Identification of damage in a ship hull sandwich plate by natural frequency

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Abstract. The damage of the sandwich plate occurs in the core material identification used for modal analysis on the ship hull using finite element analysis. This analysis detects the effect of damage. Five varied models using different damage percentage size is developed to ensure whether the hull is appropriate. This paper investigates the influence of the increasing damage percentage on the sandwich plate using the based natural frequencies as a parameter to determine the location of the damage. Five cases are being simulated for the damage. The location of the damage modelling used utilizing FEA software to adapt to the problems. Moreover, the sensitivity influence of percentage damage size, boundary condition, and application of spring element on the natural frequency behaviour of damage identification is also executing. The damage is detected by comparing the natural frequency reduction of the intact and damaged plate using free vibration analysis. The mode shape of the sandwich plate displayed to observe the location of damaged. The results show that the damage in the sandwich plate decrease the natural frequency and influence the mode shape, and evaluating both reveals the location of the damage.

Keywords: damage, identification, finite element analysis, sandwich, natural frequency,

1. Introduction
The sandwich material consists of a faceplate and a core layer. The faceplate uses steel material, while the core material uses polyurethane (PU) elastomer combined with fibreglass. The mixture of the layers will generate a good strength and decrease ship hull weight, resistance to impact loads, and increase damping to vibration. The deformation due to lateral load can be reduced [1]. Especially in a ship, the application of sandwich material has any advantages, one of that is it can reduced weight. The reduction in material weight also results in a reduction in production costs [2]. Production cost reduction is very valuable in the shipping industry [3].

Various studies on sandwich plates have been conducted at this point. Characterization of the bio-resin for sandwich plate structure has been carried out [4]. In the ship construction usually, a stiffener welded on the plate surface or the sandwich material to prevent deformation on the plate. However, the application material sandwich can reduce stiffener in the use of conventional. The stiffener reduction of the ship attains 10 to 70 % of the existing weight [5].
As a new material development, there are constraints in the application of sandwich material. Research is conducted on several core materials to obtain a suitable strength composition. After founding the best composition, there is a new problem that is related to the inspection procedure on the core material. However, the application of this core material is continuously developed. Like the study of damage that some defects and damage due to the complexity of the structure and the influence of the manufacturing process [6].

Therefore, it is essential to explore the effects of local damage on their mechanical properties, such as the characteristics of material vibrations. Identification of damage of the sandwich material purposed to ensure structural strength, unity, reliability, and safety. Because the identification of damage base on vibration is one of the frequent technique used [7], previously, the damage identification approach made by non-destructive test methods. However, it can only reach a limited or local area. Therefore, for the coverage of large and complex areas on the structure and challenging to check so that the identification of damage to the local area can be expensive and inefficient, so that required a more suitable identification technique applied. The use of vibration-based damage identification techniques becomes an option to detect damage to a wide area of coverage and is affordable to implement [8]. The parameters to identify damage to the structure can generate from the natural frequency [9-12], vibration pattern [13] and mode shape [14].

Besides, the damages identification based on vibrations, where the influence of the frequency change in structure monitors the structures condition globally. The fundamental principle of the Structural Health Monitoring (SHM) system is damaged. This structure changes the stiffness, mass, and damping thus change the dynamic response of the structure [15]. SHM recognized as Praised non-destructive evaluation techniques to ensure structural security and reliability techniques. SHM techniques used widely using capital to monitor damage in structures, with any study recognizes capital parameters as utilizing a tool to investigate damage in the structure. The use of field measurement modes may take much time and to be hard to detect [19]. However, the numerical analysis made it becomes possible. The use of numeric methods is easy to measure the value of natural frequencies [20], while it can see the shape of shape mode shapes. Although the natural frequency used looks ordinary, this method able to show the damage occurred, but do not know the amount of information damage occurs on the material sandwich. Therefore, research development implemented to know the significant damage and location of the sandwich material. In another study, reviewing random damage with vibration-based damage method in sandwich panels with truss core is analysed using limited element analysis, which combined with statistical analysis. This analysis indicates if the effect of the damaged area should be combining using technique mode shapes, damage size and boundary condition [21].

In this study, identification of damage based on vibration applied on the sandwich material, which designed for side hull of tanker ship the 17500 DWT using the Finite Element. Material sandwich plate arranged of a steel faceplate and a Polyurethane elastomer with matrix fibreglass. The kind of material sandwich identified has fulfilled the Lloyd’s Register (LR) Regulations [16], and some have used in the structure of the ship in the shipping industry. Identification of damage based on vibration used to inspected changes in the natural frequency of the material sandwich for the ship structure using Finite Element. The aims of this study are to evaluate the size of the damage, boundary conditions, and location of the damage by scheming the natural frequencies and mode shape to determine the measurement deviation.
2. Methods and material

2.1. Generating finite element of material sandwich model
The finite element analysis (FEA) is generated to investigate the effect of the damage ratio and the reduction of natural frequencies from the intact model to the damaged model. The model developed using the finite element analysis software package. The model of sandwich takes the local area on the side hull of Tanker with a plate thickness of existing is 12 mm. The configuration of the material sandwich has a thickness of 4 mm faceplate and a core of 20 mm. The local model defined to perform a side hull structure. This arrangement has fulfilled the strength index specified by LR with a value of $R \leq 1$ [16], while the model obtained an $R$-value of 0.804. The faceplate material properties are general steel for a ship or ASTM 36 with density 7850 kg m$^{-3}$ and Young’s modulus of 200 GPa, and with Poisson’s ratio of 0.3. The core material used a polyurethane elastomer (PU) composite with a density value of 1098 kg m$^{-3}$, Young’s modulus of 901.95 MPa, and Poisson’s ratio assumed of 0.36. The interest dimension model for damage inspection size is constructed by 750 mm x 750 mm x 24 mm. The plate sandwich model set to an eight-node linear brick element (C3D8R) with reduced integration. The boundary set up clamped in all edges for damage identification. All clamped conditions considered to be more accurately identifying damage by the natural frequency in this model. The dimensions of the model adapt to frame spacing, boundary condition and depth of damage made symmetrical to obtain better [23] result accuracy shown in Figure 1.

![Figure 1. Configuration of material sandwich model](image)

2.2. Identification of damage case simulation
The identification of damage has developed from artificial damage modelling simulation. Various size and depth of damage is created for analysis. The thickness of the material sandwich for simulated is consistent in the intact condition. Then, the damaged model induced to the 2 mm through the core, with a damaged ratio of 5%, 10%, 15%, and 20% illustrates in Figure 2. A total of four damage cases investigated with different size of damage ratios. To define the effect of damage size on the natural frequency, using ten modes with the same boundary condition. On [17], the natural frequency difference identified and followed by the analysis of damage identification. Then according to [14,18], the six initial natural frequency parameters can be considered sufficient to measure damage identification. Influence of the size of the damage is determined using the equation of damage ratio formulated as equation 1.
In formula (1), \( D \) represents the damage ratio, while \( A_d \) represents the damaged area, and \( A_t \) represents the total area of the material sandwich. Then natural frequency divergence [17] is defined in equation 2.

\[
\Delta \omega = \left| \frac{\omega_D - \omega_I}{\omega_I} \right| \times 100\% 
\]

where \( \Delta \omega \) is the natural frequency change becomes the damage parameter, \( \omega_D \) is the natural frequency of damaged material sandwich, and \( \omega_I \) is the natural frequency of the intact material sandwich.

Figure 2. Damaged ratio cases in the sandwich material

3. Result and discussion

3.1. Convergency study

Convergency study is a necessary step in the finite element method. It intended to obtain a stable and thorough mesh condition to balance the accuracy and timing of computing. Convergence study aims to investigate the relationship between natural frequency results generated on nonlinear static analysis. The initial step to model is used as a large size mesh and gradually scaled down. Then, to obtain a suitable mesh or convergence carried out this step repeatedly. Finally, determine the size of the element between 0.01 m and 0.0045 m analyzed to obtain a suitable mesh size. From several mesh results selected the size of 0.0045 meters because this size is most stable. Based on a convergency study that good modelling can solve the problem of vibration can be recognized. Therefore, with this method, it can validate the model. The analysis for the existing sandwich material shown in Table 1.
### Table 1: Convergence Analysis for the existing sandwich material

| Element Size (m) | $f_1$ (Hz) | $f_2$ (Hz) | $f_3$ (Hz) | $f_4$ (Hz) | $f_5$ (Hz) | $f_6$ (Hz) | $f_7$ (Hz) | $f_8$ (Hz) | $f_9$ (Hz) | $f_{10}$ (Hz) |
|-----------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|---------------|
| 0.0100          | 3.200      | 8.480      | 14.462     | 18.285     | 18.480     | 24.697     | 24.697     | 32.842     | 32.842     |               |
| 0.0085          | 3.199      | 8.475      | 14.443     | 18.277     | 18.473     | 24.657     | 24.657     | 32.838     | 32.838     |               |
| 0.0075          | 3.196      | 8.465      | 14.422     | 18.256     | 18.451     | 24.616     | 24.616     | 32.802     | 32.802     |               |
| 0.0065          | 3.196      | 8.464      | 14.418     | 18.255     | 18.451     | 24.610     | 24.610     | 32.806     | 32.806     |               |
| 0.0055          | 3.196      | 8.465      | 14.418     | 18.258     | 18.453     | 24.610     | 24.610     | 32.814     | 32.814     |               |
| 0.0045          | 3.196      | 8.465      | 14.418     | 18.259     | 18.455     | 24.611     | 24.611     | 32.819     | 32.819     |               |

3.2. The numerical result of the identification of damage

The numerical results of the finite element analyses reviewed to provide insight and understanding of the free oscillation behaviour of the damaged plate at the core interface. The influence over a large area of damaged has presented in this study. The effects of the parameters on the modal behaviour of the model. Previously, the initial study firstly reported giving information on natural frequency differences of different damaged ratio.

#### 3.2.1. Effect of damage area

One indicator of changes in the natural frequency is the presence of damage in the structure. The damaged area designed at 5%, 10%, 15% and 20%. The damage areas defined in the sandwich material model. The result of frequency reduction in each mode fully presented in Table 2.

### Table 2: Natural Frequency of the ship sandwich plate in the first ten mode

| Mode Number | 0% damage | 5% damage | 10% damage | 15% damage | 20% damage |
|-------------|-----------|-----------|------------|------------|------------|
| 1           | 3.195     | 3.159     | 2.924      | 2.735      | 1.751      |
| 2           | 8.464     | 7.186     | 6.017      | 5.106      | 4.250      |
| 3           | 8.464     | 7.188     | 6.026      | 5.116      | 4.251      |
| 4           | 14.418    | 14.087    | 9.356      | 6.905      | 6.049      |
| 5           | 18.259    | 14.779    | 13.042     | 11.166     | 8.647      |
| 6           | 18.455    | 17.336    | 14.321     | 11.263     | 8.724      |
| 7           | 24.611    | 21.337    | 17.860     | 13.107     | 10.500     |
| 8           | 24.611    | 21.342    | 17.925     | 13.193     | 10.504     |
| 9           | 32.819    | 26.613    | 25.131     | 18.292     | 13.486     |
| 10          | 32.819    | 27.680    | 25.346     | 19.450     | 13.532     |

From the results obtained, it can see if the damage experienced increased then the natural frequency will decrease. The reduction of natural frequency occurred in each mode on the ten-mode in each damage model. The deviation of natural frequency toward the effect of damage ratio to the sandwich material is summarized in Table 3. The natural frequency reduction can be observed in the Figure 3. The average value decrease in the frequency of the whole condition toward each successive damage of 11.98%, 25.20%, 41.29%, and 54.04%.
### Table 3. Natural frequency deviation due to the damage

| Mode Number | Natural Frequency (Hz) |
|-------------|------------------------|
|             | 5% damage   | 10% damage   | 15% damage   | 20% damage   | Average   |
| 1           | 1.12%       | 8.49%        | 25.67%       | 45.19%       | 20.12%    |
| 2           | 15.10%      | 28.91%       | 39.67%       | 49.78%       | 33.36%    |
| 3           | 15.08%      | 28.81%       | 39.55%       | 49.77%       | 33.30%    |
| 4           | 2.30%       | **35.10%**   | **52.11%**   | **58.04%**   | **36.89%**|
| 5           | **19.06%**  | 28.57%       | 38.85%       | 52.64%       | 34.78%    |
| 6           | 6.06%       | 22.40%       | 38.97%       | 52.73%       | 30.04%    |
| 7           | 13.30%      | 27.43%       | 46.74%       | 57.34%       | 36.20%    |
| 8           | 13.28%      | 27.17%       | 46.39%       | 57.32%       | 36.04%    |
| 9           | 18.91%      | 23.43%       | 44.26%       | 58.91%       | 36.38%    |
| 10          | 15.66%      | 22.77%       | 40.74%       | 58.77%       | 34.48%    |

#### Figure 3. Comparison of natural frequency value reduction due to damage

3.2.2. Modal analysis of the sandwich material

Damage in the structure could be resulting in changes of the natural frequency. With several damaged area in the sandwich material model, the decrease of natural frequency can be detected. **Figure 4** represents the natural frequencies changes in various damages. The damages installed in the centre part of the sandwich material.

The highest deviation on average occurs in mode four on the overall model. Overall, the deviation from the damaged area at a large 10% damage was 35.10%, at a 15% damage of 52.11%, at a 20% damage of 58.04%, except for 5% damage occurred in mode 5.
Figure 4. Natural frequencies deviation in the first ten mode of sandwich material for all damage area

The dark blue area shows in the figures obtained from the finite element analysis depicting the identified passive vibration areas. This vibration mode indicates areas where the displacement value is close to zero. Damages cause a lower level of stiffness, which leads to vibrations to be more prevalent in the damaged area. More evident frequency differences and localization of expected damage mode occur in the damaged area. Therefore, the damaged areas have the highest percentage value of decline. Additionally, damages can be detected using natural frequency observation that also prevails to static structures such as stiffened plates and dynamic structures such as hydrokinetic turbines [22], bridge structure, and other transportations.
| No | 0% damage | 5% damage | 10% damage | 15% damage | 20% damage |
|----|-----------|-----------|------------|------------|------------|
| 1  | ![Image](image1) | ![Image](image2) | ![Image](image3) | ![Image](image4) | ![Image](image5) |
| 2  | ![Image](image6) | ![Image](image7) | ![Image](image8) | ![Image](image9) | ![Image](image10) |
| 3  | ![Image](image11) | ![Image](image12) | ![Image](image13) | ![Image](image14) | ![Image](image15) |
| 4  | ![Image](image16) | ![Image](image17) | ![Image](image18) | ![Image](image19) | ![Image](image20) |
| 5  | ![Image](image21) | ![Image](image22) | ![Image](image23) | ![Image](image24) | ![Image](image25) |
| 6  | ![Image](image26) | ![Image](image27) | ![Image](image28) | ![Image](image29) | ![Image](image30) |
| 7  | ![Image](image31) | ![Image](image32) | ![Image](image33) | ![Image](image34) | ![Image](image35) |
| 8  | ![Image](image36) | ![Image](image37) | ![Image](image38) | ![Image](image39) | ![Image](image40) |
| 9  | ![Image](image41) | ![Image](image42) | ![Image](image43) | ![Image](image44) | ![Image](image45) |
| 10 | ![Image](image46) | ![Image](image47) | ![Image](image48) | ![Image](image49) | ![Image](image50) |

Table 4. Mode shape pattern due to overall damaged
4. Conclusion
This study, identification of the application developed material sandwich with polyurethane matrix fibre core for side shell hull of a ship. It evaluated damage identification base on vibration using finite element analysis. The identification of damage inspected by natural frequency and mode shapes. Based on the results of the analysis, the effect of damage to natural frequency changes resulted in decreased natural frequency value. Decreased sensitivity of the natural frequency is measured using natural frequency deviation. In this modelling, the most significant deviation occurred in mode four.

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