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RESEARCH ARTICLE

UTILIZATION OF THE INFLUENCE LINE OF DISPLACEMENT TO IDENTIFY A DECLINE IN THE STIFFNESS OF BEAMS

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ABSTRACT

The purpose of this work is to offer a method for detecting structural damage utilizing the standardized index of the beam's deflection influence line difference as input data for the evaluation procedure. The displacement influence line used in the evaluation is calculated using the findings of the behavior analysis of the reinforced concrete beam's finite element model when subjected to a moving load. SAP2000 software is used to simulate reinforced concrete beams. The mobile load is then assigned to move along the beam from its starting position to its ending position. For each mobile load example, the displacement at each survey node will be output to draw the influence line. The displacement analysis of the beams is compared before and after assuming damage for each mobile load instance in order to determine the location of the stiffness drop. From then, the findings of beam damage diagnosis are reviewed and evaluated, as well as the methods' practicality in real implementations.

KEYWORDS

displacement influence line, damage detection technique, elastic modulus reduction

1. INTRODUCTION

The science of structure monitoring has advanced rapidly in recent decades. Rytter suggests three levels of damage detection: occurrence of damage, position of damage within the structure, and stiffness reduction. In other words, the damage detection method's objective is to ascertain the occurrence of a damage, its location, and severity. In addition, the structure's behavior can be classified into two main categories: static behavior and dynamic behavior. For many years, many studies have focused on developing an efficient and reliable approach for diagnosing failures. Many scientists are interested in structural diagnosis, most notably, who used the mode shape curvature in conjunction with vibration patterns to identify beam damage (Pandey and Biswas, 1991). Min and co-authors used ANNs to determine the optimal frequency domain for determining the structure's damage pattern (Min et al., 2010). The authors extended their work two years later.

In 2012, Min and his co-authors conducted research on structures that had been damaged in a variety of ways, including aluminum beams that were subjected to changing boundary conditions and developed cracks, and also a reinforcement plate on a bridge girder subjected to a reduced bolt loosening force and developed cracks. The author concludes that ANNs can provide diagnostics for the simultaneous incidence of multiple types of damage on the structures. In the same year, measured the deformation of a beam during vibration using a strain gauge sensor (macro-strain Sensor) attached to the bottom of the beam (Hong et al., 2012). The sensor value acquired was used to determine if there was any damage to the beam. Additionally, the authors validated the method using experimental reinforced concrete beams. More investigations based on the natural frequency and the vibration mode shape have been conducted since then (Dawari et al., 2013; Miyashita et al., 2012).

However, previously established that low-order natural frequencies are insensitive to structural stiffness changes (Watanabe et al., 2014). Additionally, it is critical to have a sufficient number of measurement instruments to precisely determine the vibrational mode shape. Additionally, the method of identifying damage using static characteristics has drawn the attention of various studies due to the accuracy and speed with which static parameters can be collected using inexpensive instruments. Sheena and co-authors presented an analytical method in 1982 based on minimizing the difference between the stiffness matrixes of the elements under investigation. In 1993, Banan and co-authors devised a method for estimating each element's damage parameters based on displacement caused by a predefined static load. Wang and co-authors devised a two-step approach for detecting damaged structures based on natural frequency and static displacement discrepancies (Wang et al., 2001).

By minimizing the difference between the load vectors of destructive and non-destructive structures, Bakhtiari-Nejad and co-authors established a method for describing the change of static displacement with a predetermined degree of freedom (Bakhtiari-Nejad et al., 2005). Seven years later, Abdo used numerical analysis to explore the parameters and locate the fault location using displacement curvatures (Abdo, 2012). The findings revealed that the displacement change curve can be a valuable indication, even capable of capturing the element's position with a slight

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decrease in stiffness. In 2017, Ha and Fukada presented the displacement-based index (DBI) as a tool for detecting structural degradation in prestressed concrete girders by utilizing nodal displacement variation (Ha and Fukada, 2017). DBI, on the other hand, was a static load-based method that makes no allowance for moving loads.

The present work proposes a method for detecting damage to beams by employing a standardized index and focusing on changes in the beam's displacement influence curve. To begin, the suggested method is introduced and demonstrated in a variety of conditions for determining the damage characteristics of a simple beam finite element model. Then, vary the position, number of expected failures, and beam structure to determine the method's effectiveness. Finally, the study addresses a damage diagnostic and monitoring model for structures subject to moving loads, such as crane girders in industrial steel buildings and bridges, employing input data as the influence line of displacement.

2. Proposed Diagnostic Method

Ha and Fukada estimated the DBI and determined the damage locations by assessing the calculated deformation shapes of the girder under static load in its normal and deteriorated states (Ha and Fukada, 2017). The purpose of this study is to determine the effect of DBI when the displacement influence line obtained from the moving load is used. As illustrated in Figure 1, the influence line of displacement at point C in the elastic beam can be generated by shifting the unit load P from A to B in a sequential manner. Then, using the Maxwell–Betti reciprocal theorem's feature of the displacement influence line, the displacement of point C caused by a unit load applied to a given point is equal in magnitude to the displacement of that particular point caused by a unit load applied to point C. Because the observed displacement influence line at point C is equal to the pattern of the beam's displacement curve when a unit load is applied at point C, the DBI can theoretically be applied to the moving load.

In this study, the elastic modulus of the assumed beam is lowered in order to investigate the displacement change of the assumed beam in comparison to the sound beam. Assume a unit load is shifted from support A to support B, the following equation describes the node displacement at point C:

$$[x, u_o] = [(x_1, u_{o1}), \dots, (x_j, u_{oj}), \dots, (x_k, u_{ok})] \quad (1)$$

$$[x, u_d] = [(x_1, u_{d1}), \dots, (x_j, u_{dj}), \dots, (x_k, u_{dk})]\,, \quad (2)$$

where, x is the node position determined on the beam, $u_{o/d}$ is the displacement value of the normal/damaged beam. From the displacement matrix, the difference between u_o and u_d values is determined:

$$\Delta u_j = ||u_o| - |u_d||. \quad (3)$$

The difference in the displacement influence line values between the normal and damaged beams is used to calculate the damage localization index DBI using the equation:

$$DBI_j = \max[0; \frac{\Delta u_j - average(\Delta u_j)}{std(\Delta u_j)}]. \quad (4)$$

where Δu_j is the difference in the displacement influence line values between the normal and damaged beams at the j^{th} location, and $average(\Delta u_j)$ and $std(\Delta u_j)$ denote the mean and standard deviation of Δu_j, respectively. The DBI_j coefficient quantifies the degree of point relationship between two influence curves at the j^{th} point. DBI = 0 indicates that the structure is not harmed at the observation site, whereas DBI > 0 indicates that the structure is damaged at the observation site.

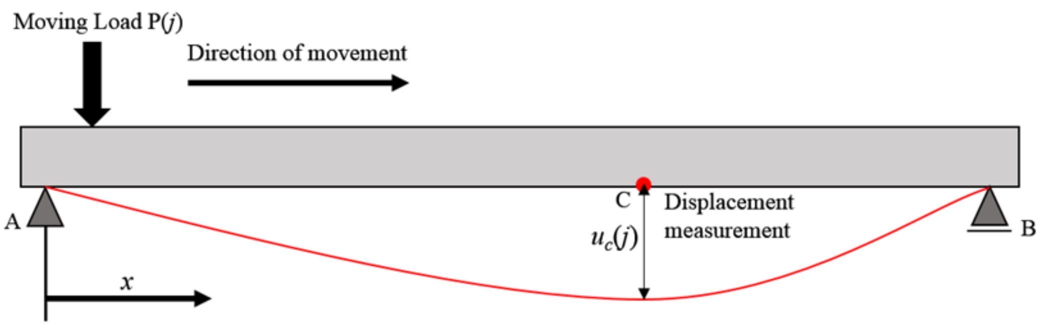


Figure 1: Illustration of the displacement influence line.

3. Investigated Problems

To demonstrate the capability of determining the location of damage within a structure using the DBI approach with the input data as the displacement influence line, the present study considers four different types of beam structures. Especially, the study evaluates the proposed method's performance on single-span simple beams, overhanging beams, cantilever beams (statically determinate structure), and two-span continuous beams (statically indeterminate structure). Numerous criteria, such as location and the number of damage, are also studied and discussed in relation to the suggested method's performance.

3.1 Single-Span Simple Beam

A simple reinforced concrete beam with a length of L = 10m (Figure 2) and a rectangular cross-section of bxh = 0.35 x 0.7 m was subjected to a simulation study under the influence of a unit movable load moving on the beam. Simulated concrete was a linear elastic material with an elasticity modulus of E = 2.7x10^7 kN/m^2 and a Poisson coefficient of v = 0.2. SAP2000 software was used to create models and assign moving loads, from which displacement influence lines at specified positions on beams can be calculated (Figure 3). Eleven points evenly spaced 1 m apart from support A to support B were chosen in this investigation to derive the displacement influence curve.

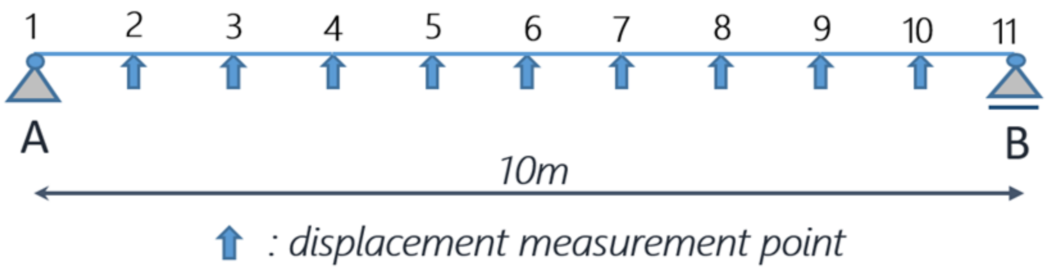


Figure 2: Illustration of single-span simple beam in SAP2000.

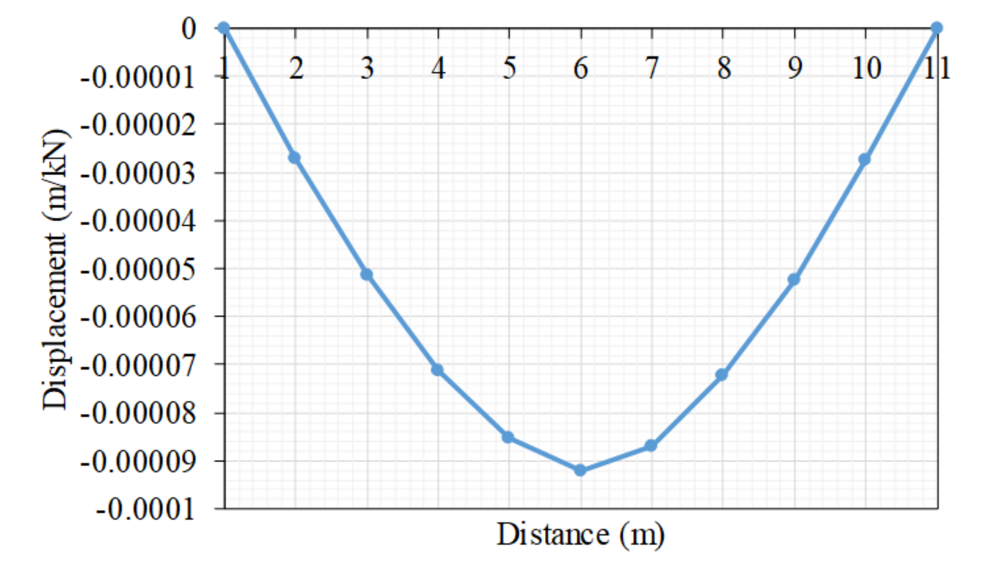


Figure 3: Influence line obtained at position 6 of healthy beam.

Damaged beams were created in this study by lowering the elastic modulus of one or two individual segments of the beam. This study examined three cases with varying damage characteristics in order to determine the efficiency of the damage detection approach based on the displacement influence line. Case 1 was based on the assumption of a damage in the second element position, on one side of the support (Figure 4). Specifically, the second element's elastic modulus was lowered to E = 1.7×10^7 kN/m^2. The remaining elements retained their typical beam material properties. Case 2 was based on an element failure in the mid-span position (6th element) (Figure 5). To investigate the feasibility of simultaneously identifying multiple damages, the third situation (Case 3) assumed two damages in the second and eighth elements (Figure 6). The displacement influence line analysis of the 6th position of the healthy beam and the beam with presumed damage in the second element is shown in Figure 7.

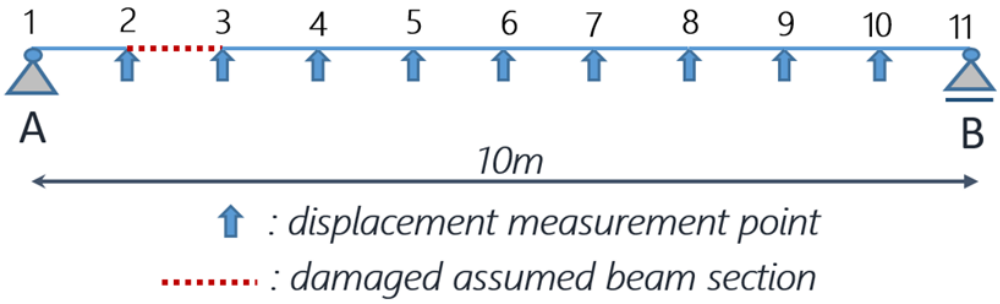


Figure 4: Simple beam diagram assuming damage at the second element.

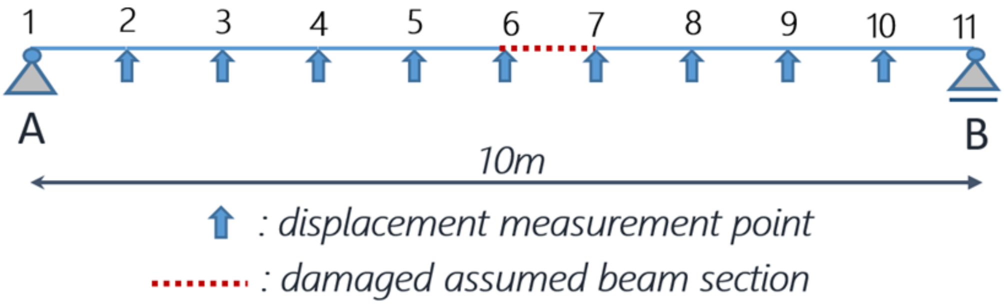


Figure 5: Simple beam diagram assuming damage at the 6th element.

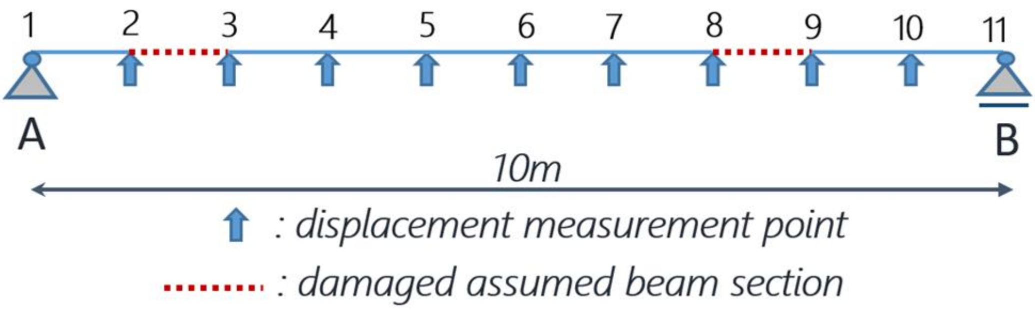


Figure 6: Simple beam diagram assuming two damages at the 2th and the 8th elements.

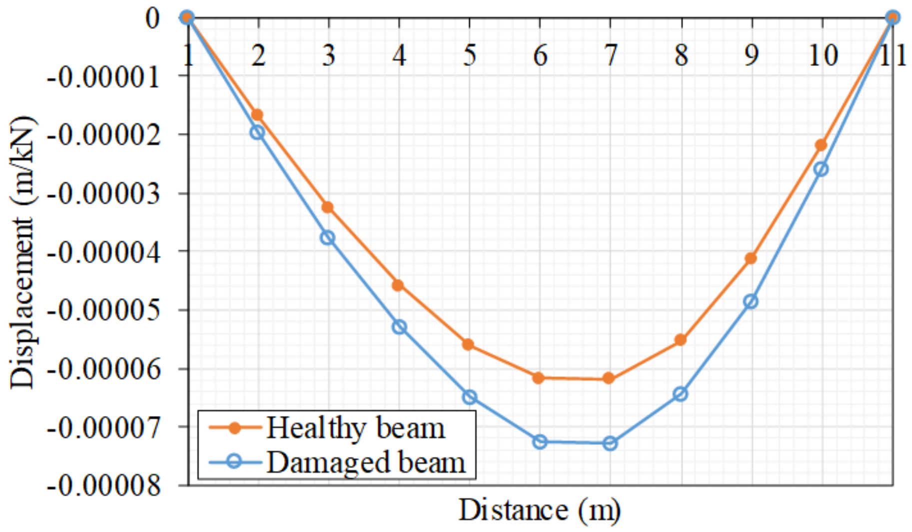


Figure 7: Influence line obtained at position 6 of healthy and damaged beams.

The figures 8, 9, and 10 depict, respectively, the results of diagnosing the damaged position of the beams in the first, second, and third cases. According to Figures 8 and 9, the DBI value is largest at positions 2 and 6, where the element has a decreased elastic modulus. Thus, in the hypothetical scenario of a loss, the DBI can pinpoint the site of the reduced stiffness. The diagnostic results for the third case's damage areas are shown in Figure 10 when the input data is used as the displacement influence line at positions 2, 4, and 10. According to Figure 10, when the displacement influence line of position 2 or position 10 is used as an input, the approach correctly diagnoses only one reduced stiffness element position; however, when the displacement influence line of position 10 is used as an input, the method correctly diagnoses up to two reduced stiffness elements. Furthermore, when displacement influence line data from position 4 is studied, DBI reveals two peaks at positions 2 and 8, which correlate precisely with the locations of the elastic modulus reduction elements. Thus, while diagnosing via the influence line of displacement, the closer the access point is to the location of the damage, the more precise the diagnosis. On the other hand, if the site of the damage is remote from the access point for the influence line, the method used to calculate the DBI factor may result in a misdiagnosis or absence of damage. Thus, when the displacement influence curve is used as an input to the DBI method for determining the location of the damage, the number of access points must be sufficient to discover any structural concerns.

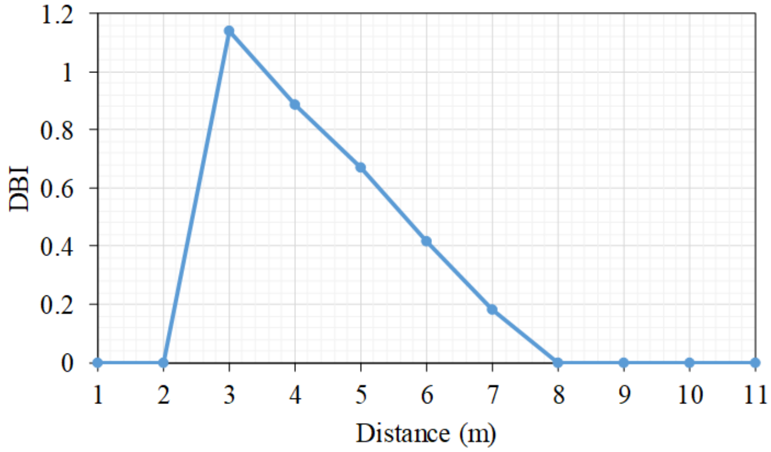


Figure 8: Diagnostic results of the damaged location of Case 1

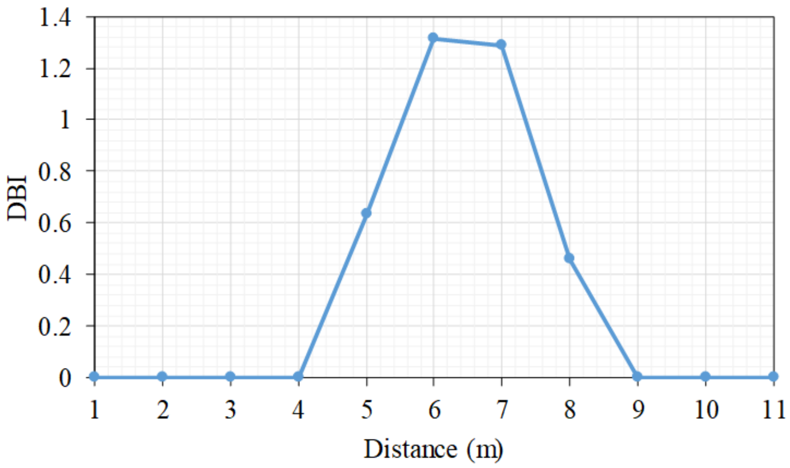


Figure 9: Diagnostic results of the damaged location of Case 2

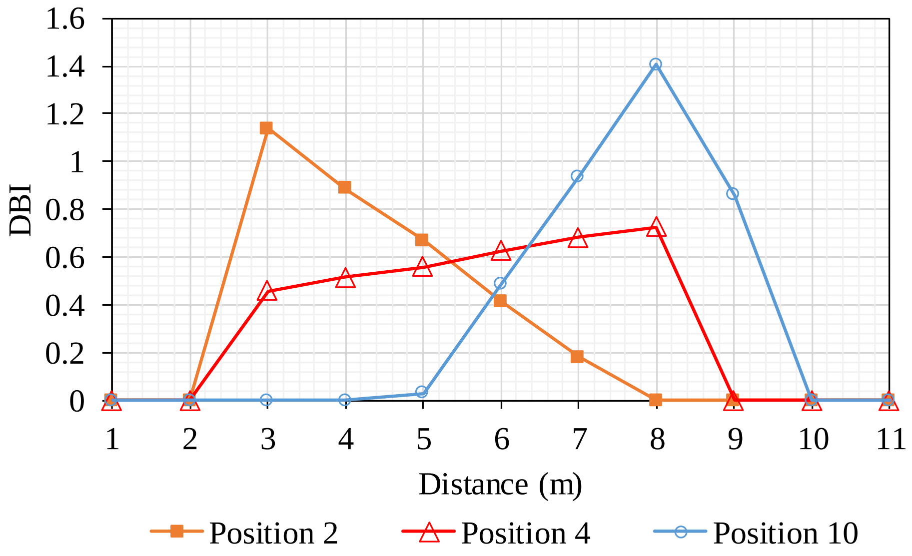


Figure 10: Diagnostic results of the damaged location of Case 3

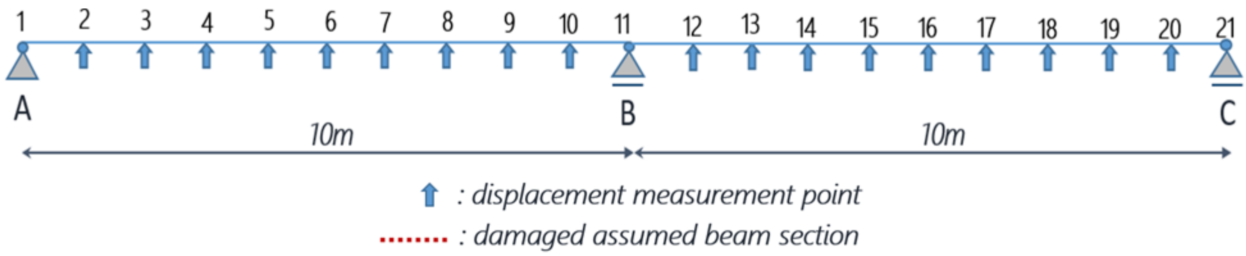
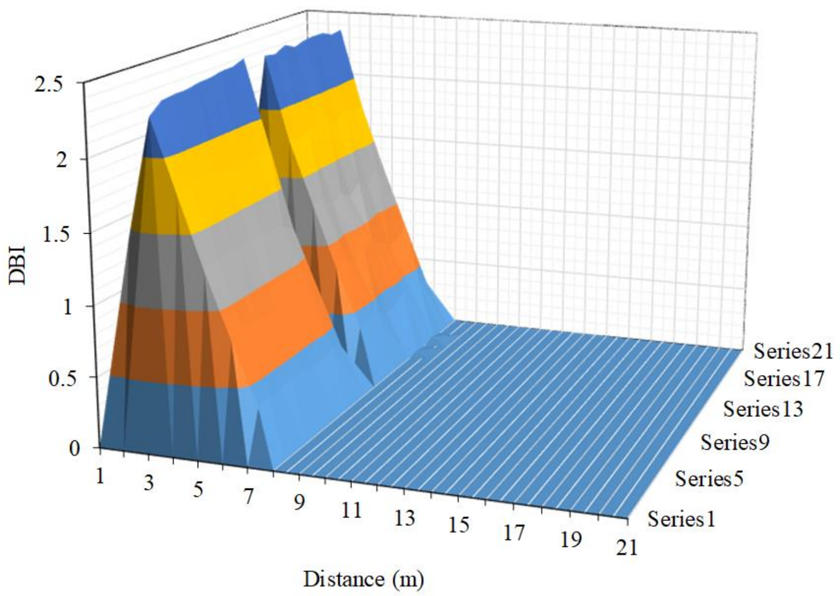


Figure 11: Illustration of two-span continuous reinforced concrete beam in SAP2000.

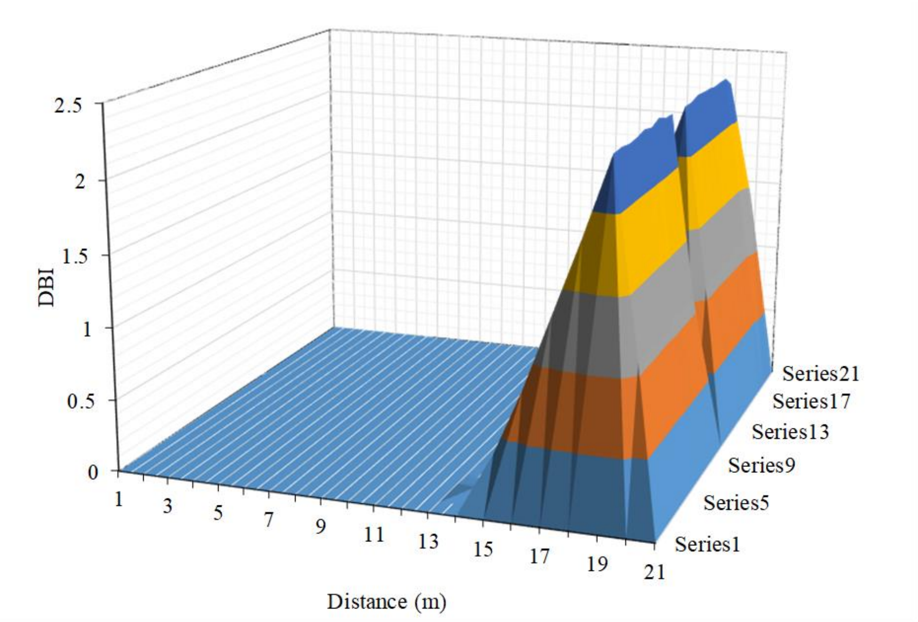
3.2 Two-Span Continuous Beam

A simulation analysis was conducted on a continuous reinforced concrete beam of length L = 20m (Figure 11). The rectangular cross-sectional dimensions and concrete material parameters are simulated similar to the simple beam problem. To extract the displacement influence line, 21 sites equidistant 1 m from support A to support B and from support B to support C are selected.

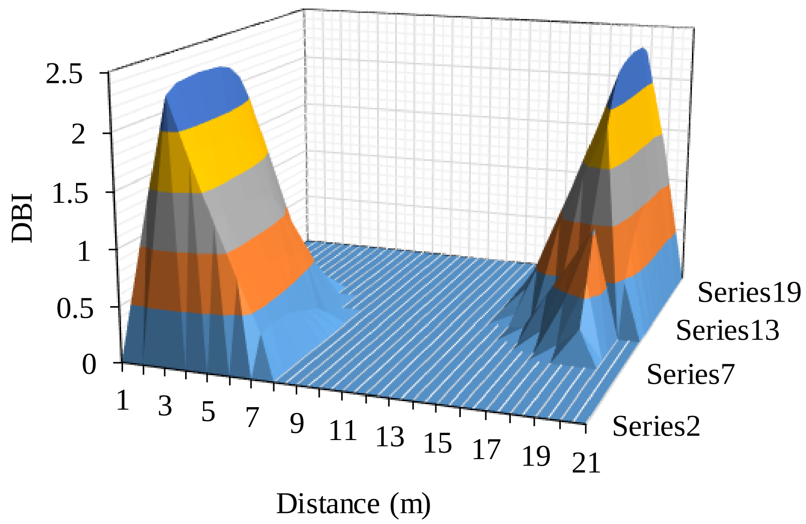
The study examines five cases with varying failure characteristics to determine the efficiency of the approach for two-span continuous beam failure diagnosis utilizing the influence line of displacement. Case 4 was predicated on the presence of a damaged element at position 2. Case 5 was constructed with the supposition of a damage at position 15. Cases 6, 7, and 8 are used to assess the method's diagnostic capacity in the event of concurrent failure of numerous elements. Case 6 entailed two failures at the second and nineteenth sites. Case 7 was built on the premise of three failures at locations 2, 9, and 19. Case 8 entailed four site failures at locations 2, 9, 12, and 19. Figures 12(a)-(e) illustrate the results of diagnosing the location of damaged beams in the 4th, 5th, 6th , 7th and 8th assumed damage cases, respectively. The charts illustrate the results obtained by analyzing the influence line of displacement at various locations along the beam. Diagnostic charts showing DBI rising and peaking at presumptive locations of beam damage. The analysis results demonstrate that the DBI can correctly identify the location of the reduced stiffness in both the case of a single element failing and the case of multiple elements failing simultaneously. However, based on the analysis presented in the previous section for the simple beam model, the number of monitoring points must be sufficient to diagnose possible beam failures when there are multiple failures concurrently.



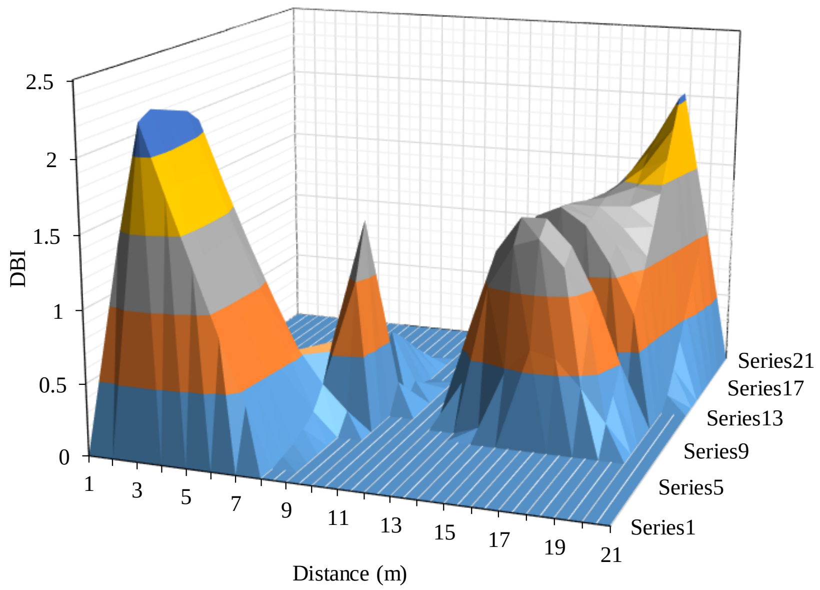
(a) Diagnostic Chart of Case 4



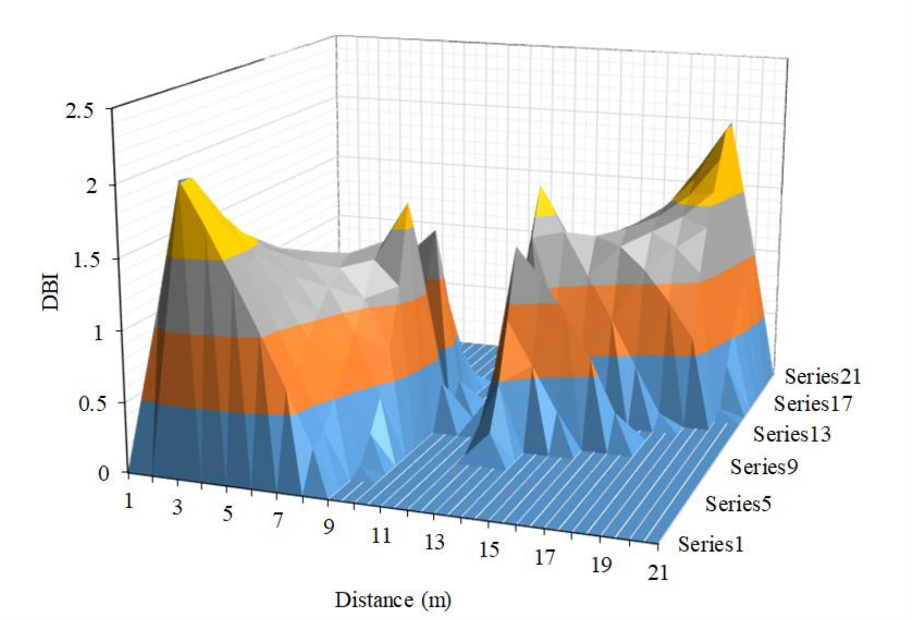
(b) Diagnostic Chart of Case 5



(c) Diagnostic Chart of Case 6



(d) Diagnostic Chart of Case 7



(e) Diagnostic Chart of Case 8

Figure 12: Diagnostic results for two-span continuous beam.

3.3 Cantilever Beam

Cantilever beams rarely exceed a span of 10m in practice. To reconcile the span with the above-mentioned beam systems, the study simulated a cantilever beam made of reinforced concrete with a length L = 10m and a rectangular cross-section size bxh = 0.35 x 0.7 m having the unit mobile load moving on the beam (Figure 13). The simulated concrete material was a linear elastic material with the same properties as the preceding examples. To extract the influence line of displacement, 11 points equidistant 1 m from the support A to the end of the beam were chosen.

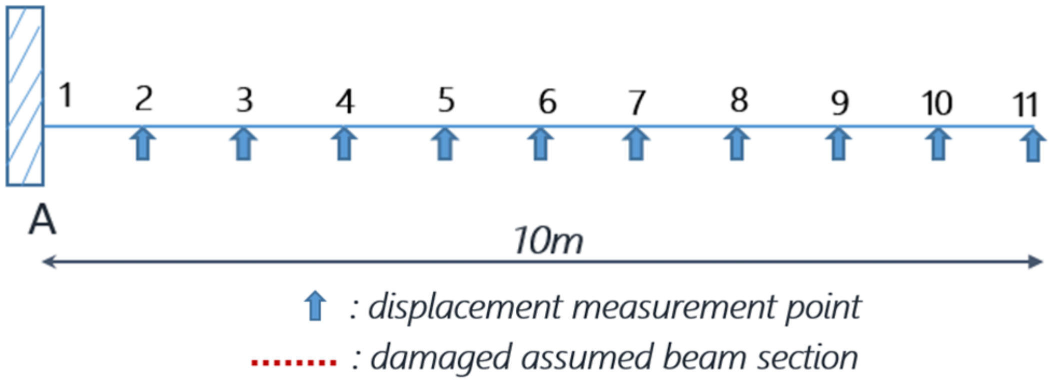


Figure 13: Illustration of cantilever beam in SAP2000.

The study investigates two cases with varying failure characteristics to determine the effectiveness of the failure diagnosis method based on the influence line of displacement for the cantilever beam structure. Case 9 assumed the existence of a defective element at position 2. Case 10 relied on the assumption the presence of two defective elements at positions 2 and 5. The results of diagnosing the damaged position of beams in the hypothetical cases of the 9th and 10th cases are shown in Figures 14(a) and 14(b). DBI can determine the location of the element with reduced stiffness based on the diagnostic chart. However, in both cases, the elevation segment is visible at the free end. Elevation of the DBI histogram at the free end, where there is almost no damage, resulted in an incorrect diagnosis. This can be explained by the geometrical displacement at the free end of the beam when it is loaded. This displacement effect interferes with the obtained values at the transposition positions near the free end. As a result, diagnostic results at the free end of the cantilever beam are inaccurate.

3.4 Overhanging Beams

The diagram of the overhanging beam is shown in Figure 15. The rectangular cross-section and simulated material properties are identical to those in the preceding examples. To extract the influence line of displacement, 11 points equidistant 1 m from the support A to the free-end segment are chosen. This study examines two cases with varying failure characteristics in order to determine the effectiveness of the damage diagnosis method based on the influence line of displacement for overhanging beams. Case 11 presupposed damage at the beam's second position between the two supports. Case 12 assumed two failures at the cantilever beam's second and ninth positions.

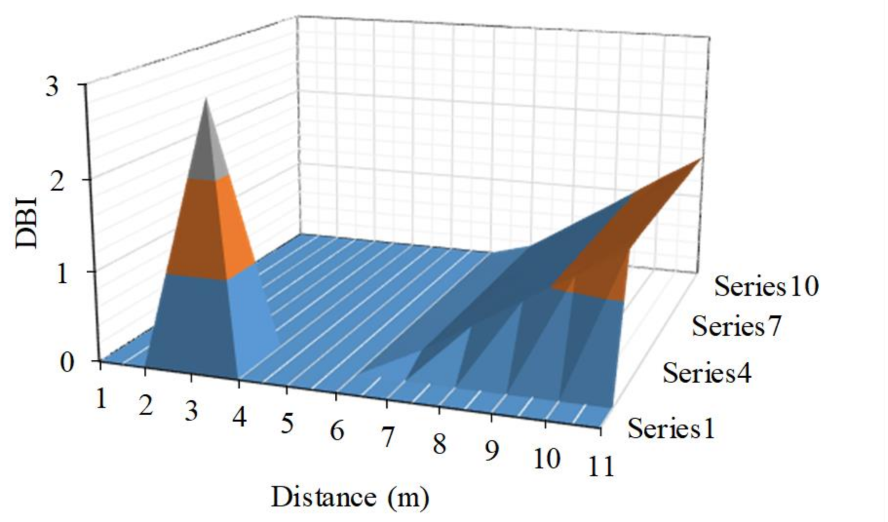
The results of diagnosing the damage location of beams in the assumed damage cases of the 11th and 12th cases are shown in Figures 16(a) and 16(b). The DBI can determine the position of the element with reduced stiffness based on the diagnostic chart. When the failure is assumed to be in the simply supported portion, the DBI diagnostic chart indicates the correct location of the failure (Sheena et al., 1982). However, in both cases, the elevation segment is visible at the free end. When damage is assumed at the overhanging portion, the DBI diagnostic chart's peak at the free end position (diagnostic noise) is significantly greater than the damage diagnostic peak at the portion between the two supports. As a result, diagnostic results in the ovehanging beam are inaccurate.

4. Application of the Proposed Methods in Structural Degradation Monitoring

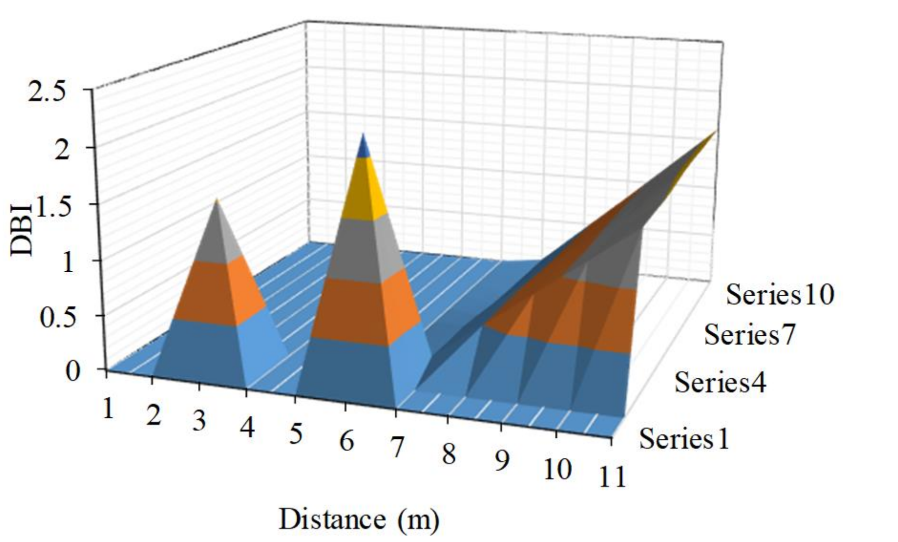
This study develops a method for diagnosing failures in beam-shaped structures by utilizing input data as the displacement influence line. As a result, this method is applicable to structures that are subject to movable loads. Indeed, the method of diagnosing structural damage via the influence line of displacement can be applied to crane girder structures in industrial steel buildings, as well as road bridges and rural roads (Rytter, 1993). Crane girders in industrial steel buildings deteriorate over time due to a variety of factors such as rebar corrosion reaction, resulting in a loss of function and posing a safety hazard during operation. Localized damage, depending on its severity, can result in a significant drop or complete failure. As a result, it is necessary to assess damage on a periodic basis and repair or reinforce as necessary. The displacement sensor is mounted beneath the crane girder in the case of crane girders (Figure 17).

The sensor will monitor and collect displacement values at a point on the crane girder caused by the movable wheel load. After determining the displacement influence line caused by wheel movement, the displacement influence line value is sent in real time to the signal receiver (Min et al., 2010). The data from the resulting signal receiver will be used to diagnose and locate any beam damage. Besides, road bridges in Vietnam are critical for the transportation of goods due to the high volume of daily traffic. For bridge structures, the sensor will be mounted beneath the bridge girder or deck slab (Figure 18). As the vehicle passes over the bridge, the sensor will determine the displacement value at a particular point, thereby establishing the influence line. The value of the displacement's influence line will be transmitted to a nearby signal receiver, which will transmit the signal to a laboratory for analysis and determination of the location of the damage.

During the actual monitoring of the structure, the signal receiver located at the tracking location collects data from the sensors and transmits it via the wireless network to the processing computer (base station) or mobile phone (Banan and Hjelmstad, 1993). This computer or mobile phone can function as a data center, collecting displacement influence line tracking data, calculating the DBI failure diagnostic index, and uploading the results to the server. It enables the administrator to remotely access the database and confirm the structure's damaged state. Due to the long communication distances associated with large bridges, data transmission from the base station may be challenging. Additional base stations would be required in this case.



(a) Diagnostic chart of case 9



(b) Diagnostic chart of case 10

Figure 14: Diagnostic results for cantilever beam.

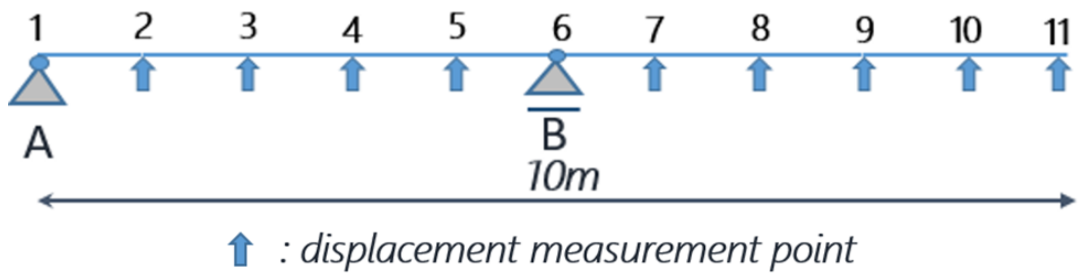
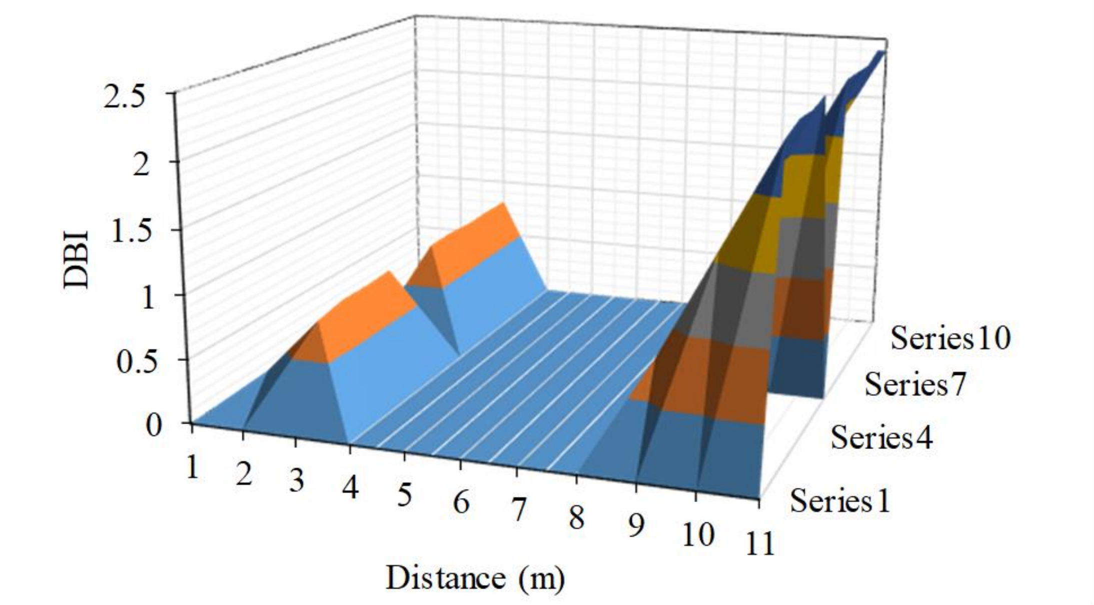
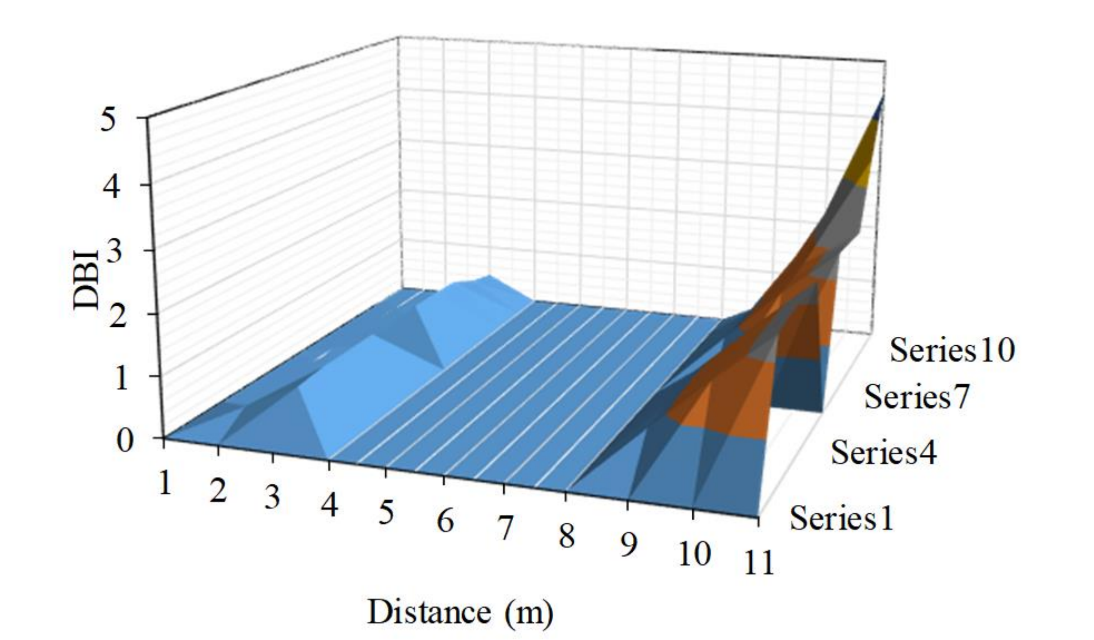


Figure 15: Illustration of overhanging beam in SAP2000.



(a) Diagnostic Chart of Case 11



(b) Diagnostic Chart of Case 12

Figure 16: Diagnostic results for overhanging beam.

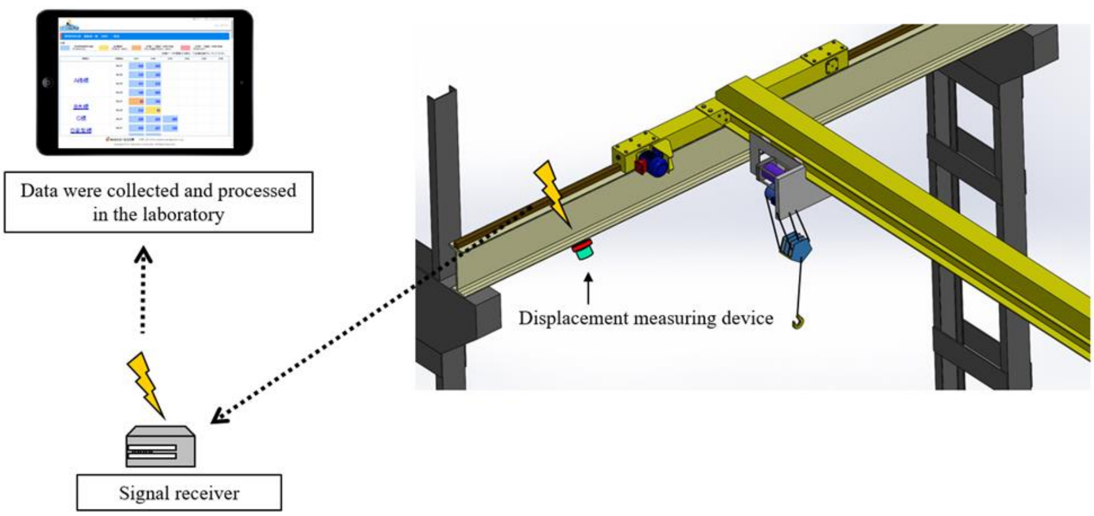


Figure 17: Proposing diagnostic procedures for crane girders.

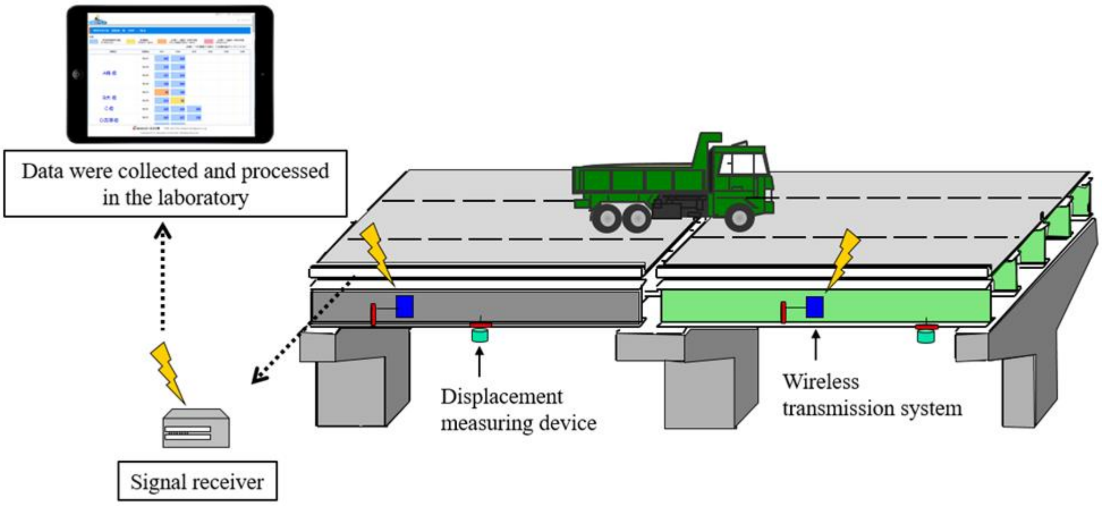


Figure 18: Proposing diagnostic procedures for bridges.

5. Conclusion

Numerous methods for diagnosing damage to beam structures have been researched and developed to date. The present study proposes a diagnostic method based on the displacement influence line. The following summarizes the findings of this study:

- The obtained results indicate that the displacement influence line method is quite effective for diagnosing single damaged beams. However, the method requires a sufficient number of displacement access points in the case of numerous damaged elements.
- The more closely located the affected line access point is to the location of the fault, the more accurate the diagnostic results. On the other hand, if the failure site is located a great distance from the retrieval site, the proposed method may result in an incorrect diagnosis.
- The method is limited in diagnosing damage to cantilever beams and overhanging beams caused by the influence of disturbances caused by geometrical displacements of the free ends.

The following study will continue to develop a diagnostic method based on the influence line of displacement for more complex structures, including diagnostics for rigid frame and actual structures, as well as further investigate the effect of noise on diagnostic results.

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