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# Influence of Single and Multiple Skin-Core Debonding on Free Vibration Characteristics of Innovative GFRP Sandwich Panels

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***Abstract*****—**An Australian manufacturer has fabricated an innovative GFRP sandwich panel made from E-glass fiber skin and a modified phenolic core for structural applications. Debonding, which refers to separation of skin from the core material in composite sandwiches, is one of the most common types of damage in composites. The presence of debonding is of great concern because it not only severely affects the stiffness but also modifies the dynamic behaviour of the structure. Generally it is seen that the majority of research carried out has been concerned about the delamination of laminated structures whereas skin-core debonding has received relatively minor attention. Furthermore it is observed that research done on composite slabs having multiple skin-core debonding is very limited. To address this gap, a comprehensive research investigating dynamic behaviour of composite panels with single and multiple debonding is presented. The study uses finite-element modelling and analyses for investigating the influence of debonding on free vibration behaviour of single and multilayer composite sandwich panels. A broad parametric investigation has been carried out by varying debonding locations, debonding sizes and support conditions of the panels in view of both single and multiple debonding. Numerical models were developed with Strand7 finite element package by innovatively selecting the suitable elements to diligently represent their actual behavior. Three-dimensional finite element models were employed to simulate the physically real situation as close as possible, with the use of an experimentally and numerically validated finite element model. Comparative results and conclusions based on the analyses are presented. For similar extents and locations of debonding, the effect of debonding on natural frequencies appears greatly dependent on the end conditions of the panel, giving greater decrease in natural frequency when the panels are more restrained. Some modes are more sensitive to debonding and this sensitivity seems to be related to their vibration mode shapes. The fundamental mode seems generally the least sensitive mode to debonding with respect to the variation in free vibration characteristics. The results indicate the effectiveness of the developed three dimensional finite element models in assessing debonding damage in composite sandwich panels.

***Keywords*****—**Debonding, free vibration behaviour, GFRP sandwich panels, three dimensional finite element modelling.

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## I. INTRODUCTION

COMPOSITES are made by combining two physically distinctive and mechanically dividable components where one forms a continuous matrix while the other provides the reinforcement. These two components are combined to achieve optimum properties, which are superior to the properties of each individual component. Fiber reinforcements are generally preferred since most materials are much stronger in fiber form than in their bulk form. Glass fibre reinforced polymer composites are two phase materials with glass fibre acting as dispersed phase and polymer as continuous phase. Glass fibers make up a significant portion of the composites used in the construction industry today as it offers low cost and ease of use, which facilitates manufacturing.

A new generation composite sandwich made up of E glass fiber reinforced polymer skins and high strength modified phenolic core material have been developed in Australia. With the use of new plant based resin technology for both the skins and the core, the panel offers unprecedented performance at a price that is comparable to traditional building material [1]. The outstanding features of this sandwich material including high strength to weight ratio, good thermal insulation and termite resistance offer this composite panel a wide range of applications in Australian construction industry as structural elements such as slabs, beams, bridge decks and railway sleepers. According to [2], during the past 16 years, there have been substantial activities in the research and development of fibre composites in the Australian construction industry incorporated in bridge systems, replacement of hardwood girders, marine structures and strengthening of existing structures.

The structural integrity of the composite panels can be severely affected by the skin-core debonding, which refers to separation of skin from the core materials. It is well known that debonding between the core and the face sheet is the predominant mode of failure for sandwich composite structures [3]. The crucial problem with debonding failures is that they are sub surface, making them difficult to detect and can therefore develop to a critical size before being detected [4]. Debonding considered here could originate during manufacturing or under service. During manufacturing, this may initiate due to imperfect bonding, matrix cracks and broken fibres. Debonding could also happen under service conditions, due to in-service loading. Experimental observations have revealed that the presence of debond in sandwich panels affects their integrity and reduces their overall stiffness and strength and, as a result, alternates their dynamic responses [5]. Although the dynamic behavior of fully bonded sandwich panels is the subject of extensive studies, papers reported on the dynamic behavior of sandwich panels with debonds are less presented in the literature [5]. As such, the modelling and detection of the influence of skin-core debonding on dynamic behavior of sandwich panels with existing single and multiple debonds are of great importance.

The finite element mothod (FEM) is today the most powerful numerical tool available for the analysis of structures. The versatility of the FEM for solving complex topological and multi-physical problems has made it a popular means in studies of debonded sandwich panels [5]. This paper deals with the investigation of free vibration characteristics of novel composite sandwich slabs with single and multiple debonding. The numerical simulations are carried out using the 'natural frequency' solver in the Strand7 finite element (FE) package using 3D FE modelling to closely represent the real behaviour.

## II. Methodology

### A. Introduction

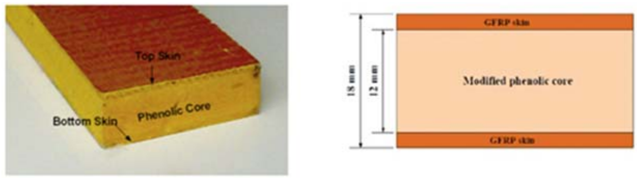
Three dimensional finite element models are developed and numerical simulations are carried out to assess the free vibration behaviour of composite sandwich slabs with single and multiple debonding. A parametric investigation is carried out to assess the influence of various parameters of concern including size of the debond, location of debond 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 modeling the composite slabs with STRAND 7, the core is modeled as three-dimensional brick solid elements while the skins by rectangular (Quad4) plate elements. The structural integrity between top and the bottom skins and the core is assured by connecting plate nodes with corresponding brick nodes at the top and bottom surface levels of the core through vertical 'rigid link' elements. Rigid link provides restraints to the nodal rotations, in addition to the translational displacements [6]. These rigid links ensure that there is no gap or sliding between the top skin and the core. Debonding area is modelled by removing the rigid link constrains between the skin and the core and replacing them with master slave links. These links are used in the finite element model to allow for sliding between interfaces of skin and core in the horizontal directions while keeping skins in contact with the core in the vertical direction to effectively simulate a debonded panel. Here debonding is presumed to be an artificial defect of zero thickness, embedded between skin and core.

### B. Verification of the Model

Awad et al. [7] conducted experimental work and 3D finite element simulation with ABAQUS to investigate the free vibration behaviour of the innovative composite sandwich panels with different sizes and support conditions. For the verification 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 in [7]. The cross sectional dimensions of the panel used for verification are illustrated in Fig. 1. The mechanical properties used in the model validation (as used in [7]) for the glass fibre composite skin and the phenolic core material are listed in Table I.

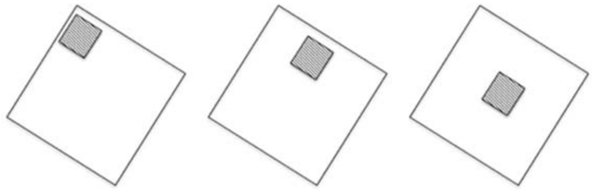
TABLE I
MECHANICAL PROPERTIES USED FOR THE MODEL VERIFICATION [7]

| 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 |




(a) (b)

Fig. 1 (a) Innovative composite sandwich panel (b) Cross sectional dimensions of the panel [7]



(a) Position 1 (b) Position 2 (c) Position 3

Fig. 2 Debonding positions considered in the analysis

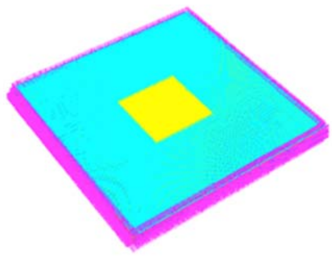


Fig. 3 Three-dimensional finite element model for C-C-C-C slab with 10% debonding in position 3

### C. Dynamic Analysis of Novel Composite Slabs with Debonding

Here, the free vibration analysis for the novel composite sandwich panels of 800 mm square section has been carried out with four end conditions of the slabs, namely, (C-C-C-C), (C-C-F-F), (S-S-S-S) and (S-S-F-F). Here 'F' denotes the free edge of the slab whereas 'S' and 'C' denote the simply supported and clamped edges, respectively. The skin and core thicknesses are 3mm and 12mm respectively as shown in Fig. 1 (b). Four different extents of debonding, namely, 0.5%, 1%, 5% and 10% by area of the panel and three different locations (positions 1, 2 and 3 as illustrated in Fig. 2) of debonding are modelled and analyzed to examine the critical locations and sizes of debonding with respect to change in dynamic behaviour.

The mechanical properties for the fiber composite skin and the core material used in [8] have been used for the present analysis as tabulated in Table II.

TABLE II
MECHANICAL PROPERTIES USED FOR PRESENT ANALYSIS [8]

| 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/m3) | 1366 | 855 |

## III. RESULTS

### A. Verification of the Model

Here, the experimental and numerical results reported in [7] for the innovative composite sandwich slabs have been used for the verification of the developed model. 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 Fig. 1 (b). 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 are glue restraints for both ends of the slabs. The results of the verification study are stated in Table III, where first and second natural frequency values in Hertz for reported experimental, and numerical analyses (with ABAQUS) are compared with the developed model with STRAND7.

TABLE III
RESULTS OBTAINED FOR FIRST AND SECOND NATURAL FREQUENCIES IN HZ FOR MODEL VALIDATION [8]

| Slab size | Support type | Restraint type | Mode number | Experimental results[7] Frequency in Hz | FEA with ABAQUS [7] 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 |

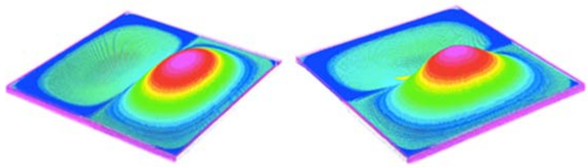
TABLE IV
NATURAL FREQUENCY VALUES IN HZ FOR C-C-C-C SLAB FOR POSITION 3

| %debonding area by total area of plate | Mode number | Fully bonded plate (Hz) | Debonded plate (Hz) | Percentage reduction |
|---|---|---|---|---|
| 0.5% total area | 1 | 139.04 | 139.04 | 0.00 |
| | 2 | 270.56 | 270.4 | 0.06 |
| | 3 | 286.26 | 286.06 | 0.07 |
| | 4 | 390.61 | 390.61 | 0.00 |
| | 5 | 474.75 | 474.74 | 0.00 |
| 1% total area | 1 | 139.04 | 139.04 | 0.00 |
| | 2 | 270.56 | 269.97 | 0.22 |
| | 3 | 286.26 | 285.52 | 0.26 |
| | 4 | 390.61 | 390.58 | 0.01 |
| | 5 | 474.75 | 474.65 | 0.02 |
| 5% total area | 1 | 139.04 | 138.88 | 0.12 |
| | 2 | 270.56 | 260.50 | 3.72 |
| | 3 | 286.26 | 273.6 | 4.42 |
| | 4 | 390.61 | 388.52 | 0.54 |
| | 5 | 474.75 | 467.77 | 1.47 |
| 10% total area | 1 | 139.04 | 138.03 | 0.73 |
| | 2 | 270.56 | 243.56 | 9.98 |
| | 3 | 286.26 | 252.96 | 11.63 |
| | 4 | 390.61 | 380.05 | 2.70 |
| | 5 | 474.75 | 436.71 | 8.01 |

### B. Results for Single Debonding in 800 mm Square Slab

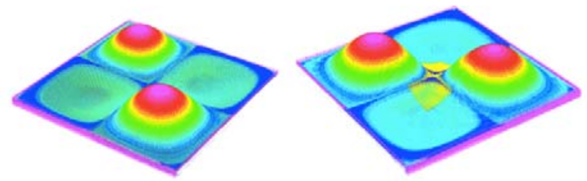
It is observed that the most adverse boundary condition giving highest drop in natural frequency due debonding in general is the C-C-C-C form and the least reduction in natural frequency is seen in S-S-F-F end condition in general. The most adverse location in terms of percentage of natural frequency shift seems dependant on the boundary condition of the slab. For C-C-C-C end condition this is position 3, whereas for C-C-F-F boundary condition the worst location is position 1. Table IV shows the percentage reduction in natural frequency due to debonding in position 3 (which is the most adverse location for C-C-C-C end condition) for different extents of debonding for 800mm slab with C-C-C-C boundary conditions.

It is of special interest to see here that when the extent of debonding is not higher than 1% of the area of the slab, the percentage reduction in natural frequency is negligible even for the worst case tabulated above. It is also seen that the influence of debonding on natural frequency does not always show an increasing trend as the mode number increases, and follows different trends depending on the vibration modes. Some modes seem more sensitive to debonding, and this sensitivity is related to vibration mode shapes as demonstrated in Fig. 5. Fig. 5 displays the comparison of mode shapes for C-C-C-C case for the fully bonded plate and 10% debonded plate (for the position 3 debonding as shown in Fig. 3). 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. Careful observation of mode shape comparisons for fully bonded and debonded slabs in Fig. 5 reveals that vibration mode 2 is more triggered by the position 3 debonding than the vibration mode 4 due to the vibration mode shape of the debonded panel with respect to the debonding location. This clarifies the greater sensitivity to debonding shown in mode 2 percentage frequency shifts compared to mode 4 variation, as tabulated in Table IV. Similar observations are perceived for other boundary conditions as well.



Fully bonded slab　　10% debonding by area of slab

(a) Comparison of mode shapes for mode 2



Fully bonded slab　　10% debonding by area of slab

(b) Comparison of mode shapes for mode 4

Fig. 4 Comparison of mode shapes for C-C-C-C fully bonded and 10% debonded for position 3

Table V shows the comparison of the percentage reduction in natural frequency for C-C-F-F boundary condition for the three positions of debonding and four different percentages of debonding. It is clear from the Table V that the most adverse position in terms of natural frequency shift for C-C-F-F end condition is position 1, on contrary to C-C-C-C case, which was position 3. It can also be pointed out that, from both Tables IV and V, the fundamental mode is generally very poorly sensitive to debonding even when the debonding extent is 10%.

Here the influence on end condition on free vibration behavior is examined for similar conditions of other parameters, namely, the extent of debonding, location of debonding and slab size. Fig. 5 illustrates the comparison of frequency shift for 10% debonding for position 3 with regard to the four different boundary conditions considered in the analysis. It is clearly visible here that C-C-C-C boundary condition shows the most adverse effect due to debonding in terms of natural frequency variation, and the least effect is seen in S-S-F-F end condition. Thus it is revealed that the influence of debonding on free vibration behavior greatly dependent on the end fixity of the slab giving the highest influence when the slab is fully restrained on all four ends.

TABLE V
PERCENTAGE REDUCTION IN NATURAL FREQUENCY VALUES FOR C-C-F-F SLAB FOR ALL THREE POSITIONS AND ALL FOUR PERCENTAGES OF DEBONDING

| %debonding area by total area of plate | Mode number | Percentage reduction | Percentage reduction | Percentage reduction |
|---|---|---|---|---|
| | | Position 1 | Position 2 | Position 3 |
| 0.5% total area | 1 | 0.02 | 0.00 | 0.00 |
| | 2 | 0.02 | 0.00 | 0.00 |
| | 3 | 0.01 | 0.01 | 0.01 |
| | 4 | 0.03 | 0.02 | 0.02 |
| | 5 | 0.04 | 0.03 | 0.00 |
| 1% total area | 1 | 0.07 | 0.00 | 0.00 |
| | 2 | 0.07 | 0.00 | 0.01 |
| | 3 | 0.01 | 0.05 | 0.01 |
| | 4 | 0.12 | 0.09 | 0.08 |
| | 5 | 0.14 | 0.11 | 0.00 |
| 5% total area | 1 | 1.49 | 0.03 | 0.03 |
| | 2 | 1.33 | 0.05 | 0.12 |
| | 3 | 0.19 | 0.90 | 0.10 |
| | 4 | 3.05 | 2.35 | 1.52 |
| | 5 | 1.60 | 1.44 | 0.05 |
| 10% total area | 1 | 5.94 | 0.25 | 0.22 |
| | 2 | 3.25 | 0.33 | 0.40 |
| | 3 | 1.19 | 3.02 | 0.58 |
| | 4 | 10.12 | 8.88 | 4.97 |
| | 5 | 2.45 | 2.32 | 0.29 |

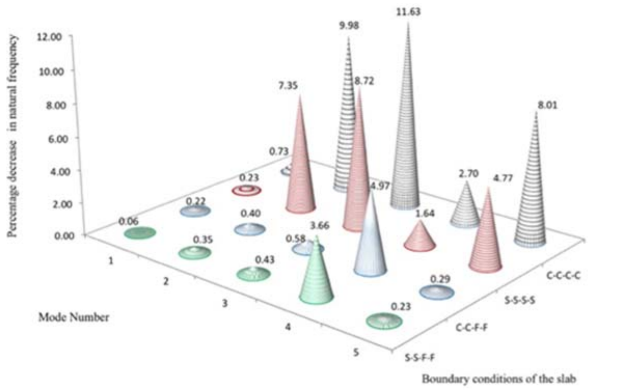



Fig. 5 Comparison of natural frequency variation for different end conditions of slab

### C. Results for Multiple Debonding in 800 mm Square Slab

In Fig. 6, comparisons are made with regards to the most adverse end condition (C-C-C-C) for double debonding at positions 1 and 2, each 5% of slab area each, with 10% single debonding at positions 1 and 2. Note here that the three cases represent similar debonding areas. It is interesting to observe here that multiple debonding is less sensitive to natural frequency variation when compared with single debonding of equivalent area. This is the case with comparisons of other boundary conditions as well. Thus it is revealed that debonding occurred in a single large area is more sensitive to natural frequency reduction than small extents of multiple debonding of equivalent area arose a distance apart in the slab.

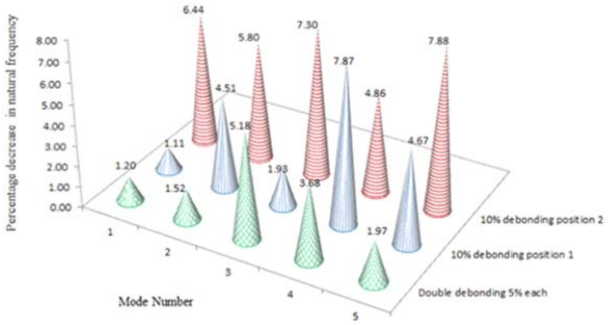
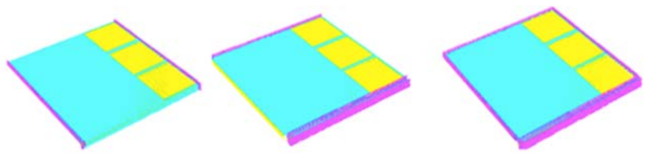



Fig. 6 Comparison of multiple debonding with equivalent area of single debonding

Fig. 8 reports the natural frequency variation in 800mm slabs with triple debonding of each 10% of slab area at positions 1,2,1 (see Fig. 7) for boundary conditions C-C-C-C and C-C-F-F. Obviously there are two distinct cases of for C-C-F-F boundary condition, one along free edge and the other case along clamped edge (as illustrated in Fig. 7). It is of special interest to observe here that multiple debonding along free end is more sensitive to natural frequency variation than the same along clamped end in C-C-F-F panel. Obviously C-C-C-C boundary condition generally gives the highest variation in natural frequency for multiple debonding as well, as was the case with single debonding.



(a) C-C-F-F along fixed end (b) C-C-F-F along free end (c) C-C-C-C

Fig. 7 End conditions and locations of debonding used for triple debonding comparison

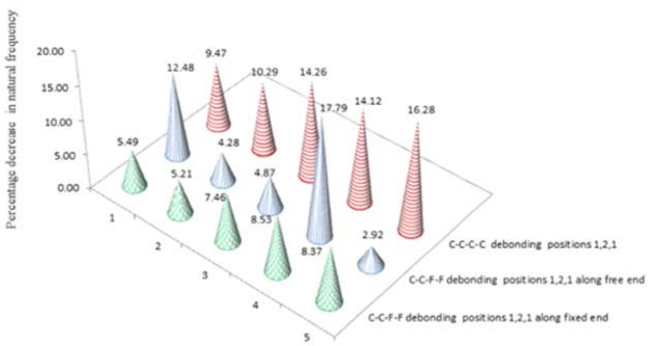



Fig. 8 Comparison of natural frequency variation for triple debonding for the three cases shown in Fig. 7

## IV. Conclusion

It is revealed that when the extent of debonding is small, its effect on natural frequency reduction is insignificant. When the area of debonding becomes great, its influence becomes much more pronounced and greatly dependent on the boundary conditions of the slab and the location of debonding. The influence of debonding on natural frequencies seems greatly dependent on the end fixity of the slab; the higher the end fixity, the greater the effect. Generally, natural frequencies tend to decrease with increasing number of mode; however this variation does not exhibit a linearly decreasing trend. Debonding appears to be more sensitive to higher modes than to the fundamental mode. This sensitivity to debonding seems also depend on the vibration mode shape of the mode of interest.

The future developments of this study incorporate investigating the performance of these debonded GFRP panels subjected to a probable seismic loading.

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