Vibration Parameters Based Debonding Defect Detection for Sandwich Plate with Pyramidal Truss Cores

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Abstract. As a kind of super-light lattice material, the sandwich plate with pyramidal truss cores has wide application prospect. In this paper, a vibration parameter based nondestructive testing method using Uniform Load Surface (ULS) curvature was proposed to detect the delamination defects of the pyramid-type lattice sandwich plate. The feasibility of the approach is that the surface smoothing method and curvature mode change rate method are adopted to overcome the dependence on the unflawed model. The validity and efficiency of the proposed methods were demonstrated through numerical simulations.

Keywords. Sandwich plate with pyramidal truss cores, debonding defect, vibration characteristics, difference method, surface smoothing method, curvature mode change rate.

1. Introduction

As a kind of super-light material, the sandwich plate with pyramidal truss cores (Fig. 1-2) has been applied in many fields. The welding defects, especially the delaminations between the inner layer and surface layer occurred during processing and service process, are the major concern for the quality control of the lattice sandwich plate as it can reduce the strength significantly [1-3]. Therefore, a reliable and convenient NDT technique is required to guarantee the safety of a structure made by the pyramid-type lattice sandwich plate. Though many method exist for detecting damage in a structure, few of them can be used to identify the debonding detects ideally. Recently, based on Uniform Surface Load (ULS) [4], Wu and Law [5] have proposed a strategy to detect damage in a plate by investigating changes in the ULS curvature that is interpolated with central difference method and Chebyshev approximation. Tian and Chen [6-7] applied this difference method to detect the debonding defect and identified all of the damages of difference numbers and locations successfully. However, those methods need the parameters of undamaged structures as the reference signal. To overcome the

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dependence problem, based on ULS curvature, two methods independent of original intact structures were adopted to identify the debonding defects of lattice sandwich plate in this paper. One is surface smooth method and the other is curvature mode change rate method. The feasibility of the approaches were investigated through numerical simulation by using commercial software for different damage configurations.

2. Numerical methods of damage detection for lattice sandwich plate

2.1. Damage detection algorithms based on difference method

The debonding defect of the pyramid-type lattice sandwich plate, which is usually caused by stress concentration around the welding zone during service, causes changes in structural physical properties. These changes in turn alter the dynamic response behavior of structure from its initial pre-damage condition. Therefore different static and dynamic characters will be presented between the damaged and normal structure.

To detect delaminations of the lattice sandwich plate, numerical simulation by using commercial software for different damage configurations were completed at first. As the second step, the ULS curvature values can be calculated from the measured modal parameters by using central difference method [6, 8]. The accuracy of the central difference method is well known depending on the density of the measurement grid. If the ULS values are estimated on a sparse grid, it will induce a very large error in calculating the curvature from differentiation [7]. The following Chebyshev polynomial in two variables was adopted to model the ULS distribution so as to avoid the error:

\[
(\mathbf{x}, \mathbf{y}) = \sum_{i=1}^{N} \sum_{j=1}^{M} C_{i,j} T_i(x) T_j(y),
\]

where, \( T_i(x) \), \( T_j(y) \) are the standard Chebyshev polynomials with the plane domain of \([-1, 1]\), \( N, M \) are their orders, and \( u(x, y) \) is the uniform load surface at point \( k(x, y) \).

\[
u(k) = \sum_{r=1}^{P} \phi_r \frac{\phi_r}{\omega_r} \omega_r, \quad \phi_r \text{ is the mass normalized mode, } \omega_r \text{ is the } r\text{-th natural frequency.}
\]

For \( P=N \times M \) measuring points, it can be written in a matrix form:

\[
\left\{ u(x_i, y_j) \right\}_{i=1}^{N} = \left[ T_i(x_j) T_j(y_j) \right]_{i=1}^{P} \left\{ c_r \right\}_{r=1}^{P}, \quad (P = N \times M),
\]

The coefficient vector \( \left\{ c_r \right\}_{r=1}^{P} \) can then be solved as

\[
\left\{ c_r \right\}_{r=1}^{P} = \left[ T_i(x_j) T_j(y_j) \right]_{i=1}^{P}^{-1} \left\{ u(x_i, y_j) \right\}_{i=1}^{N}
\]

Then the ULS curvature can be approximated by the second derivatives of the Chebyshev polynomials in Eq. (1) as
By subtracting the curvature parameters of the intact state from those of the damage state, the damage index map can be formulated as follows,

\[
d(x, y) = \left[ \alpha_{xx} \left( \frac{\partial^2 T_x^2}{\partial x^2} - T_x \right)_y - \frac{\partial^2 T_y^2}{\partial x \partial y} T_x \right] + \left[ \alpha_{yy} \left( \frac{\partial^2 T_y^2}{\partial y^2} - T_y \right)_x - \frac{\partial^2 T_x^2}{\partial y \partial x} T_y \right] + \left[ \alpha_{xy} \left( \frac{\partial^2 T_x^2}{\partial x \partial y} - \frac{\partial^2 T_y^2}{\partial y \partial x} \right) \right]^2
\]

(5)

For undamaged structure, the difference between ULS curvatures of intact structure and damage structure is only due to measurement noise. Therefore, values of the damage index map, \(d(x, y)\), slightly oscillate around zero without any distinct peak. In the contrast, peaks or slopes will clearly show up at damaged zone of the plate if the structure is damaged.

2.2. Damage detection algorithms based on surface smoothing method

Most damage detection based on a baseline or healthy data is usually unreliable for practical application, because a priori measurement in a healthy condition is affected a lot by the surroundings. To avoid this difficulty, Ratcliffe [9] and Wu [5] proposed the “Gapped-smoothing” technique to detection damages in beam and plate structure respectively. The basic idea of the method is that the ULS curvature of the sandwich plate, without any damage, has a smooth surface. The surface smoothing method can eliminate the peaks hiding in the ULS curvature caused by debonding defects. Therefore, the approximate ULS curvature without debonding defect can be established for the difference method.

Based on the surface smoothing method, the smoothed ULS curvature at each point \((x_i, y_j)\) can be approximated by the following formula,

\[
u_{\text{fitting}}(x, y) = \sum_{i=0}^{N} \sum_{j=0}^{M} C_{ij} x^i y^j
\]

(6)

where the coefficient \(c_{ij}\) for an approximate ULS curvature without debonding defect can be evaluated by a curve-fitting process. Particularly, to obtain the smoothed ULS curvature at point \((x_i, y_j)\) as shown in Fig. 3, curvature data at all the adjacent points, but not the point \((x_i, y_j)\) itself, are used to evaluate the coefficient \(c_{ij}\) in Eq (6). This process is repeated for each measuring point to give a smooth ULS curvature to model the undamaged sandwich plate structure.
So the presence of the peak in the ULS curvature due to debonding detect can then be detected by subtracting the smoothed curvature from the estimated curvature of the damaged structure. The damage index map is given as:

\[ d(x, y) = (u_{\text{measured}}(x, y) - u_{\text{fitting}}(x, y))^2 \]  

(7)

2.3. Damage detection algorithms based on curvature mode change rate

The same to the surface smoothing method, the method based on curvature mode change rate need not the parameters of the initial intact structures. Zhang, et al [10] has applied this method to a beam structure and got ideal detection results. In this paper, the detection method based on curvature mode change rate was adopted to the debonding defect identification for four-side simply supported sandwich plate by using the ULS curvature values.

The basic idea of this method is that the local stiffness degradation caused by delamination will be expressed by the volatility of change rate of ULS curvature. As the corresponding relationship between curvature mode and displacement mode, the change rate of ULS curvature is relative to structure position. Therefore, the change rate of ULS curvature \( \mu'' \) can be used to detect the local debonding defects. The calculation of \( \mu'' \) is as follows,

\[
\mu''_k = \frac{\mu''_{k(i+1)} - \mu''_k}{h}
\]  

(8)

where, \( \mu''_{k(i+1)} \) is the ULS curvature mode of the modal vector coefficient at the \((i+1)\) measurement point of the \(k\)-th unit mass-normalized mode vector, \( h \) is the uniform grid spacing in the corresponding direction.

For the delamination identification of the pyramid-type lattice sandwich plate, the defect information will be extracted by the change rate curve of ULS curvature mode.

3. Results of Numerical simulation for damage detection

3.1. Finite element model

Concrete pyramid-type lattice sandwich plates with delaminations of different configurations were adopted as examples to demonstrate the efficiency of the above methods. The constraint condition with four-side simply supported was selected for the numerical simulations.

Lattice truss structures are usually made by perforating metal sheets to create a periodic array of diamond shaped holes [11]. Therefore, it can be consider in a periodic pyramidal structure of conjoint four beams cells as shown in Fig. 4(a).
As a preliminary study, four beams which are bounded to a welding point were deleted from the finite element model to simulate a debonding defect (Fig. 4(b)). The detection of the delamination is very difficult as the complexity of the topological structure. However, the dynamic characteristics of the corresponding position on the plate change with the deletion of the inner trusses. This characteristic can be used as the basis for the debonding defect identification. As shown in Fig. 4, once such a defect occurs, the dynamic response of the five nodes that are directly related to the debonding will change significantly. Therefore, the key point of the damage recognition of the lattice sandwich plate with pyramidal truss cores is to detect the location of these five nodes.

Figure 2 shows the 3D finite element model of the pyramid-type lattice sandwich plate founded by using commercial software ANSYS. The numerical models used for feasibility analysis of the proposed method are shown in Fig.5, where, (a) is the structure of the intact plate, (b) and (c) are models with 2 and 3 debonding defects.

3.2. Damage identification results

Based on the mentioned methods, numbers of numerical simulations were completed. In this paper, only the displacements of translational DOF in direction perpendicular to the surface plate were used to calculate the ULS curvature. Eqs. (5), (7), (8) were used to calculate of the damage index based on changes in the ULS curvature. The results together with the results of central difference method are shown in Fig. 6, Fig.7, Fig.8 and Fig.9.
From Fig. 6 and Fig. 7, it can be clearly seen that there is a sharp peak located at each debonding defect. For a four-side simply supported plate, both maximum bending moment and flexural displacement occur at the geometrical center of the plate, they will decrease when the geometrical position moving to the boundary of the plate. The influence of damage to ULS curvature shows the same feature. In the case with same damage form and magnitude, the damage index shows different size.

Comparing the results of the two above, one can find that the damage index of the latter is much bigger than the former. So the latter method seems to be more sensitive than the former in delamination defect recognition of the lattice sandwich plate with pyramidal truss cores. However, in Fig. 7, some of the damage indexes are smaller than they should be, such as point P and Q in the figures. That’s because the method of data block processing was utilized in the calculation to quickly deal with data. Then, error will unavoidably exist in the data of the junction. If the delamination just located at the position of the segmentation, error will occur in the defect identification index to make the indexes smaller than they should be as shown in Fig. 7.
Figure 8. Results of surface smoothing method for four-side simply supported lattice sandwich plate

As shown in Fig. 8, independent of the unflawed model, the surface smoothing method can be used to identify the delaminations of the pyramid-type lattice sandwich plates effectively. Though there’s some noises exist in the recognition results, the number and position of the debonding defects can be properly identified.

Figure 9. Results of curvature mode change rate for four-side simply supported lattice sandwich plate

It can be clearly seen in Fig. 9 that all of the delaminations are recognized accurately by using of the ULS curvature change rate. Comparing with the results of surface smoothing method, the defect identification index is much bigger. So the latter method seems to be more sensitive than the former in debonding defect recognition of the pyramid-type lattice sandwich plate.

4. Conclusion

In this paper, based on the ULS curvature calculated by using Chebyshev polynomial, difference method, surface smoothing method and curvature mode change rate method are applied in delamination detection of the lattice sandwich plate with pyramidal truss cores. Numbers of numerical simulations are performed to verify the efficiency of the proposed methods. The major conclusions obtained are as follows:

1) All of the processing methods and numerical codes proposed in this paper were demonstrated to be effective for the debonding defect identification of sandwich plate with pyramidal truss cores.
2) The difference method based on Chebyshev polynomial approximation is more sensitive than the method of central difference method.

3) Independent of the unflawed model, the identification method based on surface smoothing method and change rate of ULS curvature can be used to identify the delaminations of the lattice sandwich plates effectively. They will have more wide application in practice than the difference method.

4) The method based on change rate of ULS curvature is more sensitive than the surface smoothing method.

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References