Research on Single Damage Identification of Multi-span Bridge Based on Influence Line

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Abstract: Bridges are an important part of traffic engineering. They play an irreplaceable role in developing national economy, promoting cultural exchanges and consolidating national defense. The structural safety of bridges is the primary prerequisite for their role. However, due to the influence of many factors such as material aging, external environmental corrosion, long-term load action and accidental impact, the bridge structure will be damaged to different degrees, and the bridge will be destroyed when the damage accumulates to a certain degree. Once the bridge is damaged, it will have a great negative impact on human life safety, property safety, and social stability. Therefore, studying the method of rapid and accurate identification of bridge structure damage has great theoretical significance and engineering value. Based on the current status and existing problems of existing bridge structure damage identification, this paper proposes a continuous beam bridge structure damage identification technology based on deflection influence lines. Firstly, using graph multiplication and other theories, the expression of influence line function on the deflection of multi-span continuous beam bridge is derived. The influence line function of continuous beam bridge without structural damage is derived from the theoretical level, and the graph is drawn. Through the formula of the deflection influence line of healthy structure, it can be confirmed that the deflection influence line obtained quickly under the visual tracking technology can identify the damage of the structure. We use software modeling to find the best identification parameters. Using MIDAS/Civil software can establish the model and simulate the deflection influence lines of different measuring points of continuous beam bridge structures with different positions and different degrees of damage under the action of moving loads. Taking the continuous beam bridge deflection influence line, the difference between the deflection influence line of the first derivative and the second derivative, the first derivative and the second derivative and other parameters as the research objects, we explore how to use the deflection influence line to identify damage. Finally, after the comparison of multiple working conditions and multiple measuring points, it is found that the damage identification effect of the first derivative of the deflection influence line difference is the best.

1. Introduction
As an important transportation infrastructure, bridges have a relatively long service period, at least more than fifty years, and the period is gradually increasing [1]. Under the combined action of various factors such as the environment, raw materials, and fatigue effects, the function of each structure of the bridge is damaged, and even more serious, it will cause catastrophic accidents [2]. As of the end of 2016, there are 830,000 highway bridges in my country, so there is an urgent need for fast and accurate structural damage identification methods to identify domestic bridges. The same is true in other countries. The United States currently has approximately 690,000 bridges, of which more than 50% have a service life
of more than 50 years. Only rapid and accurate structural inspection methods can solve the urgent need for bridge inspection.

In the research on bridge damage identification, Kou Xiaonan [3] applied the deflection influence line (including its first and second derivatives) to the field of structural damage identification for the first time. She applied the theory of mechanics to numerically analyze the simply supported beam model of reinforced concrete, so as to obtain the deflection influence line of the simply supported beam and its first derivative and second derivative. Then ANSYS was used for finite element modeling and analysis, and finally verified by experiments. It was concluded that the deflection influence line can identify the existence of damage, and at the same time, it can identify the degree of damage very weakly. Liu Yunshuai [4] chose the deflection difference influence line as the basis for identifying damage. Taking a simply supported beam as an example, he first theoretically derived the analytical formula of the influence line of the deflection difference of the simply supported beam before and after one point damage, and then further solved the curvature of the influence line. He also proposed a symmetrical loading scheme to eliminate errors caused by the finite element model. The curvature of the influence line of the deflection difference is more sensitive to damage identification and is a good identification index. Jia Yaping [5] established indicators for continuous beam bridge structural damage identification based on deflection influence lines: deflection difference influence line, first derivative and second derivative of deflection difference influence line, and second derivative of deflection influence line. Then, a three-span simulation connecting beam of an aluminum alloy plate was used to verify that these four indicators can identify whether there is damage and the location of damage. This paper adopts the method of theoretical derivation and experimental verification. Based on the related theory of deflection influence line and calculation basis, the calculation method of multi-span continuous beam deflection influence line is proposed. Through MIDAS/Civil modeling, the deflection influence line (and its first derivative, second Derivative) and the existence of damage, damage location and degree of damage to carry out the correlation study, we use the influence line (and its first derivative, second derivative) to inversely infer the beam’s damage location and degree, and obtain the structural damage identification system of the index of the deflection influence line (including its first derivative and second derivative), and the theory is verified by using the plexiglass board simulation test.

2. The theoretical deflection influence line equation of continuous beam under damage

2.1. Calculation model related parameters
Take (as shown in Figure 1) two-span continuous beam as the theoretical research object, with a span of 160cm, the left end support is a fixed hinge support, and the rest are sliding hinge supports. The deflection influence line equations of the model under healthy and damaged conditions are derived.

![Continuous Beam Model](image)

**Figure 1 Experimental model**

2.2. Deflection influence line equation under the condition of no structural loss
Taking the second-span mid-span section of the laboratory model as an example, the theoretical derivation of the influence line of the non-destructive deflection of the continuous girder bridge is carried out. As shown in Figure 2, for two equal-span continuous beams, the calculation section of the
influence line is the middle span of the second span. A unit force (F=1) acts on the structure, and the distance from F to the left of the structure is x.

![Figure 2 M Figure](image)

**Situation 1:** When the unit load is applied to the first span, the center of gravity of zone 1 and zone 2 is in the second section of the equation.

\[
\Delta = \frac{1}{EI} \left[ \frac{x^2 \cdot (1.6 - x)}{3.2} \cdot \frac{1.5}{16} \cdot \frac{2}{3} x + \frac{x \cdot (1.6 - x)^2}{3.2} \cdot \frac{1.5}{16} \cdot \left( \frac{2}{3} x + \frac{1.6}{3} \right) \right] \quad (1)
\]

It should meet
\[
\begin{align*}
1.6 &< \frac{2}{3} x + \frac{1.6}{3} \leq 2.4 \\
1.6 &< \frac{2}{3} x + \frac{3.2}{3} \leq 2.4
\end{align*}
\]

leading to \(1.6 < x \leq 2\)

**Situation 2:** When the unit load is applied to the second span, the position of the center of gravity of area 1 and 2 will be discussed separately.

(1) When the center of gravity is all in the second equation (\(y = -0.59375 x + 1.1\))

It should meet
\[
\begin{align*}
1.6 &< \frac{2}{3} x + \frac{1.6}{3} \leq 2.4 \\
1.6 &< \frac{2}{3} x + \frac{3.2}{3} \leq 2.4
\end{align*}
\]

leading to \(1.6 < x \leq 2\)

\[
\Delta = \frac{1}{EI} \left[ \frac{\left(x-1.6\right)^2 \cdot \left(3.2 - x\right)}{3.2} \left(1.1 - \frac{0.59375 \cdot \left(\frac{2}{3} x + \frac{1.6}{3}\right)}{3.2}\right) + \frac{\left(x-1.6\right) \cdot \left(3.2 - x\right)^2}{3.2} \cdot \left(0.1 - \frac{0.59375 \cdot \left(\frac{2}{3} x + \frac{3.2}{3}\right)}{3.2}\right)\right] \quad (3)
\]

When the center of gravity of Zone 1 is in the second section of the equation (\(y = -0.59375 x + 1.1\)),

The center of gravity of region 2 is in the third section of the equation (\(y = 0.40625 x - 1.3\))

It should meet
\[
\begin{align*}
1.6 &< \frac{2}{3} x + \frac{1.6}{3} \leq 2.4 \\
2.4 &< \frac{2}{3} x + \frac{3.2}{3} \leq 3.2
\end{align*}
\]

leading to \(2 < x \leq 2.8\)

\[
\Delta = \frac{1}{EI} \left[ \frac{\left(x-1.6\right)^2 \cdot \left(3.2 - x\right)}{3.2} \left(1.1 - \frac{0.59375 \cdot \left(\frac{2}{3} x + \frac{1.6}{3}\right)}{3.2}\right) + \frac{\left(x-1.6\right) \cdot \left(3.2 - x\right)^2}{3.2} \cdot \left(0.40625 \cdot \left(\frac{2}{3} x + \frac{1.6}{3}\right) - 1.3\right)\right] \quad (5)
\]

(3) When the center of gravity of Zone 1 and Zone 2 are both in the third section of the equation (\(y = 0.40625 x - 1.3\)), it leads to \(2.8 < x \leq 3.2\).

**Deflection**

\[
\Delta = \frac{1}{EI} \left[ \frac{\left(x-1.6\right)^2 \cdot \left(3.2 - x\right)}{3.2} \cdot \left(0.40625 \cdot \left(\frac{2}{3} x + \frac{1.6}{3}\right) - 1.3\right) + \frac{\left(x-1.6\right) \cdot \left(3.2 - x\right)^2}{3.2} \cdot \left(0.40625 \cdot \left(\frac{2}{3} x + \frac{3.2}{3}\right) - 1.3\right)\right] \quad (6)
\]
They use matlab to draw the function image of the theoretical deflection influence line, and the results are shown in Figure 3. When calculating the deflection influence line of the continuous beam in the case of damage, the bending stiffness $EI$ of the damaged section is reduced to $EI'$. The calculation process is the same, when it comes to the damaged section, it is multiplied separately. The theoretical derivation of the deflection influence line has the following law:

1. The deflection influence line has a cubic relationship with the moving load position $x$ at any section of the continuous beam, and the deflection influence line is continuous throughout the continuous beam structure.
2. The deflection influence line of continuous beam is directly affected by the bending stiffness $EI$, and the difference of the deflection influence line will directly reflect the change of the bending stiffness $EI$.

3. Research on identification of damage influence line of continuous beam deflection with single damage under ideal conditions

Taking the two-span continuous beam as shown in Figure 1 as the research object, Midas Civil is used to conduct the deflection influence line of the continuous beam bridge under normal conditions and key parts damage. The measuring points are respectively arranged on 1/4 point, mid-span and 3/4 point of the first and second spans. Collect and process the deflection data of key positions (1/4 of the first span, middle of the first span and 3/4 of the first span) to prove the correctness of the theory and practical applicability. We carry out the ideal model simulation (that is, define a single-point dynamic load acting on the continuous beam), the continuous beam is shown in the figure. The span of the two spans is 1.6m, and the local structure is shown in the figure. The specific research is divided into single-location damage recognition and multi-location damage recognition.

3.1. Single damage model establishment

As shown in Figure 1 for the continuous beam structure, the idealized model is that the unit load acts on the center line of the beam. Setting the structure type to X-Z plane can simplify the design process. In order to simplify the model, the material directly selects C50 concrete under the JTG3362-18 (RC) specification, concrete elastic modulus $E = 3.45 \times 10^4 \text{kN/mm}^2$, Poisson's ratio $\mu = 0.2$, and linear expansion coefficient $\alpha = 1 \times 10^{-5}/\degree C$. Add two sections, named "Normal" and "Damage". Both select solid-web rectangular section, the size of the section is 100mm*100mm. The numerical model has 321 nodes, 320 elements and boundary conditions and schematic diagrams.
The flexural rigidity of the normal material is $EI$, and the flexural rigidity of the damaged material is $EI^* \alpha$ ($\alpha$ is the reduction factor). In the Midas Civil model, the damage part only changes $I_y$ to simulate the loss.

Boundary conditions are applied at nodes 1, 161, and 321 respectively. Node 1 is a fixed hinge bearing that restricts displacement in the x and z directions, and points 161 and 321 are sliding hinge supports that only restrict displacement in the z direction.

After the boundary conditions are set, the load is arranged. In order to simplify the calculation, only one lane is arranged. No track surface is involved, so only lane lines are arranged. Run after setting the load, that is, moving load, and observe the deflection influence line.

Considering that the continuous beam bridge is damaged in multiple locations in actual engineering, 15 kinds of working conditions are numerically simulated. The damage simulations are carried out on the key positions of the continuous beams. Since the two equal-span continuous beams in the test model are symmetrical, the damage simulations are carried out only on the half-span.

The degree of damage is divided into 4 levels: 10%, 20%, 30%, and 50%. The specific working conditions are shown in Tables 1. Condition 1 represents damage occurred at 35-45 cm from the left end of the beam (as shown in Figure 5), condition 2 represents damage occurred at 75-85 cm from the left end of the beam (as shown in Figure 6), and operating condition 3 represents the damage is 115-125 cm from the left end of the beam (as shown in Figure 3-4). Each working condition continues to subdivide according to the degree of damage.

Table 1 Damage condition 1

| Condition number | condition 1-1 | condition 1-2 | condition 1-3 | condition 1-4 | condition 1-5 |
|------------------|---------------|---------------|---------------|---------------|---------------|
| Damage number    | 1             | 1             | 1             | 1             | 1             |
| Damage percentage| 0             | 10%           | 20%           | 30%           | 50%           |
| Damage section   | The area near the 1/4 section of the first span (35-45 cm) |
3.2. Research on deflection influence line and its first derivative and second derivative

3.2.1 Structural damage identification of deflection influence line
The deflection influence line refers to a graph showing the law of deflection change when a unit concentrated load (usually vertical downward) with a constant direction moves along the structure. We compare the deflection influence line curve (shown in Figures 3-5~3-6) obtained by collecting the deflection at the first span of the 1/4 measuring point of the continuous beam model under Working Condition 1 and Working Condition 2 and obtain some laws.
It can be seen from the figure that the influence of various degrees of damage on the deflection line of influence is minimal, the images of working condition 1-1 to working condition 1-5 almost overlap, and the images of working condition 2-1 to working condition 2-5. The same is true. It shows that when the measuring point of the structure is fixed, when the damage degree of a position on the continuous beam increases within the degree of no damage, it has almost no influence on the deflection influence line.

When the damage position is variable, it is shown in Figure 3-5. The damage position of condition 1 is near the first span 1/4 point (34-45cm section), and the damage position of condition 2 is near 1/2 point of the first span (75-85cm section). However, the deflection influence lines under the two working conditions almost coincide, and the trends and values are approximately equal. And when only the curve under a single working condition is studied, the information reflected by the image peak to a large extent is the position of the measuring point. Therefore, the deflection influence line of continuous beam bridge structure has no direct research significance for the identification of structural damage location.

3.2.2 Structural damage identification with first derivative of deflection influence line
Put the deflection influence lines of the structure at the same damage location and different damage levels into the same coordinate system for comparison. When the degree of structural loss is different, the image of the first derivative of the deflection influence line is slightly different. Take the first derivative image of the deflection influence line of 1/4 measuring point under working condition 1, as an example, observe from the left end of the beam. The first derivative of the deflection influence line obtained under the condition of greater damage is smaller than the first derivative of less damage. However, after passing through the damage section, the first derivative of the deflection influence line obtained under the working condition with larger damage degree is larger than that obtained when the damage degree is small. For different degrees of damage, it is impossible to quantify and clearly compare the approximate degree of damage. Therefore, the first derivative image of the deflection influence line is not suitable for the identification of the damage degree of the continuous beam bridge structure.

![Figure 9](image)

Figure 9 Working condition 1 (1-5), the first derivative of the influence line of the deflection of the first 1/4 measuring point

The following discusses the significance of the first derivative of the deflection influence line on the damage location of the continuous beam bridge. It is verified by the image law that the intersection of the first-order derivative image of the large damage and the small first-order damage on the first span is the approximate location of the damage. However, there is also a curve intersection at the second span,
and no damage occurs at this position in the actual model. Therefore, the first derivative of the deflection influence line is not desirable as a damage identification parameter.

3.2.3 Damage identification of the second derivative of deflection influence line

Derivation of the first-order derivative of the deflection influence line obtained in the previous section is again obtained, and the second deflection influence line under observation condition 1 (1-5) and condition 2 (1-5) at the 1/4 measuring point of the first span Derivative.

First study the effect of the second derivative of the deflection influence line on the identification of damage degree. From the comparison of the images, the greater the damage degree, the greater the deviation of the image from the peak position, but the numerical analysis failed to find the mathematical relationship matching the damage degree. Therefore, the second derivative of the deflection influence line is not suitable for the identification of the damage degree of the continuous beam bridge structure.

Next, we will study the role of the second derivative of the deflection influence line in identifying the location of structural damage. When damage exists, the second derivative of the deflection influence line will have a sudden change on the basis of the basic linear shape, making the image have a big difference compared with the non-destructive condition 1-1. The position of the sudden change is the position of the damage section (as shown in the figure 10-11).

![Figure 10 Working condition 1 (1-5), the second derivative of the influence line of the first span 1/4 measuring point deflection](image1)

![Figure 11 Working condition 2 (1-5), the second derivative of the influence line of the first span 1/2 measuring point deflection](image2)
To sum up, the deflection influence line of a continuous beam bridge has no direct reference value for its structural damage identification, but its first derivative and second derivative can reflect certain damage information in some cases. The first derivative of the deflection influence line can only identify the damage location after the comparison of the multiple degree of damage data of the bridge. More data is required, but accurate for location recognition. The degree of damage can be roughly judged by comparison, but the scope cannot be estimated. When the second derivative image of the influence line is known as the basic line shape of the non-destructive working condition of the measuring point, through the comparison of the measured data with the basic line shape, the damage position is the position where the large deviation occurs. The comparison of the degree of damage can only judge the degree of damage through models of different degrees at the same location, but the numerical relationship cannot be determined.

3.3. Deflection influence line difference and its first and second derivative structure damage identification

3.3.1 Condition 1 deflection influence line difference structure damage identification

![Deflection influence line difference](image)

Figure 12 Working condition 1 (2-5), the difference of the influence line of the first span 1/2 measuring point deflection

First, analyze the difference of the deflection influence line obtained from 1/2 measuring point under working condition 1 (1-5) (as shown in Figure 12). The measuring points are located at the same span as the damage position under working condition 1. The obtained deflection the contours of the influence line difference curve are roughly the same, with peaks appearing and the peaks are negative. But the values vary greatly.

Although the peak difference is large, the peak position can be clearly observed from the shape of the image. By comparing the model and data, it can be roughly confirmed that the area where the peak of the working condition 1 (including 1-5) appears is the damage position. The location of structural damage can be identified by the difference of deflection influence lines.
3.3.2 Condition 3 Deflection Influence Line Difference Structural Damage Identification

Perform image fitting on the values of working condition 3 (1-5) at the first cross-test point to obtain the image shown in Figure 13 above. Observing the image found that when working condition 3 (1-5), the structural damage location is very close to the middle node of the continuous beam, the image has two peaks—the first peak (sharp peak) and the second peak (round peak). According to the known damage location, it can be confirmed that the theoretically sharp peak location is the actual damage location of the structure. However, in the actual measurement process, considering a certain degree of test error, the distinction between the first peak and the second peak is not very obvious. Therefore, in the case of working condition 3, the convenience and accuracy of using the peak position to determine the damage location need to be improved. The practicality of the method is not very good.

3.3.3 Structural damage identification with first derivative of deflection influence line difference

When the damage location is far away from the fulcrum of the beam (corresponding to working condition 1, working condition 2), the peak position of the first derivative of the deflection influence line difference corresponds to the actual damage location. However, when the damage location is too close to the central fulcrum of the continuous beam, such as working condition 3, there will be double peaks, and the interference will greatly reduce the accuracy and rapidity of the first derivative structural damage with the deflection influence line difference. Therefore, the in-depth study of the deflection influence line difference is carried out to find the optimal parameter reflecting the structural loss.

Since the above method is mainly limited to condition 3, we will study condition 3 first. Based on the above method to obtain the deflection influence line difference value, further derivative is obtained to obtain the first derivative image of the deflection influence line difference value.

The image of the first derivative of the difference of the deflection influence lines obtained from each measuring point under working condition 3 is shown in Fig. 14~16.
Figure 14 Working Condition 3 (2-5), the first derivative of the influence line difference of the first 1/4 measuring point deflection

The first derivative of the deflection influence line difference essentially reflects the unit distance change rate of the difference between the deflection of the beam and the deflection produced when the structure is not damaged when a unit load is applied to each position of the beam. Comparing the images obtained in working condition 3, there will be a sudden change in all curves. After the sudden change, the image has a different sign, and the sudden change corresponds to the damaged section of the bridge. On the whole, the first derivative of the deflection influence line difference is very intuitive and accurate for the structural damage identification of working condition 3.

3.3.4 Structural damage identification with the second derivative of deflection influence line difference

Figure 15 Working condition 1 (2-5), the second derivative of the influence line difference of the first 1/4 measuring point deflection
In order to find the best identification parameters, the second derivative of the deflection influence line difference is studied. From the image of the second derivative of the deflection influence line difference under each working condition measured at the 1/4 point of the first span, it can be concluded that the deflection influence line difference is two the first derivative image will have a single peak, and the peak position has nothing to do with the measurement point, it reflects the damage position. The degree of structural damage is proportional to the peak image. However, during data processing, it is also found that the test model is limited by the accuracy of data selection (accurate to $10^{-9} m$) and the size of the model, and the deflection affects the line difference second derivative image with many fluctuations, so in its practical application, there are many restrictions on the bridge.

4. Conclusion
This paper fits the deflection influence line and the first and second derivatives of the continuous beam bridge when the damage occurs at a single position and multiple positions, and the difference between the deflection influence line and the first and second derivatives of the image [6]. By comparing different positions, the identification methods and performance of each index under different degrees and different measuring points were evaluated, and then the optimal identification parameters were selected as the key parameters for continuous beam bridge structural damage identification based on visual tracking technology to locate the damage. The universal structural damage identification indicators are the second derivative of the deflection influence line, the first derivative of the deflection influence line difference and the second derivative of the deflection influence line difference. In addition to the damage location, there are still mutation points in the second derivative of the deflection influence line, and the image features are not obvious and difficult to identify. The second derivative of the deflection influence line difference needs to be measured with a high-precision instrument, which is difficult to fit, but it can also roughly identify the damage location. Therefore, using the second derivative of the deflection influence line difference has extremely high requirements on the accuracy of the instrument. Considering all the factors mentioned above, the first derivative of the deflection influence line difference is the best damage identification parameter, which is superior to other parameters in terms of convenience and accuracy of observation [7].
Due to time and personal reasons, this study still has certain shortcomings. There are no multiple identifications or the identification of specified parts in the damage identification, which will affect the comprehensiveness of the research results. This is also the focus of the next research.

Reference

[1] Yunbo Long. Analysis of uncertain factors in construction control of long-span bridges[J]. Highway Traffic Science and Technology (Applied Technology Edition), 2015, 000(007):210-210.

[2] Tianbao Wan. Performance requirements for dampers to improve the durability of bridge structures[J]. Bridge Construction, 2016, 46(004):29-34.

[3] Xiaona Kou. Preliminary research on damage identification method of bridge structure based on deflection influence line [D]. Chongqing transportation University, 2008.

[4] Yunshuai Liu. Research on the Damage Identification of Simply Supported Girder Bridge Based on the Influence Line of Deflection Difference [D]. Lanzhou University of Technology, 2009.

[5] Yaping Jia. Research on continuous beam bridge structural damage identification based on deflection influence line [D]. Guangzhou University, 2014.

[6] Joseph Redmon, Ali Farhadi. YOLOv3: An Incremental Improvement [DB]arXiv: 1612.08242v1, 2018.

[7] Finite element analysis of vehicle–bridge interaction[J]. Leslaw Kwasniewski, Hongyi Li, Jerry Wekezer, Jerzy Malachowski. Finite Elements in Analysis & Design. 2006 (11)