Effective elastic constants of corrugated core sandwich plate microstructure considering imperfection in adhesive bonding

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Abstract. Imperfection of adhesive bonding in the corrugated core sandwich plate microstructure is commonly occured due to inaccuracies in fabrication process or environmental effect. Considering the geometrical changed due to the adhesive imperfection, it could influence the mechanical properties of sandwich plate structure. Hence, this paper was carried out to predict the effective elastic constants of corrugated core sandwich plate microstructure by considering the effect of adhesive imperfection. Unit cell of corrugated core microstructure with variation of adhesive imperfection was developed using multiscale finite element software named Voxelcon. Homogenization method was integrated with probability function to predict the effective elastic constants of corrugated core sandwich plate structure. The proposed method could potentially be extended to other types of periodic microstructure in predicting the reliable homogenized properties of heterogeneous materials.

1. Introduction

Corrugated core sandwich plate microstructures are commonly used as structural part in various applications. Sandwich plate structure [1], [2] is consist of two thin stiff and high performance composite faces that bonded (adhesive) to a thick lightweight core. As for the result its create structures that high tensile strength to density ratio and corrosion resistance. Adhesive bonding is one of famous technique to join two different materials. It high tensile strength to weight ratio and other advantages has attracted numerous interest from researchers [3]–[5] and also demand in industries. While the design and analysis of non-defect structures in adhesive bonding has rapidly grown today, there is still less progress has been made in understanding the defect structures. Adhesives come in forms of film, paste, and liquid. Sandwich structures may contain a number of various defects induced during the manufacturing process such as debond, insufficient adhesive, etc. or inherent imperfections in core material like flaws and voids.

The application of adhesive is critical in the overall structure of sandwich plate because the mechanical properties of sandwich plate is strongly dependant on bonding capability. The defects on adhesive can cause stress concentration that could lead to reducing the mechanical strength of the sandwich plate structure. Grove et al. [6] mentioned that any sandwich plate structural construction (particularly tensile strength) is relies on upon the nature of the adhesive bond quality in the middle of core and skin. The structural strength or quality is depends on the arrangement of filet in the adhesive between cell divider and skin at the interface [7].
Moreover, the defects in adhesive of sandwich plate structure are commonly occurs due to inaccuracies of fabrication process or even environmental effects. One of the adhesive imperfection is inconsistency in amount of adhesive bonding between the sandwich plate structures. Hence, this study was undertaken to predict the effective elastic properties of sandwich plate microstructure considering inconsistency of adhesive volume using integrated homogenization method and modified probability function.

2. Homogenization Theory
Homogenization method was employed in the present study to calculate the effective properties of corrugated core sandwich plate microstructure [8], [9]. Since the homogenization method has been established and used extensively in numerous studies [10], [11], only the outline of this theory is highlighted in this paper. Equation (1) was analysed for sandwich plate microstructure model with periodic boundary condition, where D is the elastic tensor.

\[
\int_{Y} \frac{\partial D_{ijkl}}{\partial y_{i}} \frac{\partial \delta u_{l}^{i}}{\partial y_{j}} dY = \int_{Y} \frac{\partial D_{ijkl}}{\partial y_{i}} \frac{\partial \delta u_{l}^{i}}{\partial y_{j}} dY \quad \forall \delta u_{l}^{i}
\]

Here, \( \chi \) is a periodic function with respect to the microstructure, known as the characteristic displacement to represents the microscopic perturbation of displacement due to the heterogeneity. Once the characteristic displacement is obtained, the macroscopic homogenized elastic tensor is computed using eq. (2).

\[
D_{ijkl}^{H} = \frac{1}{|Y|} \int_{Y} \left( D_{ijkl} - D_{ijkl}^{\chi} \right) \frac{\partial \chi^{ijkl}}{\partial y_{i}} dY
\]

where \( D_{ijkl}^{H} \) is homogenized elastic properties, \( Y \) is the region of the microstructure model and \( |Y| \) is the volume of microstructure model. Then, eq. (3) which is the macroscopic equation, coincides with the classical micromechanics theory is written as,

\[
\int_{\Omega} \frac{\partial D_{ijkl}^{H} \frac{\partial u_{l}^{i}}{\partial x_{i}}}{\partial y_{j}} d\Omega = \int_{\Gamma} t_{y} \delta u_{l}^{i} d\Gamma \quad \forall \delta u_{l}^{i}
\]

\( t \) denotes the traction applied on the surface \( \Gamma \) of domain \( \Omega \). Hence, macroscopic response such as displacement can be obtained based on eq. (3).

3. Geometrical model
Figure 1 shows the dimension of unit cell and the periodic microstructure of sandwich plate. Imperfection on adhesive bonding was modelled based on inaccuracy in amount of adhesive. During fabrication process, the amount of adhesive used commonly is not consistent throughout the microstructure. Hence, five unit cell models were developed with variation of adhesive imperfection, which is categorised as insufficient bonding (80% and 90% of adhesive), perfect bonding (100% of adhesive) and excessive bonding (110% and 120%).
Figure 1. Unit cell of sandwich plate microstructure. (a) Dimension of unit cell (in mm). (b) Periodic microstructure.

Figure 2. Geometrical model of sandwich plate with variation of adhesive imperfection. (a) 80% of adhesive, (b) 90% of adhesive, (c) 100% of adhesive, (d) 110% of adhesive, and (e) 120% of adhesive.

4. Computational Implementation

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used. As demonstrative example of the present calculation, AISI type 304 stainless steel with Young's modulus of 210 GPa and Poisson's ratio of 0.3 was used as plate whereas epoxy with Young's modulus of 1.3 GPa and Poisson's ratio of 0.38 was assigned as adhesive. Both materials was set as linear isotropic.

Finite element models of sandwich plate's unit cell were created using Voxelcon (Quint Corp., Tokyo). The meshed size was determined based on convergence test that yield at 0.1 mm. The element type was cubical eight-node element.

In order to predict the effective elastic constants with considering variation of adhesive imperfection, the probability function based on normal distribution (as shown in figure 3) was applied. Each
category of adhesive bonding was assigned with probability (Pr). Hence, the effective constant can be calculated as eq. (4)[12].

\[
(D^H)_{\text{effective}} = \sum_{i} (Pr_i)(D^H_i),
\]

(4)

where \(i\) represents the category of imperfection number which is five in total.

![Normal Curve](image)

**Figure 3.** Normal distribution curve with percentage of probability for each interval.

**5. Results and Discussion**

Figure 4 shows the effect of adhesive imperfection on Young's modulus of unit cell in sandwich plate microstructure. Obviously, the increase of adhesive percentage from insufficient to excessive bonding increased the Young's modulus in all directions. Although the highest Young's modulus was obtained in \(E_{22}\), however its increment rate was found lower compared to \(E_{11}\) and \(E_{33}\). It seems that \(E_{22}\) not sensitive to fluctuations in adhesive volume. Increment rate between \(E_{11}\) and \(E_{33}\) was found similar.

![Graphs](image)

**Figure 4.** Effect of adhesive imperfection on Young's modulus. (a) \(E_{11}\), (b) \(E_{22}\), (c) \(E_{33}\).
In contrary, Poisson's ratio of sandwich plate microstructure was found not significantly influenced by the amount of adhesive bonding as shown in figure 5. Only the slight different was obtained for $\nu_{12}$, $\nu_{23}$ and $\nu_{31}$ with respect to increase of adhesive bonding. Hence, this result suggest that inconsistency in adhesive bonding on sandwich late microstructure did not affected the Poisson's ratio, at least for the present case which is $\pm 20\%$ of adhesive imperfection.

On the other hand, effect of adhesive imperfection on shear modulus is shown in figure 5. Shear moduli of $G_{12}$, $G_{23}$ and $G_{31}$ were increased with respect to the increase of adhesive volume. $G_{12}$ obtained the highest shear modulus. The shear modulus and increment rate between $G_{23}$ and $G_{31}$ was found almost similar. Moreover, the effective elastic constants of the proposed method and comparison to elastic constants with perfectly bonded (100% adhesive volume) is listed in Table 1. The predicted effective elastic constants in Young's modulus and shear modulus were found slightly low compared to the elastic constants obtained in sandwich plate with perfectly bonded. However, the predicted Poisson's ratio was found not sensitive to the variation of adhesive imperfection.
Figure 6. Effect of adhesive imperfection on shear modulus. (a) $G_{12}$, (b) $G_{23}$, (c) $G_{31}$.

Table 1. Comparison between effective elastic constants and elastic constants with 100% adhesive.

| Effective Elastic Constants | Elastic Constants with 100% adhesive |
|-----------------------------|-------------------------------------|
| $E_{11}$ (MPa)              | 22677.080                          |
|                             | 22953.000                          |
| $E_{22}$ (MPa)              | 35216.270                          |
|                             | 35644.000                          |
| $E_{33}$ (MPa)              | 146.736                            |
|                             | 148.490                            |
| $\nu_{12}$                  | 0.191                              |
|                             | 0.193                              |
| $\nu_{23}$                  | 0.310                              |
|                             | 0.314                              |
| $\nu_{31}$                  | 0.008                              |
|                             | 0.008                              |
| $G_{12}$ (MPa)              | 11680.140                          |
|                             | 11822.000                          |
| $G_{23}$ (MPa)              | 501.834                            |
|                             | 509.670                            |
| $G_{31}$ (MPa)              | 482.636                            |
|                             | 494.110                            |

6. Conclusion
The presents study was carried out to predict the effective elastic constants by considering the variation of adhesive imperfection. The increase of adhesive volume contributed to the increase of elastic constants in Young’s modulus and shear modulus. The effective elastic constants was predicted well since the value obtained slightly lower compared to the value of sandwich plate with perfectly bonded. The predicted value much more realistic because the fluctuation of adhesive volume that commonly occurred due to inaccuracies in manufacturing process was considered in the calculation. The method proposed in this paper could potentially be extended to other periodic microstructures with variation of uncertainties in heterogeneous materials.

7. References
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