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EXPERIMENTAL STUDIES ON PRESTRESS FORCE AND APPLIED LOAD IDENTIFICATION IN PRESTRESSED CONCRETE BOX GIRDER

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Prestress force (PF) and the applied loads are two significant aspects that relate to the safety of in-service prestressed concrete bridges (PCBs). The PF directly governs the load carrying capacity of the bridge, and the prestress losses would decrease the effective value of PF which would in turn reduce the strength of the bearing members or even lead to bridge failure; while the applied loads caused by vehicles are critical for bridge diagnosis and maintenance. Overloading would damage the bridge deck and substructure resulting in a large reduction of the structure's lifespan. These potential safety hazards raise the need to monitor these two forces and maintain them in a safety range. In this paper, the PF and unknown load applied on a simply supported box girder bridge are determined simultaneously through a synergic identification method which takes advantage of virtual distortion method (VDM), Duhamel integral and load shape function (LSF). The feasibility of this method is examined in a comprehensive laboratory test. Results show that the method attains a good degree of accuracy and efficiency in assessing PF and stationary force, and has good robustness to noise.

Keywords: SHM, synergic identification, prestress force, general excitation, laboratory test

1 Introduction

In the 21st century, Structural Health Monitoring (SHM) systems are being installed onto important structures globally (Chan and Thambiratnam 2011). However, little attention has been paid to prestressed concrete bridges (PCBs). Due to degradation, traffic load increases and more stringent design codes, many of these bridges may not meet the current standards. Hence it is necessary and indeed urgent to have SHM systems installed in a large number of PCBs, not only to ensure their structural and operational safety but also to warn of unexpected hazards.

Two aspects that would affect the safety of the PCBs should be highlighted. The prestress force (PF) in prestressed concrete is the most important parameter in PCBs, which dominates the load carrying capacity of the bridges. But prestressed concrete may lose its PF as a result of some immediate losses like elastic shortening and frictional loss between tendon and concrete as well as some time dependent losses like creep and shrinkage of concrete, steel relaxation, etc. which in turn would reduce the strength of the beam, shorten the lifespan of the bridge or even lead to catastrophic failures. Therefore, one of the most important roles in SHM systems should be to identify the PF value in PCBs. Another aspect related to the state of structural health is the information related to the loading forces to which a PCB is subjected to. Especially its applied load due to the excitation force (stationary or moving), which is critical for bridge design, diagnosis, and maintenance. Besides, overloading can damage the bridge deck and substructure resulting in a large reduction of the lifespan of the structures. Thus, applied load monitoring should be included in SHM systems as well.

Concerning to solve these two problems effectively and efficiently, a synergic identification method has been proposed by the authors to assess the existing PF and general excitation simultaneously (Xiang et al. 2015, Xiang et al. 2017, Xiang et al. 2016). In this paper, the experimental validation of this study has been carefully presented. A prestressed concrete box girder model was well designed and constructed. Two unbonded prestress cables were post-tensioned. The existing equivalent PF as well as the stationary excitation was identified by the synergic identification method. The achievement of the this paper will provide insight for the practical application of the method, the PF will be able to be determined in a quick bridge test that simply uses one stationary force to excite the bridge and this excitation even does not need to be known.

2 Methodology of the synergic identification method

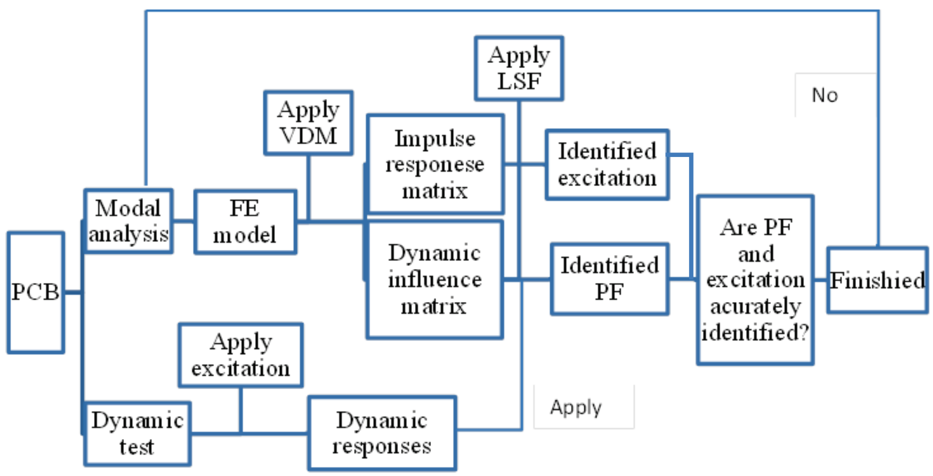


Figure 1. Methodology of synergic identification

The synergic method takes advantages of three methods: firstly, it applies the concept of Virtual Distortion Method (VDM) (Kolakowski et al. 2006) to transform the internal PF into external pseudo-loads, so the synergic identification problem becomes a multi-force identification of the pseudo-loads and excitation force. Then it uses a basic time domain method - Duhamel integral (Chan et al. 2001) to determine these forces. At last, it introduces Load shape function (LSF) to regularize the integral and enhances the computational efficiency (Zhang et al. 2010). According to this idea, the frame in Figure 1 demonstrates the practical application methodology. For a real PCB， the application is separated into two routines: modal analysis and dynamic test. The former is used to obtain the modal parameters of the bridge, which provides information in establishing a corresponded FE model. Applying VDM, the prestressed model is transformed into the original model (no PF) subjected to the general excitation and pseudo-load respectively. Then the impulse response matrix and dynamic influence matrix can be calculated from the two models according to Duhamel integral. Meanwhile, applying excitation to the PCB in a dynamic test, the measured responses are supplemented to the integral for the identification. During the inversion of Duhamel integral, LSF is introduced to enhance its robustness to the noise and improve its computational efficiency. If the results are not accurate, the routine will go back to the FE model and conduct a model updating procedure in order to develop a more precise system matrix and then the identification routine is repeated.

3 Laboratory validation

A 6m long box girder model with two parabolic unbonded prestressing strands was designed based on Madhavi et al. (2006)'s research, which were 1/6 scaled down model of the girders used in the Mass Rapid Transit System Bridge in Chennai, India. The dimensions are shown in Figure 2. The tendon profile was selected as parabolic with eccentricity; the distance of each tendon to the bottom slab along the longitudinal direction is shown in Table 1.

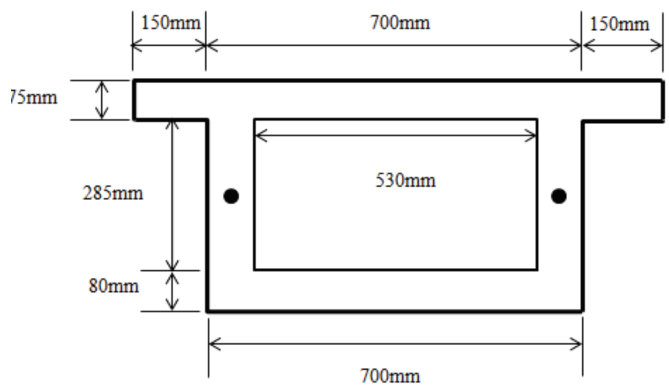
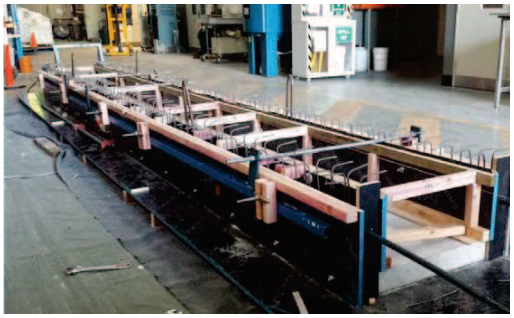


Figure 2. Cross section of the prestressed box girder

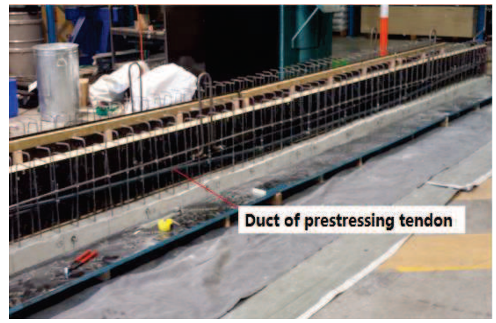
Table 1. Prestressing tendon arrangement

Longitude (mm)	0	500	1000	1500	2000	2500	3000
Distance (mm)	235	209	184	163	146	134	130

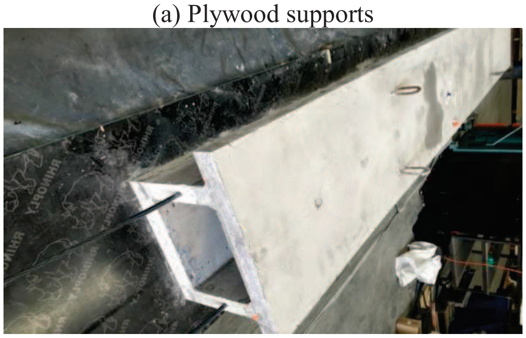
The construction of a box girder was complicated. A supportive formwork using plywood was arranged before concreting as presented in Figure 3(a). Sufficient reinforcements were fixed according to the design, whereas the longitudinal and lateral steel bar ratios were 0.01134 and 0.12261 respectively. Two ducts of the prestressed cables were embedded in the webs as shown in Figure 3(b). The final model is illustrated in Figure 3(c). When the concrete box girder was well fabricated, two prestressing cables were passed through the ducts and anchored to the girder (Figure 3(d)). A cellular load cell was installed between the anchor and the concrete end to monitor the effective PF in the tendon when a hydraulic mono jack was post-tensioning the tendons. (Figure 3(e)). Meanwhile, an electrical displacement transducer was placed close to the anchorage (see Figure 3(f)). An obvious camber of the girder edge due to the prestressing can be observed. The effective PF was measured as 171.277kN.



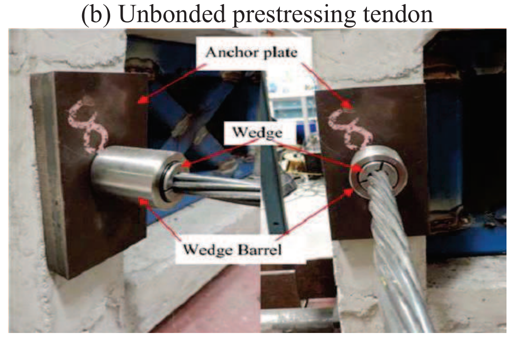
(a) Plywood supports



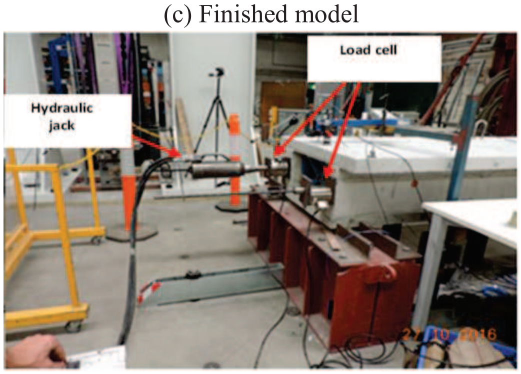
(b) Unbonded prestressing tendon



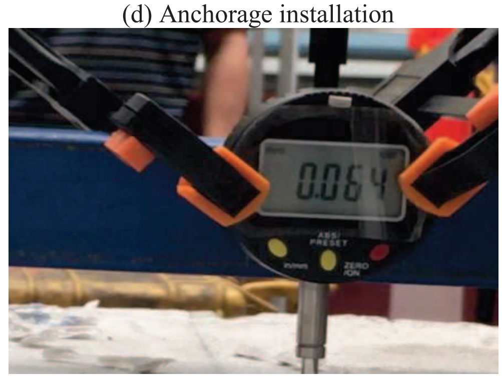
(c) Finished model



(d) Anchorage installation



(e) Hydraulic jack and load cells



(f) Edge camber during prestressing

Figure 3. Model construction and post-tensioning

According to the methodology in Figure 1, a model test was conducted in the laboratory to identify the modal parameters of the non-prestressed model (original model) by Output-only Modal Analysis (OMA). In the OMA, ambient excitation was simulated by alternate hammer hitting, and the data were processed using ARTeMIS Extractor software (Nguyen et al. 2014).

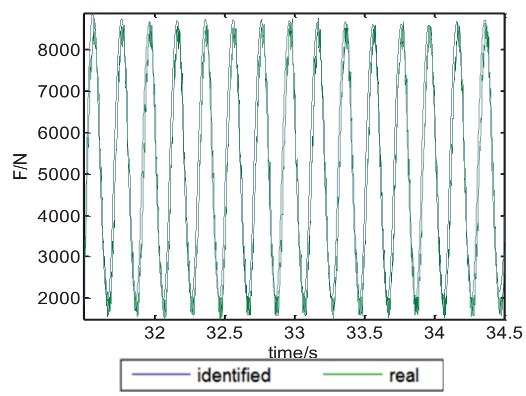
The FE model of the non-prestressed box girder was updated to calculate the system matrices required in the later step of the synergic identification. The test model was found not to be well constructed during the modal testing. The lateral restraint was not tight enough, allowing the girder to move slightly. Because of this, the boundary condition of the FE model was adjusted to a flexible vertical restraint and elastic lateral restraint using nonlinear elastic supports in ANSYS. On the other hand, the material properties of the model were found to be sensitive to vibration parameters. For convenience, overall properties were considered in the updating, the values of density and elastic modulus were adjusted by a trial and error method. The final density and Young's modulus of the concrete were determined as 2.68×10^3 kg/m^3 and 28.66 GPa. Table 2 shows the natural frequency of the matched modes respectively.

Table 2. Detected and updated Natural frequency of the model

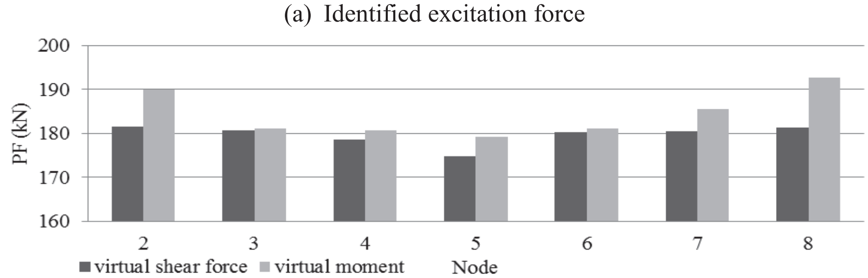
Mode order	Frequency		
	Lab model (Hz)	Updated FE model (Hz)	Error (%)
1	23.025	23.182	0.68
2	43.785	43.091	1.58
3	57.768	56.700	1.85
4	61.745	-	-
5	89.229	86.584	2.96
6	94.720	-	-
7	127.154	129.76	2.05
8	136.044	-	-

In the dynamic test, a stationary sinusoidal force was subjected in the centre of the mid-span, which was generated by a Moog® control loading system. Its value was 1/6 scaled down from a light van (1.8t – 6t), and the measuring duration was 3s.

The synergic identification results are shown in Figure 4. The determined excitation force presented in Figure 4(a) shows very good agreement with the actual force except for some small errors at peaks. The relevant percentage error (RPE) is limited to 9.98%, indicating clearly that this method has great robustness to the measurement noise due to the development of LSF.



(a) Identified excitation force



(b) Identified PF

Figure 4. Synergic identification results

The determined PFs in Figure 4(b) indicate the real PF value (171.277kN) clearly. The results are more accurate in the nodes close to the mid-span, while the results of nodes at the supports are subject to a larger error. This is because that the dynamic influence matrix formulated from the FE model was assumed to be simply supported but the laboratory model was not fully simply supported where the vertical displacements at its supports might therefore not be zero. Thus, the results of boundary nodes are not taken into account in the figure. Moreover, it can also be found that mostly the results from the former have a better performance than those from the latter. This can be attributed to the identification accuracy of virtual force and moment. As rotation at the node was difficult to measure in practice, the nodal angles in this experiment were calculated from vertical response data, which was obviously subject to a larger error. Nevertheless, the RPE of the determined value to the real PF still keeps in a low rate as 6.25%.

4 Conclusions

This paper has briefly introduced how the synergic identification method determines the PF and general excitation through measured responses, and has elaborated how this method was applied to a prestressed concrete box girder in laboratory to identify its PF and the applied load. The design, construction, as well as the modal and dynamic analyses according to the methodology has all been demonstrated. From the findings in the test, the PF and stationary excitation were both determined with high accuracy. In addition, good robustness was observed to the measurement noise in this method. Implementing the method to real bridges will benefit a quick safety diagnosis concerning the remaining PF in box girder bridges. Requiring only one undetermined stationary excitation and very short duration during the bridge test, the PF, along with this excitation can both be assessed in a reliable and effective manner.

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