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Research on Damage Identification of Reinforced Concrete Cantilever Beams Based on Dynamic Response Characteristics

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Abstract: Structural damage identification based on dynamic response characteristics has become an important approach in structural health monitoring because of its high efficiency, non-destructive nature, and practical applicability. In this study, a reinforced concrete cantilever beam was selected as the research object to investigate the effectiveness of vibration mode and curvature mode methods for damage identification. A three-dimensional finite element model was established in ABAQUS, and one intact beam together with four damage scenarios of different damage extents were simulated by reducing the elastic modulus within the damaged region. The first three natural frequencies and corresponding mode shapes were extracted, and damage identification was carried out by comparing the changes in vibration modes and curvature modes between the intact and damaged beams. The simulation results indicate that the natural frequencies decrease gradually with increasing damage severity, allowing qualitative assessment of structural damage. Although the vibration mode difference method can roughly identify the damaged region, its sensitivity to local stiffness degradation is limited and it cannot accurately determine the damage location or extent. In contrast, the curvature mode method exhibits significantly higher sensitivity to local stiffness changes and provides more accurate localization of the damaged area under different damage conditions. The results demonstrate that curvature-based damage identification is more reliable and effective than conventional mode shape comparison for reinforced concrete cantilever beams. This study provides a theoretical basis and numerical reference for vibration-based structural health monitoring and damage assessment of reinforced concrete structures.

Keywords: Reinforced concrete cantilever beam; Structural health monitoring; Damage identification; Modal analysis; Finite element analysis

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1. Introduction

Structural health monitoring technology has always been a topic that attracts the attention of scholars both at home and abroad. The structural damage identification method based on dynamic characteristics has become a hot topic of current international academic and engineering research due to its practicality, rapidity and simplicity [1].

Zeng conducted a finite element analysis on a beam, calculated the displacement modes, and used the central difference method to calculate the curvature modes based on the displacement modes, confirming that the curvature modes are a good damage identification indicator [2]. Abdel et al. studied the application of modal curvature changes in the detection of prestressed concrete bridges [3]. Using simulated data, tests were conducted on simply supported beams and continuous beams with damaged components at different positions, and a damage indication marker called "curvature damage factor" was introduced. This technology was further applied to actual structures. Peng Hua et al. verified the method using a standard beam example [4]. The example showed that this method has accurate identification capabilities for the location and degree of damage to the structure. Based on this, according to two linear assumptions, a simple and effective calculation method for evaluating the structure's lifespan was proposed. Through in-depth research on curvature, it was applied to more practical engineering projects [5,6]. Chen Hai et al., based on matrix perturbation theory, expressed the mass matrix and stiffness matrix of the structure as functions of element damage parameters, and proposed a method for structural damage identification based on frequency and mode perturbation [7]. Zhang Jin et al., through theoretical analysis, discovered and pointed out that the curvature mode difference indicator also has two shortcomings: one is that it is not sensitive enough to damage at the curvature mode nodes, and the other is that it cannot effectively reflect the degree of damage [8]. Therefore, the curvature mode difference indicator was improved, and a superimposed curvature mode change rate indicator was proposed, which theoretically overcame the shortcomings of the original indicator. Domestic and foreign scholars have achieved certain research results in damage identification using curvature [9-12], but they are still limited by the specific application scope and shortcomings of each indicator, and lack a universal and effective damage quantification indicator. This study takes the reinforced concrete cantilever beam as an example to investigate the applicability and accuracy of the vibration mode and curvature mode identification methods, in order to serve the algorithm analysis and innovation related to damage identification in subsequent engineering.

2. Numerical design of reinforced concrete cantilever beam

2.1. Parameter design of cantilever beam

The basic parameters of the reinforced concrete cantilever beam: the span is 4m, the section size is 250 mm × 500 mm, the concrete strength is C30, the reinforcement ratio is 2.357%, the steel grade is HRB400, and symmetrical reinforcement is adopted. The spacing of the dynamic measurement points is set at 40mm. The material properties are shown in **Table 1** and **Table 2**. The specific setting of the damage conditions is detailed in 2.2 below [6].

Table 1. Characteristics of concrete materials for cantilever beams

Concrete cube compressive strength f_{cu} (MPa)	Elastic modulus E_c (MPa)	Poisson's ratio μ
30	24000	0.20

Table 2. Characteristics of reinforcement materials for cantilever beams

Project	Longitudinal reinforcement bars		Transverse stirrup
	Under tension	Under pressure	
Poisson's ratio μ	0.25	0.25	
E_s (MPa)	2×10^5	2×10^5	
f_t (MPa)	360	360	210

2.2. Damage condition setup

To investigate the damage caused by loading, four damaged beams were designed based on the bending moment-curvature relationship of the test piece during its service period. Each beam represents different degrees of damage and different damage ranges at the cracking stage, and the damage positions are set at 20% of the distance from the fixed end of the beam.

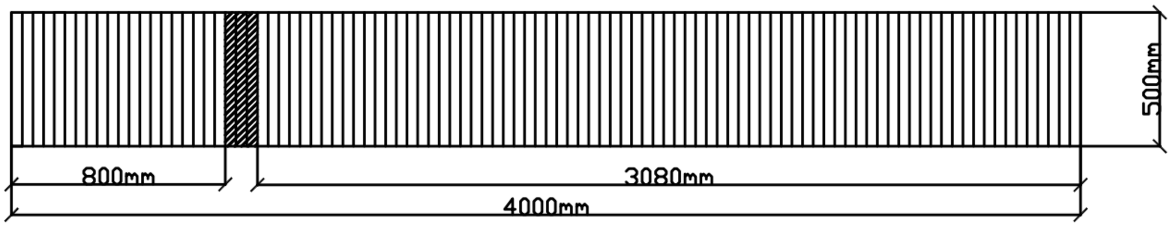


Figure 1. Schematic diagram of damage setting for the cantilever beam condition 1.

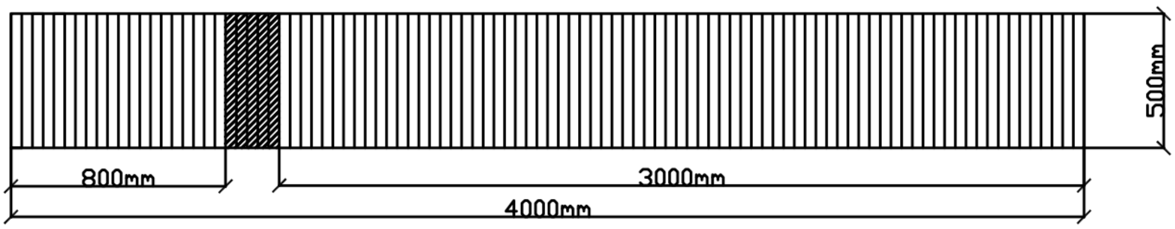


Figure 2. Schematic diagram of damage setting for the second case of the cantilever beam condition.

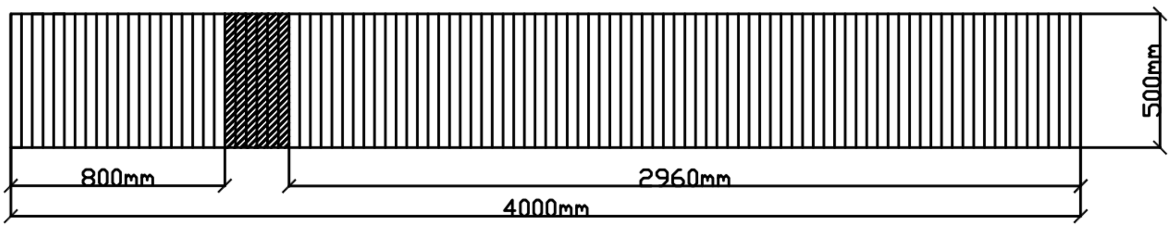


Figure 3. Schematic diagram of damage settings for the cantilever beam condition 3.

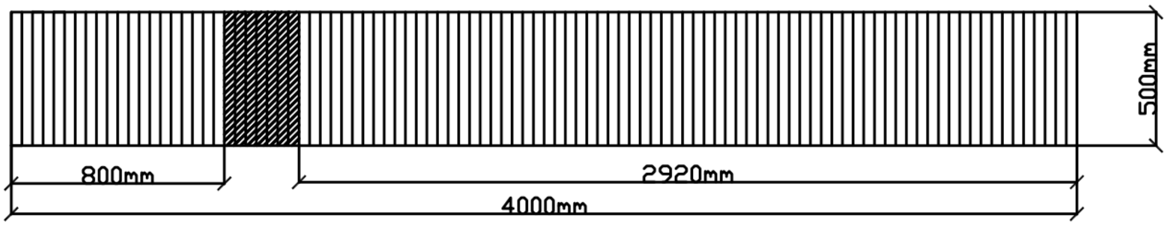
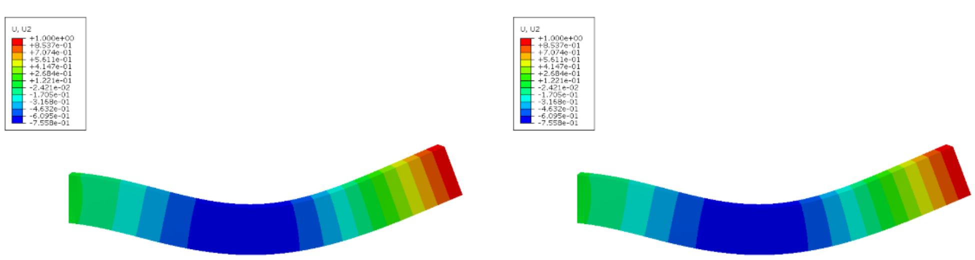


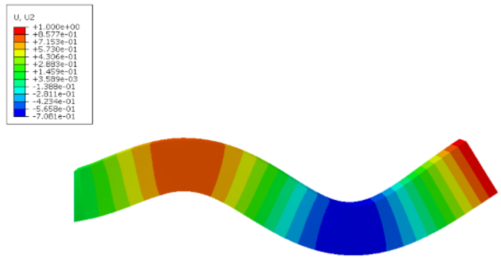
Figure 4. Schematic diagram of damage settings for the cantilever beam condition 4.

There are also 100 units in the length direction of the component. The damage of the cantilever beam occurs at the 20% position of the beam, that is, starting from the 21st unit, the damage is set.

For different damage conditions, the width of the damage zone and the degree of damage vary. As shown in **Figure 1**, in the length direction, this damage zone occupies 3 unit lengths, and the length of the damage zone is 120 mm. When the structure fails, the damage closer to the fixed end reaches yield and failure first. Assuming the failure starts from the 21st unit, the maximum stiffness reduction is set at the corresponding stiffness reduction value of 25%Mn. Then, a relatively smaller stiffness damage is set at the 22nd unit, set at 13%, and then decreases successively. The 23rd unit is set at 10%. In **Figure 2**, the damage zone occupies 5 unit lengths, and the length of the damage zone is 200mm. The damage setting process is the same as that in condition 1, and the maximum damage reaches the stiffness change corresponding to condition 2. In the 21st unit, the stiffness reduction is set at 22.05%, and then the stiffness reduction is set at 20.41% in the adjacent unit 22, 18% in the 23rd unit, 15% in the 25th unit, and 10% in the 26th unit. In **Figure 3**, the damage zone occupies 6 unit lengths, and the length of the damage zone is 240mm. The unit stiffness reduction is set as follows: in the 21st unit, 21.76% is set; then the stiffness reduction is set at 20.41% in the adjacent unit 22, 18% in the 23rd unit, 15% in the 24th unit, 13% in the 25th unit, and 10% in the 26th unit. In **Figure 4**, the damage zone occupies 7 unit lengths, and the length of the damage zone is 280mm. The unit stiffness reduction is set as follows: in the 21st unit, 22.14% is set; then the stiffness reduction is set at 22.05% in the adjacent unit 22, 21.76% in the 23rd unit, 20.41% in the 24th unit, 18% in the 25th unit, 15% in the 26th unit, 13% in the 27th unit. The finite element simulation is shown in **Figure 5**. After setting the boundary conditions, the healthy cantilever beam is simulated to obtain the first three modal shapes.



(a) First-order modal shape (b) Second-order modal logic



(c) Third-order mode

Figure 5. The first three vibration modes of the healthy cantilever beam in the finite element model.

3. Analysis of damage identification methods

From **Table 3**, it can be seen that for the reinforced concrete beam, the frequency calculated by ABAQUS finite element simulation is compared with the theoretical value. The relative error of the first-order natural frequency of the intact beam calculated by ABAQUS is 0.58% compared with the theoretical value; the relative error of the second-order natural frequency is 1.81%, and the relative error of the third-order natural frequency is 2.35%. This indicates that the established model is accurate and can be used for damage identification.

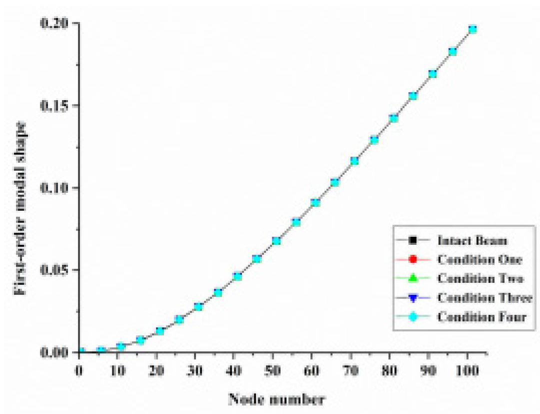
As the degree of damage increases, the damaged area expands, the overall stiffness of the structure decreases, and the natural frequency drops. The initial damage of the reinforced concrete beam can be qualitatively determined through the frequency, but it cannot indicate the location of the damage (positioning) or the degree of damage (quantification) of the structure.

Table 3. Measurement results of cantilever beam frequency

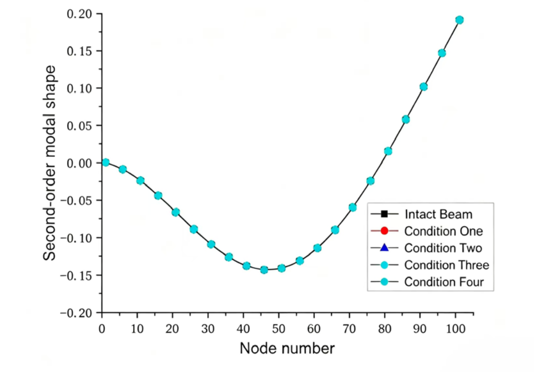
Frequency	Theoretical value (Hz)	Intact Beam (Hz)	Condition 1 (Hz)	Condition Two (Hz)	Condition 3 (Hz)	Condition 4 (Hz)
First-order frequency	19.176	19.288	19.093	19.012	18.927	18.874
Second-order frequency	120.175	122.35	121.75	121.42	121.06	120.86
Third-order frequency	336.493	344.41	343.19	342.68	342.24	342.08

3.1. Damage identification analysis based on mode changes

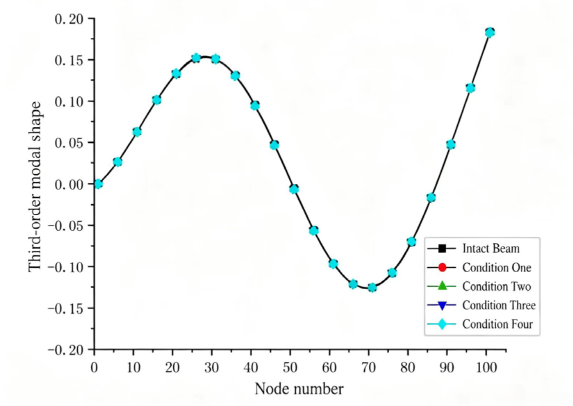
By comparing the vibration modes of the damaged test beams with those of the intact structure, it can be observed from the first three modes of **Figure 6** and **Figure 7** that the peak positions of each order in the four different conditions have corresponding positional relationships.



(a) First-order vibration mode



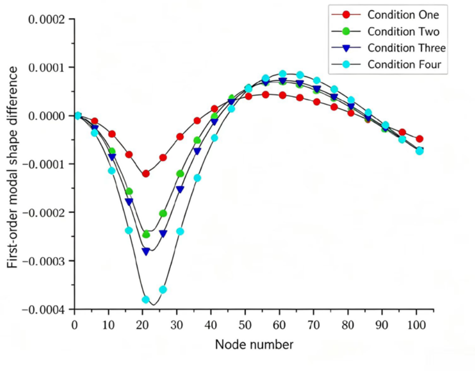
(b) Second-order vibration mode



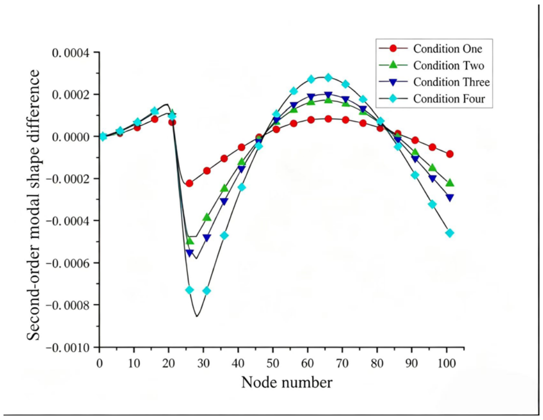
(c) Third-order vibration mode

Figure 6. Fingerprints of the third-order vibration mode of the cantilever beam under various conditions.

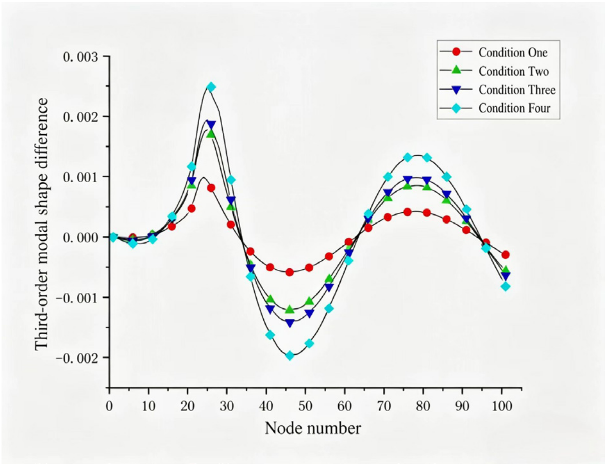
In the first-order mode difference, it can be observed that all four damage conditions point to the same location, demonstrating a good damage identification effect. The second-order mode difference provides the same damage indicators, all within the same range. Its peak point is shifted further towards the free end compared to the first-order mode difference, because as the damage increases, cracks also keep increasing, so the damage range becomes larger and its peak point keeps moving. From the third-order mode difference, it can be seen that the trend is also moving towards the free end, presenting the same situation as the first and second-order mode differences. Therefore, based on the displacement mode change, the damage location can be identified, but it cannot accurately identify the specific location. It can only provide a reference position, knowing that there is damage within this large range, and relative to this, the damage size can be compared. It is difficult to detect the difference between the steel bar elastic modulus locally decreasing beam and the intact beam from the displacement mode vibration pattern. That is to say, the displacement mode vibration pattern and the strain mode vibration pattern are not sensitive to this type of damage where the local elastic modulus of the steel bar decreases. Therefore, it is necessary to use other sensitive parameters to distinguish this type of damage from cases where the local elastic modulus of the steel bar decreases.



(a) First-order mode difference



(b) Second-order mode difference

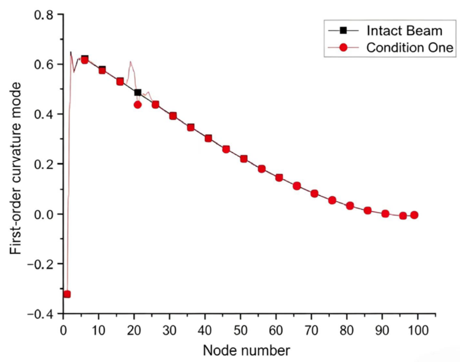


(c) Third-order mode difference

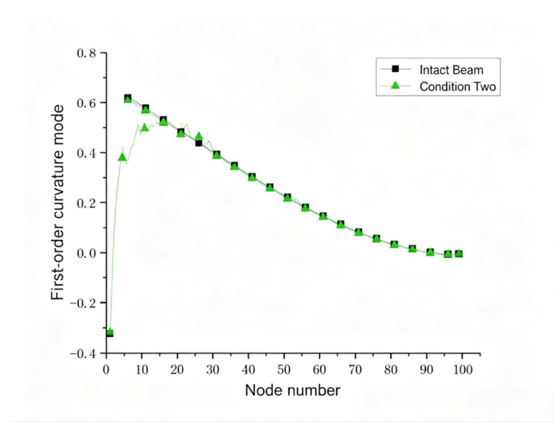
Figure 7. Third-order mode differences of the cantilever beam under various conditions.

3.2. Damage identification analysis based on curvature changes

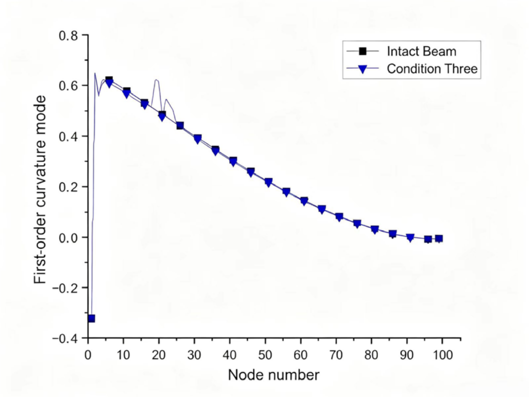
When the structure suffers from damage, the curvature mode will undergo corresponding changes at the damaged location. Using ABAQUS, the displacement modes of the cantilever beam in the healthy state and under different damage conditions can be extracted. Then, by fitting, the discrete points can be plotted to form mode curves. Subsequently, through Euclidean normalization, the displacements can be normalized, and the curvature can be calculated using the central difference method. Finally, a comparative analysis can be conducted to make the damage zone more clearly visible. As shown in **Figures 8–10**.



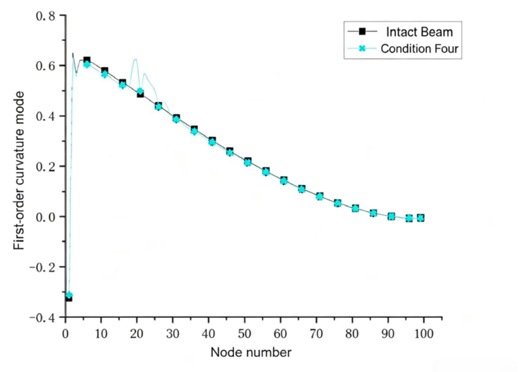
(a) Condition One



(b) Condition Two

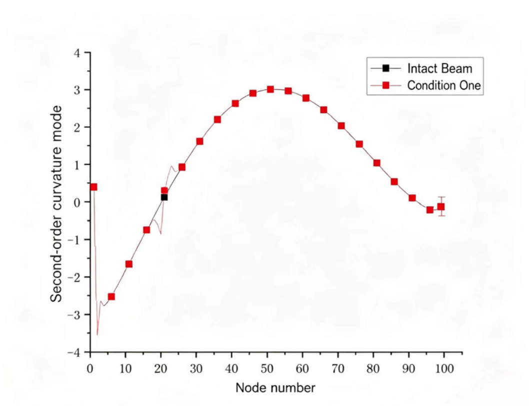


(c) Condition 3

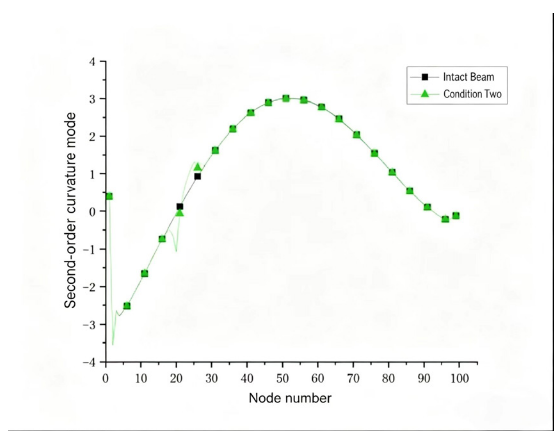


(d) Condition 4

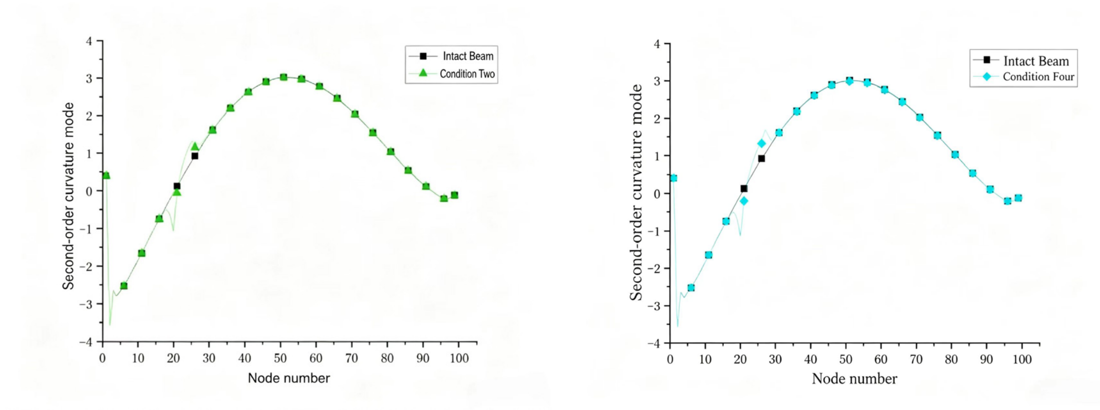
Figure 8. Comparison of the first-order curvature mode shapes of the damaged beam and the healthy beam under various conditions.



(a) Condition One

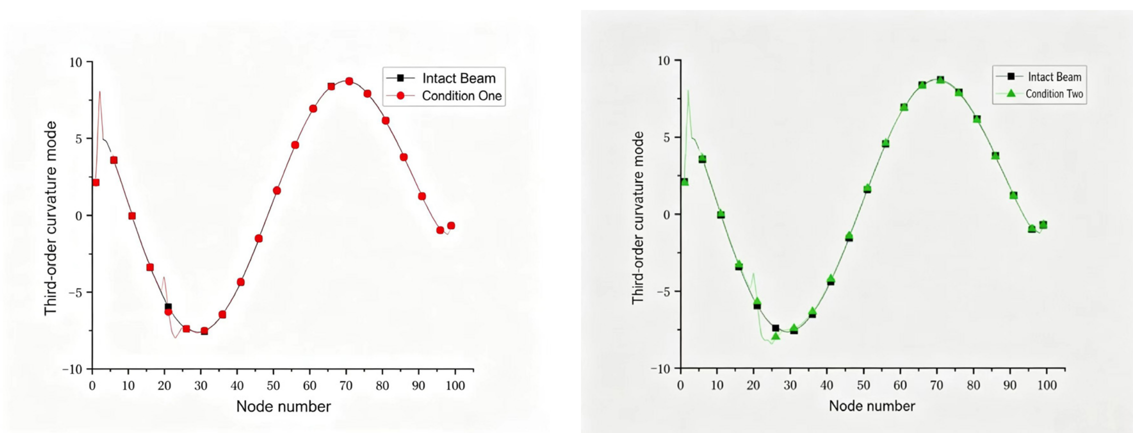


(b) Condition Two

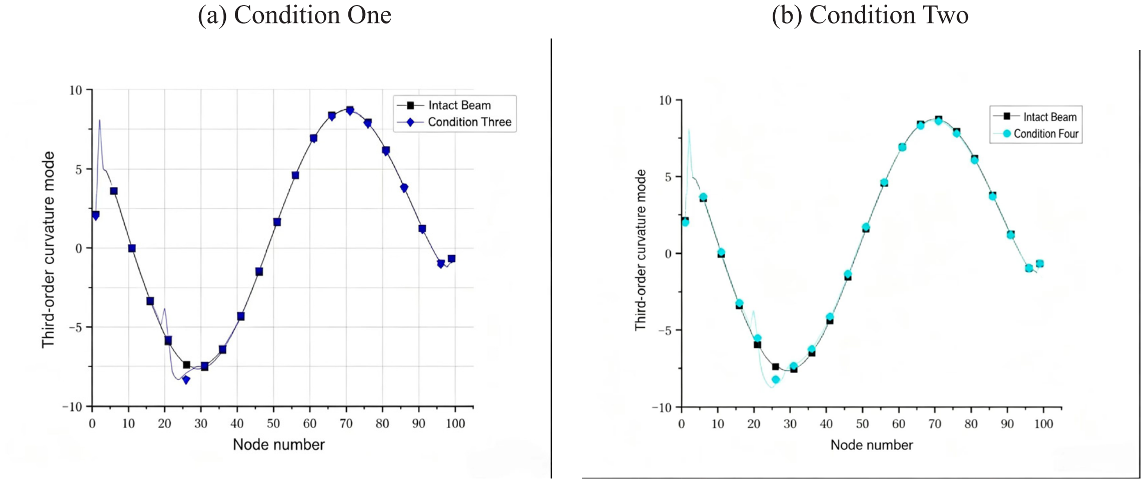


(c) Condition 3 (d) Condition 4

Figure 9. Comparison of the second-order curvature mode shapes of the damaged beam and the healthy beam under various conditions.



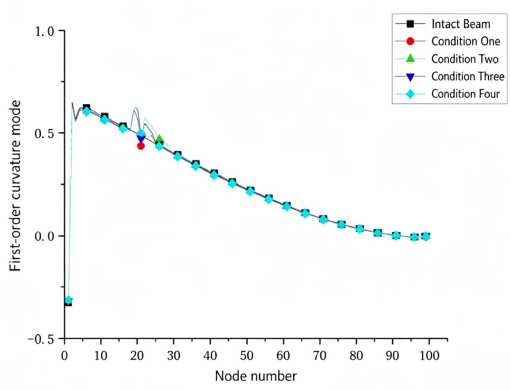
(a) Condition One (b) Condition Two



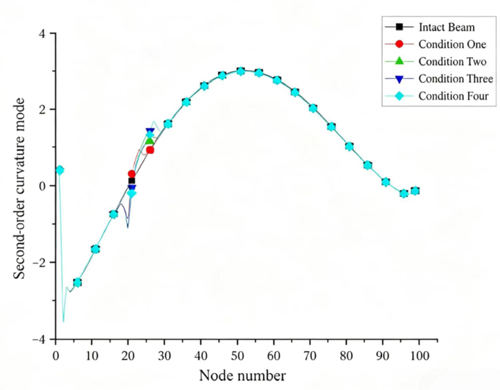
(c) Condition 3 (d) Condition 4

Figure 10. Comparison of the third-order curvature mode shapes of the damaged beam and the healthy beam under various conditions.

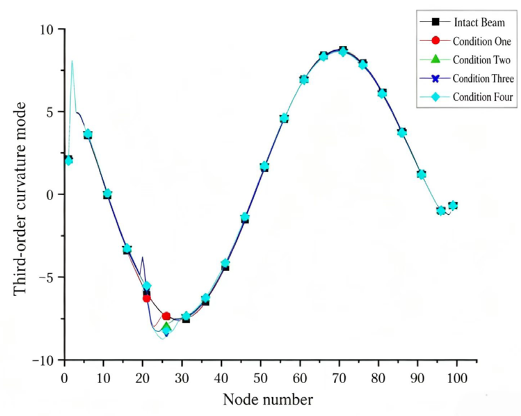
For the location of the damage, in conditions 2, 3 and 4, the first-order curvature mode indicated the damage zone from node 19 to node 24, while condition 1 gave a damage zone of nodes 19 to 21. Considering the rapid change in stiffness, the damage change of the 21st unit was covered by that of the 20th unit, making it less obvious. Therefore, the curvature change at node 22 was very small and there was no significant sudden change. In the second-order curvature mode, the damage zone indicated by the damage area was 20–23, 20–25, 20–26, and 20–27. The starting points of the damage zone were different from the first-order, and it showed the change of the damage zone, as shown in **Figure 11(b)**. It can be seen that the change of the damage area was very obvious. In the third-order curvature mode, the damage zones discriminated for the four conditions were 20–23, 20–25, 20–26, and 20–28, which were more precise in damage location compared to the actual damage position.



(a) First-order curvature mode



(b) Second-order curvature mode



(c) Third-order curvature mode

Figure 11. Comparison of the first three curvature mode shapes of the damaged beam and the healthy beam under various conditions.

As can be seen from **Figure 11**, in the first curvature mode, the damage at the center of the beam is relatively small. This is because at this time, the beam has just cracked and the degree of damage is relatively small. As the damage increases, when it reaches damage condition two, it indicates that the cracks of the beam are continuously expanding and the degree of damage gradually increases. The curvature test results show that a large amount of damage has occurred in the beam span, and the curvature mode values have increased, indicating a very obvious development of the damage.

4. Conclusion

This study conducted a modeling of the cantilever beam, setting up a healthy beam and four different damage conditions, with varying degrees and all located at 20% of the length from the fixed end of the structure. Through the reduction of the elastic modulus, the damage degree was simulated. Two different damage identification methods that are relatively easy to implement in engineering were used for damage identification, analysis, and evaluation. The main conclusions are as follows:

(1) For the reinforced concrete cantilever beam structure, the frequency can also effectively identify whether it has suffered damage, so the frequency can also be used as a qualitative indicator for damage identification.

(2) The mode shape change method is not sensitive to the damage of the reinforced concrete beam structure and cannot locate the damage. The curvature mode is very accurate for damage identification and can stably indicate the range of the damage location.

Disclosure statement

The authors declare no conflict of interest.

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