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Research Paper

A novel application to evaluate the bridge health after retrofitting using vibration and static measurements

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ABSTRACT

This paper proposes a novel method based on vibration and static measurement data to evaluate bridge health. This method is verified in Kênh 7 bridge. Kênh 7 Bridge is located in Long An district, Vietnam. The structural condition of the bridge was surveyed in July 2016. At that time, the girder was in good condition, whereas the deck's concrete spalled in many areas. Then the deck was decided to punch out and be replaced with the new ones. The dynamic and static experiments of both before and after retrofitted bridges were carried out in the campaign. This research analyses the vibration data and the main girder deflection under the static load to evaluate the stiffness condition of the bridge girder, deck, and cross beam. A finite element (FE) model of the bridge is created in FE software. The Grey Wolf Optimizer algorithm will be used to update the unknown parameters. By model updating, the natural frequency and the main girder deflection differences between the experimental and the numerical results are minimized, and the concrete properties of each component are estimated. Comparing the stiffness between the before and retrofit bridge, the conclusion about the health of the Kênh 7 bridge after repair can be made. It is recommended that the cross beam should be strengthened.

1 Introduction

Many existing bridges are replaced or repaired based on the decision made from the structural assessments event. The structural assessment of a bridge can help the bridge safety by considering the load carrying, making sure the bridge is in good condition, considering the cracking in the concrete bridge, and evaluating the function related to deformations or vibrations. Monitoring the damage at the earliest possible stage is pervasive throughout the civil engineering communities. Current localized experimental damage-detection methods such as acoustic or ultrasonic methods, magnet field methods, radiographs, eddy-current methods and thermal field methods only can detect damage on or near the surface of structures. Therefore, developing global damage detection methods that detect damage based on changes in the dynamic characteristics of the structure is needed. These methods are based on the simple idea that dynamic parameters (natural frequencies, mode shapes, and damping ratios) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore,

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damage that changes the physical properties will change the modal properties. The vibration-based damage detection method literature reviews are presented by Doebling, Farrar [1] and Sohn, Farrar [2].

Visual or localized experimental damage detection methods such as ultrasonic methods, thermal field methods, and radiographs require the pre-known and readily accessible damaged area [3]. Experimental methods that can detect damage on or near the surface of the structure are especially needed for complex structures like bridges. Therefore, the global damage detection methods examining changes in the dynamic parameters of the structure are used in many research [4–6]. The natural frequencies are often used as objective functions to calibrate the FE model and real-life conditions. Young Modulus are most common updating parameter. The damage in the Z24 bridge is identified by updating Young Modulus using the first five eigenfrequencies as objective functions [7]. The PSO and GA algorithms are proposed to find uncertainty parameters of the Nam O bridge [8]. In this work, the first ten modes of the bridge are used to verify the FE model and experimental results. By comparing the first four natural frequencies and mode shapes of a bridge prototype and experimental results, the FE model of a slab bridge is updated [9]. Liu, Sun [10] update the FE model of a bowstring arch bridge using a novel method based on component mode synthesis. Besides dynamic characteristics, the static response is used for updating purposes in many works. The FE model of Hong Tang Bridge is updated by using static response [11]. A model updating method that defines the fitness function as the combination of natural frequency and static displacement was introduced by Shan, Li [12]. This method has a clear physical meaning, and FE model of a bridge structure can be updated successfully. In this work, not only the frequencies obtained from the dynamic experiment but also the deflection got from the static experiment will be used to update the FE model of a bridge.

Thanks to the development of optimization algorithms, optimization problems can be solved with high accuracy. The technique using vibration data and optimization algorithms to update complex structures such as bridges is getting more and more attention [13–15]. The Grey Wolf Optimizer (GWO) algorithm is one of the nature-inspired algorithms. This algorithm is high-quality solutions, quickly found potentially optimal solutions in practice [16]. GWO has been successfully used to solve different optimization problems in many fields including medical, bioinformatics, engineering, and machine learning [17]. GWO combined with mode shape proves its effectiveness when used to determine the location and severity of damage in skeletal structures [18]. The effectiveness of GWO and some well-known optimization algorithms in damage identification of different structures with single damage and multiple damages are presented in Ref [19]. GWO and other metaheuristic algorithms are used to predict the structural health monitoring of a 3D truss structure [20].

Most of the recent works related to vibration based damage detection method use natural frequency as an objective function. However, only frequency is not very sensitive to damage in large structures. In this work, the objective function based on both natural frequency and static deflection at the middle of bridge girders is effective. GWO algorithm shows reliable results about the bridge health before and after retrofit based on this objective function.

2 Description of Kenh 7 bridge and experimental measurements

Kenh 7 bridge is located in Duc Hoa district, Long An province, Vietnam (Fig. 1). The total length of the bridge is 60.93m, including three simply supported spans. The first and the last span is 15m, and the middle span is 25.54 m in length. The bridge is made of prestressed concrete. Visual inspection discovered many vertical and longitudinal cracks on the deck. The quality of the concrete made of the deck is not ensured. Therefore, a retrofit plan was made.

Before the retrofit, the cross-section of the bridge has six girders as shown in Fig. 2. The deck's width and height are 9m and 18cm, respectively. The girder is high 114cm and in good condition. 4 cross beams are distributed equally along the span length. Both dynamic and static experiment was set up on the campaign to monitor the bridge's health.

The distance between the first and the middle axle is 3.3 m, and between the middle and the last axle is 1.3m. In the transversal direction, the distance between two axles is 2.05m. Table 1 describes the weight of each truck axle.

Dynamic experiment: the natural frequency of the bridge was analyzed by using accelerometer data from VP-5123HHV sensors. The dynamic exciter was the truck running across the bridge with a velocity of 20, 30, and 40 km/h (Fig. 3).

Static experiment: The deflection at the middle of each girder was recorded. 6 indicators were attached to the bottom of the main girder at the middle. Six labels V1 to V6 in Fig. 4 indicate these indicator locations on the drawing and the field. Two trucks standing in the middle of the span were used to measure the static deflection. Fig. 5 expresses the location of two trucks in the transversal direction. The truck has three axles.



Fig. 1 – Kanh 7 Bridge location

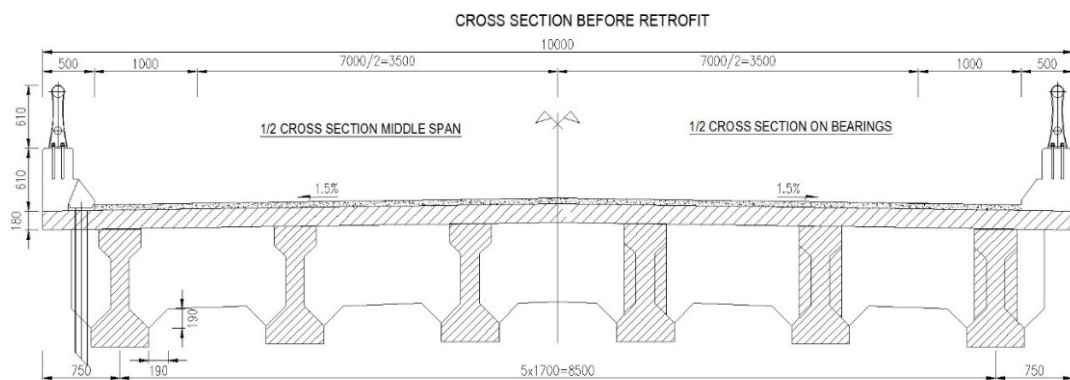


Fig. 2 – Kanh 7 bridge cross-section

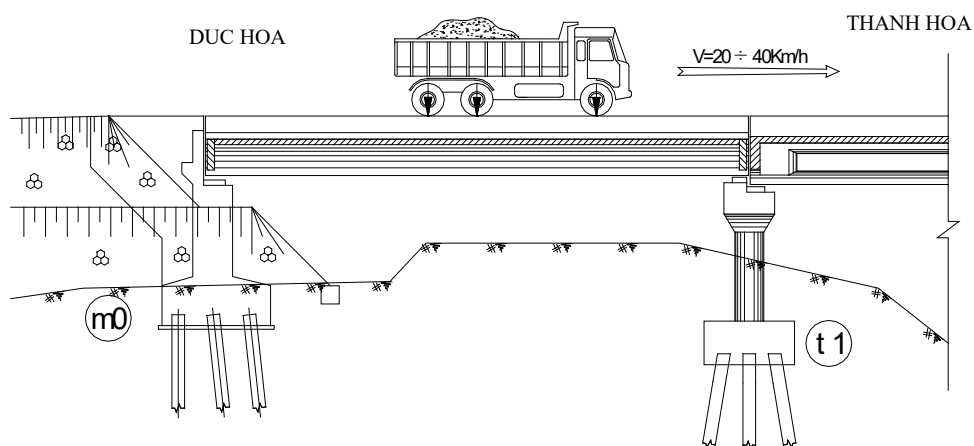


Fig. 3– The dynamic experiment organization

Before the retrofit, the six main girders were in normal condition health. The girder does not crack at the service limit state. However, the concrete deck appears longitudinal and transversal cracks. The quality of the concrete deck does not meet the design requirements. Wheel load can be one of the causes of cracking in the longitudinal direction. The continuous opening and closing of these cracks can cause them to increase in width and lead to a decrease in deck stiffness and an adverse change in the load distribution between girders. The repair plan is to replace the existing deck with 30Mpa self-compacting concrete width of 23 cm, with additional reinforcements.

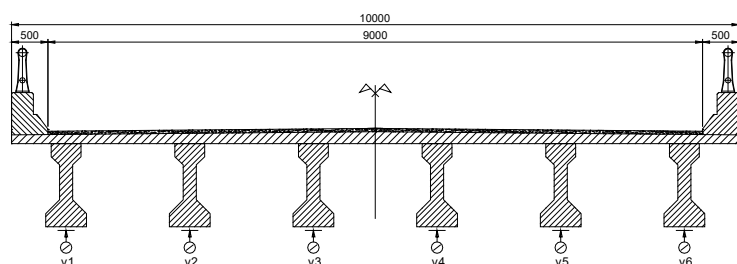


Fig. 4 – Indicator locations

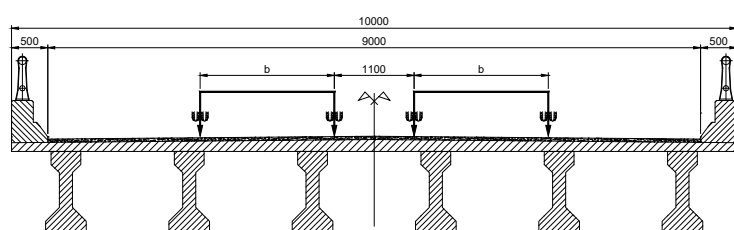


Fig. 5 – The truck location for static experiment

Table 1 – The experimental truck characteristic

	No	P1 (Ton)	P2 (Ton)	P3 (Ton)	ΣP (Ton)
Before Retrofit	1	5.79	11.31	11.80	28.90
	2	5.81	11.17	11.97	28.95
After Retrofit	1	5.60	11.20	11.25	28.05
	2	5.65	11.20	11.22	28.07

3 Finite Element Model of Kenh 7 Bridge

The FE model of bridge was created in CSIBridge software. The material characteristics of the deck, main girders, and cross beam are shown in Table 5, the before-update value. These are the theory value of concrete characteristics at the survey time. The beam elements were used to model six main girders and cross beams; shell elements were used to model the concrete deck. The boundary condition of the main girder was simply supported. The vehicle load was modelled as the added mass to get the beam deflection showing a simulation of the static experiment. For dynamic experiments, the vehicle acted like an excited load. The shell element height of 18cm was used to model the bridge deck before the retrofit, and height of 23cm was used to model the bridge deck after the retrofit. Fig. 6 shows the first two modes of the bridge before and after the retrofit. The difference between the natural frequencies of the experiment and the FE model is high. Therefore, the properties of the concrete material should be updated. Based on the updated value, the condition of the bridge components can be estimated, and the effectiveness of the retrofit can be discussed.

4 Model updating

4.1 Grey Wolf Optimizer

Grey Wolf Optimizer (GWO) is inspired by the leadership hierarchy and hunting mechanism of grey wolves (*Canis lupus*) in nature [21]. Four types of grey wolves and the three main steps of hunting, searching for prey, encircling prey, and

attacking prey, are implemented. Three leader wolves named α , β and δ guide the algorithm to find the best solution. Three step are described below.

Step 1: Encircling

The encircling behavior of grey wolves is modelled as the following mathematical equations

$$D = |C \times X_p(t) - X(t)| \quad (1)$$

$$X(t+1) = X_p(t) - A \times D \quad (2)$$

where X_p is the position of grey wolves and t is the current iteration.

A and C are coefficient vectors calculated by Eq (3-4).

$$A = 2a \times r_1 - a \quad (3)$$

$$C = 2 \times r_2 \quad (4)$$

where r_1 and r_2 are random vector in $[0,1]$. a is the linearly decrease vector from 2 to 0 over the course of iterations.

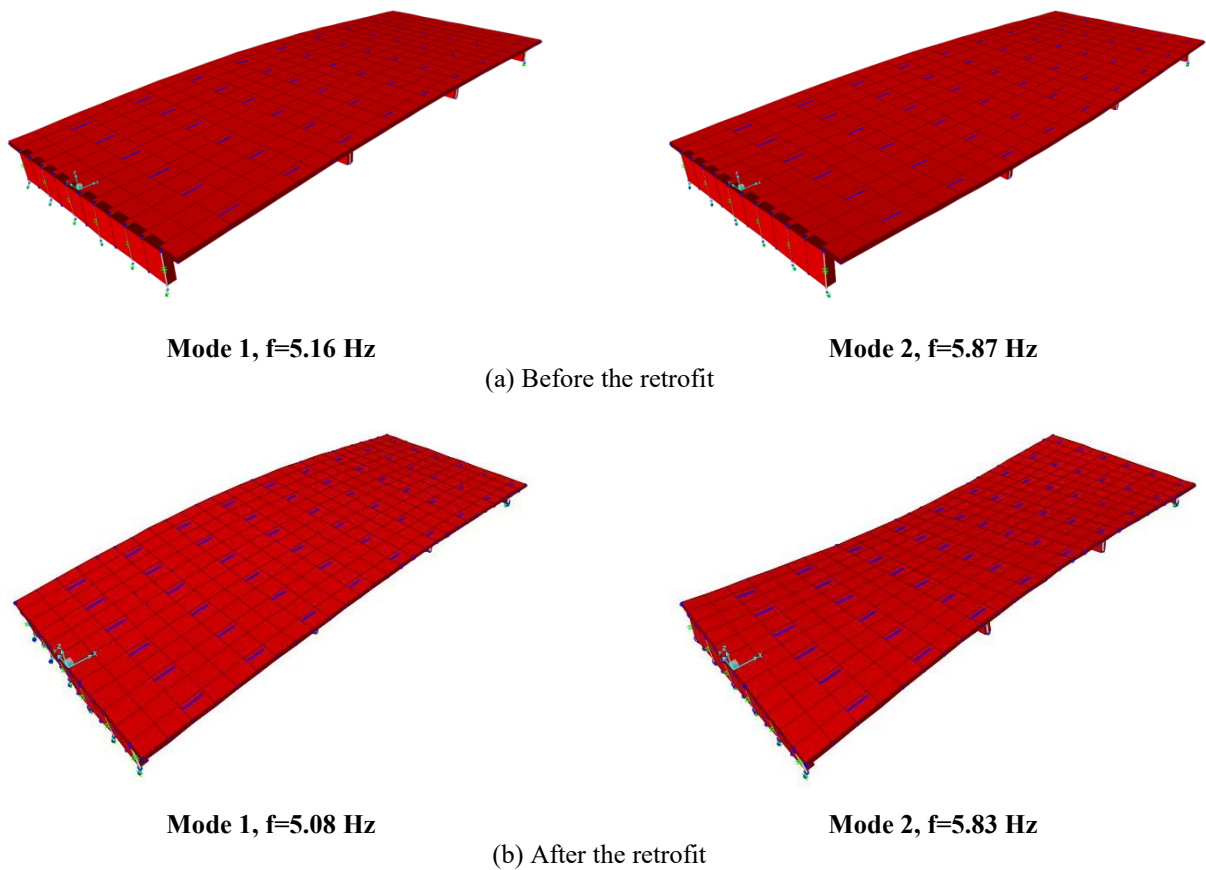


Fig. 6 The first two mode of FE bridge model

Step 2: Hunting

For hunting, Grey wolves find location of the prey and encircle them. In mathematically model, α , β and δ are the best, second and third best solution (prey) and will be guide ω , rest of the candidate solutions (wolves). The following expression are proposed in this regard.

$$D_\alpha = |C_1 X_\alpha - X| \quad D_\beta = |C_2 X_\beta - X| \quad D_\delta = |C_3 X_\delta - X| \quad (5)$$

$$X_1 = X_\alpha - A_1 D_\alpha \quad X_2 = X_\beta - A_1 D_\beta \quad X_3 = X_\delta - A_1 D_\delta \quad (6)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (7)$$

Step 3: Attacking

When the prey stops moving, the grey wolves attack them and stop hunting. To perform this, the value of a is reduced. Therefore, A is also reduced and A is a random value in the interval $[2a, 2a]$. When $|A| < 1$, the wolves attack the prey. Finally, the best location of prey can be located based on a position.

4.2 Objective function

Two natural frequencies of the Kenh 7 bridge were estimated through dynamic experiments and the FE model. The uncertainty parameters are the elastic modulus of material made of the deck, girder and cross beam. Static experiments provide the deflection of six main girders in the middle. The main girder deflection was used as an objective function also. Eq. (8) below describe the objective function.

$$\text{Objective function} = \sum_{i=1}^2 \left[\frac{f_{Exp} - f_{FE}}{f_{Exp}} \right]^2 + \sum_{j=1}^6 \left[\frac{\delta_{exp} - \delta_{FE}}{\delta_{exp}} \right]^2 \times \omega \quad (8)$$

where:

f_{Exp} , f_{FE} : the natural frequencies were identified from the experiment and FE model, respectively. Only the first two modes are considered for Kenh 7 bridge problems.

δ_{exp} , δ_{FE} : the deflection of six main girders in the middle span were identified from the static experience and FE model, respectively.

ω : weight parameters, based on the level of accuracy between dynamic and static experiment. In this work, $\omega = 1/10$.

4.3 Results

4.3.1 Before Retrofit

The deck was divided into 3 sections. Each section was assigned with different elastic modulus. Young's modulus of the girders and cross beams are defined as uncertainty parameters. In total, 5 elastic modulus E1, E2, E3, E4, E5 are considered as uncertainty parameters (Fig. 7). E1, E2, and E3 are elastic modulus of the deck. E4 and E5 are the elastic modulus of the girder and cross beam, respectively. GWO optimization algorithm is chosen to find the stiffness of each element of bridges. The objective function was defined as in Eq.(4). Table 2 shows the natural frequencies of the first two modes before and after updating. Before updating, the differences between the FE model and measurement are 47.43% and 38.11 % for mode 1 and mode 2, respectively. However, after updating, the differences reduce and equal to 0.29% and 0 % for mode 1 and mode 2, respectively. Moreover, the value of objective functions for girder deflection presented in Table 3, reduces from 4795E-04 to 1721E-04. Fig. 8 shows the value of the objective function versus the number of iterations. The value of fitness reduces fast at the very first iteration and is steady after 50 iterations. The value of the objective function is minimized. Therefore, the numerical model is successfully updated.

Table 4 presents the range variation of uncertainty parameters used in the optimization algorithm. Damages are recognized in the deck; therefore, the lower elastic modulus values are set equal to zero. The upper values are set equal to theoretical values. Table 5 presents the value of the deck, girder and cross beam elastic modulus after updated. The differences between updated and theoretical values are very high, around 90% for E3 and E5. The spalling and damage on the deck surface reduce its stiffness. The cross beam contribution to the global bridge stiffness is very weak. Because the stiffness of the deck was reduced by 32.89% for E1 and 85.56% for E3, the old deck is peeled off and replaced by a new one.

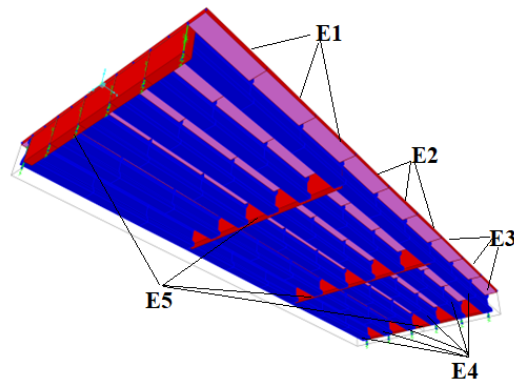


Fig. 7 Definition of updated parameters on the bridge

Table 2 – The modal frequencies from the FE model and measurement of before retrofit bridge

Mode	Before modal updating (Hz)	Model updating (Hz)	Measurement (Hz)
1	5.16 (47.43%)	3.51 (0.29 %)	3.5
2	5.87 (38.11%)	4.25 (0 %)	4.25

Table 3 – The deflection from the FE model and measurement of before retrofit bridge

Girder No	1	2	3	4	5	6	fobj
Measurement (mm)	5.3	6.26	9.89	9.1	5.2	3.9	
Before (mm)	5.3	5.3	5.2	5.1	4.8	4.6	4795E-04
After updating (mm)	5.49	6.9	7.27	6.45	5.56	4	1721E-04

Table 4 – The range variation of uncertainty parameters (before retrofit)

	E1	E2	E3	E4	E5
Lower (GPa)	0	0	0	0	0
Upper (GPa)	2.597	2.597	2.597	3.50	2.597

Table 5 – Value of uncertainty parameters before and after update (before retrofit)

	E1	E2	E3	E4	E5
Before (GPa)	2.597	2.597	2.597	3.50	2.597
After (GPa)	1.743	2.592	0.375	3.50	0.013
Differences (%)	32.89	0.19	85.56	0	99.50

4.3.2 After Retrofit

The bridge is repaired by replacing a new deck. The deck is now in good condition then E1, E2, and E3 are defined for the same value. E4 and E5 are still the elastic modulus of the main girder and cross beam, respectively. Only dynamic test was done to evaluate the bridge condition. Table 6 shows the natural frequencies of the bridge before and after updating. Because the bridge is in good condition, the differences between the FE model and measurements before and after updating are both small. Before updating is 6.95% and 11.05%, after updating is 0.29% and 0.19 % for modes 1 and 2, respectively. Table 7 indicates the value of uncertainty elastic modulus after updating. The value of the objective function for each iteration is presented in Fig. 9. After nearly 150 iterations, the value of objective function is stable.

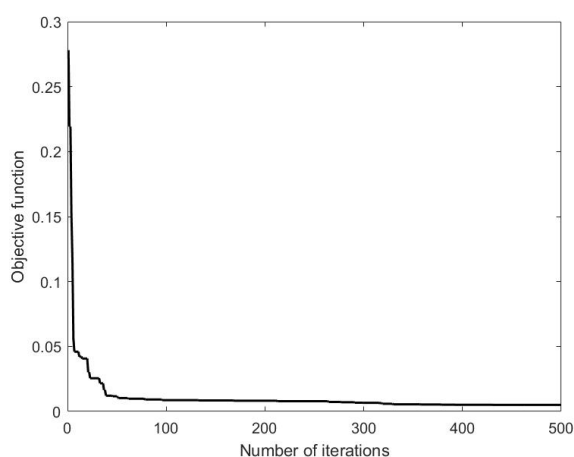


Fig. 8 Iteration vs Objective function (before retrofit)

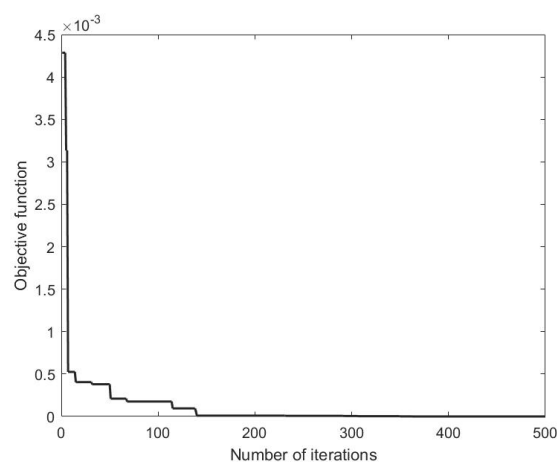


Fig. 9 – Iteration vs Objective function (after retrofit)



Fig. 10 – Cross beam in Kanh 7 Bridge

Table 6. The modal frequencies from the FE model after model updating and measurement (after retrofit)

Mode	Before modal updating (Hz)	Model updating (Hz)	Measurement (Hz)
1	5.08 (6.95 %)	4.74 (0.29 %)	4.75
2	5.83 (11.05 %)	5.24 (0.19 %)	5.25

The differences between the updated value and theoretical value are now reduced significantly compared with before the retrofit. The deck stiffness is increased after the retrofit. This proves that the repair method is beneficial. The stiffness of the cross beam is not increased much. The replaced deck helped to increase the stiffness of the cross beam because it strengthened the connection between the deck and the cross beam. The stiffness of the girder is still high for both before and after retrofit. To conclude, the retrofit is benefit. However, it will be better if the cross beam is repaired. Fig. 10 displays the current status of the cross beam to check the recommendation from the proposed method. Visual observation shows cracks on the concrete surface. Therefore, the global stiffness of the bridge will be much better if the cross beams are repaired.

Table 7. Value of uncertainty parameters before and after update (after retrofit)

	E1	E2	E3	E4	E5
Before (GPa)	2.597	2.597	2.597	3.50	2.597
After update (GPa)	2.077	2.077	2.077	3.377	0.332
Differences	20.02	20.02	20.02	3.5	87.21

5 Conclusion

Based on the vibration data, the natural frequencies of Kanh 7 bridge can be found and used to find the stiffness of bridge components such as the deck, main girder, and cross beam. Inspection results raised a problem about the condition of the deck. That is the damage, spalling on the surface of the bridge deck, the stiffness of the deck reduced by up to 90%, a repair method needs to plan. A thicker deck was constructed to replace the old one. Data get from the dynamic and static experiments can analyze that problem more clearly. Using experiment data and an optimization algorithm to update the FE model shows the benefit of the retrofit method. Moreover, the optimization results indicate that the stiffness of the main girder almost reaches the theoretical value. However, the stiffness of the cross beam is not increased significantly. Therefore, one recommendation for the bridge owner is to strengthen the cross beam.

Based on Kanh 7 bridge case study, vibration data combined with static response can be used to monitor the health of the bridge. Optimization algorithms can be used to update the FE model based on the dynamic test and the static load test. The beam deflection analyzed from the static load experiment makes the updated results more reliable. Based on the updated value of uncertainty parameters, each bridge component's damage severity and stiffness contribution can be estimated and used for reference for the repair method. The proposed method for the health monitoring goal is effective and has a high potential for application.

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