Damage Detection of Bridges: 
Experimental Research with Strain Mode Approach

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NOMENCLATURE

\( i \) : location of a cross-section
\( M \) : bending moment on a cross-section
\( EI \) : flexural rigidity of a cross-section
\( \rho \) : radius of curvature
\( \varepsilon \) : strain
\( h \) : distance between measuring point and neutral surface
\( x \) : coordinate along the beam
\( l \) : length of the deformed girder segment
\( \Delta l \) : deformation of girder segment
\( x_m \) : horizontal displacement of test point m

ABSTRACT

This paper describes authors’ experimental research on damage detection of bridges by using strain mode technique. Experiments with two freely supported beams and a cable-stayed bridge were reported. Key in these experiments was to determine the dynamic strain by displacement measurement approach. Experimental results demonstrated that the dynamic strain could be gained under steady-state vibration very well. Under the non-steady-state vibration, results were not satisfactory. Higher instrumentation requirements were proposed. Finally some issues about damage detection of bridges while using strain mode approach were discussed.

1 INTRODUCTION

In the past decades, many bridges approached or exceeded their design life. Many sudden bridge failures suggested the necessity of damage detection of bridges. Bridge’s damage always results in the change in structural parameters. Since the 1980’s, local parameter such as the strain mode was investigated as the index of damage instead of global parameters such as natural frequency, damping ratio and modal shapes, because the former is more sensitive to bridge’s damage\(^{[1-2]}\).

The bottle-neck of the strain mode method for damage detection is how to determine the dynamic strains of bridges. To measure strain or stress, strain gauges must be cemented to the damaged positions. This is very inconvenient in case of large structures. Moreover, creep and aging of strain gauges will reduce the reliability for a long-period test. Attention has been put on optical fiber strainometer embedded in smart structure. However, its usage is limited because of the difficulty of its maintenance and the complexity of the measurement system.
A new approach for bridge damage detection based on strain mode has been proposed in authors’ papers[3-4]. Experiments were carried out on several beams and bridges. The most important goal of the experiments is to calculate the dynamic strain through displacement measurement. Measuring instrument and the results were described, and the feasibility of the displacement measuring approach and the requirement on the instrument were discussed.

2 THEORY OF THE STRAIN MODE METHOD

Curvature mode[2] provides an indirect method for stress and strain test by using displacement measurement. The static relationship of straight girder under bending can be described as

$$\frac{1}{\rho_i} = \frac{M_i}{E_i I_i}$$

(1)

where \(i\) denotes the location of a cross-section, \(M_i\) is the bending moment at the \(i\)th cross-section, \(E_i I_i\) is the flexural rigidity of the \(i\)th cross-section, \(\rho_i\) is the radius of curvature, and \(\frac{1}{\rho_i}\) is the curvature.

Thus, the longitudinal strain \(\varepsilon\) is related to the flexural rigidity as

$$\varepsilon = -\frac{h}{\rho} = -h \frac{M}{EI}$$

(2)

where \(h\) is the distance between the measuring point and the neutral surface.

Apparantly, equation (2) indicates that the curvature mode is directly related to the strain mode. The change in flexural rigidity can be evaluated from a strain mode or a curvature mode test. Thus damage can be detected too. Numerical similation on a standard freely supported T-beam bridge demonstrated that the strain mode can indicate the existence, location and degree of damage very clearly, preceding traditional modal parameters, such as the natural frequency and the modal shape[3].

A longitudinal strain is defined as

$$\varepsilon = \frac{\Delta l}{l}$$

(3)

where \(l\) is the length of the deformed segment of girder, \(\Delta l\) is the deformation of the segment. If the horizontal vibration displacements of the deformed segment's ends can be surveyed, the average strain of the segment is calculated as:

$$\varepsilon = \frac{x_{m+1} - x_m}{l}$$

(4)

where \(x_{m+1}, x_m\) is the horizontal displacements of the two ends. Equation (4) shows that the strain of girders could be obtained from the results of horizontal displacement measurement. Thus, the problem of damage detection of bridges can be changed to a problem of determination of horizontal vibration displacement of bridges.

3 EXPERIMENTS ON DYNAMIC STRAIN MEASUREMENT

Experimental research was carried out on two freely supported beams and a cable-stayed bridge. The property of dynamic strain measurement and requirements of instrumentation under the work condition of steady-state vibration and transient vibration were investigated.
3.1 INSTRUMENTATION

Numerical simulation showed that the measurement system should be able to resolve the vibration amplitude in microns or sub-microns. The permissible error is only 1% of the measured value. In addition, the main natural frequencies of large-span bridges are always very low. For low frequency vibration, it is difficult to recognize displacement amplitude in micron dimension through a twice integrations of the signal picked by an accelerometer. Therefore, it is important to select proper signal pick-up device. A kind of new low frequency absolute vibration transducer (DP transducer) can meet above requirements and was chosen for the experiments[4].

Strain gauges and a dynamic strain indicator were used in laboratory experiments to compare with the results of the new approach.

Shown as Fig. 1, two DP displacement transducers were placed flatly and longitudinally at two adjacent test points of the beam to measure the horizontal displacement. From Equation (4), the average strain of the beam segment between the two test points could be estimated from the output signal of the two DP transducers. A strain gauge was stuck lengthways at the middle point of the two DP transducers.

![Fig.1 Sensor arrangement for the experiments](image)

After amplification and conditioning, the displacement signal and the strain signal were collected synchronously by a computer through an A/D board.

3.2 EXPERIMENTS

3.2.1 I-beam experiment

A 12m I-beam was freely supported at its two ends. The beam is undamaged.

The experiment was performed under hammering excitation. Because the damping ratio is very low, the dynamic response of the beam can be considered as a steady-state vibration after a long time of hammering. This experiment was just designed for comparing the average strain estimated by displacement measurement with the 'point' strain obtained by traditional strain gauges.

The strain gauge is stuck at the 1/4 span and mid-span of the I-beam. DP transducers were placed beside them along the beam with a spacing of 2m (Δ=2m). The I-beam and the sensors are shown in Fig. 2, and the instrument system is shown in Fig. 3.
3.2.2 Square-tube beam experiment

A 6m square-tube aluminum beam was freely supported at its two ends. Damage was made at its mid-span by sawing the beam. Thus the flexural rigidity of the 1/2 cross-section was reduced to 2/3 or 1/2 of the original.

Phase step excitation was utilized in this experiment by adding a load on the beam or removing it. Such a design was to examine the quality of average strain reckoned from displacement test under the transient vibration condition.

The placement of sensors and the instrument system was similar to that of the I-beam experiment.

3.2.3 Cable-stayed bridge experiment

The cable-stayed bridge experiment was carried out on the 628m main span of Nanjing No.2 Yangtze River Bridge in China. The bridge was excited by the normal traffic load.

DP transducers were placed flatly beside the mid-span along the main span. Different from above experiments, this time no stain gauges were used. One DP displacement transducer was placed vertically at the mid-span cross-section to verify the quality of the average strain. The amplitude and phase of the vertical vibration signal of one point on the bridge’s surface reflect the strain of that point. So we can use the vertically placed DP transducer as a substitute of strain gauge.

3.3 RESULTS OF EXPERIMENTS

3.3.1 Result of the I-beam experiment

Fig.4 shows one result curve of I-beam experiment, where Fig.4(a) and Fig.4(b) show two DP displacement transducers’ signals respectively. In this test, DP transducers were put beside the 1/2 cross-section, so curve(a) and curve(b) are in opposite phases. In Fig.4(c), the solid line represents the dynamic ‘point’ strain gained by strain gauge, while the dotted line represents the average strain reckoned from curve(a) and curve(b). It’s shown that the average strain can follow the ‘point’ strain fairly well.

Results of other tests in this experiment also showed the same conclusion. From equation (4), there is a coefficient between the average strain and the ‘point’ strain due to different operating condition. In one experiment, the coefficient should be a constant. Table 1 lists the value of coefficient (λε=average strain/‘point strain) in different tests. It is obvious that the value of λε approaches a constant. That is to say, under steady-state vibration condition, the dynamic strain could be gained by only placing two DP transducers on the bridge and simply processing the output vibration signal. This method is much more convenient on large-scale bridges than the traditional strain gauge approach.
Table 1 Values of $\lambda_e$ in different tests in I-beam experiment

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>test</th>
<th>Value of $\lambda_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammering at 1/2 cross-section</td>
<td>G02</td>
<td>0.861</td>
</tr>
<tr>
<td></td>
<td>G03</td>
<td>0.877</td>
</tr>
<tr>
<td>Hammering at 0 cross-section</td>
<td>G04</td>
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<tr>
<td></td>
<td>G06</td>
<td>0.856</td>
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<tr>
<td>Hammering at 1/4 cross-section</td>
<td>G08</td>
<td>0.886</td>
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<tr>
<td></td>
<td>G14</td>
<td>0.900</td>
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<td>G15</td>
<td>0.849</td>
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<td>Hammering at 1/2 cross-section</td>
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<tr>
<td></td>
<td>G11</td>
<td>0.843</td>
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</tbody>
</table>

3.3.2 Result of square-tube beam experiment

Fig. 5 shows the result of the square-tube beam experiment, where the black line and the red line represent the average strain and the 'point' strain respectively.

There were two step excitations during this test. The load was removed from the beam firstly. Then it was added to the beam again. From Fig. 5, it can be seen that the average strain can not follow the 'point' strain especially at the beginning of step excitation. The error is due to the dynamic response time of the DP transducer. It's too long to follow the transient input. Since the DP transducer can be considered as a high-pass system, direct current signal can not be reflected correctly by it. Proper signal processing is necessary before using the average strain information under transient excitation condition.

The blue line in Fig. 5 represents the filtered average strain by a 3Hz high-pass filter. After the filtering, the average strain can follow the dynamic 'point' strain. But the direct current information was lost.
3.3.3 Result of cable-stayed bridge experiment

Fig. 6 shows the result of the cable-stayed bridge experiment. In Fig.6(a), the black line represents the signal of the vertically placed DP transducer and the red line represents the enlarged differential value (D-value) signal of the two flatly placed DP transducers by a product 20. As mentioned above, the signal of the vertically placed DP transducer can represent the ‘point’ strain to some extent. So, it can be seen that the average strain can follow the ‘point’ strain partly in this case. When the vibration of the bridge is steady, the follow is acceptable. When the bridge’s vibration response is unsteady, for example there is a car passing by the test point, the follow is unacceptable.

Through the auto-power spectrum analysis, we can find out the cause of the error. Fig.6(b),(c),(d) show the auto-power spectrums of the horizontal displacement signal, the enlarged differential value (D-value) signal and the vertical vibration signal respectively. It can be seen that the main component of the horizontal displacement signal is lower than 0.2Hz. In fact the natural frequency of the DP transducer is 0.2Hz. That is to say the horizontal signal is not within the pass band of the transducer. The transducer’s measuring error cannot be ignored here.

Comparing Fig. 6(c) with (d), the main difference is the spectrum under 0.2Hz.

From this experiment, it can be seen again that the characteristics of the DP transducer is very important in dynamic strain measuring, especially under the non-steady-state vibration condition. Improvement should be made to reduce the nature frequency of DP transducer for the use in large-scale bridge. In addition, compatibility in amplitude characteristics and phase characteristics of the two DP transducers will also affect the strain test precision. A theory analysis showed that the relative error of amplitude characteristics between the two DP transducers should be less than 2%, and the phase characteristic error between the two DP transducers should be less than 1°.
4 CONCLUSIONS

Detecting damage of bridges through strain mode parameters is a theoretically effective method. Reckoning dynamic strain from vibration displacement provides a new approach to forward the strain mode method to practice.

Experimental research demonstrated that the average dynamic strain could be calculated from the signals of two special arranged displacement transducers. Thus the strain status or even damages of girders could be estimated. To get this goal, the transducers must be chosen very carefully. They should be used in their pass-band range. In addition, the two transducers should be highly compatible both in their amplitude characteristic or phase characteristic.

In field test of bridges, the working condition is very complex. For example, there is always a bituminous surface treatment on bridges. The strain of the bitumen surface can’t reflect the damage status of the girder. Thus the transducers should be put into the inner of the bridges. In short, there is a long way to go to detect damage of bridges through stain mode method.

ACKNOWLEDGEMENT

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REFERENCES