Damage identification of bridge structures based on curvature mod

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Abstract. Based on the modal analysis theory of bridge dynamic characteristics, a pre-damaged reinforced concrete model beam is established by ANSYS as the object of analysis. The regularity of modal parameters such as displac, ement mode and curvature mode of the model beam at the preset damage location and different damage degree and the identification of modal parameters in structure damage are studied by finite element numerical analysis. Sensitivity. The results show that the displacement mode is difficult to identify the damage of the structure effectively, but the curvature mode can reflect the damage of the structure more accurately. The damage identification method based on the curvature mode can be applied to the damage diagnosis of the structure in practical engineering.

1. Introduction
During the operation and use of bridges, the long-term impact of various loads will continue to occur various types of damage, different damage gradually accumulated to a certain extent will have an impact on the safety of bridge structures [1]. Therefore, the detection of bridge structure location and the identification of damage degree have important research significance. The finite element numerical analysis is used to restore the original state information of the structure as much as possible, and the damage of the structure is identified by comparing it with the measured information. In this paper, ANSYS finite element analysis software is used to establish reinforced concrete beam bridge models with different crack damage conditions [2-3]. Curvature modal analysis method of bridge dynamic characteristics is used to locate structural damage location and identify damage degree. The curvature mode based on modal analysis can not only locate the damage location effectively, but also be more sensitive to local damage than displacement mode.

2. Strain mode and curvature mode theory
The displacement mode of beam body is an important parameter in the analysis of bridge dynamic characteristics. Strain mode is the first derivative of displacement mode. The distribution of strain mode corresponds to that of displacement mode one by one. Curvature mode is the deformation mode in the middle of the structure, which is the same as strain mode. According to the theory of material mechanics, the bending curvature of the beam is as follows:

\[ \rho = \frac{M}{EI} \]  \hspace{1cm} (1)
Formula: $\rho$ is curvature; $M$ is bending moment; $EI$ is Flexural rigidity.

The differential equation of beam vibration is:

$$\frac{\partial^2}{\partial x^2} \left[ EI(x) \left( \frac{\partial v(x,t)}{\partial x} + a \frac{\partial^3 v(x,t)}{\partial x^3} \right) + m(x) \frac{\partial^2 v(x,t)}{\partial x^2} + c(x) \frac{\partial v(x,t)}{\partial t} \right] = f(x,t)$$  \hfill (2)

Formula: $v(x,t)$ is transverse displacement of x axis section x at time t; $a$ is stiffness proportional coefficient; $EI(x)$ is flexural stiffness at x; $m(x)$ is quality of x; $c(x)$ is damping at x.

The stress $\sigma$ after change is:

$$\sigma = E(\varepsilon + a_1 \Delta \varepsilon)$$  \hfill (3)

Formula: $E$ is modulus of elasticity; $\varepsilon$ is initial strain; $\Delta \varepsilon$ is variation of strain.

According to the modal theory of structural dynamic characteristics, the solution $v(x,t)$ of formula (3):

$$v(x,t) = \sum_{i=1}^{n} \phi_i(x) q_i(t)$$  \hfill (4)

Formula: $\phi_i(x)$ is displacement mode shapes; $q_i(t)$ is Modal coordinates.

In the theory of material mechanics, the curvature function of an elastic beam is obtained by calculating the second derivative of the displacement function, and then the curvature change at any section x is as follows:

$$\rho(x) = -\frac{\partial^2 v(x,t)}{\partial x^2} = \rho^\sigma(x) = \sum_{i=1}^{n} \phi_i^\sigma(x) q_i(x)$$  \hfill (5)

Formula: $\phi_i^\sigma(x)$ is curvature mode shape.

When the bending deformation occurs, the curvature formula of the neutral plane in the beam body is as follows:

$$\rho(x) = -\frac{v^\prime(x)}{(1+v^\prime(x))^2} \approx v^\sigma(x)$$  \hfill (6)

It can be seen from the formula that when cracks and other local damages occur in the beam body, the dynamic structural parameters such as elastic modulus of the corresponding damaged beam body decrease, the local bending stiffness of the structure decreases, and the increase of curvature causes a sudden change in the smooth curvature modal curve without damage. According to the observed curvature modal curve, the damage of the beam body can be identified location [4-7].

The steps of solving the curvature mode of the beam are as follows:

(1) The displacement modes $\phi(r)$ of each measuring point of the beam body are measured to form the displacement mode of the beam body:

$$\phi(r) = [\phi(1), \phi(2), \ldots, \phi(r)]$$  \hfill (7)

(2) Solving the corresponding curvature mode $\rho(r)$ by central difference method for each measuring point:

$$\rho(r) = \frac{\phi(r-1) - 2\phi(r) + \phi(r+1)}{d_{r,r+1} - d_{r,r-1}}$$  \hfill (8)
Formula: $r$ is measure point; $d_{r+1}$ and $d_{r-1}$ represents the distances between adjacent measuring points $r$, $r+1$ and $r-1$, respectively.

(3) The curvature modes of the beam are as follows:

$$P(r) = [\rho(1), \rho(2), \ldots, \rho(r)]$$

(9)

3. Finite Element Model of Pre-Damaged Reinforced Concrete Beams

The pre-damaged reinforced concrete model beams are 7 meters long, 0.3 meters wide and 0.5 meters high, respectively. The strength grade of concrete is C60, and the density is $3 \times 10^3$ kg/m$^3$. The thickness of concrete protective layer is 0.5 meters, two compressive longitudinal bars are 25, three tension longitudinal bars are 25, stirrups are 9, the spacing of stirrups is 0.15 meters, the elastic modulus of steel bars is 200 GPa, and the density is $8 \times 10^3$ kg/m$^3$. Poisson's ratio is 0.25.

Beam damage is a transverse crack with a width of 2 mm precast along the beam height at the bottom of 1/4 span, 1/8 span, 1/2 span, 3/4 span and 3/8 span. The crack depth is 5%, 10%, 15%, 20%, 25%, 30%, respectively, i.e. 0.025 m, 0.05m, 0.075 m, 0.1 m, 0.125 m and 0.15m (case 1-case 5), finite element model and beam damage. The cross section is shown in Figures 1 and 2.

3.1. Displacement Modal

The first five displacement modes of reinforced concrete beams under non-destructive condition are shown in figure 3.
In the displacement mode diagram shown in Figure 3, the displacement mode deformation of each node at the same height and the same horizontal position is the same. The minimum preset damage of the model beam is 5% of the beam height. Therefore, the displacement mode is extracted as the displacement variation of the second layer of the model layer, that is, the displacement of 49 nodes at 0.0125 position from the bottom of the beam. The distance between the two nodes in the model is 0.15 meters. The displacement modes under different damage states are shown in Fig. 4.

(a) First-order displacement mode shapes  (b) Second-order displacement mode shapes

(c) Third-order displacement mode shapes  (d) Fourth-order displacement mode shapes

(e) Fifth-order displacement mode shapes

Fig. 3 The displacement modes
From the displacement mode shapes of different damage states in Fig. 4, it can be seen that the coincidence degree of displacement mode shapes is better. Only in the fifth-order displacement mode shapes, slight changes of displacement mode and non-destructive state can be seen under different damage conditions, but it can’t accurately reflect the existence of structural damage, nor can the location of damage be judged. Displacement modes can’t reflect the structural damage sensitively, nor can they accurately identify the structural damage of reinforced concrete girder bridges by relying solely on displacement modes.

3.2. Curvature Mode Shape

The displacement mode shapes obtained from the above finite element analysis are calculated according to the formula (7) ~ (9) and the corresponding curvature mode shapes under different damage degrees are calculated according to the solving steps of the curvature mode of the beam. The fifth order curvature mode shapes under five damage degrees are shown in Fig. 5.
From the curvature mode shapes obtained by the above finite element numerical simulation, it can be seen that: (1) the curvature mode shapes at different damage locations have obvious abrupt changes on both sides of the damage location. The abrupt change of the mode shapes at the damage location reaches the maximum, and the abrupt change increases with the deepening of the damage degree, and the curvature mode energy. It can better reflect the damage location and degree of structural damage. (2) The first-order curvature modes fluctuate dramatically in the midspan, while the higher-order curvature modes do not. It can be seen that the order selection of modal modes is very important for judging the damage of structures, besides considering the arrangement of measuring points, in the damage diagnosis of vibration systems of bridge structures. Important role. (3) The sudden change direction of the curvature mode is consistent with the peak direction of the order mode. The local damage of the structure results in the decrease of the local stiffness of the structure, which leads to the increase of the curvature...
of the damage location. Similarly, the strain at the damage location increases significantly due to the stress concentration, so the direction of mode change is consistent with the peak value change at the mutation location.

4. Conclusion
The results of curvature modal analysis of reinforced concrete beams under different damage conditions show that:

(1) The damage degree of displacement modal structure of reinforced concrete finite element model beams increases and shows a small change rule. It is difficult to measure in actual engineering monitoring. When the damage amount is large enough, some displacement modal modes at different damage locations of model beams are slightly distorted. It is also difficult to identify the damage of the bridge structure, which further proves that the displacement modes are insensitive to the damage of the structure, that is, the structural damage can’t be effectively identified by the displacement modes.

(2) The curvature mode has a sudden change at the structural damage, which can identify the location of the preset damage more accurately, and the mode distortion increases with the increase of the damage degree of the structure. The direction of the sudden change of mode shape is the same as the corresponding peak direction of the second mode. In engineering practice, in order to obtain more accurate results in structural damage identification, high-order modal modes are reasonably selected according to different damaged parts of the tested structure. As far as possible, it is avoided to select modal modes located at modal nodes to identify structural damage.

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