Influence of fabrication imperfections on dynamic response of a sandwich composite panel of a ship deck structure

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Abstract. The dynamic behavior of bonded sandwich plates at the skin/core interface is analysed. The finite element code COSMOS/M is used to analyse natural frequencies and mode shapes of the sandwich plates with an ellipse shape debonding area. The delamination model has been developed by using the surface-to-surface contact option. In case of surface-to-surface contact, the FE meshes of adjacent plies do not need to be identical. The influence of the diameters ratio of the debonded area, on the modal parameters of clamped sandwich plates is investigated. Parametric calculus of the sandwich plate, having various diameters ratios (Dx/Dy = 0.5; 0.75; 1) for delaminated area, have been considered. It has been observed that all the above mentioned ratios are contributing to the changes in dynamic responses of the sandwich plate.

1. Introduction
Due to many advantages as low weight related to strength and toughness, sandwich composites are used in a wide range of engineering applications. In shipbuilding, the system is commonly used in the manufacture of cargo containers, ship interiors, small boats and yachts. The increasing use of sandwich composites has challenged the need to understand their main mode of failure, that is delamination (or debonding between the skin and core) and the influence on the own characteristics. The stiffened composite panels are the most used structural elements in ship structures made of advanced materials. The composite sandwich panels are often used so in shipbuilding industry and in engineering constructions. Many maritime applications have been performed due to need to avoid corrosion problems occurring in steel or aluminium alloys or to protect environmental degradation when is using other materials like wood. But one of the main reasons to use composite was to reduce the ship hull weight, especially the topside weight of ships [1].

One of the most important advantages of Sandwich Panels is related to damping characteristics. An attractive property of core is its damping property if is used a certain material having such feature. Vibration and impact tests have demonstrated that the response amplitude function for elastomeric material is much less than steel and the damping coefficient is up to 5 times greater than steel [2]. Additionally, due to the core, loads are less likely to be transmitted inside the ship hull (e.g. slamming).

The effect of skin-core delamination on the interlaminar stress distribution in sandwich composites is analysed [3]. In the study the Solid 187 element with 10-nodes from ANSYS is used. The variations of interlaminar stresses, due to the presence of debonding area of different sizes are illustrated.
Parametric calculus has been performed, by using three parameters for analysis (size of delamination, thickness of skins and types of loading).

For vibration (free, forced, torsional and due to shock loading) studies of sandwich panels with different types of core cross section these plates may be transformed into equivalent homogeneous orthotropic thick continua plate [4].

Closed-form solutions for the natural and forced vibration response of orthotropic sandwich panels are noticed in [5] and [6].

Certain papers are developing formulations to determine the natural frequencies of layered composite and sandwich plates. The results of new class of strain finite element formulations of Reddy's higher-order theory are presented in [7]. The author used these formulations to determine the natural frequencies of layered composite and sandwich plates. The dynamic characteristics of sandwich composite plates with holes at various locations are investigated both experimentally and through numerical simulations in [8]. According to the parametric study the parameters which affect the natural frequencies of such plates are the core and face sheet thicknesses, diameter and location of the holes and aspect ratio of the plate.

A study to detect, localize and quantify the damage, by using free vibration analysis (modal parameters, frequency and mode shapes) is described in [9]. The package ANSYS is used for the finite element analysis, to analyse an perfect and debonded sandwich plate. The results of the debonded plate are compared with the intact one. A parameter called Modal Strain Energy Change Ratio (MSECR) is used to predict the location and extension of damage.

Damage of the sandwich plate can produce structural failure. Suddenly, the occurring of failure during big load operations may cause catastrophic consequences. To maintain the integrity and safety of structures it is necessary to predict and detect at early stages the damage.

Natural vibrations of the sandwich plates are performed in [10]. Three-Dimensional finite elements are used for modelling and analyzing to obtain their natural frequencies of the sandwich plates. The confirmation of the accuracy of the proposed model is performed by comparison of the results in certain case with those of the plate theories.

Unfortunately, the sandwich panels are sensitive on geometrical and mechanical imperfections like different dimensions versus the design ones. Another kind of imperfection is related to material. Because fabrication technologies of composite materials are hand made based, the probability to occur the defects is quite too high.

These defects are of various types: directions of fibers are different of the design, variations in skin thickness, inclusions, initial transversal deformations.

Transient response of laminated composite and sandwich plates with delaminations is presented in [11]. The authors propose a theory and numerical solution is obtained using the finite elements with four or nine nodes. Effects of delamination size and their location through the plate thickness are analysed.

Dynamic behaviour of sandwich plates with flexible cores and a debonding area between the skin and core interface is studied with finite element code ABAQUS in [12]. The influence of the debonding size, debonding location and types of debonding on the modal parameters is investigated. The results of dynamic analysis illustrated that they can be useful for the non-destructive damage detection of debonded sandwich plates.

Ship structure plates are subjected to combination of in plane loads or out of plane loads during application. Due to the geometry, mass, stiffness, material and general load of the ship hull, local natural vibrations criteria represents one of the most important failure criteria.

The aim of the paper is to analyze the influence of delamination (debonding between skin and core) on the dynamic behaviour of ship deck plates made of composite sandwich.

A sandwich structure is made out of two thin, stiff and strong faces separated by a thick lightweight core. The aim of sandwich structure is to be obtained so stiff and light. Due to this purpose, this type of structures are lightweight compared to metallic structures, have high stiffness related to their weight and have cost effective compared to other composite structures.
The choosing of core materials for certain applications, leads to a specific production technology used for the sandwich structure that is crucial (for example, wet-layup, prepreg, infusion etc.)

In the paper, an orthotropic delamination model, describing the mode of debonding, by using COSMOS/M soft package, is applied. Parametric calculus has been performed for an ellipse’s diameters of the delamination area placed in the middle of the plate.

In the parametric calculus, the various diameters ratios (Dx/Dy = 0.5; 0.75; 1) were considered and the hypothesis is that the delamination (debonding) has the same area for all cases.

2. Plate characteristics
The plane plate has quadratic shape with sides dimensions a = b = 300 mm and the x axis ellipse diameter Dx = 80mm. The skins have thickness of 1mm. The core is of 20 mm thickness.

Skins made of E-glass/polyester having the material characteristics: three biaxial layers having the thickness t = 0.33mm.

The skins material is E-glass epoxy with the following characteristics

\[ E_x = 3.86 \text{ GPa}, \quad G_{xy} = 4.1412 \text{ GPa}, \quad \mu_{xy} = 0.26 \]
\[ E_y = 8.27 \text{ GPa}, \quad G_{yz} = 4.1412 \text{ GPa}, \quad \mu_{yz} = 0.26 \]
\[ E_z = 8.27 \text{ GPa}, \quad G_{xz} = 4.1412 \text{ GPa}, \quad \mu_{xz} = 0.26 \]

The resistances (tension-T and compression-C) of the skins material are:

\[ R^T_x = 1.062 \text{ GPa}, \quad R^C_x = 0.61 \text{ GPa}, \quad R^T_y = 0.031 \text{ GPa}, \quad R^C_y = 0.118 \text{ GPa}, \quad R_{xy} = 0.72 \text{ GPa} \]

The skins are layered composites, having three biaxial layers with the thickness t = 0.33 mm.

The core is made of SAN Foam 103kg/m\(^3\) (SAN-styrene acrylonitrile) with density of 103 kg/m\(^3\), Young modulus E=85MPa, Shear modulus G=32.602MPa and Poisson rate of 0.3. The plate is considered as being a zone located between two pairs of stiffeners from the panel of the ship deck.

The square plates has been considered as clamped on the all sides.

3. FEM calculus
The two areas (perfect and debonded) have been modelled as following:
- the debonded area is concerning two overlayed plates, being initially in contact;
- the rest of plate is considered perfect.

On the outline of the debonded area were imposed conditions of continuity for displacements.

The location of the delamination was considered to be between skin and core. All cases of Dx / Dy rate diameters were considered in analysis.

An initial delamination may close due to the applied load. To avoid the two adjacent layers from penetrating, a simple numerical contact model is used.

The delamination (debonding) model has been developed by using the surface-to-surface contact option[13,14].

The ellipse’s diameters of the delaminated (debonded) area placed in the middle of the plate are considered from the condition to have the same area for all cases [15].

In the parametric calculus, the following diameters ratios have been considered: Dx/Dy=0.5; 0.75; 1.0. For the material model, linear behaviour has been considered.

To select the optimum number of elements on a side a series of sequential static analysis have been performed. According to this analysis the number of elements on the side of the plate has been selected to be 60.

| Table 1. Frequencies of the natural vibration of debonded plateDx/Dy. |
|-----------------|-----------------|-----------------|-----------------|
| f1[Hz]          | perfect plate   | 0.5             | 0.75            | 1               |
|                 | 170.1           | 168.2           | 166.1           | 163.2           |
| f2[Hz]          | 339.12          | 344.25          | 342.77          | 340.88          |
| f3[Hz]          | 520.16          | 532.28          | 530.11          | 518.95          |
Figure 1. The mesh of the perfect plate.

Figure 2. The mesh of the plate with debonded area having $\frac{D_x}{D_y} = 0.5$.

Figure 3. The mesh of the plate with debonded area having $\frac{D_x}{D_y} = 0.75$.

Figure 4. The mesh of the plate with debonded area having $\frac{D_x}{D_y} = 1$.

Figure 5. The shape of the first natural vibration mode.

Figure 6. The shape of the second natural vibration mode.
In figures 1-4 the mesh of the plate for each diameters ratio are illustrated.
The variation of the natural frequency versus ellipse’s diameters ratio in the case of the material model, has been observed.
In figures 5-7 the modal shape of the first three vibration modes of the sandwich plates are illustrated.
In table 1 the frequencies of the natural vibration modes are presented.
The table 1 shows natural frequency results of intact composite sandwich plate and composite sandwich plates with debonds placed in the middle of the plate. It is observed that a significant reduction of about 1.1-4.1% has been occurred.

4. Conclusions
The influence of the diameters ratio of the interface skin/core debonding (ellipse shape) on the vibration responses of damaged sandwich plates is studied by comparing frequencies of free vibration both for perfect and debonded sandwich plates.
Investigations have been performed for a clamped rectangular sandwich plate with elliptical debonded area between skin and core in the middle of the plate. It has been observed that all the above mentioned ratios are contributing to the changes in dynamic responses of the sandwich plate. The results obtained for debonding area size varying set is compared with the results obtained for intact plates.
The natural frequencies reduction is observed for the damaged plates. Also, the frequency is decreasing since the diameters ratio is increasing for all three vibration modes.
For the first mode, the frequencies of imperfect plates are smaller than the frequency of the perfect plate ($f_1 = 170.1$ Hz), since for higher modes the frequencies of imperfect plates are bigger than the frequency of the perfect plate ($f_2 = 339.12$ Hz and $f_3 = 520.16$ Hz).

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