DYNAMIC BEHAVIOUR OF FIBRE COMPOSITE MULTILAYER SANDWICH PLATES WITH DELAMINATIONS

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ABSTRACT

Composites are continuing to gain prominence for structural as well as non-structural applications all over the world. A structural composite multilayer slab can be manufactured by gluing several of the composite sandwiches together to form a laminated composite slab. Delamination between layers is one of the major failure modes which threaten the reliability of composite structures. Delamination can also cause changes to dynamic behaviour. Dynamic analysis of three dimensional models of structures enables more realistic assessment of their free vibration behaviour.The dynamic behaviour of fibre composite multilayer sandwich plates with different configurations of delamination is presented in this paper. A parametric investigation is carried out to assess the influence of parameters including length, width and location of delamination, size and support conditions of the plates on the free vibration behaviour, using three dimensional modelling with Strand7 finite element software package. Plate elements for skins and brick elements for core of each sandwich layer are used in the model development for plates representing their actual behaviour. It is revealed that the decrease in natural frequency with the increase in the extent of debonding is greatly dependent on the boundary conditions, location of the debond and also on the mode number.

KEYWORDS

Free vibration, delamination, three dimensional modelling, dynamic behaviour.

INTRODUCTION

Composite sandwiches can be fabricated by attaching two thin but stiff glass fiber skins to a thick core, which can be used for plate or slab type structural applications. A structural composite plate or slab can be manufactured by gluing several composite sandwiches together to form a laminated composite. Fiber Reinforced Polymer (FRP) laminated panels are gaining acceptance in numerous engineering applications all over the world as they are light weight, durable and cost effective substitute to reinforced concrete for new constructions as well as for rehabilitation of bridges and walkways (Dey et al. 2013). It is well known that debonding between the core and the face sheet is the predominant mode of failure for sandwich composite structures (Mousa and Uddin 2012). Modeling and detection of delamination in composites plates have been studied mainly with classical lamination theory (CLT) and first order shear deformation theory (FSDT) where CLT completely ignores transverse shear deformations and FSDT accounts for them through shear correction factors (Karunasena 2010).

An Australian manufacturer has fabricated a new structural GFRP sandwich panel made from E-glass fibre skin and a modified phenolic core for the civil engineering applications such as floors, pedestrian bridges and railway sleepers (Awad et al. 2012a). Investigation of the free vibration behaviour of the fully bonded GFRP sandwich by experimental and numerical methods was carried out by Awad et al. (2012b). Although experimental and numerical research has been conducted on the examination of the free vibration behaviour of the fully bonded GFRP sandwich floor panels, there has been only a limited investigations on the free vibration behaviour of the debonded GFRP panels. This paper deals with the investigation of free vibration behaviour of multilayer composite sandwich slab panels with debonding using Strand7 software package. Three dimensional modelling has been carried out to closely model the actual behaviour.

METHODS AND MATERIALS

Method of Analysis and Model Development

The method adopted here is to develop a finite element model and conduct numerical simulations to assess the dynamic behaviour of debonded composite sandwich slabs using three-dimensional modelling and analysis. A parametric investigation is carried out to assess the influence of various parameters of concern including size of the debond, location of debond, size and support conditions of the structural element on the free vibration behaviour. Numerical simulations are carried out using FE code Strand7, using 3D finite element models of the structures to precisely represent their real behaviour. In modelling the composite plates with Strand7, the core is modeled as three-dimensional brick solid elements while the skins by plate elements. Linear elastic orthotropic top and bottom skins are modelled using 4-noded rectangular (Quad4) plate elements. Core is modelled using 3D brick elements (Hexa8). These elements take care of any shear deformations happening in the thick core. Core 3D FE mesh is generated by extruding the Qaud4 plate element mesh using the ‘extrude’ command in strand7. This ensures that a vertical line through corresponding plate nodes in the top and bottom skins will pass through corresponding brick nodes in the core. The structural integrity between top skin and core is assured by connecting plate nodes with corresponding brick nodes at the top surface level of the core through vertical ‘rigid link’ elements. Rigid link provides restraints to the nodal rotations, in addition to the translational displacements (Strand7 2010). The FE model for the debonded beam is obtained by converting the rigid links within the debonded region to ‘master slave links’ in Strand7 with appropriate degrees of freedoms. Here debonding is assumed to be an artificial flaw of zero thickness, embedded between skin and core.

Model Validation

The developed numerical model has been verified and validated for accuracy through comparison of the results with published experimental and numerical results. For the validation of the model, the natural frequencies from the proposed model for the innovative GFRP panels of four different sizes are compared with published experimental and numerical results reported by Awad et al. (2012b). The effective mechanical properties used in the present model validation (which are also the same values used by Awad et al. 2012b) for the fibre composite skin and the core material are listed in Table 1.

Table 1. Effective mechanical properties of fibre composite skin and core used for model validation

Property	Skin	Core
Young’s modulus along long direction (MPa)	12360	1350
Young’s modulus in transverse direction (MPa)	10920	1350
Poisson’s ratio	0.3	0.2
Density (kg/m^3)	1425	950

Dynamic Analysis of Novel Composite Plates with Debonding

Free vibration analysis for the novel composite sandwich panels of 800 mm and 1000 mm square section having skin and core thicknesses as in Figure 1, has been carried out with four boundary conditions, namely, all four ends clamped (C-C-C-C), two ends clamped and the other two ends free (C-C-F-F), all four ends simply supported (S-S-S-S) and two ends simply supported and the other two ends free (S-S-F-F). Different sizes (0.5%, 1%, 5% and 10% of plate area) and locations (position 1, 2 and 3 as shown in Figure 2) of debonding are considered to examine the critical locations and sizes of debonding with respect to change in dynamic behaviour. The effective mechanical properties for the fiber composite skin and the core material used by Jayatilake et al. (2013) have been used for the present analysis of the sandwich panel and the relevant properties are listed in Table 2.

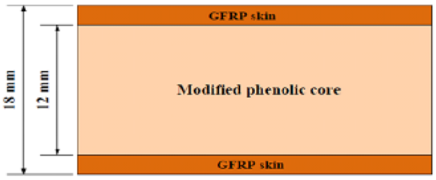


Figure 1. GFRP sandwich slabs cross sections (Awad et.al. 2012b)

Table 2. Effective mechanical properties of fibre composite skin and core for present analysis (Jayatilake et al. 2013)

Property	Skin	Core
Young’s modulus along long direction (MPa)	15380	1150
Young’s modulus in transverse direction (MPa)	12631	1150
Poisson’s ratio	0.25	0.30
Density (kg/m^3)	1366	855

RESULTS AND DISCUSSIONS

Model Validation

For the verification of the accuracy of the results for the finite element model used in this study, the natural frequencies from the proposed model for novel composite single layer sandwich slabs are computed and compared with experimental and FEA results reported by Awad et al (2012b). Awad et al. (2012b) conducted experimental work and 3D finite element (FE) simulation with ABAQUS to investigate the free vibration behaviour of the GFRP sandwich panels with different sizes and support conditions. The typical novel composite sandwich panel has a 12 mm core thickness and 3 mm GFRP skin thickness in the top and bottom faces, as shown in Figure 1. The total thickness of the panel is 18 mm. Four different sizes were used for the verification, namely 400, 600, 800 and 1000 mm one way square slab panels. The end condition considered here was fixed (glue) restraints for both ends of the slabs. The results of the verification study are reported in Table 3, where first and second natural frequency values in Hertz for reported experimental, and FEA analyses are compared with the developed model with Strand7.

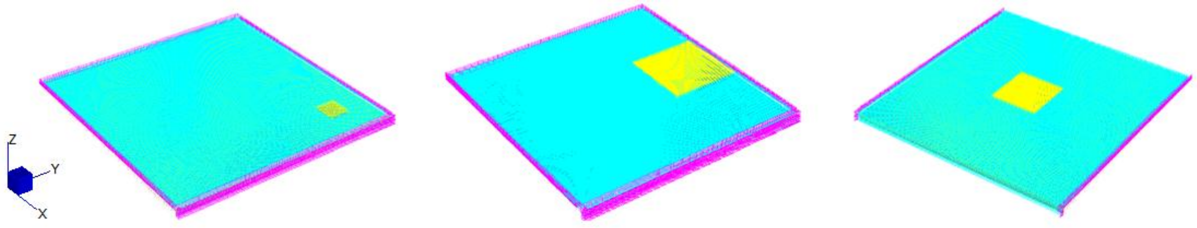
Table 3. Results obtained for first and second natural frequencies in Hz for model validation

Slab size	Support type	Restraint type	Mode number	Experimental results (Awad et al. 2012) Frequency in Hz	FEA with ABAQUS (Awad et al. 2012) Frequency in Hz	Present analysis with Strand7 Frequency in Hz
400×400	One-way	Glue	1	193	194	195
400×400	One-way	Glue	2	230	226	234
600×600	One-way	Glue	1	95	96	90
600×600	One-way	Glue	2	123	114	121
800×800	One-way	Glue	1	49	51	52
800×800	One-way	Glue	2	70	64	70
1000×1000	One-way	Glue	1	28	29	34
1000×1000	One-way	Glue	2	41	37	45

Results for the Present Analysis

Results for 800 mm single layer square panel

Three different positions of debonding and four different percentages of debonding (0.5%, 1%, 5% and 10% by area of the plate) have been investigated and some typical 3D models developed are shown in figure 2 to show the different scenarios used.



(a) Position 1(C-C-C-C) 1% debonding (b) Position 2 (C-C-C-C) 10% debonding (c) Position 3 (C-C-F-F) 5% debonding

Figure 2. Typical 3D models created using Strand7 for the analyses

Note here that the results for some critical cases only, have been presented due to page limitations. Generally the most critical end condition giving highest reduction in natural frequency due to debonding is the C-C-C-C scenario. The most critical location in terms of percentage reduction in natural frequency for C-C-C-C end condition is position 3 which is the delamination located at the middle of the plate, whereas for C-C-F-F boundary condition the worst location is position 1. The results for these two scenarios are presented graphically in Figures 3 and 4 respectively.

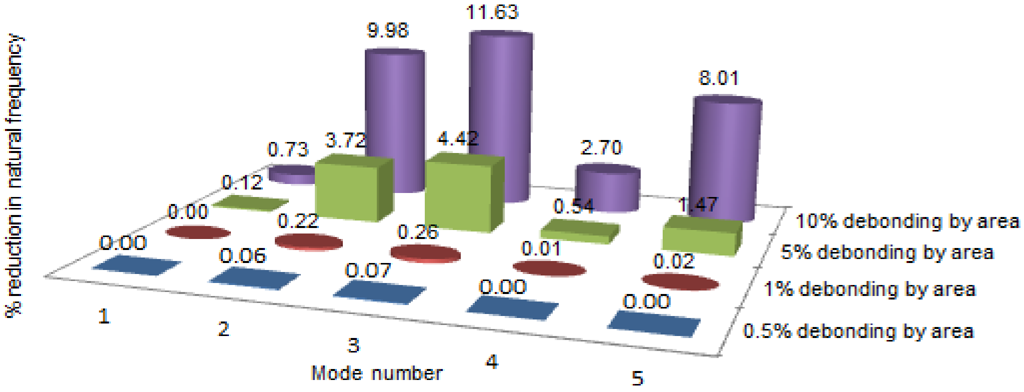


Figure 3. Comparison of percentage natural frequency reduction for different extents of debonding in 800 mm C-C-C-C plate for debonding position 3

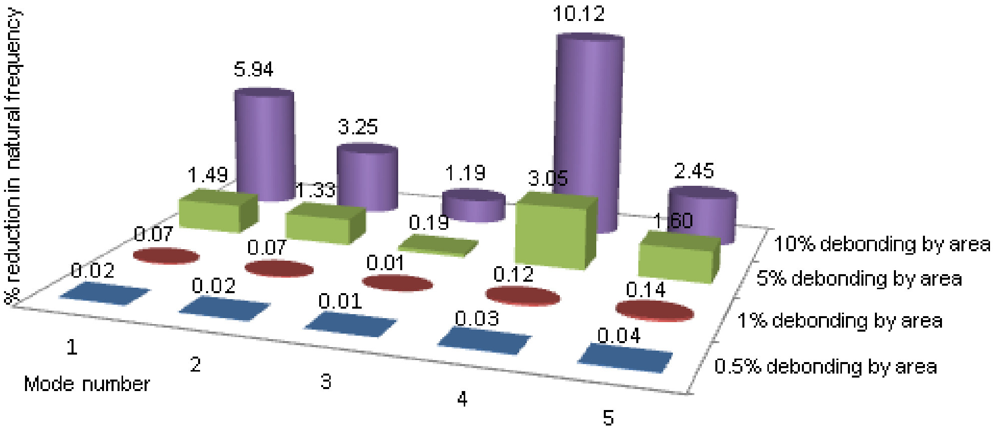


Figure 4. Comparison of percentage natural frequency reduction for different extents of debonding in 800 mm C-C-F-F plate for debonding position 1

It is evidenced from Figure 3 and 4 that some modes are more sensitive to debonding, and it seems that this sensitivity is related to vibration mode shapes as illustrated in Figure 5. Figure 5 shows the comparison of mode shapes for C-C-C-C case for the fully bonded plate and 10% delamination plate (for position 3 delamination). Here the mode shapes for the second and fourth modes of vibration are compared where (a) and (b) correspond to mode 2 and mode 4 comparisons respectively. Note here that the slab lies in X-Y plane (as illustrated in Figure 2) and the mode shapes as viewed from X-Z plane are shown in Figure 5 to show the deflected shape clearly. It is evident from mode shapes in Figure 5 that vibration mode 2 is more effected by the position 3 delamination than mode 4. This explains the higher sensitivity to delamination shown in mode 2 frequencies compared to mode 4 frequencies that were evidenced by the extent of frequency reduction values reported in Figure 3.

Fully bonded 10% delamination
(a) Comparison of mode shapes for mode 2

Fully bonded 10% delamination
(b) Comparison of mode shapes for mode 4

Figure 5. Comparison of mode shapes for mode 2 and mode 4 for C-C-C-C fully bonded case and 10% delamination (position 3) case

It is interesting to observe that when extent of debonding is not greater that 1% of the surface area of the panel, the percentage reduction in natural frequency is less than 0.3% even for the worst case. Furthermore, these reduction in natural frequencies not only depends on the extent of debonding but also on boundary conditions, position of the debond and mode number. It is revealed that C-C-C-C end condition has the most significant effect on free vibration behaviour when compared with the other three end conditions. It is of special interest to observe that the effect on debonding does not always exhibit an increasing trend as the mode number increases, and follows different trends depending on the boundary condition, extent of debonding, vibration mode shape and location of the debond.

Results for 1000 mm two layer square plate

In this section the results for the two layer 1000 mm square panel are presented. The 10% debonding area scenario which gives highest reduction in natural frequency is presented for comparison of single layer and multilayer debonding. Here, debonding between the top skin and core as well as both top and bottom skins and the core of the top layer of double layer panel (as illustrated in Figure 6) for debonding position 3 are presented for comparison.

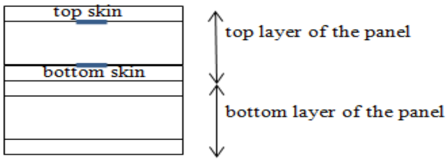


Figure 6. Debonding locations considered for 1000 mm square two layer composite sandwich panel

Figure 7 shows the comparison of percentage reduction in natural frequency with regards to the position 3 debonding location for both single and double layer debonding as illustrated in Figure 6. It is of special interest to observe here that the double layer debonding gives nearly double the extent of reduction in natural frequency when compared to single layer debonding. The extent of reduction is mode dependent as was the case with the 800 mm panel.

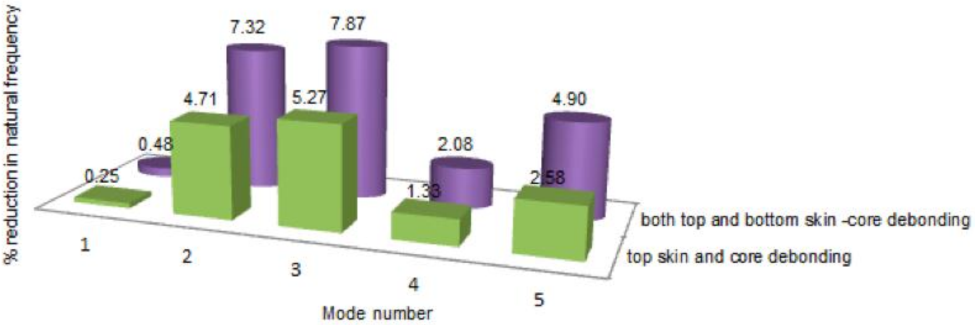


Figure 7. Comparison of percentage natural frequency reduction for single and double layer debonding in 1000 mm C-C-C-C plate for debonding position 3

CONCLUSIONS

It is of special practical interest to observe that when the extent of debonding is small, its effect on natural frequency reduction is negligible. When the area of debonding becomes large, its influence becomes much more pronounced and the extent of variation is mode dependent. Although generally there is a tendency that the extent of natural frequency variation with respect to debonding increases with the mode number, this does not show the same trend for all cases. The decrease in natural frequency with the increase in the extent of debonding is greatly dependent on the boundary conditions, location of the debond and also on the mode number. For similar extents and locations of debonding, the effect of debonding on natural frequencies seems greatly dependent on the end conditions of the panel, giving greater reduction in natural frequency when the panel is more restrained. Thus it is revealed that the more the supports are restrained, the greater the influence on free vibration characteristics. Multilayer debonding does cause significant reductions of natural frequencies compared to single layer debonding.

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