STRUCTURAL HEALTH MONITORING OF LAYERED STRUCTURE BY STRAIN MEASUREMENTS

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Structural Health Monitoring (SHM) is a very important technology to realize the sustainable society. Various researches are being conducted for SHM, and it is effective because it avoids accidents and predicts behaviour of structures. In this research, we proposed a method of SHM for a layered structure, in which the abnormal hierarchy of the structure was identified by strain measurement. First, in the normal condition, the location where the strain is almost 0 on the outer wall of each hierarchy is specified and the strain at that points are always measured. Then, when an abnormality occurs in a certain hierarchy, a significant value of strain appears in the abnormal hierarchy where the strain is originally 0. We verified the proposed method by numerical simulation. We considered a 3-layerd structure and it was modelled as a cantilever beam. Abnormality was assumed as the decrement of stiffness at a certain element and it was shown that the effect of abnormality appeared in the whole structure in the natural vibration mode while it appeared locally in the strain measurement. Then the random response was calculated by the numerical integration, and the hierarchy where the abnormality occurred can be identified by using the proposed method. As a result, it was shown that the method was possible to identify the hierarchy where an abnormality occurred.

Keywords: SHM, strain measurement, layered structure, natural vibration mode, random response

1. Introduction

Structural Health Monitoring (SHM) is a very important technology to realize the sustainable society.\(^{(1),(2)}\) For that reason, it is important to monitor the condition of the structure constantly, and to diagnosis and predict the health condition. Structures vibrate due to the external forces such as wind and earthquake, so by measuring the vibration, it is possible to obtain the characteristics and its fluctuation of the structure. Various researches are being conducted for SHM so far. For example, there is a research that by measuring the vibration of the structure at multiple points and gathering up the results, and monitor the health from the behaviour of structures against earthquakes and deterioration\(^{(3)}\), a research of monitoring the influence on structural health by earthquake using MEMS vibration sensor\(^{(4)}\), a research to evaluate the deflection of structure by artificially exiting the structure\(^{(5)}\), a research by constantly measuring ambient vibration by wind and find out the change in natural frequencies and damping ratio\(^{(6)}\). Furthermore, there are researches that detects the damage on beam by wavelet transformation\(^{(7)}\), and FBG sensor\(^{(8)}\).

In this research, we proposed a method of SHM for a layered structure, in which the abnormal hierarchy of the structure was identified by strain measurement. First, in the normal condition, the location where the strain is almost 0 on the outer wall of each hierarchy is specified and the strain at
that points are always measured. Then, when an abnormality occurs in a certain hierarchy, a significant value of strain appears in the abnormal hierarchy where the strain is originally 0. We verified the proposed method by numerical simulation.

2. Proposed method

2.1 Mathematical model

The proposed method is explained by using a three-layer structure as shown in Fig.1(a) as an example. This three-layer structure was modelled by a cantilever beam as shown in Fig.1(b). The beam is discretized into \( n \) beam elements. The \( i \)-th element is assumed to be the floor, then the density of the element is adjusted to correspond to the floor. The variables in the vicinity of the \( i \)-th element are shown in Fig.2. Since the degree of rotational freedom is constrained at the floor part, the following equation can be used,

\[
w_i = w_{i-1}, \quad \theta_i = \theta_{i-1} = 0.
\]

Regarding the variables in Fig.2, the coordinate transformation is carried out as follows,

\[
\begin{bmatrix}
w_i+1 \\
\theta_i+1 \\
w_i \\
\theta_i \\
w_{i-1} \\
\theta_{i-1} \\
w_{i-2} \\
\theta_{i-2}
\end{bmatrix}
= \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
w_i+1 \\
\theta_i+1 \\
w_i \\
\theta_i \\
w_{i-1} \\
\theta_{i-1} \\
w_{i-2} \\
\theta_{i-2}
\end{bmatrix}.
\]

2.2 Specifications of the three-layer structure

The beam model used in this study is shown in Fig.3 and the specifications of the beam model are shown in Table 1. The beam is divided into 33 elements (\( n = 33 \)), and each layer is composed of 10 elements. The floor is represented by one element, and the density of the element is five times heavier than the beam element. The floors are the elements No.11, 22, 33 and are between node No. 10-11, 21-22, and 32-33, respectively. The rotational freedom is restricted to zero at the connection between the floor and the outer wall. The lower order natural frequencies are 13.2 Hz, 38.7 Hz, and 58.8 Hz.
Table 1: Beam Specifications

|                      |       |
|----------------------|-------|
| Length [mm]          | 660   |
| Width [mm]           | 35    |
| Thickness [mm]       | 1.6   |
| Young’s modulus [GPa]| 206   |
| Density [kg/m³]      | 7860  |

2.3 Behavior of natural vibration mode and strain at normal and abnormal situations

In this section, the first natural vibration mode and the strain of the model are shown. The strain was obtained by differentiating the vibration mode in the longitudinal direction. The abnormal condition is expressed by decreasing the Young’s modulus of No. 10 element to 25 %, where is the ceiling of the first layer. Since the lower order vibration mode is considered to be dominant in the actual response, the results near the first natural frequency are shown in Fig.4.

Fig.4 shows the natural vibration mode and strain at normal and abnormal conditions. The lowest point of the graph is the node number 0, which represents the fixed position with the ground. The blue line is the normal result and the red one is the abnormal result. The natural frequency of the first vibration mode is 11.4 Hz, which is lower than the one in normal condition due to the reduction of Young’s modulus. Characteristics of behaviour of the natural vibration mode and strain in case of abnormality are shown in the following. In the natural vibration mode, the influence of abnormality occurring at No. 10 element appears in the entire structure. In the strain, the influence of abnormality appears largely in the hierarchy where the abnormality occurred. The influence also appears in the strain of the other layers. The distinguished feature of the strain is that the strain at No. 5, No. 16, and No. 27 which are located near the centre of each layer is almost zero in the normal case. And, in the case of abnormality, only the strain near the centre of the first layer has a significant value, and the strain near the centre of the second and third layers remains almost unchanged. In this research, we will construct an effective SHM method by using this characteristic appearing in strain.

2.4 Dynamic behaviour by random excitation

Measurement of ambient vibration is assumed in actual SHM. The problem of SHM using ambient vibration is that the change of magnitude of response cannot be evaluated because the magnitude of the excitation force is unknown. To obtain ambient vibration with simulation, numerical integration is carried out by applying random external force to the floor element of the cantilever beam in the perpendicular direction to the beam. The random external force is the normally distributed random number, whose average value is 0.0 and standard deviation is 5.0. The random external force is shown in Fig.5. As a result of numerical integration, random response shown in Fig.6 was obtained as an example. This random response includes multiple natural vibration modes. The frequency analysis was carried out for these random responses by 4000 times averaging while time shifting. And the Hanning window was used in the frequency analysis.
Figure 5: Time history of random external force
Figure 6: Time history of random response

The abnormality is set in the ceiling of the first layer as same as Section 2.3. Fig.7 shows results of frequency analysis of response and strain. The blue line is the normal result and the red one is the abnormal result.

In the normal situation, the amplitude of response increases as the floor rises, because the characteristics of the primary natural vibration mode in Fig.4 appears. Strain is very small near the centre of each layer compared with the ceiling and floor. The reason is that the characteristics shown in Fig.4 appears. When an abnormality occurs, the natural frequency decreases. Therefore, the peak frequency of the response and strain decrease. In the case of response, the amplitude of response increased as same as the normal case as the floor rises. Since the influence of the abnormality appears in the entire structure, it is difficult to specify the point where the abnormality occurs.

In the case of strain, the amplitude increases as a whole when an abnormality occurs. Since the abnormality occurred in No. 10 element, the amplitude of strain near the ceiling on the first floor remarkably increased. However, the strain is not always measured at the position where the abnormality occurred. Considering the strain characteristics obtained in Section 2.3 and investigating the amplitude of strain at the centre of each layer, it is recognized that the strain in the centre of the layer where the abnormality occurred increases significantly, and the strain in the centre of the other layers shows little change.

There is a problem that the change in magnitude of ambient vibration cannot be used to evaluate the health monitoring of the structure because the magnitude of the external force cannot be measured. However, the method proposed in this study uses the fact that a significant value appears at a place where the strain is almost 0 at normal condition, the conventional problem does not occur. And, it is necessary to quantitatively evaluate the degree of significant changes.

The acceleration is considered to be measured in actual cases, so the result of the frequency analysis of the acceleration of the floor is shown in Fig.7. In the case of abnormality as well as in the normal condition, the amplitude of acceleration increased as the floor rises. Since the acceleration has relation with the displacement, influence of the abnormality appears in the entire structure, it is difficult to specify the point where the abnormality occurs. In the numerical example, the No.10 element was set to be abnormal, the similar results were obtained when the abnormality occurred in the floor part of the first layer, the floor part and the ceiling part of the second floor, the floor part and the ceiling part of the third floor.

Therefore, it was confirmed that abnormality diagnosis could be carried out by monitoring the change in the strain at the position where the strain is almost 0 at the normal condition.
2.5 Amplitude of strain near the centre

In this method, it is possible to detect the abnormal hierarchy by checking a significant value at the point where the strain is almost 0 in the normal condition. In this section, the change in the amplitude of the strain is shown when the measuring point is not the exact location of strain 0.

As same as Section 2.3, abnormality is set on the ceiling of the first layer, and the random external force which is the same as Section 2.4 acts on the structure. Fig.9 shows the values of strain at each node on the first floor at the normal and abnormal condition. The blue line is the result for normal condition and the red one is the abnormal result. In case of normal situation, the strain values at No. 4, No. 5, and No. 6 which are near the centre are almost 0. However, when an abnormality occurs, the values of No. 4 and No. 5 rose but the No. 6 dropped.

As a result of the strain in Fig.4(b), due to the abnormality, the position where the strain was originally 0 moved. As a result, in order to detect an abnormal hierarchy, it is necessary to measure the strain at the accurate location of strain 0 at normal condition.
2.6 Diagnosis accuracy for various degree of abnormality

In the analysis so far, the abnormal condition was expressed by decreasing the Young's modulus of No. 10 element of the ceiling of the first layer to 25%. In this section, the relationship between the abnormal value and the strain is shown when the Young's modulus of the No. 10 element of the ceiling of the first layer is decreased to 80%, 60%, and 40%.

Table 3 shows the normalized values of the peaks of strain at all nodes in normal situation and abnormal cases. Random external forces which are the same as Section 2.4 are applying. The peak values are normalized with the one of normal case.

From Table 3, as an example, the judgment criterion of abnormality is set to be 5 times larger than the normal value. When the Young's modulus is 80%, the value of strain of the first floor of the abnormal hierarchy is 3.3 times larger than the normal value, and 1.6 times of the second and third floors of the normal hierarchy. If setting the judging criterion of abnormality is 3 times of the normal value, when the external force doubles, the 2nd and 3rd floors of the normal hierarchy will be 3.2 times larger and judged to be abnormal. Therefore, by setting the judgment criterion of abnormality to 5 times of the normal value, it is possible to judge an abnormality of 60 and 70% or less.
### Table 2: Peak value of strain

| Element number | 1.0 | 0.8 | 0.6 | 0.4 | 0.25 |
|----------------|-----|-----|-----|-----|------|
| 0              | 1.60| 1.17| 1.34| 2.47|
| 1              | 1.61| 1.19| 1.37| 2.57|
| 2              | 1.63| 1.21| 1.43| 2.75|
| 3              | 1.66| 1.27| 1.55| 3.11|
| 4              | 1.75| 1.43| 1.91| 4.20|
| 5              | 3.30| 7.73|18.69|58.16|
| 6              | 1.41| 0.81| 0.53| 0.02|
| 7              | 1.49| 0.96| 0.86| 1.01|
| 8              | 1.51| 1.01| 0.97| 1.35|
| 9              | 1.72| 1.38| 1.79| 3.80|
| 10             | 1.92| 1.75| 2.64| 6.48|
| 11             | 1.56| 1.10| 1.17| 1.99|
| 12             | 1.56| 1.10| 1.17| 1.98|
| 13             | 1.56| 1.10| 1.17| 1.98|
| 14             | 1.56| 1.10| 1.16| 1.97|
| 15             | 1.56| 1.09| 1.16| 1.95|
| 16             | 1.59| 1.13| 1.24| 2.15|
| 17             | 1.57| 1.10| 1.17| 1.99|
| 18             | 1.56| 1.10| 1.17| 1.98|
| 19             | 1.56| 1.10| 1.17| 1.98|
| 20             | 1.56| 1.10| 1.17| 1.97|
| 21             | 1.56| 1.10| 1.16| 1.97|
| 22             | 1.56| 1.08| 1.14| 1.93|
| 23             | 1.55| 1.08| 1.14| 1.93|
| 24             | 1.55| 1.08| 1.14| 1.93|
| 25             | 1.55| 1.08| 1.13| 1.92|
| 26             | 1.54| 1.07| 1.12| 1.91|
| 27             | 1.57| 1.09| 1.17| 1.96|
| 28             | 1.56| 1.09| 1.15| 1.94|
| 29             | 1.55| 1.08| 1.14| 1.93|
| 30             | 1.55| 1.08| 1.14| 1.93|
| 31             | 1.55| 1.08| 1.13| 1.93|
| 32             | 1.55| 1.08| 1.13| 1.93|
| 33             | 1.55| 1.08| 1.13| 1.93|

### 3. Conclusions

In this research, we propose a method to specify the hierarchy when an abnormality occurs in layered structure. Firstly, in the normal condition, the location where the strain is almost 0 on the outer wall of each hierarchy is specified and the strain there are always measured. Then, when an abnormality occurs in a certain hierarchy, an abnormal hierarchy is detected checking a significant
value of strain where the strain is originally 0. We verified the proposed method by numerical simulation.

From the behaviour of natural vibration mode and random response, when an abnormality occurs, the influence of the abnormality appears in the entire structure. From the behaviour of strain, when an abnormality occurs, the significant values appeared at the specified point where the original strain data 0.

The ambient vibration of the structure is simulated by acting the random excitation to the floor. In case of abnormality, it is difficult to detect the abnormal hierarchy by the information of displacement and acceleration. However, since strain has a significant value in the centre of the layer where the abnormality occurred, it is possible to detect the abnormal hierarchy. Moreover, it is shown that the strain has to be measured at the accurate location of strain 0 in the case of normal condition. Furthermore, by setting the judgment criterion of abnormality to 5 times of the normal value, it is possible to judge an abnormality of 60 and 70% or less.

The proposed method is for identifying the hierarchy where the abnormality occurred at an early stage. Precise diagnosis is necessary to determine the kind of abnormality following this identification method.

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