibration of the debonded sandwich
166 structures by using ABAQUS [37] software. Three dimensional (3D) models were estab-
167 lished according to the geometries (see Table 2) of the structures used in the hammer tests.
168 The models included a core and two 4-layer CFRP facesheets. A model of the intact struc-
169 ture (i.e. without face-core debonding) is presented in Figure 1a. The mechanical properties
170 mentioned above were imported into the models (see Table 1). Material orientations were
171 assigned to each layer of the facesheets to represent the effect of fibre direction in the real
172 structures. The facesheets and the core in the models were adhered by “tie constraint” at
173 the bonded interfaces. For the debonded regions, “surface to surface contact” was applied at
174 the interfaces to prevent overlapping. To meet the free-free boundary condition in the tests,
175 no constraint was applied to the models. The element type C3D8, an 8-noded element, was
176 selected to mesh the structures and the Lanczos method was used for simulating the vibration
177 behaviours. The frequency range was set as 100 to 10000 Hz. The frequency range of 0 to
178 100 Hz was not used to avoid rigid body motion in the simulations.

179 Before conducting the simulations, a convergence study was carried out. The model
180 used for convergence study was an intact sandwich structure with unmodified epoxy as the
181 core and matrix of the facesheet CFRP with $[0^\circ]_4$ stacking orientation. This led to a model
182 with 60000 elements (40000 for the facesheets and 20000 for the core) being accepted for
183 good convergence and saving of computational time. This mesh was subsequently used for
184 simulating the other sandwich structures.

5. Results and Discussion

5.1. Introduction

The natural frequencies of sandwich structures are positively correlated to the stiffness of the structures. In the present work, hammer impact tests and finite element simulations were conducted to analyse the effects of different factors on the vibration behaviours of sandwich structures. These factors include the debonding length, facesheet CFRP stacking orientation, material change (affected by modifiers in the resin and matrix) and double debonding. The effect on the natural frequencies of these factors are presented and discussed.

5.2. Effects of Debonding Length

The natural frequencies of the first five modes of the intact sandwich structures using the unmodified epoxy resin for the core and the matrix of the CFRP facesheets are shown in Table 3. The simulated mode shapes of the structure using $[0^\circ]_4$ facesheets are shown in Figure 2. The simulation and experiments show a maximum difference of about 12.2 % for the first five modes. By comparing to the published literature, the differences are acceptable since the common differences are also typically about 10 %. The natural frequencies of the first five modes of the 80-mm-debonded sandwich structures using the unmodified epoxy resin are shown in Table 4. The simulation and experimental results of the 80-mm debond configuration generally show differences less than 10 %, while a difference about 22.62 % is noted for the second mode of the structure using $[+45^\circ/-45^\circ]_s$ facesheets. The differences may result from experimental errors, including the manufacturing process and the test set-up, and from simulation factors such as the mesh density, the element type used to mesh the models, variations in the measured material properties used as input parameters, and the analysis method selected.

Figure 3 shows the relative natural frequencies ($f_n/f_{n,intact}$, where the subscript n indicates the mode) of the first five modes of the structures having a central debonded region. (Note that in Figure 3 and the subsequent Figures, the three mode types are indicated using the same colours: blue for bending, green for lateral and red for torsion.) It is clear that when the debonded region become longer, the natural frequencies decrease more. For the 2nd bending

mode of the structures using $[0^\circ]_4$ facesheets, the natural frequency decreases by 57 % when there is an 80 mm centre debond (see Figure 3a). This is because the debonded regions lead to the reduction of stiffness of the structures. Since the natural frequencies are positively correlated to the stiffness of the structure, a longer debonded region reduces the stiffness more significantly, which results in a greater reduction in the natural frequencies. It is also noted that for all three types of facesheet stacking used in this research, the natural frequencies of the lateral mode show little influence of debonding. This is because the debonded region is in the horizontal direction, so the effect on the stiffness in the lateral direction is less significant, therefore the natural frequency of the lateral mode decreases little.

From Figure 3, it can also be seen that different modes have different sensitivities to debonding, which are related to the materials, the facesheet stacking orientation and the location of the debonded regions. These factors can result in changes to the mode shape sequence. For example, for the intact structure using unmodified resin and $[0^\circ]_4$ facesheets, the 2nd, 3rd and 4th modes (in ascending frequency order) are: 1st torsion (2095.4 Hz), 1st lateral (2986.4 Hz) and 2nd bending (3890.3 Hz) (see Table 3); while for the structures using the same material composition and having an 80 mm central debonded region, these three modes become 2nd bending (1671.9 Hz), 1st torsion (1673.2 Hz) and 1st lateral (2959.3 Hz) in sequence. This change of the mode shape sequence also occurs in the structures using $[90^\circ]_4$ and $[+45^\circ/-45^\circ]_s$ facesheets.

5.3. Effects of CFRP Stacking Orientation

Different facesheet stacking orientations also affect the structures' reaction to debonding. Comparing the same mode in Figure 3, the three facesheet stacking ($[0^\circ]_4$, $[90^\circ]_4$ and $[+45^\circ/-45^\circ]_s$) orientations result in different reductions in the natural frequencies for the same mode shape. For the bending modes, it is significant that the natural frequencies of the structure using $[0^\circ]_4$ facesheets decrease most (decrease by 57 % for 2nd bending with 80 mm debonding), while the natural frequencies of the structure using $[90^\circ]_4$ facesheets decrease least (decrease by 19 % for 2nd bending with 80 mm debonding). For the structure using $[+45^\circ/-45^\circ]_s$ facesheets, the reduction for the same condition is 30 %. The reason for this dif-

ference is that CFRP is an anisotropic material and this results in anisotropy of the sandwich structures. The $[0^\circ]_4$ facesheets have the highest Young's modulus in the longitudinal direction and this results in the highest flexural stiffness of the sandwich structure. However, when there is a debonded region, the stiffness decreases the most significantly, which leads to the greatest reduction of natural frequencies. On the other hand, the $[90^\circ]_4$ facesheets have the lowest Young's modulus in the longitudinal direction and this results in the lowest stiffness of the structure, so the debonded region reduces the stiffness of the structures less significantly, therefore the natural frequencies decrease the least.

The same effect also occurs for the torsion modes since the shear moduli are different for the three types of facesheet stacking. The natural frequency of the 1st torsion mode of the structure using $[+45^\circ/-45^\circ]_s$ facesheets decreases by 40 % when there is an 80 mm debonded region, while for the structures using $[0^\circ]_4$ and $[90^\circ]_4$ facesheets, the reductions are only 20 % and 25 % respectively.

5.4. Effects of Material Change

The changes of materials are achieved by using different modifiers in the core epoxy resin and the matrix of the facesheet CFRP.

By plotting the natural frequencies of the same bending mode versus $\sqrt{E_{1,\text{flex}}/\rho}$ (where $E_{1,\text{flex}}$ is the flexural modulus and ρ is the effective density of the sandwich structures using different modifiers, see Table 1), it is noted that the plot shows a positive linearity (see Figure 4a). The parameter $\sqrt{E_{1,\text{flex}}/\rho}$ comes from the calculation of the natural frequencies of beams in bending modes, e.g. [38]. When the density of the structure decreases or when the flexural modulus increases, $\sqrt{E_{1,\text{flex}}/\rho}$ increases and this results in the increase of natural frequencies. The gradient, m , describes the sensitivity of the structure's natural frequencies to the change of materials due to the addition of modifiers (silica nanoparticles and graphene). A larger m indicates that the natural frequencies of the structures are more sensitive to material change. For example, the gradient is $6.11 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ for the 1st bending mode of the intact sandwich structure using $[0^\circ]_4$ facesheets, and it is $12.81 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ for the 2nd bending mode of the same structure, which means that for this structure, the natural

frequency of the 2nd bending mode is more sensitive to material change.

According to Figure 4b, increasing the length of the debonded region reduces the gradient m . Therefore, the structure with a longer debonded region is less sensitive to the change of materials. For the intact structure mentioned above, the gradients of the 1st and 2nd bending modes are $6.11 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ and $12.81 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ respectively, while for the same structure with an 80 mm debonded region, the gradients are $5.44 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ and $4.14 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ respectively. On the other hand, it is also noted that even when the structures have different facesheet stacking orientations, the plot still shows the same linearity for the same mode (see Figure 4c).

5.5. Effects of Double Debonding

From Figure 5, it is clear that different facesheet stacking orientations show the same trend for the same mode under different debonding conditions. It should be noted that a central 80 mm debonded region can be considered as two 40 mm debonded regions without separation (i.e. $\Delta 0$). Like the effect of CFRP stacking orientation (subsection 5.3), the structure using $[0^\circ]_4$ facesheets has the largest reduction in natural frequencies for bending modes; and for the torsion mode, the structure using $[+45^\circ/-45^\circ]_s$ facesheets has the greatest reduction.

Increasing the distance between two debonded regions, i.e. $\Delta 0$ (80 mm in Figure 1b), $\Delta 20$ (see Figure 1c) and $\Delta 40$ (see Figure 1d), does not confirm the reduction or increase of natural frequencies, as the trends depend on the vibration modes. For example, according to Figure 5a, for the 1st bending mode of the structures using unmodified resin and $[0^\circ]_4$ facesheets, the natural frequency decreases when the separation increases from $\Delta 0$ to $\Delta 40$; while for the 2nd bending mode the natural frequency increases. The reason for the different trends is the locations of the vibration nodes and debonds. For the 1st bending mode, there are two vibration nodes (see Figure 2a). When increasing the distance between the two debonds, the debonded regions become close to the nodes (for $\Delta 20$) and overlap the nodes (for $\Delta 40$). This results in a greater reduction in the natural frequency as the facesheet and core are not bonded together at the node, allowing relative movement, hence there is a greater reduction in the stiffness of the structure. For the 2nd bending mode, there are three vibration nodes (see

Figure 2d). Increasing the distance between the two debonds makes the debonded regions away from the central node and no debonded regions overlap the nodes. Therefore, the natural frequency is reduced by less than for the 80-mm-debonded ($\Delta 0$) structure. However, it still decreases compared to the intact structure.

For the structures with two debonded regions on the same side ($\Delta 20$), diagonal (D) or symmetric (S) positions (each with the same distance of 10 mm to the centre axis, see Figure 1), it is noted that the natural frequencies of condition $\Delta 20$ and D are very close at lower modes (see Figure 5), therefore it is hard to distinguish between these two debonding conditions in real applications by only measuring the resonant frequencies. Although the 1st and 2nd bending modes show a decrease of natural frequencies (e.g. the relative frequency of the 2nd bending mode changes from 0.85 to 0.73 of that of the intact structure having $[0^\circ]_4$ facesheets, see Figure 5a), for the 1st torsion mode the natural frequency decreases, while for the 2nd torsion mode it increases (e.g. the relative frequency of the 2nd torsion mode changes from 0.87 to 0.88 for the same structure, see Figure 5b). Therefore this still doesn't confirm a certain pattern but the change depends on the mode. On the other hand, it is noted that for the bending modes, condition S shows a greater reduction than $\Delta 20$, which results from the greater reduction in stiffness due to the debonded regions being located at the same places for both upper and lower facesheets, and this effect has also been reported previously [21]. It is also noted that the reduction in the natural frequencies of the bending modes are different for conditions D and S, this is because the locations of the debonded regions are different, which affects the decrease of stiffness and therefore results in the different reduction in the natural frequencies.

6. Conclusions

Sandwich structures are used in many applications in the aerospace and marine industries, however, delamination can reduce the stiffness and strength of the structures, reducing safety and affecting the vibration behaviour. By finite element simulation and impact hammer tests, this research has discussed the effects of face/core debonding, facesheet stacking orientation, modifiers and multi face/core debonding. The core was epoxy modified with silica nanopar-

325 ticles or graphene, and the facesheets were CFRP infused with the same epoxy formulation
326 as the core. The results of simulation and experiments showed excellent agreement.

327 For a single debonded region at the centre, a longer debonded region reduces the natural
328 frequencies more significantly, this is because the stiffness of the structure decreases more
329 with a longer debonded region. An 80 mm debonded region reduces the natural frequency of
330 the 2nd bending mode of the sandwich structure (unmodified resin and $[0^\circ]_4$ facesheets) by
331 57 %. The natural frequencies of the different modes have different sensitivities to debonded
332 regions: the lateral mode is less sensitive to a horizontal delamination. The presence of the
333 debonded region can also change the sequence of different modes.

334 The facesheet stacking orientation makes the sandwich structures have a different reac-
335 tion to debonded regions. For the structure using $[0^\circ]_4$ facesheets, the reduction of natural
336 frequencies of bending modes is more significant than for the other two types of stacking;
337 while for $[+45^\circ/-45^\circ]_s$ facesheets, the reduction of torsion modes is more significant. The
338 reason is that CFRP is an anisotropic material and results in anisotropy of sandwich struc-
339 tures. The structure with $[0^\circ]_4$ facesheets has the highest flexural stiffness, however, when
340 there is a debonded region, the stiffness also decreases most, which results in the greatest
341 reduction of natural frequencies of bending modes.

342 For bending modes, the natural frequencies are positively linearly correlated to the struc-
343 ture's $\sqrt{E_{1,\text{flex}}/\rho}$. The gradient m of the linearity describes the structure's sensitivity to the
344 change of materials. The gradient of the 1st bending mode of the intact structure with $[0^\circ]_4$
345 facesheets is $6.11 \times 10^3 \text{ Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$ and for 2nd bending mode it is 12.81×10^3
346 $\text{Hz}/(\text{GPa}/\text{kg}/\text{m}^3)^{0.5}$, which means that the 2nd bending mode of this structure is more sen-
347 sitive to material change. It is also noted that a longer debonded region reduces the gradient
348 more, which indicates that a longer-debonded structure is less sensitive to material change.

349 For multi debonding, $[0^\circ]_4$ facesheets also result in the greatest reduction of natural
350 frequencies of bending modes. Increasing the distance between two horizontally-arranged
351 debonded regions does not confirm the reduction or increase of natural frequencies, it de-
352 pends on the locations of the debonded regions and vibration nodes. On the other hand,
353 comparing two debonded regions with 20 mm horizontal separation ($\Delta 20$), diagonal (D) and

354 symmetric (S) arrangements, the natural frequencies of condition $\Delta 20$ and D are very close
355 at lower modes, therefore it is difficult to distinguish these two debonding conditions in real
356 applications only by measuring the resonant frequencies. However, for bending modes, con-
357 dition S (debonded regions being located at the same place) shows a greater reduction than
358 conditions $\Delta 20$ and D, this is because the debonded regions located at the same location for
359 both upper and lower facesheets reduces the stiffness of the structure more significantly.

360 In conclusion, a longer debonded region causes the natural frequencies of sandwich struc-
361 tures decrease more significantly, by almost 60% in some cases. Other factors like facesheet
362 stacking, materials, mode shapes and locations of debonded regions also influence the vibra-
363 tion behaviours of sandwich structures.

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371 **Appendix A. Supplementary data**

372 The raw and processed data required to reproduce these findings cannot be shared at this
373 time as the data also forms part of an ongoing study.

374 **References**

375 **References**

- 376 [1] Steeves CA, Fleck NA. Material selection in sandwich beam construction. *Scripta Materialia*
377 2004;50(10):1335–9.

- 378 [2] Hsieh TH. Dynamic properties of composite beam and sandwich structure with MWNTs re-
379 inforcement in polymer matrix. Master thesis; National Tsing Hua University; Hsinchu City,
380 Taiwan; 2006.
- 381 [3] Gojny F, Wichmann M, Fiedler B, Schulte K. Influence of different carbon nanotubes on the
382 mechanical properties of epoxy matrix composites - a comparative study. *Composites Science*
383 *and Technology* 2005;65(15-16):2300–13.
- 384 [4] Allaoui A, Bai S, Cheng HM, Bai JB. Mechanical and electrical properties of a MWNT/epoxy
385 composite. *Composites Science and Technology* 2002;62(15):1993–8.
- 386 [5] Hsieh TH, Kinloch AJ, Taylor AC, Sprenger S. The effect of silica nanoparticles and carbon
387 nanotubes on the toughness of a thermosetting epoxy polymer. *Journal of Applied Polymer*
388 *Science* 2011;119(4):2135–42.
- 389 [6] Rafiee MA, Rafiee J, Wang Z, Song H, Yu ZZ, Koratkar N. Enhanced mechanical properties of
390 nanocomposites at low graphene content. *ACS Nano* 2009;3(12):3884–90.
- 391 [7] Potts JR, Dreyer DR, Bielawski CW, Ruoff RS. Graphene-based polymer nanocomposites. *Poly-*
392 *mer* 2011;52(1):5–25.
- 393 [8] Bray DJ, Dittanet P, Guild FJ, Kinloch AJ, Masania K, Pearson RA, et al. The modelling of
394 the toughening of epoxy polymers via silica nanoparticles: The effects of volume fraction and
395 particle size. *Polymer* 2013;54(26):7022–32.
- 396 [9] Kinloch AJ, Mohammed RD, Taylor AC, Sprenger S, Egan D. The interlaminar toughness
397 of carbon-fibre reinforced plastic composites using ‘hybrid-toughened’ matrices. *Journal of*
398 *Materials Science* 2006;41(15):5043–6.
- 399 [10] Zhang B, Asmatulu R, Soltani SA, Le LN, Kumar SSA. Mechanical and thermal properties
400 of hierarchical composites enhanced by pristine graphene and graphene oxide nanoinclusions.
401 *Journal of Applied Polymer Science* 2014;131(19):40826.
- 402 [11] Manjunatha CM, Taylor AC, Kinloch AJ, Sprenger S. The tensile fatigue behaviour of a silica
403 nanoparticle-modified glass fibre reinforced epoxy composite. *Composites Science and Tech-*
404 *nology* 2010;70(1):193–9.

- [12] Sprenger S. Fiber-reinforced composites based on epoxy resins modified with elastomers and surface-modified silica nanoparticles. *Journal of Materials Science* 2014;49(6):2391–402.
- [13] Raville ME, Ueng CES. Determination of natural frequencies of vibration of a sandwich plate. *Experimental Mechanics* 1967;7(11):490–3.
- [14] Lee LJ, Fan YJ. Bending and vibration analysis of composite sandwich plates. *Computers & Structures* 1996;60(1):103–12.
- [15] Yuan WX, Dawe DJ. Free vibration of sandwich plates with laminated faces. *International Journal for Numerical Methods in Engineering* 2002;54(2):195–217.
- [16] Hohe J, Becker W. Assessment of the delamination hazard of the core face sheet bond in structural sandwich panels. *International Journal of Fracture* 2001;109(4):413–32.
- [17] Mouritz AP, Thomson RS. Compression, flexure and shear properties of a sandwich composite containing defects. *Composite Structures* 1999;44(4):263–78.
- [18] Mujumdar PM, Suryanarayan S. Flexural vibrations of beams with delaminations. *Journal of Sound and Vibration* 1988;125(3):441–61.
- [19] Baba BO, Thoppul S. Experimental evaluation of the vibration behavior of flat and curved sandwich composite beams with face/core debond. *Composite Structures* 2009;91(1):110–9.
- [20] Kim HY, Hwang W. Effect of debonding on natural frequencies and frequency response functions of honeycomb sandwich beams. *Composite Structures* 2002;55(1):51–62.
- [21] Della CN, Shu D. Free vibration analysis of composite beams with overlapping delaminations. *European Journal of Mechanics - A/Solids* 2005;24(3):491–503.
- [22] Araldite LY556. Material datasheet; Huntsman; Everberg, Belgium; 2017.
- [23] Albidur HE600. Material datasheet; Evonik; Geesthacht, Germany; 2008.
- [24] UT-C300. Material datasheet; Gurit; Newport, UK; 2015.
- [25] NANOPOX F400. Material datasheet; Evonik; Geesthacht, Germany; 2014.

- 429 [26] xGnP Grade M graphene. Material datasheet; XG Sciences; Michigan, USA; 2013.
- 430 [27] Araldite 2014. Material datasheet; Huntsman; Basel, Switzerland; 2007.
- 431 [28] BS EN ISO 527-1. Plastics - Determination of tensile properties - Part 1: General principles.
432 BSI; London, UK; 2012.
- 433 [29] BS EN ISO 527-2. Plastics - Determination of tensile properties - Part 2: Test conditions for
434 moulding and extrusion plastics. BSI; London, UK; 2012.
- 435 [30] ASTM D3039-14. Standard Test Method for Tensile Properties of Polymer Matrix Composite
436 Materials. ASTM International; West Conshohocken, USA; 2014.
- 437 [31] ASTM D3518-13. Standard Test Method for In-Plane Shear Response of Polymer Matrix Com-
438 posite Materials by Tensile Test of a $\pm 45^\circ$ Laminate. ASTM International; West Conshohocken,
439 USA; 2013.
- 440 [32] ASTM D792-13. Standard Test Methods for Density and Specific Gravity (Relative Density) of
441 Plastics by Displacement. ASTM International; West Conshohocken, USA; 2013.
- 442 [33] ASTM D2320-98(2017). Standard Test Method for Density (Relative Density) of Solid Pitch
443 (Pycnometer Method). ASTM International; West Conshohocken, USA; 2017.
- 444 [34] Impact Hammer Model: 086E80. Technical datasheet; PCB Piezotronics; New York, USA;
445 2015.
- 446 [35] Accelerometer Model: 352B10.010AC. Technical datasheet; PCB Piezotronics; New York,
447 USA; 2013.
- 448 [36] The MathWorks. MATLAB R2015b. 2015. URL: [https://uk.mathworks.com/products/
449 matlab.html](https://uk.mathworks.com/products/matlab.html).
- 450 [37] Dassault Systemes. Abaqus 6.14. 2014. URL: [https://www.3ds.com/products-
451 services/simulia/products/abaqus/](https://www.3ds.com/products-services/simulia/products/abaqus/).
- 452 [38] Rao SS. Mechanical vibrations, Fifth Edition. Singapore: Prentice Hall Upper Saddle River;
453 2011.

Table 1: Materials and mechanical properties

	Bulk epoxy			CFRP of 0° lay-up						
	Density (kg/m ³)	E (GPa)	ν	Density (kg/m ³)	E_1 (GPa)	E_2 (GPa)	ν_{12}	ν_{23}	G_{12} (GPa)	G_{23} (GPa)
unmodified	1154	2.8	0.35	1557	122.6	6.7	0.33	0.48	4.5	2.3
5 wt% silica	1163	3.3	0.37	1527	139.3	6.5	0.37	0.58	4.0	2.1
10 wt% silica	1174	3.4	0.36	1557	132.9	7.4	0.34	0.51	3.6	2.4
15wt% silica	1249	3.6	0.36	1550	127.8	7.0	0.36	0.55	3.7	2.2
0.5 wt% graphene	1105	2.9	0.36	1525	131.0	6.1	0.35	0.53	3.4	2.0
1.0 wt% graphene	1155	2.9	0.39	1566	120.3	6.7	0.36	0.55	4.1	2.2

Note: $E_2 = E_3$, $\nu_{12} = \nu_{13}$, $G_{12} = G_{13}$

Table 2: Sandwich structure geometry

	Length (mm)	Width (mm)	Thickness (mm)
Core			6
Facesheet CFRP	200	25	1.3/piece
Sandwich Structure			8.6

Table 3: Natural frequencies and mode shapes of intact structure using unmodified resin

Facesheet stacking	Mode	FE. (Hz)	Exp. (SD.) (Hz)	Difference (%)	Shape
[0°] ₄	1	1645.8	1512.9 (11.9)	-8.1	bending
	2	2095.4	1880.9 (87.2)	-10.2	torsion
	3	2986.4	2910.7 (22.9)	-2.5	lateral
	4	3890.3	3603.1 (199.8)	-7.4	bending
	5	4273.6	3921.2 (145.3)	-8.2	torsion
[90°] ₄	1	452.3	447.5 (4.4)	-1.1	bending
	2	1092.6	1134.1 (3.5)	3.8	lateral
	3	1223.7	1227.7 (10.6)	0.3	bending
	4	2072.0	1818.9 (84.4)	-12.2	torsion
	5	2336.4	2460.3 (191.7)	5.3	bending
[+45°/-45°] _s	1	655.84	616.8 (3.1)	-5.95	bending
	2	1431.9	1394.5 (9.2)	-2.61	lateral
	3	1759.9	1616.4 (81.3)	-8.15	bending
	4	3320.6	3224.4 (104.1)	-2.90	bending
	5	3435.7	3212.2 (321.5)	-6.51	torsion

Table 4: Natural frequencies and mode shapes of 80-mm-debonded structure using unmodified resin

Facesheet stacking	Mode	FE. (Hz)	Exp. (Hz)	Difference (%)	Shape
[0°] ₄	1	1542.4	1389.5	-9.9	bending
	2	1671.9	1609.0	-3.8	bending
	3	1673.2	1565.6	-6.4	torsion
	4	2959.3	2868.4	-3.1	lateral
	5	3686.2	3600.0	-2.3	torsion
[90°] ₄	1	449.1	475.8	5.9	bending
	2	985.2	907.8	-7.9	bending
	3	1084.9	1119.5	3.2	lateral
	4	1544.9	1463.3	-5.3	torsion
	5	2077.8	2200.0	5.9	bending
[+45°/-45°] _s	1	647.74	683.2	5.47	bending
	2	1231.2	952.73	-22.62	bending
	3	1418.6	1346.88	-5.06	lateral
	4	2064	1946.48	-5.69	torsion
	5	2705.6	2354.69	-12.97	bending

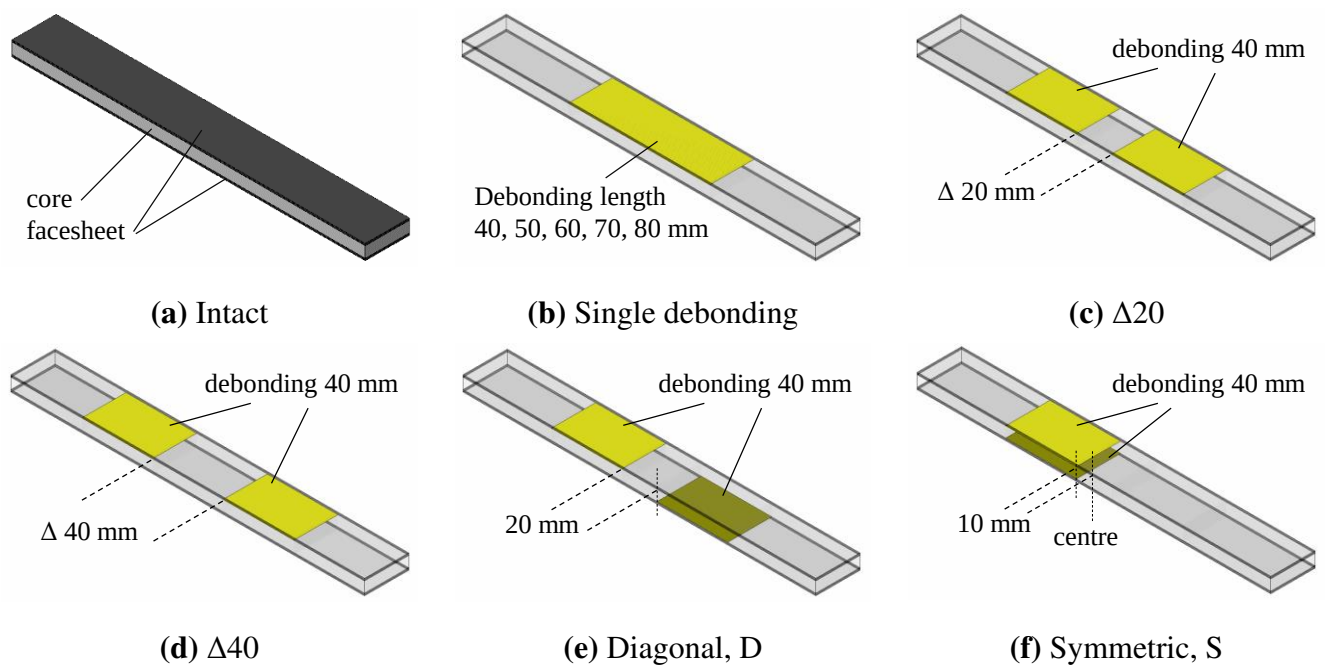


Figure 1: Models of sandwich structures and debonding positions (shown in yellow)

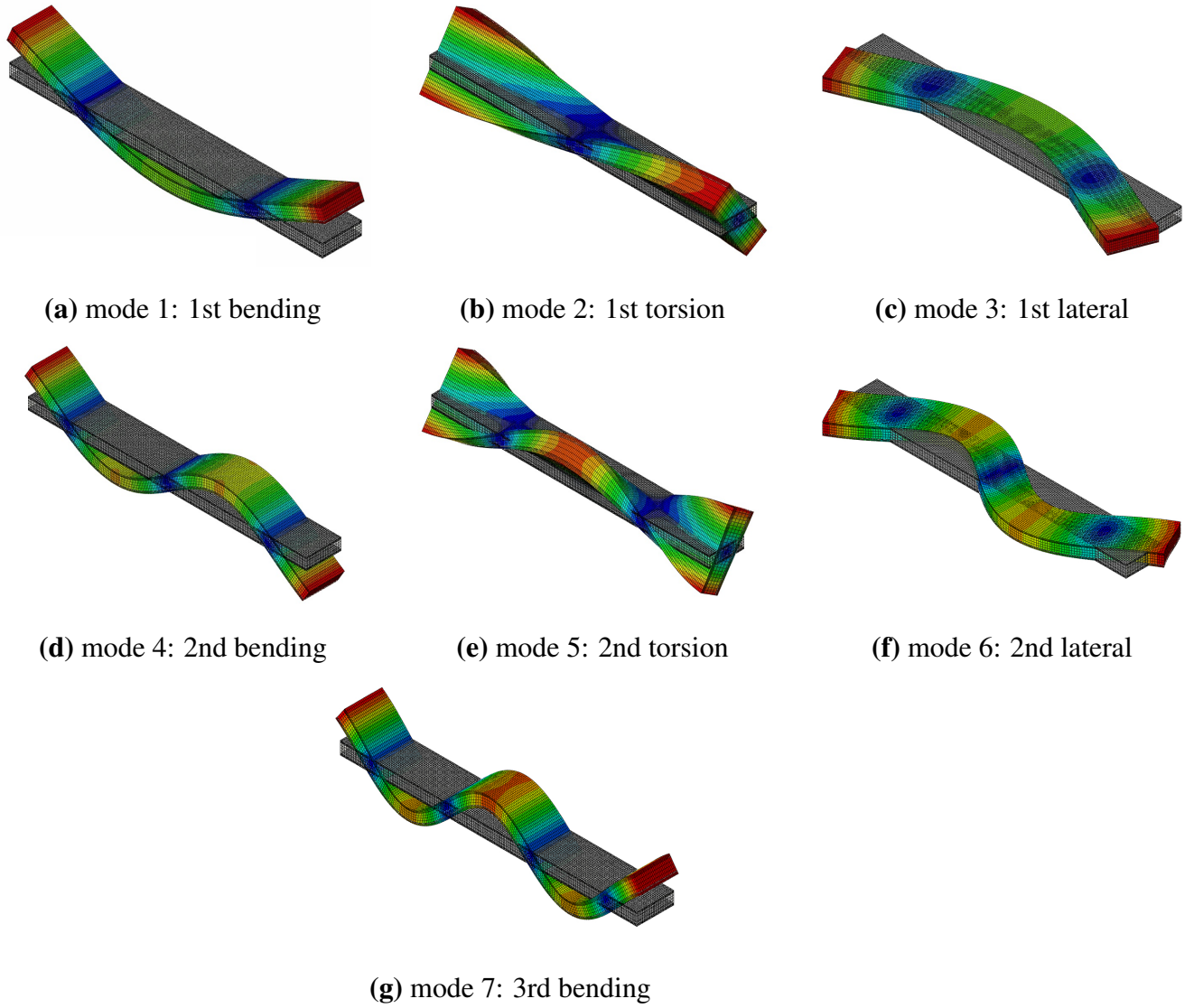
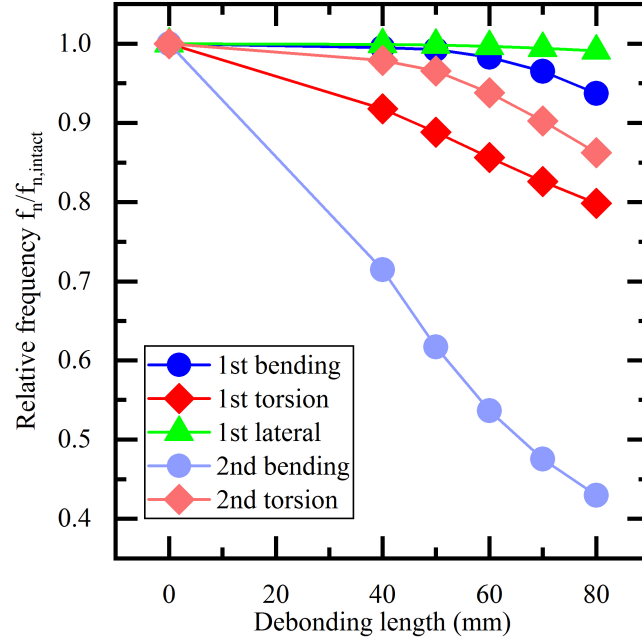
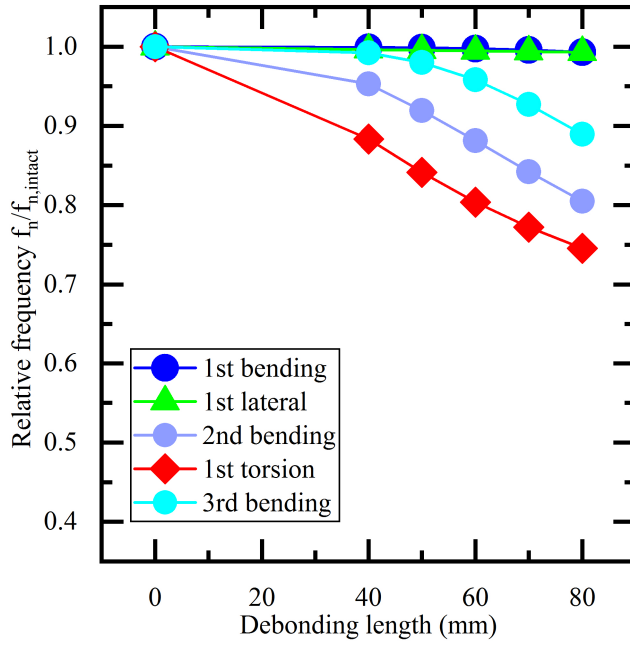


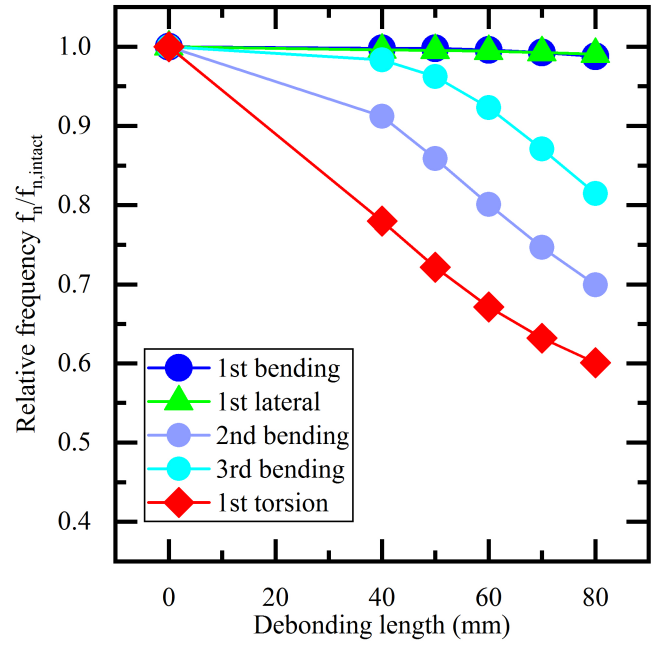
Figure 2: Simulation mode shapes of intact structure using unmodified resin and $[0^\circ]_4$ stacking



(a) $[0^\circ]_4$ facesheets

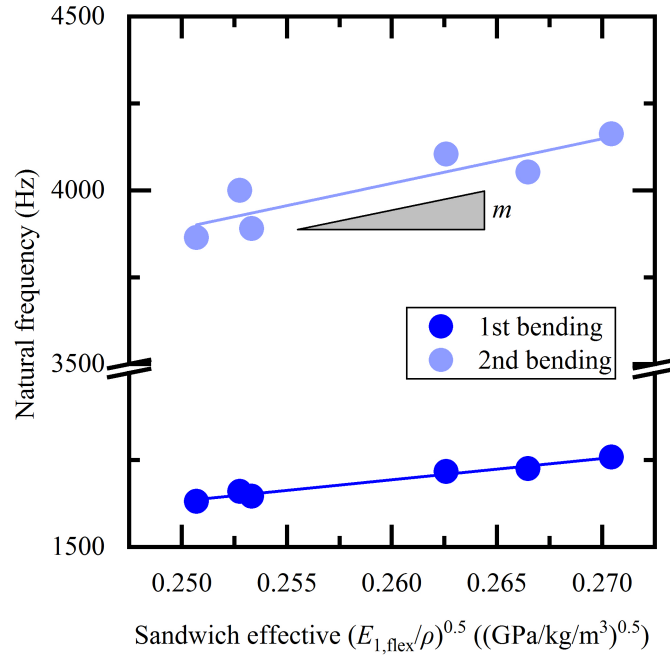


(b) $[90^\circ]_4$ facesheets

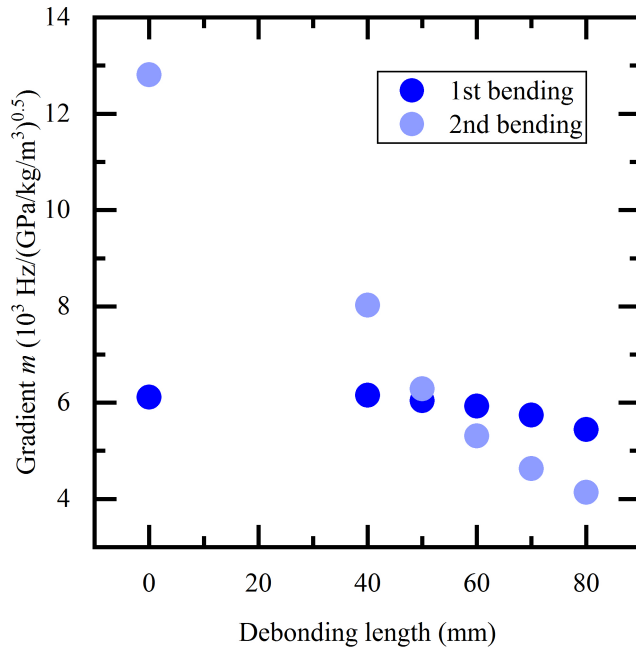


(c) $[+45^\circ/-45^\circ]_s$ facesheets

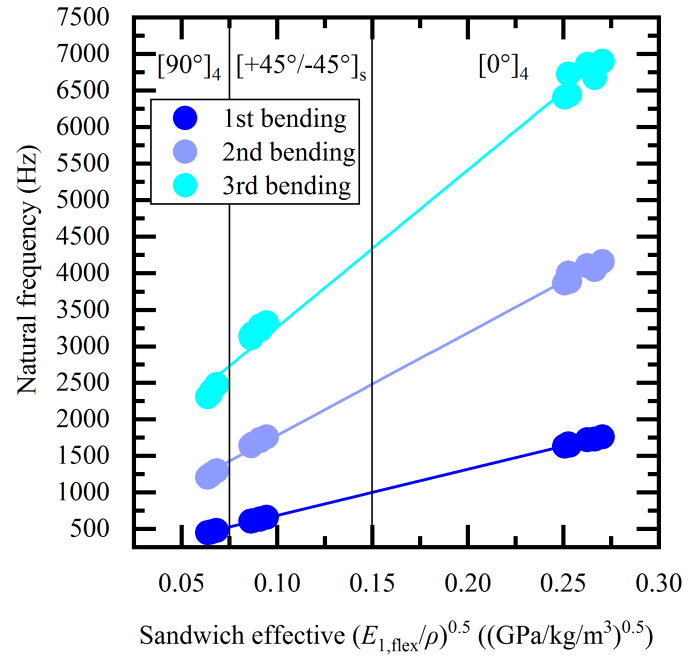
Figure 3: Relative natural frequencies affected by central single debonding (simulation results). The order of modes in the legends follows the increasing of natural frequency



(a) Bending frequencies of intact structures, $[0^\circ]_4$ facesheets, different modifiers

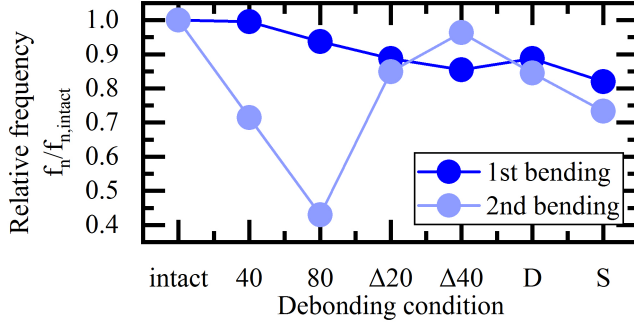


(b) Gradient m of debonded structures, $[0^\circ]_4$ facesheets

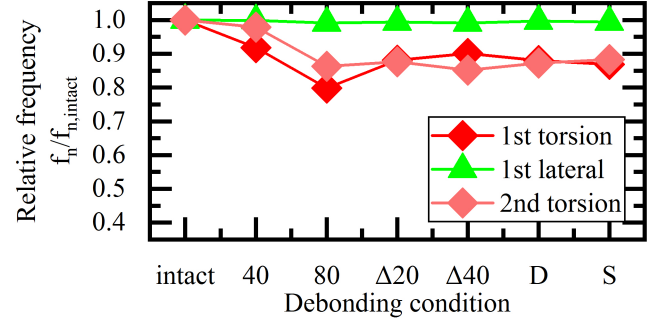


(c) Bending frequencies of intact structures using different modifiers

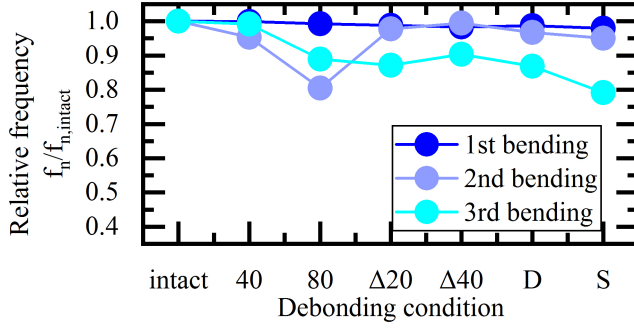
Figure 4: Influence of material change on the natural frequencies of sandwich structures (simulation results)



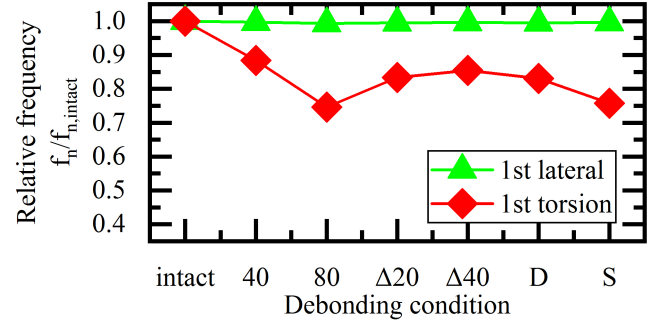
(a) $[0^\circ]_4$ facesheets, bending



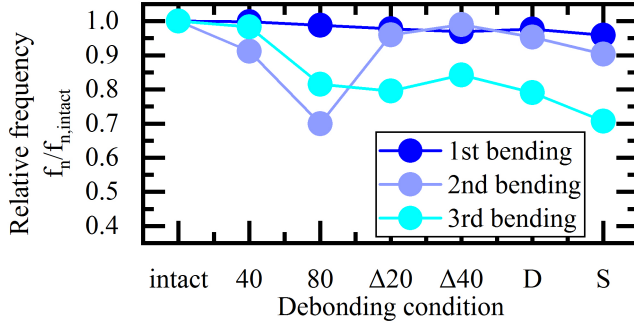
(b) $[0^\circ]_4$ facesheets, torsion and lateral



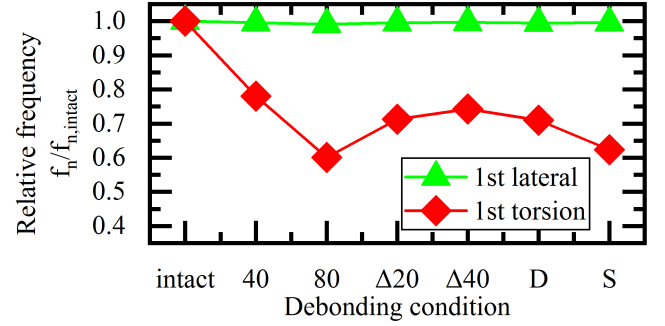
(c) $[90^\circ]_4$ facesheets, bending



(d) $[90^\circ]_4$ facesheets, torsion and lateral



(e) $[+45^\circ/-45^\circ]_s$ facesheets, bending



(f) $[+45^\circ/-45^\circ]_s$ facesheets, torsion and lateral

Figure 5: Relative natural frequencies affected by double debonding (simulation results)