

Dynamic response for structural health monitoring of the Penang (I) cable-stayed bridge

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Abstract. The paper discusses the dynamic response of the Penang (I) cable stayed bridge structure under various moving load representing typical traffic load of the bridge. The bridge has a total span of 440 m excluding the transition bridge that assumed to be not connected structurally to the main bridge structure. The bridge that links the fast growing Pinang Island and the Malaysian Mainland Peninsula has been known to be fully utilized which leads to the construction of Penang (II) bridge and now the third one. Due to highly traffic use of the bridge that may lead to reduction of the bridge design life, the dynamic response of the bridge becomes important to predict critical part of the bridge structure elements including the main girder and the 144 stay cables. The present study reveals that, due to flexible nature of the cable stayed bridge, the moving load that interacts with the natural dynamic characteristics of the bridge, gives significant stress increment compare to proportional static load especially when the moving load is un-symmetric. For this reason, several classes of typical vehicle passing the bridge with various vehicle speeds are investigated to demonstrate their effect on the bridge displacement, internal forces and stresses. The results can be used for further fatigue assessment of the bridge.

1. Introduction

Rapid growth of economy and societies demand for highly functional transportation infrastructures such as bridges, which are designed to carry loads and expected to serve effectively. Bridges infrastructures are supposedly function to operate safely and work for decades [1]. However, they may expose to exponentially heavy traffic. In addition, despite the satisfactory in design, they may experience deterioration over a period due to unpredictable environmental conditions. In order to control such conditions and to maintain the reliability as well as integrity of these infrastructures, continuous monitoring of the structures is of a paramount importance.

The bridge monitoring system is vital as a technique to measure operation, loading environment and the critical responses to track and evaluate the symptoms operation incidents, anomalies and deterioration indicator that may affect the serviceability or safety reliability of a structure [2]. In this context, the monitoring means to distinguish the condition of the bridge where the parameters to be



investigated and bridge responses are simulated with finite element (FE) method, then analyzed by modeling and equated with calculation for accuracy [3]. The monitoring aspects can be assessed based on two behavior of bridge infrastructures i.e. static and dynamic loads. The static behavior verifies the changes to static parameters of its components and material while the dynamic verifies to the vibration mode [4]. Ref [5 - 9] explored the areas i.e. bridge monitoring based on static and dynamic load. They conducted static load field test of the cable stayed bridge in Taiwan. Ref. [5] developed FE model to compare the bridge responses at the field. The structure load test revealed the linear superposition features and gave considerable agreement with model analysis [5]. In another investigation, numerical analysis and field dynamic tests of a 605m main span, cable-stayed bridge in China is conveyed by [6]. The study has disclosed that FE modeling gives description of the bridge physical and modal characteristic, whereas the experimental modal analysis at the dynamic field tests provides information to validate drawing-based idealized FE model. Also, the developed model shows the structure displacements and achieves a good correlation with measured modal parameters identified from the dynamic field tests. Such model can be used to serve as baseline in structural dynamic for long duration health monitoring, damage detection, dynamic predictions and other condition assessment of the cable stayed bridge.

The static dead and traffic, wind, temperature effects and their combinations on long cantilever truss bridge in United States is investigated in [7]. The study is to evaluate how structural health monitoring can be used to reduce the uncertainties of phenomena that are difficult to model. The inquiry is focused in particular on the temperature changes to determine the reliability of the entire bridge members. The analysis at [7] has revealed that temperature-induced strains is vital factor to be included to determine the reliability of the bridge components since the temperature levels changes during the yearly seasons. From the perspective of improving the design and maintenance, dynamic stress response of three spans of highway composite steel girder bridge is assessed in [8]. Field measurement was carried out to monitor the dynamic response developed due to passing by truck of weight 25ton. Then numerical model to predict the vibration is setup. The model is verified through the comparison between the measured data and the calculated results. The investigation has revealed that the bridge natural frequencies and the global dynamic stress response are in good agreement with the measurement. Another study of dynamic analysis is carried out in [9]. The investigation is based on three selected parameter indexes including vehicle load, speed and road surface condition effects. The FE Model of the concrete – filled steel tube arch bridge [9] and vehicle coupled system is developed and validated with field test. The results have disclosed that the dynamic impact factors differ between the selected structure members / locations and are greatly altered by the proposed parameters [9]. The results also show that the well noticeable level of the bridge vibration is highly affected by the surface road state and vehicle loading situation. In addition, the ride comfort level of the bridge is reduced as the road surface state worsen [9].

Other researchers have employed monitoring instruments to assess the reliability of bridge components [10]. Wind loading field test is conducted at one of the three towers cable bridge in China. The study adopted Global Positioning System (GPS), accelerometer and anemometer to acquire the quasi-static and dynamic responses of the middle tower displacement [10]. At first, Fast Fourier Transform (FFT) algorithm is utilized to identify the dominant frequencies. Next the displacement measurements of the noisy GPS and data of the accelerometer are de-noised by utilizing the Vondrak filter. Then noise-mitigated accelerations are used to the low frequency noise elimination and displacement reconstruction scheme. Meanwhile, the adaptive recursive least squares (RLS) filter is employed to the total horizontal displacement of the pylon which improved measurement accuracy so that they can be reconstructed. The initial natural frequency of 0.17Hz is determined from the data of the GPS and is validated and compared with that of the accelerometer data. The method of [10] improves the accuracy of the pylon displacement under the influence of the extreme winds. The stability of a bridge is assessed under loading condition.

Another research [11] has investigated the structural stability under buckling failure of cable stayed bridge decks. The study has presented that decks sensitivity is depended on several parameters such as

span and deck stiffness, cable spacing, towers height, pattern of live load at deck and side intermediate piers. Subsequently, statistical methods have become significant to identify automatically the damage at a bridge structure for structural health monitoring. Multivariate statistical analysis approach is explored to determine the abnormality at the main cables of suspension bridge model for structural health monitoring. one main cable of the bridge is damaged and subjected to wind loading [12]. The study considered the natural frequencies as a mean to detect abnormalities of the structure. The technique of Principle component analysis is used and applied to the response data of long-duration pseudo-experimental buffeting. The results have shown feasibility of wind-excited to bridges creating relative changes at the most sensitive natural frequency lower than 0.1%. Consequently, [13] has carried out vertical vibration-based damage identification utilizing time-series analysis technique to the three spans bridge supported by five steel girders. The study has measured vibration (velocity) before and after damage. The method is employed for detecting damage. FE models are developed to determine the bridge behavior at undamaged and damaged state. Frequencies and modes shapes from numerical simulations are compared with that obtained from fields tests. FE models are adjusted utilizing field tests vibration data and compared with each damage scenario. The damage detection approach is considerably reliant on the damage location and vibration measurement noise.

The concept of multi-loading is carried out in [14] to assess the condition of a structure for structural health monitoring purpose. The research conducted fatigue analysis using multiple loadings of railway, highway and wind to Tsing Ma suspension bridge in Hong Kong. Their work used integrated computer simulation and measured data from wind and SHM system (WASHMS). The study has conducted computationally efficient method for the dynamic stress analysis under the discussed loading scenario. Then establish the critical locations of the fatigue at the bridge elements. The time histories of the dynamic induced stresses of singular loading can be created based on databases in their work [14].

In the present paper the dynamic response of one unit moving load applied on a cable-stayed bridge is investigated. The objective is to determine the displacement, internal forces and stress under the influence of dynamic effect due to moving vehicle along one lane. Comparison between the responses of the bridge structure having undamaged and damaged cables is conducted. Several cases involving the failure of critical cables having highest stress loading are selected to assess the influence of the damage cables to the overall response of the bridge structure.

2. Brief description of Penang (I) cable-stayed bridge

Penang (I) bridge is a cable-stayed, concrete girder bridge with harp configuration as presented in figure 1. The construction was began in 1982 and completed in 1985. The main bridge has three span segments, two flanking spans at the approach level of 107. 5m and main span of 225m. The deck is carried by 148 cables attached to two twin towers with the height of 101.5 m as shown in figure 2. The width of the deck is 29.7 m in total, narrows up at the main piers to 24.7m so that it can accommodate the inside tower faces. The carriageway consist of three lanes of each side. Figure 3 portray the superstructure which is constructed of 98 edge girder segments and 147 floor-beams [15].



Figure1. The oblique view of Penang Bridge

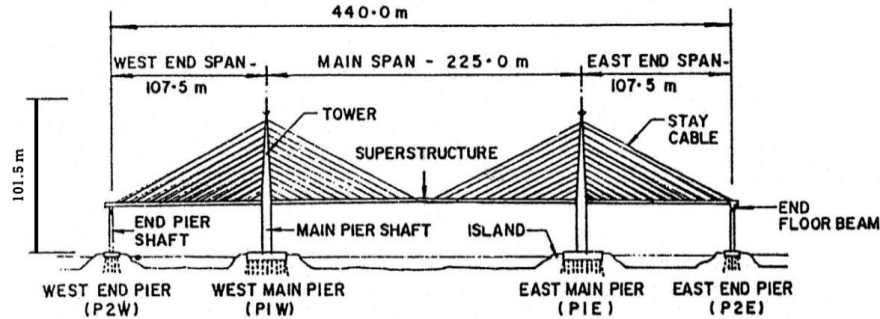


Figure 2. Penang (I) cable bridge longitudinal profile [15]



Figure3. Edge girder segments and floor-beams

3. Finite element modelling of the bridge

According to [16] cable stayed bridges show nonlinear performance under either static or dynamic loads. Such characteristic is the result of: (I) sagging consequences in the geometrical alteration of cables, (II) interaction between the forces of bend-moment and axial of towers and deck; (III) alterations of bridge geometry resulted from the structure deflects. The bridge is exposed to traffic loading which causes significant changes in its mechanical properties. The effect of traffic flow has been investigated to evaluate the ultimate bridge displacement /strain, internal forces and stresses in an effort to preserve the structure integrity from replacement [17, 18]. To exercise structural analysis finite element model is created using Nastran and Patran program as depicted in Figure 4.

The structural model consists of 554 grid points, 671 CBAR beam elements, 192 CQUAD4 plate elements and 144 CROD truss elements. The structure has fixed supports at the bottom of the bridge tower piles. The static analysis of the model has been reported in [19].

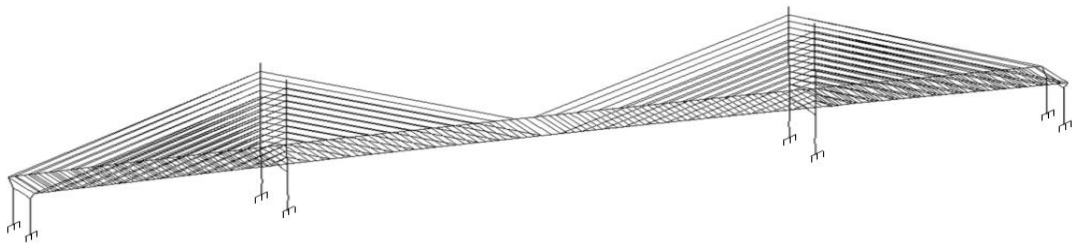
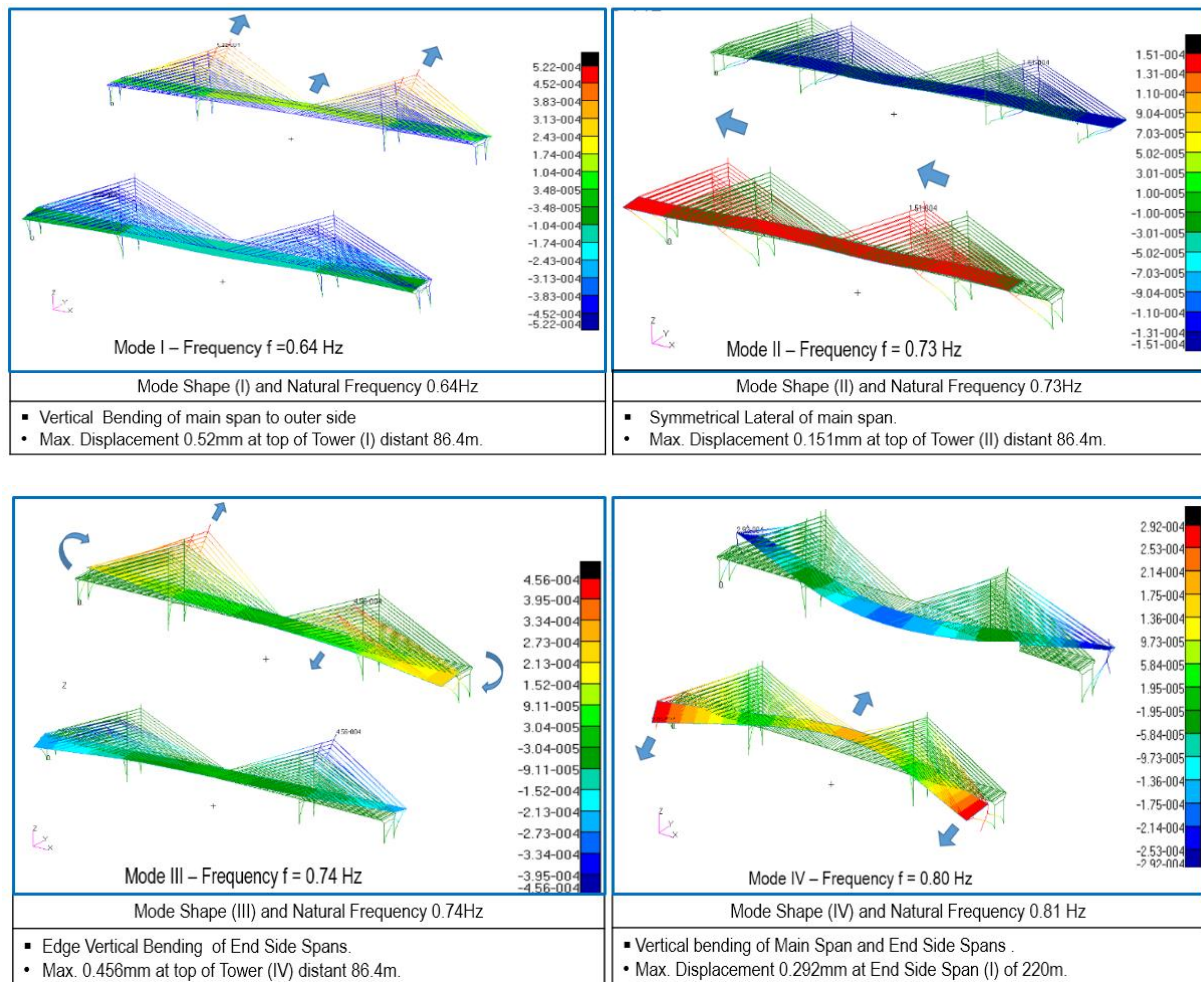
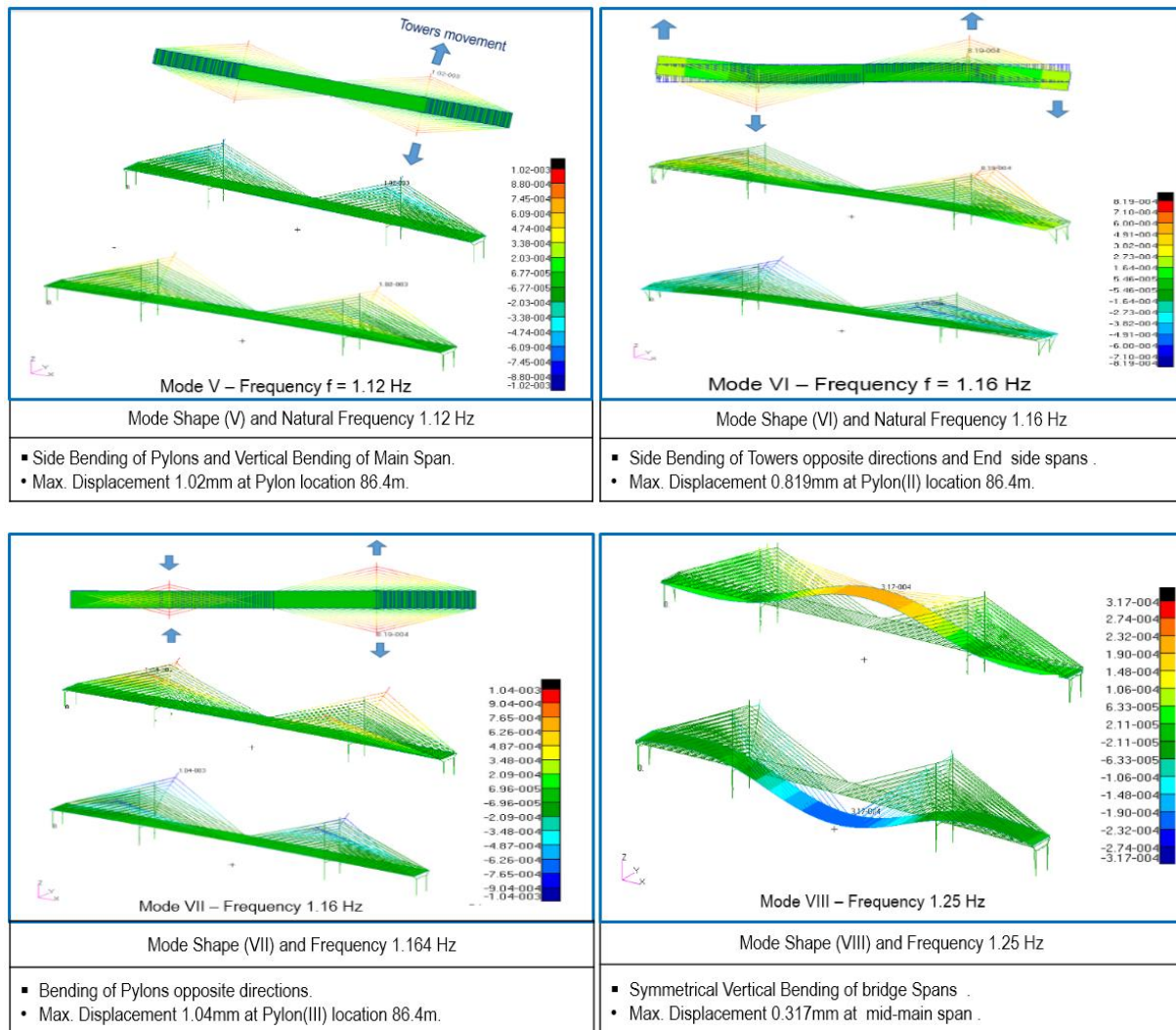


Figure 4. FE model of Penang (I) Bridge.

4. Modal analysis of the bridge

Modal analysis is carried out using FE model of Penang (I) Bridge in similar manner as [20]. The natural frequencies and resembling mode shapes of the first 8 vibration modes of 15 mode shapes are provided in Table 1 and the related shapes are portrayed in figure 5.



**Figure 5.** Mode shapes of the bridge displacements

Mode	1	2	3	4	5	6	7	8
Frequency (Hz)	0.64	0.73	0.74	0.81	1.12	1.16	1.16	1.25

Table 1. Natural frequencies at of undamaged bridge structure

5. Dynamic Analysis of One Unit Moving Load

The motion of a one-unit load is illustrated in figure 6. The impact of the unit load moving with certain velocity is evaluated through the displacement, inner force and stress levels on the bridge such as performed by [21]. The study is carried out on mid-main span grid 14 and element 9156 located at 112m from the left end side span support for assessment.

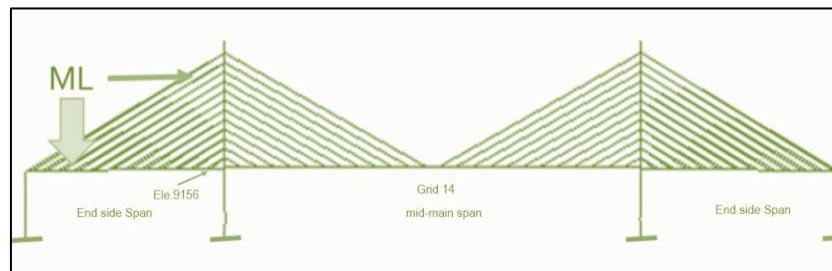


Figure 6. Moving one-unit load along bridge spans

The results obtained are portrayed in figure 7. The dynamic response due to this one unit moving load can be further used to simulate the dynamic response due to more realistic load such as truck, bus, car or other vehicles by using superposition methods.

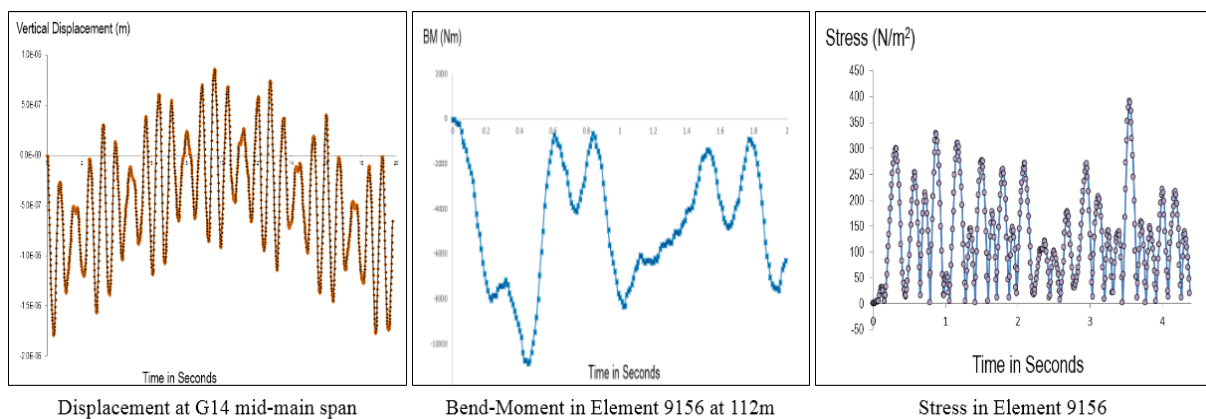


Figure 7. Dynamic responses of the parametric study

6. Dynamic response of the bridge structure having damaged cables

The dynamic response is further investigated to find the influence of any failure on the bridge structure. Particularly, in the present work, the focus is on the influence of the bridge cables. The static loading analysis is first conducted and the axial cable force is established as portrayed in figure 8. The data shows that cable C9 experiences the highest stress level compare to others. The study introduces failure at the cable to determine their dynamic response. The second highest stress level after C9 is C8 cable such that the failures of both C8 and C9 are also important to be investigated.

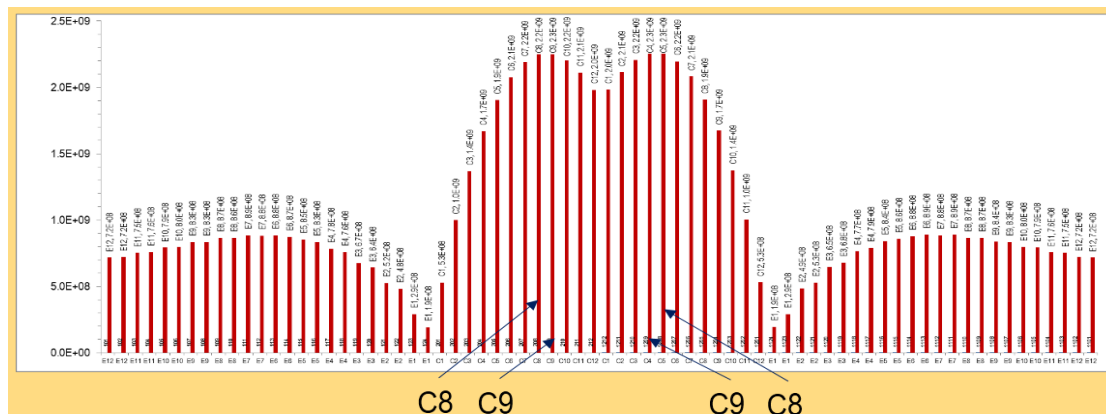


Figure 8. Maximum Stress of Cables at static loading

In case (I) the inactive of cable C9 has resulted an increase of the displacement at Grid 14 which is the mid span point and increase of the stress level in Cable E7 /112 as presented in Figure 9 and 10 respectively. It should be noted that the bridge structure is still can carry the load with the damaged of cable C9.

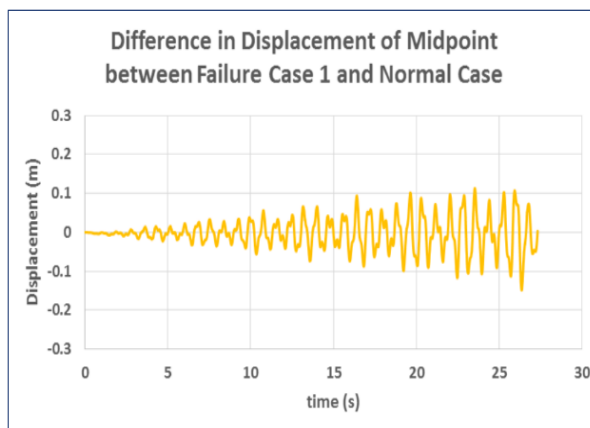


Figure 9. Case (I) Displacement at Grid 14

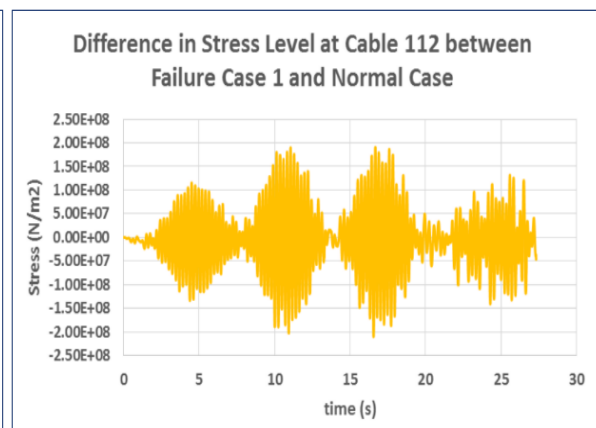


Figure 10. Case (I) Stress at Cable E7/112

Furthermore, in case (II) where cables C8 and C9 are both fail, the response in the form of increment of displacement at Grid 14 and stress at Cable E7/112 are shown in Figures 11 and Figure 12 respectively. Similarly, the bridge is still intake with the loss of the cables C8 and 9. Both cases clearly show different pattern of dynamic responses which can be used to further identify the failure of the structural components.

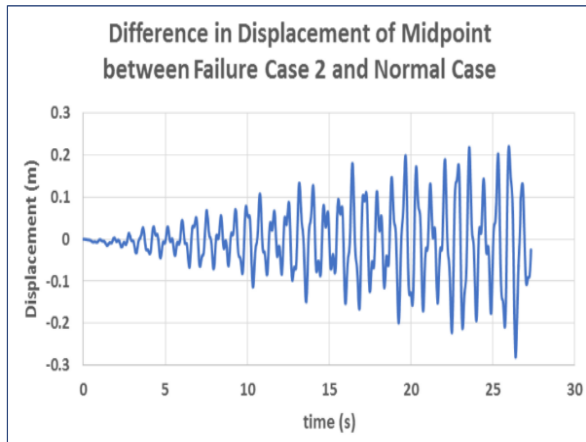


Figure 11. Case (II) Displacement at Grid 14

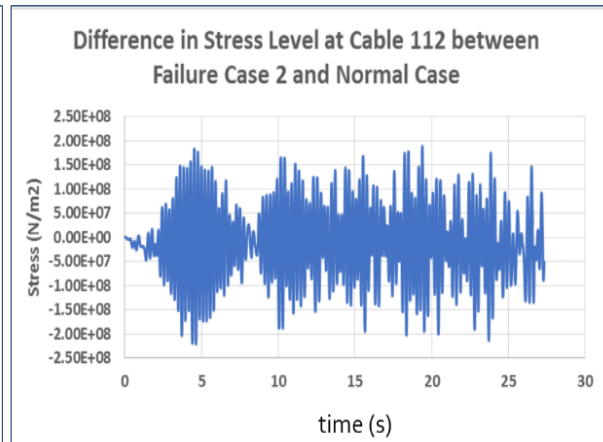


Figure 12. Case (II) Stress at Cable E7/112

7. Structure Health Monitoring (SHM)

The analytical dynamic analysis has indicated that each cable failure contributes different dynamic response characteristics. Therefore, by analyzing the response of several parameters such as displacement and stress level in several parts of the structure, it is possible to estimate which part of the structure is inactive. This procedure can be conducted if the bank data of the dynamic response of normal and failure structures is available.

For example, if the SHM equipment is planted in Grid 14 and Cable E7/112, the dynamic response at these positions can be compared with the data of figures 9 - 12 to check if the possible failures are due to Cable 9 or combination of Cables 8 and 9. This checking will involve a huge number of cases which can be performed using digital computer.

8. Conclusion

The study has proposed several scenarios of loading effect on Penang (I) bridge to assess the structural behavior for SHM. The dynamic response in each scenario is validated by the corresponding displacement, bending-moment force and the induced stress. The work has demonstrated that SHM can be conducted by detecting the dynamic response of the bridge due to particular moving load, such as truck, bus, or car, provided that their data are known. The dynamic response that can be monitored includes structural stress, force or displacement. These stress, force and displacement response data due to the failure of each structural member and their combination should be stored for SHM.

Reference

- [1] Estes A and Frangopol D 2001 Bridge lifetime system reliability under multiple limit states *J. Bridge Eng.* **6** pp523-8.
- [2] Aktan A, Catbas F, Grimmelsman K and Tsikos C 2000 Issues in infrastructure health monitoring for management *J. Eng. Mech.* **126** pp 711-24.
- [3] Chang, P. C., Flatau, A., & Liu, S. C. (2003). Review paper: health monitoring of civil infrastructure. *Structural health monitoring*, **2** pp 257-267.
- [4] Brownjohn, J. M. (2007). Structural health monitoring of civil infrastructure. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **365** pp 589-622.

- [5] Fang I, Chen C and Chang I 2004 Field static load test on Kao-Ping-Hsi cable-stayed bridge *J. Bridge Eng.* **9** pp 531-540.
- [6] Ren W, Lin Y and Peng X 2007 Field load tests and numerical analysis of Qingzhou cable-stayed bridge *J. Bridge Eng.* **12** pp 261-270.
- [7] Catbas, N, Susoy M, and Frangopol M 2008 Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data *J Eng. Structures* **30** pp2347-2359.
- [8] Su D, Laomenit J and Fujino Y 2011 Traffic-induced response prediction of highway bridges *J. Procedia Eng.* **14** pp1071-1078.
- [9] Wang W, Yan W, Deng L and Kang H 2014 Dynamic analysis of a cable-stayed concrete-filled steel tube arch bridge under vehicle loading *J. Bridge Eng.* **20** pp 04014082.
- [10] Han H, Wang J, Meng X and Liu H 2016 Analysis of the dynamic response of a long span bridge using GPS/accelerometer/anemometer under typhoon loading *J. Eng. Structures* **122** pp 238-50.
- [11] Pedro J J O, and Reis A, 2011 Stability of Composite Cable-Stayed Bridges *Proc. of 6th European conf. on steel and composite structures* pp 1263-68.
- [12] Comanducci G, Ubertini F and Materazzi A 2015 Structural health monitoring of suspension bridges with features affected by changing wind speed *J. Wind Eng. and Industrial Aerodynamics* **141** pp 12-26.
- [13] Farahani R V and Penumadu D, 2016 Damage identification of a full-scale five-girder bridge using time-series analysis of vibration data *J. Eng. Structures* **115** pp 129-39.
- [14] Chen Z, Xu Y, Xia Y, Li Q and Wong K 2011 Fatigue analysis of long-span suspension bridges under multiple loading: Case study *J. Eng. Structures.* **33** pp 3246-56.
- [15] Kee C F 1988 *The Penang Bridge Planning, Designing, and Construction* (Kuala Lumpur: Lembaga Lebuhraya Malaysia)
- [16] Chang C, Chang T and Zhang Q 2001 Ambient vibration of long-span cable-stayed bridge *J. Bridge Eng.* **6** pp 46-53.
- [17] Caprani C, OBrien E and McLachlan G 2008 Characteristic traffic load effects from a mixture of loading events on short to medium span bridges *J. Structural Safety.* **30** pp 394-404.
- [18] Freire A, Negrao J and Lopes A 2006 Geometrical nonlinearities on the static analysis of highly flexible steel cable-stayed bridges *Computers and Structures* **84** pp2128-2140.
- [19] Mohammed I M, Mustapha F, Hrairi M, Sulaeman E, Khairol A, Dayang L and Hojazi F 2013 Penang Bridge 1 Loading Analysis using British Standard and Finite Element Method for Structural Health Monitoring *Proc. of 2nd Int. Conf. on Mechanical, Automotive and Aerospace Engineering.*
- [20] Ren W, Peng X and Lin Y 2005 Experimental and analytical studies on dynamic characteristics of a large span cable-stayed bridge *Eng. Structures* **27** pp 535-548.
- [21] Yu Y, Zhao X, Shi Y and Ou J 2013 Design of a real-time overload monitoring system for bridges and roads based on structural response *Measurement* **46** pp 345-352.