Vibration-response due to thickness loss on steel plate excited by resonance frequency

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Abstract. The degradation of steel structure due to corrosion is a common problem found especially in the marine structure due to exposure to the harsh marine environment. In order to ensure safety and reliability of marine structure, the damage assessment is an indispensable prerequisite for plan of remedial action on damaged structure. The main goal of this paper is to discuss simple vibration measurement on plated structure to give image on overview condition of the monitored structure. The changes of vibration response when damage was introduced in the plate structure were investigated. The damage on plate was simulated in finite element method as loss of thickness section. The size of damage and depth of loss of thickness were varied for different damage cases. The plate was excited with lower order of resonance frequency in accordance estimate the average remaining thickness based on displacement response obtain in the dynamic analysis. Significant reduction of natural frequency and increasing amplitude of vibration can be observed in the presence of severe damage. The vibration analysis summarized in this study can serve as benchmark and reference for researcher and design engineer.

1. Introduction

Damage due to corrosion is the most insidious form of damage in steel structure which may form due several factors such as lack of maintenance, aging and environmental attacks. Presence of severe corrosion in the structure may give significant effect towards the performance and stability of the structure. Hence the continuous or periodic damage assessment is vital to minimize loss to the structure and secure the safety especially for marine structure that required to withstand continuous hit by ocean wave and wind. The inspection practice utilizing the non-destructive testing (NDT) technique such as ultrasonic technique where higher frequency of excitation was applied to assess the structural damage condition [1], acoustic emission technique which utilize the release of energy from localize source to detect damage in the structure [2] and x-ray technique where radiation was induced to structure to capture the structural damage [3], utilize sophisticated instrument and focus on localized damage inspection.

The presence of the damage cause changes in the physical characteristics of the structure including stiffness, mass and damping. This leads to changes in the dynamic properties which cause switch of eigen-frequency, changes in mode shape and frequency response function [4]. The vibration-based damage detection provides global damage information on the structure. It is one of the promising methods for structural damage detection and has gained tremendous attention by researchers and engineers of same field [5,6]. Utilizing this method is advantageous in cases where the location of the
damage has not to be known in advance. Moreover, only few accessible points are needed for overall coverage of monitored structure. The study by [5] had reviewed damage identification based on vibration characteristics, classifying it into four major categories; 1) natural frequency based, 2) mode shape based, 3) curvature or strain mode shape based, and 4) methods combining both natural frequency and mode shape.

The present study emphasised on the usage of vibration data for evaluating the damage in the steel plate. The damage cases in this study were designed to simulate the corrosion problem of a plated marine structure with the concentration of corrosion in centre part of the thin plate. The aim of this study is to apply simple vibration test on plate structure in order to summarize the relation between plate vibration responses by nodal displacement with average remaining thicknesses of the plate. A numerical finite element method (FEM) implemented by the finite element package called as Abaqus was used for modal simulation and further solve excitation of plate structure undergoing loss of thickness section. In the first part, the modal parameter of intact plate model was obtained. The resonance frequency was further used to excite intact and damaged plate model. The presence of severe damage in the structure is expected to cause increase of deflection of the structure under loading and further change the structural dynamic properties such as natural frequency and mode shape.

2. Methodology
The step taken for investigation of the changes of vibration characteristic in plate structure undergoing loss of thickness section was summarize in this stage. The damage simulation was performed on thin square plate model and the plate was excited on the specified location on the surface of the plate.

2.1. Finite element model (FEM)
The plate model has been constructed using a three dimensional (3D) finite element method with a programming language called Abaqus, version 6.14 [7]. To obtain natural frequencies and mode shapes, the eigen-value analysis was performed with the use of Lanczos eigensolver to solve the matrices. The plate was modelled according to S4R elements that consist of four node conventional shell elements with reduced integration. The material properties of the steel was set as; density, \( \rho = 7850 \text{ kg/m}^3 \); Poisson’s ratio, \( v = 0.3 \); and Young’s modulus, \( E = 210 \text{ GPa} \). Simply supported boundary conditions were applied for all edges of plate models. The dimension of the plate consider in this study is 1.2m×1.2m having intact thickness, \( h = 9\text{mm} \).

2.2. Damage case simulation
In this study, the damaged area was modelled by decreasing its flexural stiffness. The reduction of flexural stiffness was achieved by reducing the thickness of elements in damaged regions. Constant plate flexural stiffness as indicated in Equation 1 was set for all elements in the baseline model while the damaged plate was modelled by reducing the flexural stiffness of the selected elements. The damage in structure was more or less frequently found in localized regions, thus the damage case was modelled in localized areas instead of uniform damage. The damage cases varied in size and cut of depth in order to investigate effect of these parameters on the dynamic response.

The level cut of depth were increased from 0% of intact plate up to 80% represent as ratio of \( \frac{t}{t_0} \) where \( t \) is remaining thickness and \( t_0 \) is intact thickness. The ratio \( \frac{t}{t_0} = 1 \) is intact model while ratio \( \frac{t}{t_0} = 0.2 \) represent severely corroded plate. The damage area also varies from large damage up to small damage and represented by ratio of \( \frac{a}{a_0} \). The ratio \( \frac{a}{a_0} = 1 \) is large damage while \( \frac{a}{a_0} = 0.2 \) represent small and localized damage. Area surrounded by the exciter denoted as \( a_0 \) on the other hand, a represent the damage area. Figure 1 present the schematic diagram of the damage case simulation on the plate. Eight number of exciter was utilized with distance of 0.05m between each of the exciter and the measurement point was set in the middle of the plate to measure the dynamic response of plate. Eight number of points’ load where each load having force of 100N and excited with resonance frequencies were used to denote as the exciter. The 100mm×100mm area surrounded by exciter was set constant for all damage cases model evaluated in this study.
3. Results and discussions

3.1. Validation of FEM results

The results of natural frequency obtained from FEM was further verified with the natural frequency by theoretical equation. Equation 1 and Equation 2 for simply supported boundary conditions in all edges of the plate from [8] has been used and is expressed as:

\[
D = \frac{Eh^3}{12(1 - \nu^2)} \tag{1}
\]

\[
\omega_{mn} = \sqrt{\frac{D}{\rho h}} \left( \left( \frac{m\pi}{a} \right)^2 + \left( \frac{n\pi}{b} \right)^2 \right) (m, n = 1, 2, ..., \infty) \tag{2}
\]

where \( m \) and \( n \) are integer numbers; \( D \) is the flexural stiffness; \( \rho \) is the density of the plate; \( h \) is the thickness of the plate and \( a \) and \( b \) are the length and width of the plate respectively. Table 1 summarizes the result of natural frequency from FEM and theoretical equation. The results shows good agreement between both of two methods applied.

Table 1. Results of frequency parameter from finite element analysis and theoretical equation of intact steel plate for the first 11 modes.

| Mode | FEM   | Theoretical by Eq. (1) | Percentage of deviation (%) |
|------|-------|------------------------|----------------------------|
| 1    | 30.73 | 30.73                  | 0.01                       |
| 2    | 76.81 | 76.83                  | 0.03                       |
| 3    | 76.81 | 76.83                  | 0.03                       |
| 4    | 122.86| 122.93                 | 0.06                       |
| 5    | 153.60| 153.66                 | 0.04                       |
| 6    | 153.60| 153.66                 | 0.04                       |
| 7    | 199.59| 199.76                 | 0.08                       |
3.2. Modal parameter of intact model

The pattern of vibration of the plate structure differed compared to beam, where in each of the plate mode shape consist of two perpendicular motions along x and y coordinate. Table 2 summarize the mode shape and natural frequency of first three m and n value. Based on these results, three resonance frequency were selected for further damage assessment. The vibration mode 1 with n =1 and m = 1, vibration mode 5 where n = 3 and m = 1, and vibration mode 11 where n = 3 and m = 3 are selected for damage assessment in plate. Mode 1, mode 5 and mode 11 were selected because of active vibration in the middle of the plate. The middle region of the plate was the interest to extract the nodal displacement from the vibration response of intact damaged model. The occurrence of resonance vibration was expected on middle point of the selected mode since the observed point was located outside of nodal line and nodal region. The excitation of the structure by lower resonance frequency is among the interest in order to prevent the presence of others out of band mode.

Table 2. Results of vibration mode and natural frequencies of intact plate model.

| Mode | m = 1          | m = 2          | m = 3          |
|------|---------------|---------------|---------------|
| n = 1| Mode 1 = 30.73 Hz | Mode 2 = 76.81 Hz | Mode 5 = 153.60 Hz |
| n = 2| Mode 3 = 76.81 Hz | Mode 4 = 122.86 Hz | Mode 7 = 199.59 Hz |
| n = 3| Mode 6 = 153.53 Hz | Mode 8 = 199.59 Hz | Mode 11 = 276.12 Hz |

3.3. Modal parameter of damaged model

The loss of thickness in the structure was associated with localized loss of stiffness and switch in vibration frequency. As per interest of this study, only the changes of vibration frequency of mode 1, mode 5 and mode 11 towards loss of thickness section were discussed. Mode 11 was indicate as local mode among the observed mode because it possess of nine localize independent vibration region. The plate was excited by mode 1, mode 5 and mode 11, and the deviations of natural frequency obtained in damaged models was summarize in Figure 2, Figure 3 and Figure 4 respectively. From the graph, the line represent result from intact model was constant indicating absence of damage. The results show that the simulated damage scenario caused the first modal frequency to shift from intact value. The shift of natural frequency increased with the increasing of damage severity and it was clearly shown in the graph obtained.
The results of natural frequency deviation of mode 5 and mode 11 showed a smaller change from 80% until 100% of damage size represented by \( \frac{a}{a_0} = 0.8 \) and \( \frac{a}{a_0} = 1 \). However the reduction of natural frequency still could be observed. The reduction of natural frequency was associated with the location of damage on the observed mode of vibration. Since mode 1 is global mode, where the whole plate was vibrated up and down simultaneously when excited in its resonance frequency, thus roughly uniform reduction of natural frequency was obtained. However, for mode 5 and mode 11, the pattern of plate vibration as indicated in Table 2 consist both active together and passive vibration region. Therefore, it can be inferred that the lesser changes of natural frequency on bigger size of damage area in excitation of plate by mode 5 and mode 11 were due to presence of damage in the nodal region, specifically the zero displacement region. Nodal region is known to possess lower and passive vibration region of the observed mode, showing less frequency change even in the state of severe damage. Overall, the changes in natural frequency alone was not enough as indicator to quantify the severity of the damage occurrence in the structure. This is because the reduction of natural frequency is associated with the position of damage in the observed mode where small and almost zero reduction of natural frequency occur in nodal region.

![Figure 2. Deviation of natural frequency of mode 1.](image)

![Figure 3. Deviation of natural frequency of mode 5.](image)
3.4. Vibration response of damaged plate

The eight points load was applied perpendicularly to the plate surface and simulated in the FEM to represent the exciter. The plate was excited in accordance to the resonance frequency. The vibration response was simulated to be captured by sensor at the middle of the plate. The nodal displacement result was obtained and summarized in this section. Figure 5 present the time domain response of plate model with damage size of $a/a_0 = 1$ in intact thickness. The plate was subjected to 30.73 Hz of ten cycle cyclic load. The frequency domain graph of Figure 5 was presented in Figure 6. The peak value obtained was associated with the excitation frequency.

Figure 7, Figure 8 and Figure 9 present the out of plane displacement when plate was excited by vibration frequency mode 1, mode 5 and mode 11 respectively. Roughly, according to the results obtained, the magnitude of vibration response decreased as the plate was excited by higher order of resonance mode. Besides, the increasing of damage severity caused the amplitude of vibration to increase. However, only the excitation of mode 1 showed the consistency of the results as compared to excitation by mode 5 and mode 11. The summary of vibration response on excitation of plate by mode 5 and mode 11 as indicated in Figure 8 and Figure 9 showed inconsistent results when the damage with larger area give smaller amplitude of vibration. This was related with the presence of other mode which is below the frequency of the excitation. Overall, only mode 1 showed as the most consistent result because of lowest cut-off frequency. Due to this reason, only mode 1 will be further consider in order to summarize the amplitude of out of plane displacement with the average remaining thickness.
Figure 7. Out of plane displacement of plate excited by mode 1.

***Table*** summarize the results out of plane displacement of plate excited by mode 1 which has been graphically shown in Figure 7. The results summarize in this table was the reference value to be used to relate with the average remaining thickness in the area of 100x100mm monitored plate. The user was able to predict the average remaining thickness in specified monitored region of the plate structure by this simple vibration testing. In order to confirm the suggested method, the verification by experimental work is necessary. In the near future, this potential of the method presented in this study will be explored in large scenario subjected to upcoming work.
Table 3. Details results of out of plane displacement of plate excited by mode 1 (m)

| $\frac{a}{a_0}/t_0$ | $\frac{a}{a_0} = 0.20$ | $\frac{a}{a_0} = 0.40$ | $\frac{a}{a_0} = 0.60$ | $\frac{a}{a_0} = 0.80$ | $\frac{a}{a_0} = 1.00$ |
|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1.00                 | 4.22E-03             | 4.22E-03             | 4.22E-03             | 4.22E-03             | 4.22E-03             |
| 0.80                 | 4.26E-03             | 4.32E-03             | 4.36E-03             | 4.39E-03             | 4.40E-03             |
| 0.60                 | 4.33E-03             | 4.42E-03             | 4.51E-03             | 4.58E-03             | 4.63E-03             |
| 0.40                 | 4.41E-03             | 4.54E-03             | 4.64E-03             | 4.74E-03             | 4.83E-03             |
| 0.20                 | 4.42E-03             | 4.56E-03             | 4.70E-03             | 4.82E-03             | 4.92E-03             |

4. Concluding remark

The present study emphasis on the changes in the vibration responses when damage was introduce in plated structure. The plate was excite with the out-of-plane loads with specific resonance frequency. This study concluded that:

1. The reduction of natural frequency increased as damage severity increased in the simulated damage scenario.
2. There was increase in magnitude of displacement when the severity of damage in term of level cut of depth level and damage area were increased. However, the magnitude of displacement value reduced as the plate was excited by higher order of resonance mode.
3. The excitation of resonance mode 1 was the most consistent mode of excitation as compared to higher order resonance modes (mode 5 and mode 11). The main cause was due to presence of other mode below the excitation frequency.

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