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Structural damage detection from dynamic responses of the bridge deck under a moving load using discrete wavelet transform

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Abstract

Early detection of structural damages and making necessary interventions to repair them are one of the main challenges in structural health monitoring. The wavelet transform is one of the common methods for this purpose, and its efficiency is proven by many researchers. In the present study, this approach is used to assess the performance of Sani-khani bridge with single and multiple-damage scenarios. For this purpose, the displacement response difference between the intact and damaged bridge decks under a moving load is analyzed by discrete wavelet transform (DWT). In the present study, 10 sensors and one-time sampling are used, In fact, the proposition of a method that uses the minimum number of required sensors for practical damage detection. To verify the reliability of the suggested method, not only different damage locations were considered, but also 5% noise is considered for the input signals. The attained results proved that even in the presence of the noise, the proposed approach can detect the damage locations with acceptable accuracy. The accuracy of the method for middle and side damages is higher than corner damages.

Keywords: Structural health monitoring, Damage detection, Discrete wavelet transform, Sensor noise, Vibrational response, Bridge deck

1 Introduction

Performance evaluation and health monitoring of structures during their service life are important issues to ascertain their desirable performance and prevent possible financial consequences and casualties caused by structural failures. One of the proposed methods for this purpose is the Structural Health Monitoring (SHM), in which the data provided by a series of sensors, installed on the structure to determine available damages, is processed to estimate the remaining life of the structure (Erazo et al. 2019; Bolourani et al. 2021). In general, these systems evaluate dynamic responses of structures continuously or periodically, for early warning during emergencies to help engineers make better decisions about maintenance and the operation of structures. Therefore, the SHM procedure consists of four main steps: a) data collection, b) system identification, c) performance evaluation, and d) decision making (Sony et al. 2019). Eventually, it is possible to take necessary actions based on the results of this process, which leads to the extension of the service life of structures and reduction of their maintenance costs.

In general, the health monitoring methods are categorized into two groups: Destructive Tests (DT) and Non-Destructive Tests (NDT). DT methods apply to limited projects due to the destruction of parts of the structural components. Therefore, the application of NDT approaches for structural health monitoring has developed further (Khosraviani et al. 2021a). NDT approaches can be divided into two sub-categories of local and global techniques. In the local methods, limited parts of the structures with exposed members and components are monitored. Needless to say, there are instances of damage scenarios in which the damage location is not exposed and is even out of reach. So, it is not possible to utilize the local NDT methods in such cases (Lam 1994). Therefore, the global methods have been used mostly by various researchers in the past decades.

The global NDT methods are divided into static, dynamic, and combined techniques (Antunes et al. 2012). The static approaches are based on evaluating strains and deformation of structures. These types of tests are performed by static loading, which is in contrast with the real nature of most loads applied to structures. Moreover, due to neglecting time-dependent information in these techniques, damage detection is faced with various difficulties and challenges (Soh et al. 2012). Accordingly, most research studies in this field are focused on the dynamic approaches, which detect damages to the structures based on variation in the signals and vibrational characteristics of structures. The previous studies on the dynamic NDTs were based on either modal data or signal processing (Sohn et al. 2003). In the modal -based methods, variations in the evaluated modal parameters including resonance frequency, modal damping, mode shapes, etc. are used to determine the physical or dynamic changes in the structure. Despite the widespread application of these techniques in various studies, in some cases, extraction of system modal data for the higher modes requires very advanced devices and science. Especially in structures with a large number of degrees of freedom, which makes the application of this technique very difficult and even sometimes impossible (Ghaderi and Shabani 2019; Farrar and Jauregui 1998). In the vibration-based methods, by processing time-history analysis of the structure or its response spectrum using different algorithms, the variation of damages to the structure are detected. This group of NDT techniques can further be classified as time-domain, frequency-domain, and time-frequency-domain methods (Ghiassi and Lourenço 2018). It is stated in various researches that damages to the structures have no significant effect on the structural responses in the time-domain (Lu and Tang 2018). This leads to an increase in the number of performed investigations in the frequency domain. In the frequency domain analysis, the time and location signals are eliminated and this problem becomes more important in the case of non-static signals, because the structural signals, including displacement and acceleration, are non-static (Qiao et al. 2008, 2012). Therefore, researchers tend to utilize the time-frequency domain approach to remedy the problems of the frequency-domain method. In most of the performed investigations in this field, multi-stage algorithms such as wavelet transform have been used (Solís et al. 2013; Zitto et al. 2015). The advantages of the wavelet transform include clearing the noise in the signal without disturbing its performance, and the ability to perform a local analysis of a large signal. Moreover, it is noteworthy that based on the performed studies, signals including sudden changes (failures) are easily analyzed using the wavelet transform (Huang et al. 2009). The wavelet transform performs like a magnifier that can detect minor changes in the signal.

Newland first discovered the capabilities of wavelet transform for analysis of vibration signals in 1993 (Newland 2012), and then Staszewski published a state-of-the-art review about the progress of wavelet analysis in damage detection up to that year (Staszewski 1998). The first application of this analysis method in the damage detection of structures was related to the crack detection of beams, which was performed by Liew and Wang in 1998 (Liew and Wang 1998). Many researchers have proven the effectiveness and efficiency of Wavelet Transform (WT) in the damage detection of civil structures (Hou et al. 2000; Zhong and Oyadiji 2011). Initially, researchers used WT to analyze the structural mode shapes. In one of these studies, Lee et al. utilized the mode shape wavelet transform to detect damage to beams (Lee et al. 2000). Also in 2003, Douka et al. identified the location and size of cracks in the beams using the wavelet transform of vibrating modes (Douka et al. 2003). Fan and Qiao used this technique to detect damage to plate structures and pointed out the high ability of wavelet transform (Fan and Qiao 2009). However, calculating the modal shape as the input signal of a wavelet transform in real structures requires complex calculations and numerous experiments. Due to the availability of a wide range of sensors for measuring structural responses (especially displacement and acceleration), the tendency to use these signals as wavelet transform inputs has increased and many researchers have used structural response signals for damage detection (Kim and Melhem 2004; Taha et al. 2006; Pakrashi et al. 2007). Wang and Deng also recommended that wavelet transform can be applied directly to the response signals of structures such as displacement, strain, or acceleration (Wang and Deng 1999). Accordingly, Zhu and Law used the displacement responses of a beam under moving load as input signals of a wavelet transform in damage detection and introduced a new method for detecting cracks in bridge girders. They also experimentally verified the results of their study and concluded that the proposed method can accurately determine the locations and speed of moving load without sensitivity to noise measurement (Zhu and Law 2006). In 2009, Huang et al. utilized a two-dimensional wavelet transform of the displacement responses of a damaged plate to detect single and multiple damages on the plate (Huang et al. 2009). Other studies on the use of structural responses as wavelet transform input in damage detection. For example, Hester and Gonzalez used the bridge acceleration response (Hester and González 2012). Moyo and Brownjohn also used a variety of responses such as acceleration and strain to monitor the health of a real bridge during and after construction (Moyo and Brownjohn 2002).

In recent years, more researchers have turned toward the use of structural vibration responses for damage detection. For example, Santos et al. used the displacement and rotational responses of an aluminum beam to detect its damages (dos Santos et al. 2020). Azim et al. also applied the acceleration response of a metal beam and a sample truss bridge for this purpose (Azim et al. 2020). Also, Nguyen et al. utilized the displacement signals as wavelet inputs to detect multiple cracks in beams (Nguyen et al. 2020). Mousavi et al. proposed a new method based on which the difference in the displacement signal of an intact and damaged simple beam under moving load was used for damage detection (Mousavi et al. 2020). In 2021, Khosraviani et al. used both acceleration and displacement responses of a 6-story steel structure to detect its damages (Khosraviani et al. 2021b).

The performed literature review shows that despite the high capabilities of the wavelet transform method, most of the previous studies were focused on beam-like structures. Although in some cases plate structures are investigated, most of those studies suffered from the shortcoming of using mode shapes as input wavelet signals. As mentioned previously, this method has its complexities and also requires the use of a large number of sensors, which results in high costs. Accordingly, in the present study, both problems of modal analysis difficulties and using a dense network of sensors across structures are solved. To the authors' best knowledge, it is the first time that the difference between the displacement signals of intact and damaged structures are used as inputs of wavelet transform for damage detection of plate structures subjected to moving load. Another advantage of the present study is the use of a limited number of sensors with a simple configuration for the health monitoring of a bridge deck. In addition, the ability of the proposed method in detecting different single and multiple damage scenarios in a real structure (Sani-khani bridge) in the presence of noise is evaluated. The application of discrete wavelet transform (DWT) instead of continuous transform has solved the problem related to the selection of the correct range of scale factors, which is mentioned in previous studies.

The manuscript is organized in the following order: the mathematical theory of DWT and its application in damage detection are presented in section 2. The details and framework of the proposed method for damage detection using DWT are introduced in section 3. The verification of the suggested approach is presented in Section 4. Sani-kahni bridge, which is used to evaluate the performance and efficiency of the proposed method is introduced in section 5. The results attained from the developed models are given in sections 6 and 7. Finally, the overall conclusion is presented in section 8.

2 Discrete wavelet transform (DWT)

In general, a wavelet is a wave-shaped signal with an effectively limited duration and an average value of zero. Wavelet analysis consists of breaking up a signal into shifted and scaled versions of the original wavelet. By wavelet analysis, one can detect aspects of data like breakdown points, discontinuities, and trends in a signal or its higher derivatives. Wavelet transform has two different continuous and discrete types, that the continuous wavelet transform (CWT) of a time signal $x(t)$, can be defined based on Eq. (1) (Misiti et al. 1997).

$$C(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi\left(\frac{t-b}{a}\right)dt \tag{1}$$

Where $\psi(t)$ is the mother wavelet that is scaled by factor a and shifted by factor b. Both factors are sets of real numbers, while the scale factor a should also be positive (Nishat Toma and Kim 2020). Therefore, the scale and location factors are continuous numbers, and therefore an infinite number of mother wavelets should be used for the scaling and shifting. Computation of the wavelet coefficients $C(a,b)$, at all possible scales may result in the production of very large data, which increases computation time. Therefore, in contrast to continuous wavelet transform, in which scale and location factors vary continuously, subsets of factors are used in the DWT. Therefore, it is possible to interpret the DWT as a simpler and sometimes more applicable form of representation of continuous wavelet transform (Alturki et al. 2020; Alafeef and Fraiwan 2020). Accordingly, the values of the two factors a and b in DWT are determined using Eq. (2) and on a binary scale:

$$a = 2^j, b = k.2^j \tag{2}$$

In the previous equation, j and k can include values from a set of integers. Substituting these values in Eq. (1), the relationship related to the DWT $D(j,k)$, of a time signal $x(t)$, is obtained according to Eq. (3):

$$D(j,k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} x(t)\psi\left(2^{-j}t - k\right)dt \tag{3}$$

The DWT always plays the role of a filter that decomposes the input signal into approximation and detail coefficients using two filters (low-pass and high-pass filters, respectively). In other words, the main signal can be established according to Eq. (4) and based on approximation and detail coefficients of the DWT. By doing this, the signal is divided into two parts: a signal with high-frequency content and a signal with low-frequency content.

$$x(t) = A_i + \sum D_i \tag{4}$$

In this equation, A_i and D_i are the approximation (low-frequency content) and detail (high-frequency content) signals, and i determines the order of decomposition. In other words, the approximation coefficients resulting from each decomposition can be decomposed again into two approximation and detail parts, and by repeating this operation, it is possible to have decompositions of a signal several times. The decomposition process is repeatable and theoretically can continue indefinitely, but in practice, the choice of the appropriate number of decomposition times depends on the nature of the given signal. A schematic view of the DWT process is shown in Fig. 1.

Coefficients of DWT have different applications depending on the nature of the signal. For example, in the case of using the modal shapes or static deflection of a beam as the input signal of wavelet analysis, the low-frequency content is related to the response of an intact structure (without damage) and the high-frequency content is related to failure

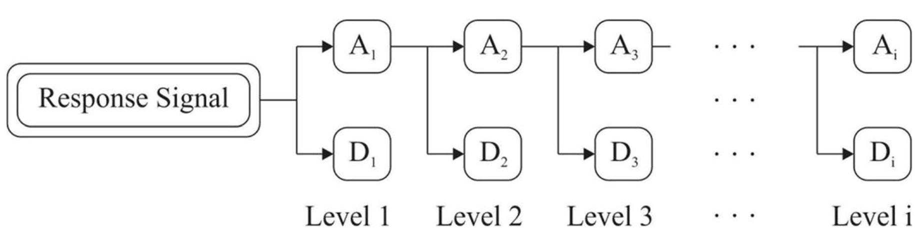

Fig. 1 Schematic view decomposition process of a signal using DWT

or noise in the system. Therefore, in this study to detect damage using this method, by decomposing the response of the structure into two parts of approximation (related to healthy structure) and details (related to failure and noise) and analyzing them, the location, and severity of damages can be determined.

3 Utilized algorithm for damage detection

Following the escalation of bridge-related incidents in recent years, and in particular the collapse of I-35 bridge in Minnesota, USA, in 2007, the inefficiency of manual bridge inspection methods was demonstrated (Ahmadi and Anvari 2018). Given the importance of this issue, providing an efficient method with minimal facilities and efforts can play an important role in reducing damages. Therefore, the main purpose of this study is to provide a simple method for damage detection of a bridge deck with the least number of response measurement sensors.

To identify the damage based on the proposed method, it is necessary to determine the displacement response of the bridge deck subjected to load at the location of the sensors for the intact state (S_{intact}). Then, after applying the damage scenario, the response of the structure must be obtained again under the specified load ($S_{damaged}$). Then the difference between the response signals of the intact and damaged structure (ΔS) for each sensor is calculated according to Eq. (5).

$$\Delta S = S_{intact} - S_{damaged} \tag{5}$$

In the next step, the calculated difference signal for each sensor is analyzed using DWT and their ninth-order approximation coefficients (A_9) are extracted. Finally, by drawing the curve of approximation coefficients and contours appropriate to the location of each sensor, the possible positions of deck surface damage can be identified. The steps of the proposed method are shown schematically in Fig. 2.

It should be noted that in practice when measuring the structural responses, the presence of noise in the sensors is inevitable. So, in this study, Eqs. (6) and (7) are applied to

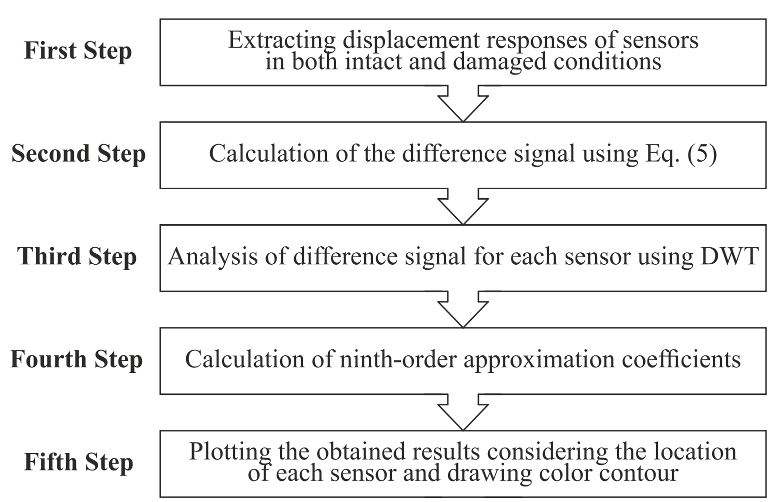

Fig. 2 Flowchart of the algorithm used in bridge deck damage detection

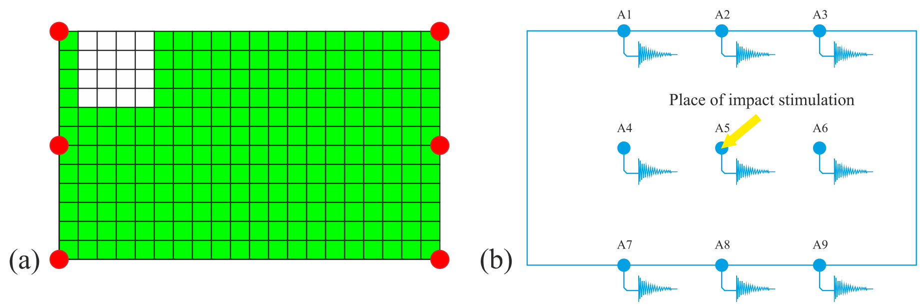

Fig. 3 View of the studied concrete slab (Ahmadnejad Zarnaghi and Tarighat 2018). **a** Meshed concrete slab with the position of hinge supports and damage scenario, **b** Location of accelerometers and position of impact load

Table 1 Coordinates of sensors (Ahmadnejad Zarnaghi and Tarighat 2018)

Axis	A1	A2	A3	A4	A5	A6	A7	A8	A9
x	2.5	5	7.5	2.5	5	7.5	2.5	5	7.5
y	6	6	6	3	3	3	0	0	0

add noise to the initial signal, which is the displacement response (Abdulkareem et al. 2019).

$$SNR = 20\log_{10}(1/n) \tag{6}$$

$$S_n = awgn(x, SNR) \tag{7}$$

In these equations, SNR, n, S_n and x stand respectively for signal-to-noise ratio, the noise level in percent, noisy signal, and noise-free signals. Also, *awgn* is a MATLAB function which adds white Gaussian noise to the vector signal x.

4 Verification

In this section, to ascertain the accuracy of the modeling process, structural analysis, extraction of results, use of wavelet transform, and damage detection, a report of the performed verification is presented. To perform verification, the model studied by Ahmadinejad Zarnaghi and Tarighat has been evaluated (Ahmadnejad Zarnaghi and Tarighat 2018). In their study, they identified various types of damage scenarios of a concrete slab with dimensions of 6 × 10 m and a thickness of 0.2 m, using the slab acceleration response at 9 points under impact load. In this impact, the load is reduced from 5 kN to zero in 0.1 seconds. The properties of intact materials including Young's modulus, Poisson's ratio, and weight density are 21,000 MPa, 0.2, and 2403 kg/m3, respectively. 4-node finite elements are used to model the concrete slab with a 0.5 × 0.5 square mesh. The view of this slab, the position of the supports, sensors, impact location, and damage position are shown in Fig. 3. Also the coordinates of the location of sensors on the slab (in meters) are presented in Table 1.

All damage scenarios in this study are modeled as stiffness reduction in the damage location, which is applied as a 10% reduction in the slab thickness. In the mentioned

Table 2 Comparison of verification results from modeling and the reference paper

Sensor	RDI		NDI	
	Reference (Ahmadnejad Zarnaghi and Tarighat 2018)	Calculated	Reference (Ahmadnejad Zarnaghi and Tarighat 2018)	Calculated
1	1.025	1.0246	5.888	5.8800
2	0.983	0.9829	1.55	1.5500
3	0.975	0.9746	0.723	0.7230
4	0.991	0.9906	2.376	2.3700
5	0.976	0.9761	0.826	0.8260
6	0.971	0.9712	0.31	0.3100
7	0.975	0.9752	0.723	0.7230
8	0.971	0.9711	0.31	0.3100
9	0.968	0.9683	0	0

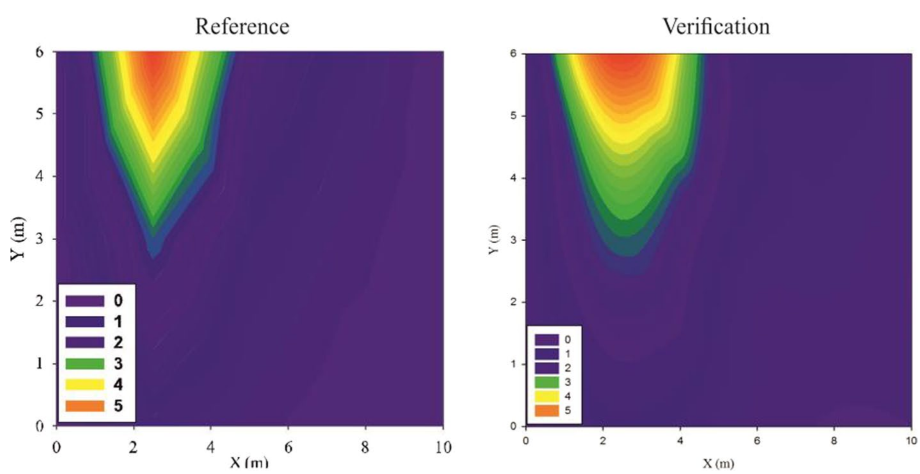

Fig. 4 Comparison of damage severity and extent detected by the performed modeling with the reference paper

paper, to extract the wavelet transform coefficients, the eight-order Daubechies mother wavelet has been used and based on the wavelet coefficients of each sensor, the energy density function (wavelet power spectrum) and then, the total wavelet energy have been calculated. Finally, the damage position is determined by calculating the values of the two damage indices, RDI (Routine Damage Index) and NDI (New Damage Index), for each sensor. The values of these two damage indices for the SD1 damage scenario derived from the performed verification and the reference paper are presented in Table 2. These indices have higher values near the damage location. In addition, the exact location and severity of the damage resulting from the validation and the reference paper are shown as color contours in Fig. 4.

Finally, according to Fig. 4 and also based on the results presented in Table 2, it can be concluded that the results of modeling are in good agreement with the results presented in the reference paper.

5 Numerical modeling

As mentioned previously, to evaluate the proposed damage detection method, Sani-khani bridge located in the southern part of Tehran has been studied in this paper. This bridge, which was put into operation in 2000, is a two-component bridge (beam-slab) that requires health monitoring due to its duration of the operation. For this purpose, the second span of this bridge with a length of 25.00 m has been modeled in CSi Bridge software. The views of the modeled span are shown in Fig. 5. Each span of this bridge is located on 10 girders, with an axis-to-axis span length of 2.10 m. A section of this span is demonstrated in Fig. 6. Also, the general properties of the concrete used for this bridge are presented in Table 3.

The deck of Sani-khani bridge has an 0.18 m thickness. To model the components of the bridge deck, 4-node (square) finite elements have been used. These elements have three different dimensions of 0.50×0.50, 0.625×0.50, and 0.70×0.50 m depending on the position of the deck supports. To extract the displacement response of the bridge, 10 displacement sensors have been used, which were located in the direction of the deck

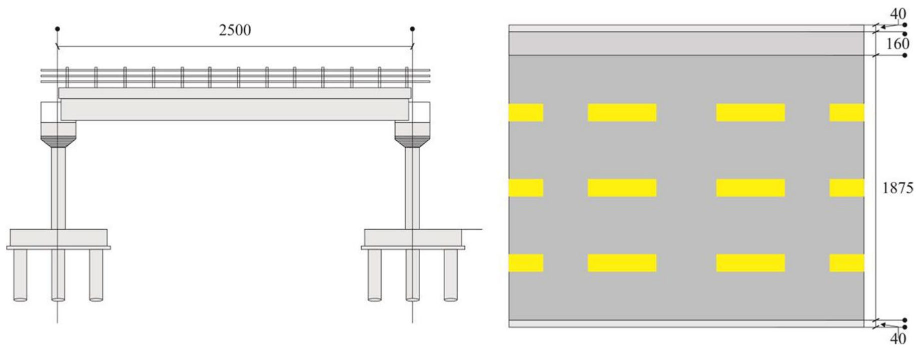

Fig. 5 Plan and elevation views of Sani-khani Bridge

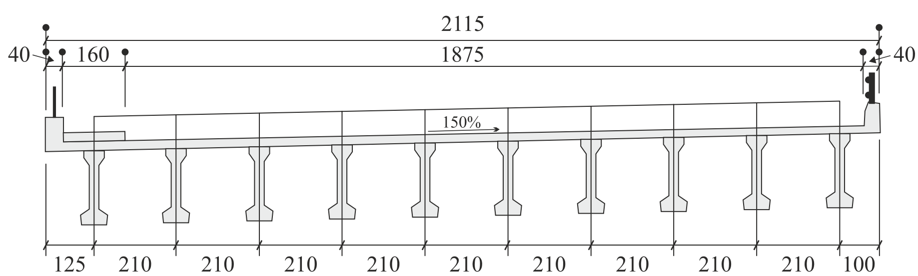

Fig. 6 Cross-section view of the studied bridge

Table 3 General properties of concrete used in the studied bridge

Property	Value
Compressive strength (MPa)	25
Tensile strength (MPa)	3
Density (Kg/m3)	2500
Poisson's ratio	0.2
Elasticity modulus (GPa)	20

supports, and the coordinates of the location of these sensors on the deck (in meters) are presented in Table 4. Moreover, a view of the modeled bridge deck with the position of the supports and sensors is depicted in Fig. 7.

To detect the damage using the proposed method, it is necessary to apply a certain excitation on the deck and receive displacement response signals at specific points. For this purpose, a moving load of 5 tons at the constant speed of 1 m/s has been applied in the direction of the centerline of the bridge, which is shown in Fig. 7.

To evaluate the efficiency of the studied method, 12 damage scenarios have been defined on the bridge deck to cover the entire deck surface. These scenarios are generally divided into two categories: single-damage (SD) and multiple-damage (MD). Nine single damage scenarios and 3 multiple damage scenarios are demonstrated in Figs. 8 and 9, respectively. Since the damage is simulated as a reduction in stiffness, in this study, each damage scenario is modeled as a reduction of the bridge deck thickness by 10% in the area related to the damaged elements. Also, the dimensions of all the damages are considered equal to 2.80×2.00 m (equivalent to approximately 1% of the total deck area).

As mentioned previously, according to the proposed method, the displacement difference signal, which is one of the simplest damage indices, has been used for damage detection. To calculate the displacement difference signal, the amount of vertical displacement recorded by each sensor of the damaged structure is subtracted from the displacement values of the intact structure according to Eq. (5). This signal is then decomposed based on the wavelet transform using Eq. (3). To achieve the desired results, the appropriate mother wavelet must be selected. In this study, the trial-and-error method was used to select the mother wavelet. After performing several trial-and-error signal decompositions using wavelet transform, the eighth order (db8) Daubechies mother wavelet was selected to provide the best damage detection results. Finally, to increase the reliability of the introduced method, in addition to the ideal signals, the efficiency of this method has been demonstrated in the presence of noise sensors and for various damage scenarios. For this purpose, the signal-to-noise ratio of 26 (5% noise level) has been used, which has been applied to the response signal using a code developed in MATLAB software environment which takes advantage of the Gaussian awgn noise function.

6 Signal processing and damage detection in noise-free mode

In this section, the performance of the proposed method is evaluated in the ideal state without noise in the sensors. As mentioned in the previous sections, the difference between the response signal of the intact and damaged states is used to detect the damage location. For instance, this difference signal in the direction of the *X*-axis of the bridge deck for 3 single-damage scenarios, and each of 10 sensors in the time domain is demonstrated in Fig. 10.

According to the presented algorithm for the proposed method, after calculating the difference signal, the ninth order coefficients of the difference signal are extracted using wavelet transform. These difference signals in the direction of the X-axis of the bridge deck and for the data recorded by 10 sensors and 9 single-damage scenarios are demonstrated in Fig. 11. The coordinates of the defined damage range in the X direction are shown using two black dashed lines. Also, according to the performed

Table 4 Coordinates of sensors used for the response extraction process

Axis	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9	Sensor 10
x	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50	12.50
y	1.25	3.35	5.45	7.55	9.65	11.75	13.85	15.95	18.05	20.15

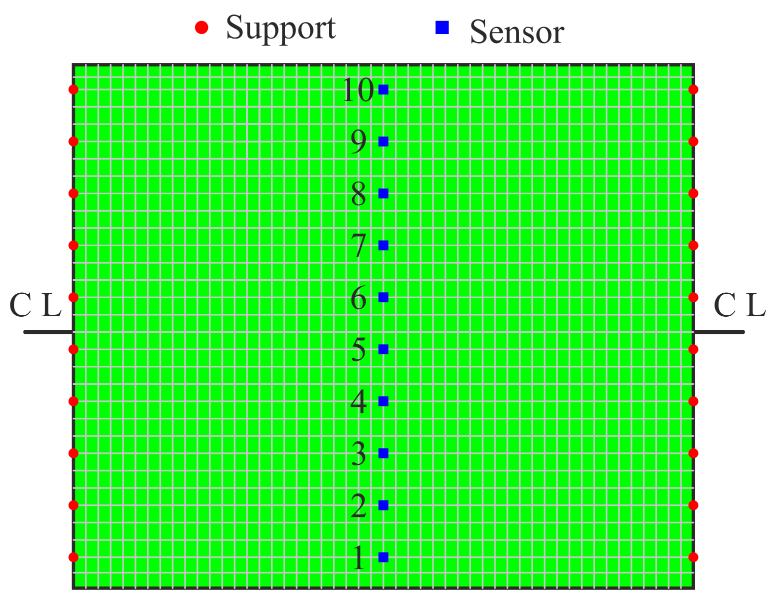

Fig. 7 Finite element view of the bridge deck and the position of the sensors and supports

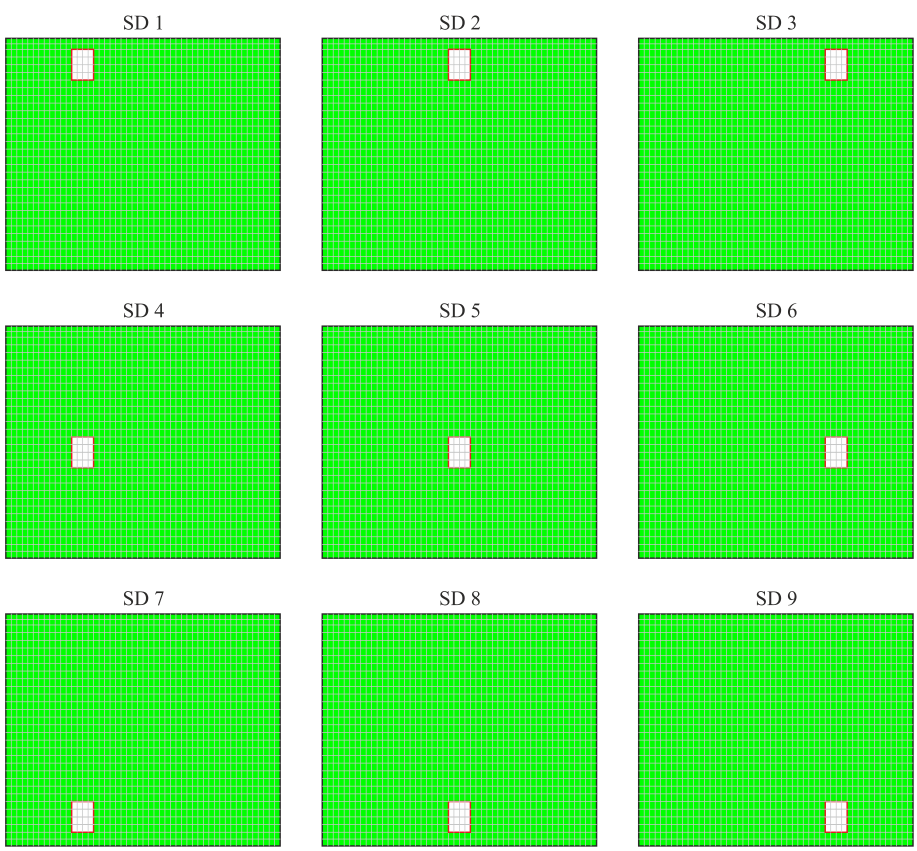

Fig. 8 9 single-damage scenarios

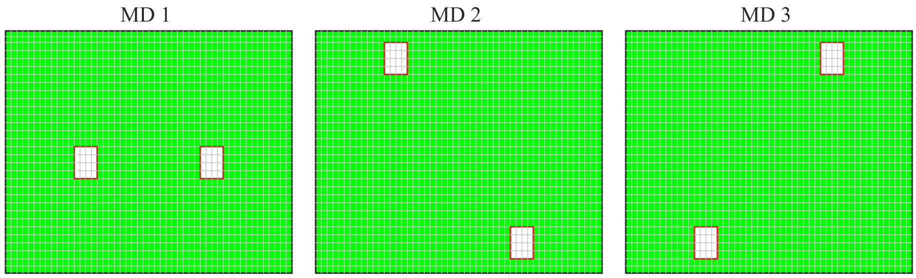

Fig. 9 3 multiple-damage scenarios

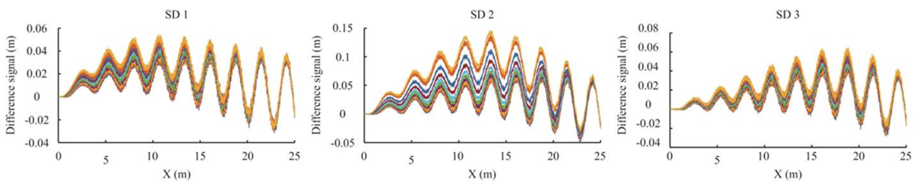

Fig. 10 The difference in the displacement signal of intact and damaged structure in the noise-free mode for 3 single-damage scenarios

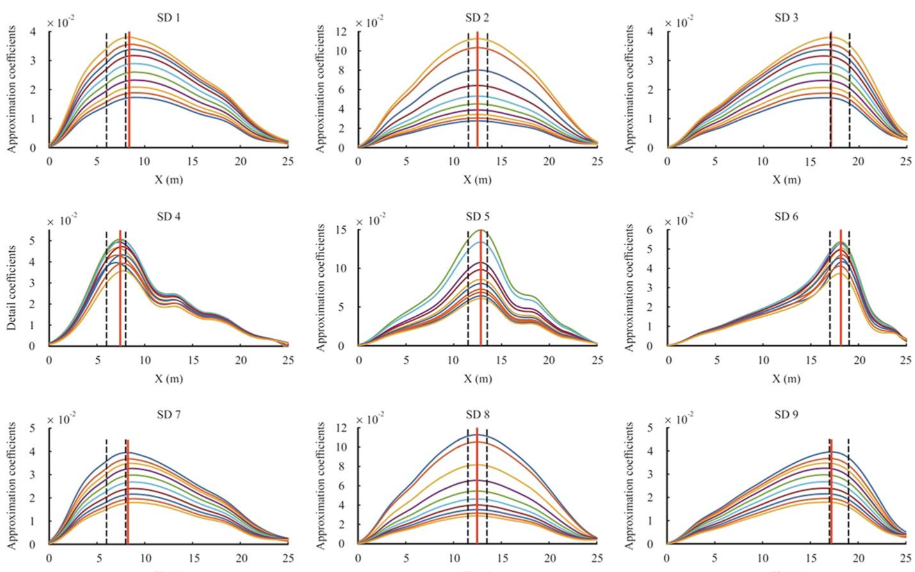

Fig. 11 The ninth order approximation coefficient curve of the signal in the direction of the X axis for 9 single damage scenarios in the noise-free mode

analysis, the coordinates related to the maximum coefficients of the wavelet transform indicate the damage location, which is demonstrated by a red solid line in Fig. 11 for each damage scenario. This line is derived based on the average maximum coefficient of each of the 10 sensors. According to the results presented in this figure and to accurately review the results and also extract applicable results, the single damage scenarios can be divided into two categories of damages in the deck corner (corner damage) and damages in other locations (middle damage). The results show that the middle damage scenarios are detected with great accuracy. Therefore, the red line showing the position of the damage center is located exactly between the lines related to the defined damage range. Regarding the scenarios related to corner damage, it is concluded that the proposed method can detect the damage with acceptable accuracy and very close to the exact damage range. Moreover, there is a specific correlation between all 10 sensors in which all the peaks represent the location of the damages on the X-axis simultaneously. According to the extracted results, it is clear that the proposed algorithm can verify itself.

For better perception of damage location, color contours are used based on the damage index and the location of the sensors. These contours for SD damage scenarios can be seen in Fig. 12. In other words, this figure shows the obtained wavelet coefficients at the deck surface. The red color part represents the maximum decomposed signal coefficients, which indicates the damage location. This figure clearly shows the accuracy and ability of wavelet transform and the proposed method against minor and sudden variations. The detected damage locations in this figure are predefined according to the damage scenarios, which shows the ability of the proposed method to easily and properly detect the damage location in single damage scenarios. In addition to damage localization, the extent of the damage can also be seen in this figure.

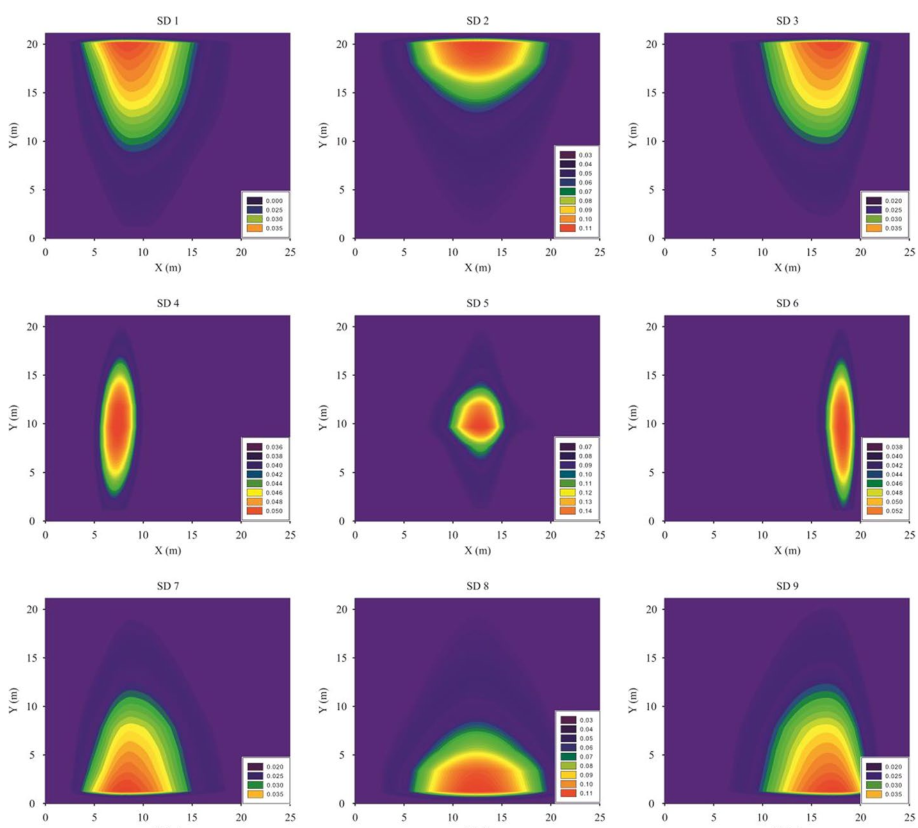

Fig. 12 Two-dimensional view of the detected damage extent for 9 single damage scenarios in noise-free mode

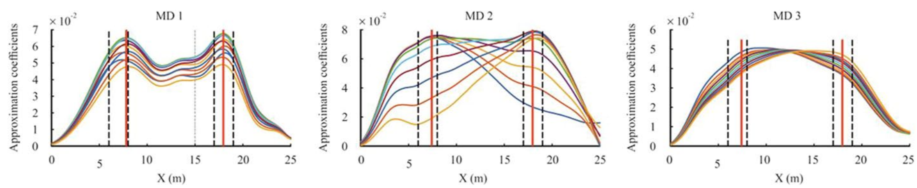

Fig. 13 The ninth order approximation coefficient curve of the signal in the direction of the X axis for 3 multiple damage scenarios in the noise-free mode

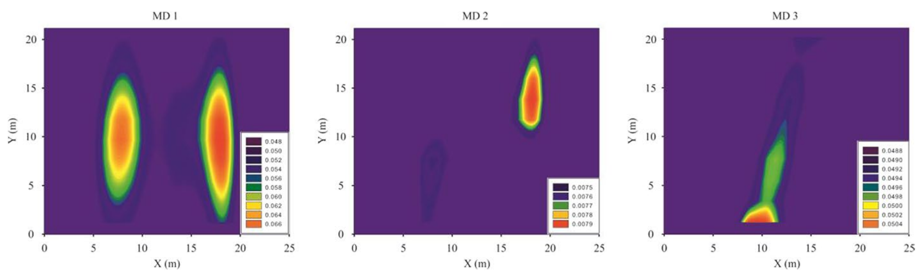

Fig. 14 Two-dimensional view of the detected damage extent for 3 single damage scenarios in the noise-free mode

The attained results about MD damage scenarios are shown in Figs. 13 and 14, respectively. As mentioned previously, the maximum approximation coefficients represent the damage location in the *X*-direction. Therefore, it can be seen in Fig. 13 that both damage locations are detected accurately in the MD1 scenario, but in the other two multiple damage scenarios, the peaks of the approximation coefficients are not as exact. This can be attributed to the presence of corner damages in the other scenarios. However, by carefully examining the curves and plotting the mean of the maximum coefficients of each of the 10 sensors, the X-axis coordinates of the damages can be extracted with appropriate accuracy. It is also inferred from Fig. 14 that despite detecting the coordinates of the X-axis damages, Y-coordinates of the damages were not detected correctly in both the MD2 and MD3 scenarios. It is due to the presence of corner damages. However, in both mentioned scenarios, the proposed method has ascertained the presence of multiple damages on the deck surface.

7 Signal processing and damage detection in the presence of noise

The results in the previous section were presented in order to evaluate the capability of the proposed method, in the ideal noise-free condition. In this section, the results of damage detection using the proposed method in the presence of 5% noise are presented.

Figure 15 shows the difference in the deck displacement signal between the 5% noise and noise-free conditions in the intact structure. For the sake of magnification, only 3 seconds is demonstrated in this figure. In addition, the time history of the difference between the displacement signals of the 5% noise and noise-free conditions for the SD1 damage scenario and sensor number 1 is plotted in Fig. 16. According to this figure, in the noise-free condition, it is possible to detect the damage location based on the maximum response without performing wavelet analysis. However, in the presence of noise, this cannot be done without wavelet analysis. Moreover, in the presence of noise, no

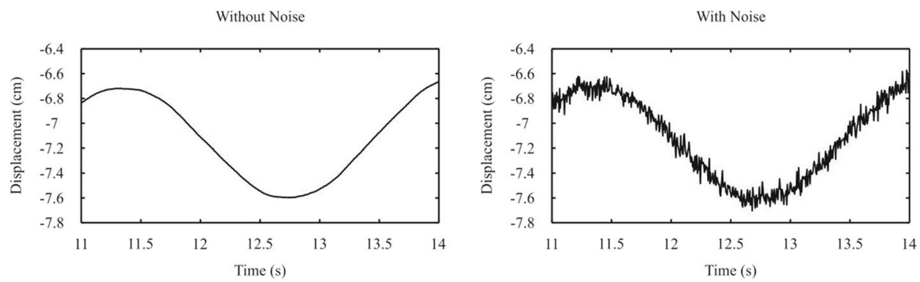

Fig. 15 The displacement response signal of the intact bridge deck in the ideal and noisy state

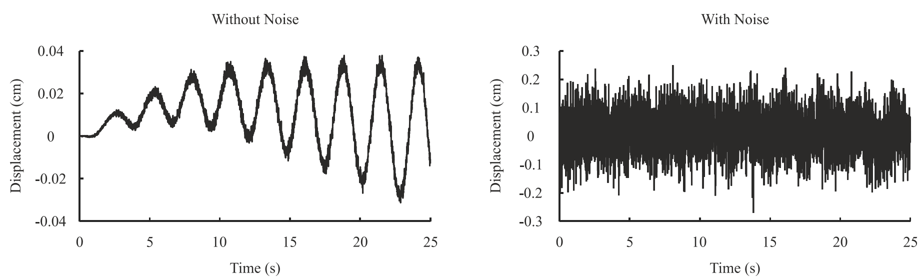

Fig. 16 The difference between the displacement signal of intact and damaged structure in the presence of noise and noise-free conditions for SD1 scenario and sensor number 1

prior perception is available before performing a wavelet transform analysis. This indicates the high ability of the wavelet analysis in the analysis of vibration signals, which is still able to detect damage location despite the large disturbances in the input signal.

The curves of the approximation coefficient for the nine SD scenarios in the presence of noise are presented in Fig. 17. As can be seen, the proposed method can also detect the middle damages with high accuracy in the presence of noise. For example, in the SD5 damage scenario, the peak corresponding to the wavelet transform coefficients is formed in the x-coordinate of 12.91 m, which coincides exactly with the defined location of the damage (the range between 11.5 to 13.5 m of the X-axis). In the case of corner damages, similar to the noise-free modes, very accurate results close to the actual damage locations are derived. Another point of this figure is the lack of balance and correlation among the results of the sensors in the cases of corner damage. This makes it difficult to detect damages using the results of only one sensor. The reason for this inconsistency in the results of corner damages can be the effect of side distortions and the presence of noise. In other damages, however, almost all sensors show the same maximum coefficients. The presence of perturbations in Fig. 17 compared to Fig. 11 indicates the negative effect of noise, which is also evident in the contours depicted in Fig. 18. However, these perturbations did not pose a major challenge to damage detection, because the damage location is well detected as shown in Figs. 17 and 18.

Same as the noise-free mode, to investigate the two-dimensional damage location and extent on the bridge deck surface, the color contours are presented in Fig. 18 separately for the single damage scenarios based on combining the results from all 10 sensors. In general, the results of the single damage scenarios show that despite all the mentioned

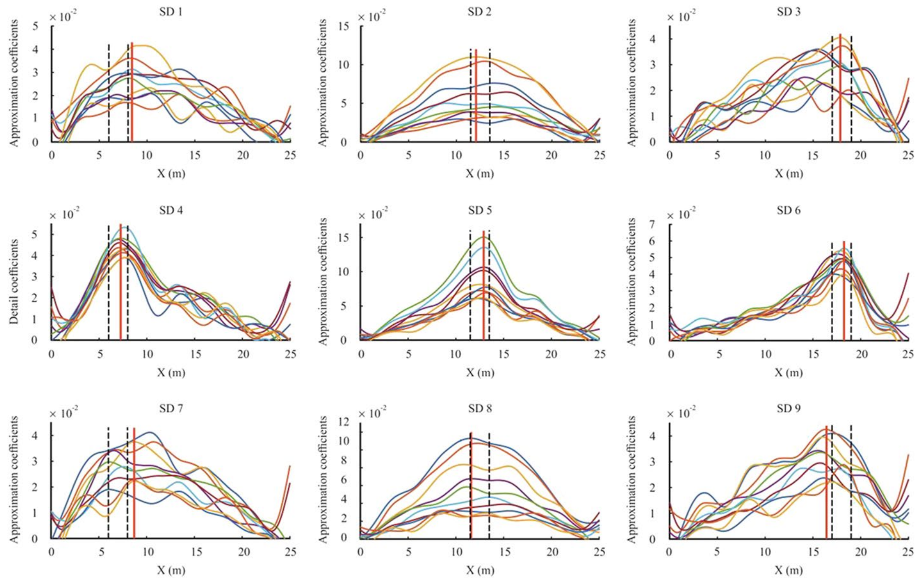

Fig. 17 The ninth order approximation coefficient curve of the signal along the X axis for 9 single damage scenarios in the presence of noise

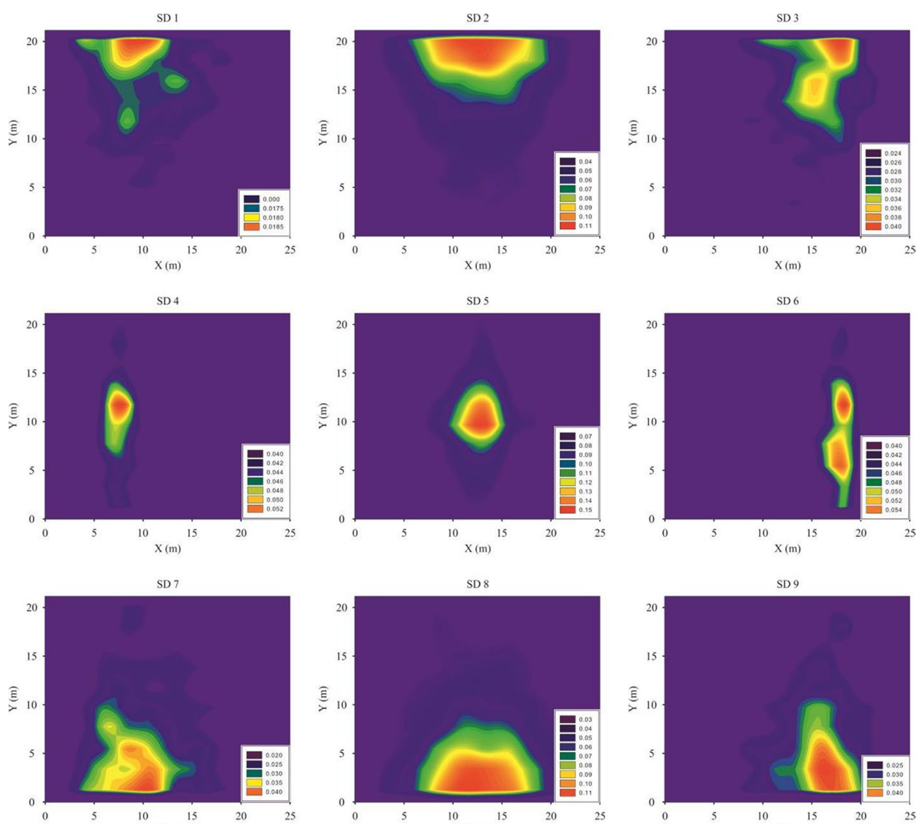

Fig. 18 Two-dimensional view of the detected damage extent for 9 single damage scenarios in the presence of noise

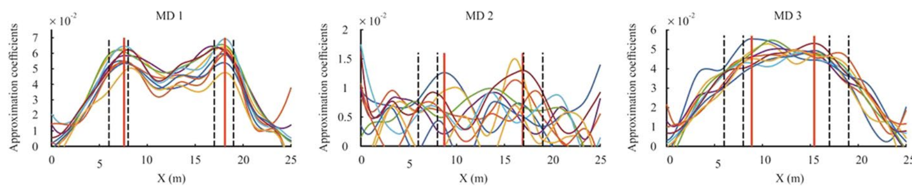

Fig. 19 The ninth order approximation coefficient curves of the signal along the X axis for 3 multiple damage scenarios in the presence of noise

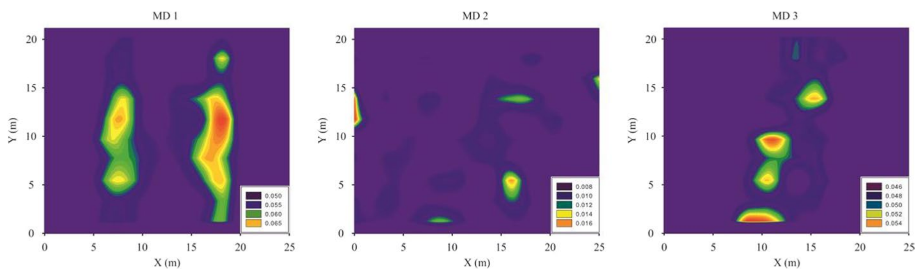

Fig. 20 Two-dimensional view of the detected damage extent for the 3 multiple damage scenarios in the presence of noise

issues, including the presence of noise, the proposed method can detect the location of damages with great accuracy. However, in some scenarios, very small levels of false damage are detected, which were not observed in the noise-free mode and are caused by the noise applied to the response signal. Nevertheless, it is important to note that the suggested method was able to detect the location of the damage in the presence of noise in the sensors.

Figures 19 and 20 demonstrate the results in the presence of noise in the sensors for the three multiple damage scenarios. It is demonstrated in Fig. 19 that despite accurate detection of X-axis coordinates of the damage, the presence of corner damage in both MD2 and MD3 scenarios makes the task difficult. The scattering in the sensor responses is also clearly visible. According to Fig. 20, the importance of side distortion in corner damages is evident, which makes detection of the exact coordinates difficult. Also, the incorrectly detected damages caused by noise can be seen in this figure. However, the relative position of the damages (especially their X-coordinates) has been determined. In this study, the proposed method was based on an initial assumption that the maximum amount of A9 (wavelet coefficient) will occur at the moment when the moving load passes through the damaged locations. According to the attained results, this assumption was correct.

8 Conclusion

In this study, a method based on the wavelet transform using the minimum number of required sensors is presented to detect damages to the deck of Sani-khani bridge in Tehran. In the proposed method, the difference in the bridge deck displacement between two intact and damaged conditions is used as the input signal of the wavelet transform signal. Various damage scenarios have been evaluated at the deck level in the presence of noise. The results can be summarized as follow:

- The location and extent of single damages in the middle of the deck (excluding corners) are detected 100% correct both in the noise-free state and in the presence of noise.
- As mentioned in many of the previous studies, the existence of corner damages in all scenarios, both single and multiple, due to the effect of side distortion, has made it difficult to detect the damage location. However, the proposed method can accurately detect the damage location in single corner damage and to determine at least the coordinates of damage location in the direction of one axis with high accuracy for multiple corner damages.
- In the noise-free mode, because of the consistency in curves of the coefficients of 10 sensors for each of the single scenarios, it is possible to identify the damage location on the X-axis accurately using the results of only one sensor. However, the presence of noise decreases the balance and correlation between the results of the sensors in the damage scenarios related to corner damages.
- The results show the high sensitivity of the proposed method to sudden and minor changes in response, which has led to an increase in the reliability of this method.
- Based on previous studies, it is obvious that due to the uncertainty in the number of sensors, the more the number of sensors, the more reliable and desirable results will be achieved. However, the proposed method with 10 sensors has been able to provide accurate and appropriate results for damage locations. In general, the attained results prove that the use of the wavelet transform method based on difference displacement signal results in accurate damage detection.

Abbreviations

DWT	Discrete Wavelet Transform
SHM	Structural Health Monitoring
DT	Destructive Tests
NDT	Non-Destructive Tests
CWT	Continuous Wavelet Transform
SD	Single Damage
MD	Multiple Damage

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Authors' contributions
Seyyed Ali Mousavi Gavgani: Formal analysis, Investigation, Writing - original draft. Amir Ahmadnejad Zarnaghi: Validation, Data analysis. Sajad Heydari: Conceptualization, Supervision, Writing - review & editing. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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