Sensor placement based on FE modal analysis: Dynamic characteristic of cable stayed Penang (I) bridge

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Abstract - *There is a fast-growing interest to monitor the dynamic behavior of cable stayed bridges due to their long spans leading to complexity of their structures. These bridges are evolved for a long term structural health monitoring method since their performance is challenged with mixture type of traffic loading daily. This paper is aimed to propose sensors positioning at dead load condition. Finite element analysis is effective and accurate approach to certain extend used to determine the highly stressed grid points due to vibration of the bridge members. The bridge in concern is cable stayed Harp type of Penang (I) bridge. The findings based on analytical modal analysis reveals that the number of sensors to be positioned were 66 locations of the cable stayed bridge.*

Key Words: **cable stayed bridge, structural health monitoring, sensors placements, dead load.**

1. INTRODUCTION

Bridges are heritage, economy pulse and expensive to be replaced at many countries. In the past, bridges are thought to serve for a longer period of time from designing the prospective view, however as global environmental consequences changes and transportation of growing live load has improved to a higher level than the bearable designed requirement, thus their service life-cycle are reduced and become ageing.

Up to that time, the majority of these structural systems were built and constructed according to the old codes of designing. Concerning to these aspects have led to the establishment of inspection concept to prolong the integrity and safety of bridges. This is to limit deficiency consequences from further developed in the future.

In the past decade, bridge maintenance was routinely performed by visual inspection. The method is based on inspection of the outer surface of the structures and significant for small size bridges. Its limited contribution is investigated by many scholars [1-6].

Following to that, long term monitoring such as structural health monitoring (SHM) has caught interest by many researchers in recent years. In addition, the development activities in health monitoring has established in several fields, and one of which is bridge civil structure. In order to identify damages and fatigues at the structural members of bridges, SHM has introduced technologies which were based on implementing remote sensing. The implementation of SHM is the systematic assessment of bridge parameters which provides the current status of the bridge durability and reliability to operate effectively [7].

Meanwhile, several scholars agreed that the introduction of SHM technique of seasoning at the early stage of bridge construction would assure safe performance [8-12]. Besides, economical level has contributed for more development of the existing bridge structures to certain extend.

In the meantime, one of the techniques used by many is finite element method. Finite element analysis is a qualitative exploring technique which investigate bridge components that are influenced by range of relevant loads concentrated in real-time concept. The consequence of the modeling is to provide practical analytical data of bridge components functioning behavior at static and dynamic impact in state of dead and traffic loadings. Furthermore, finite element design influences decision making for the most likely activities to be carried out to accomplish an effective configuration / design [14-23].

In this prospect, the dynamic behavior of cable stayed bridge was evaluated by many scholars such as [24] that investigated the bridge dynamic characteristics. A comparison of frequencies and mode shape from field test measurement and finite element bridge model were conducted to determine the bridge performance. The test frequency was measurement of structural ambient vibration due to traffic and wind. The measurements were recorded and identified from Fourier amplitude spectra of the accelerogram. The analysis reveals that the computed frequencies from the test were larger than that of the finite element model utilized in the bridge designing.

Similarly, [25] developed finite element model of Qingzhou cable stayed model which was validated with the field test data. The frequencies and the mode shapes obtained from the ambient vibration tests were correlated with developed 3D model. Many essential issues were raised such as equilibrium configuration owing to dead load state, including concrete slab in modeling, the longitudinal restraints of the end expansion joints, deck shear connection and geometrical nonlinearities to improve modelling.

In addition, [26] introduced the multi-scale modeling approach to assess the condition of Tsing Ma cable stayed bridge. The developed approach was mixing dimensional coupling technique which was exercised to examined the bridge wielded joints. It was then employed to compare its model of natural frequencies and vertical displacement of the finite element original modal with the measured data under the influence of train loading. For the first few frequencies and mode shape, the results revealed they were match between these two techniques.

Further work has been done by [27], where they combined the static and dynamic measurements with finite element model to improve the assessment of the single arch - Svinesund bridge. The modelling included parameters of manual model refinements and non-linear optimization. As a result, the introduced parameters reduced the errors in modelling and hence the objective of this study was achieved.

On the other hand, other scholars interested to introduce unit mass / vehicle model in order to determine the dynamic behavior of the bridges and identify their frequencies and mode shapes such as [28-32].

Moreover, [33] reviewed the application of piezoelectric material to regulate the vibration of civil structures and classified as 'smart structures'. The review focused upon the use Piezoceramic material for being easy to be implemented, lightweight and low cost. Apart from that, the material shows its ability to be as sensor and actuator for active vibration regulator. However, Piezoceramic material limitation as actuator provide small displacement. Nevertheless, the study has successfully overcome such issue. Additional, limitation highlighted was during condition of active control it requires for power source which would not be useful in activities such as seismic / earthquake.

Meanwhile, studies of proposing sensors placement based on static analysis at Penang (I) bridge in state of dead load and traffic load corresponding to British Standard were carried out [34] and [35]. The sensors were set as a result of the structure responses to loading states producing high displacement deflection and deformation stresses at the bridge members.

In this regard, the study is intended to determine the sensors locations due to bridge dynamic characteristic at dead load condition. Finite element analysis was used for the purpose. The modeling included manual tuning and convergent method previously adopted in static modal analysis, as to identify errors within bridge model. frequencies and the associated shape modes achieved from the vibration to identify the critical grid points at the bridge members. Thus, sensors locations were placed consequently.

1. METHOD

1.1 Penang (I) Bridge Geometrical Description

Penang (I) bridge is cable-stayed with concrete girder structure as portrayed in Figure 1 [36]. The bridge spans have two end side spans of 107.5m and main span of 225.0 m long. The bridge has two pairs 'H' type towers of 101.5 m long. The deck cross section is 29.7 m where the 6 lanes occupy 24.70 m. The deck is carried by 148 stayed cables. Their length is ranged from 14 m to 125 m. The harp cables arrangement includes 12 pairs carrying the end side span and 11 single cables carrying each side of the main span. The superstructure comprises of 98 edge girder segments and 147 floor beams with deck slab segments [37]. Figure 2 depicts the bridge geometry.

Fig - 1: View of Penang (I) bridge in Malaysia (source: Hendy, C. R. Highway &Transport Atkin)

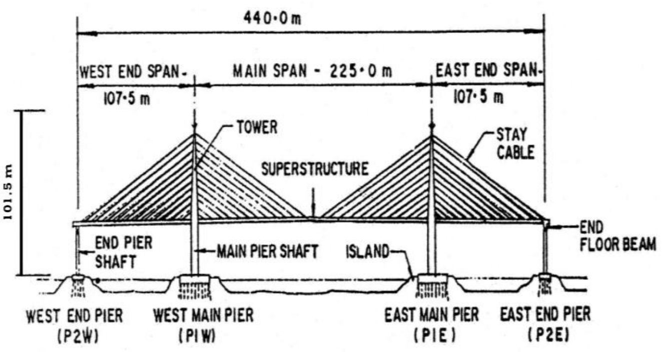

Fig - 2: Penang (I) bridge structural geometry. (Source: Chin, 1988)

1.2 Construction of Penang (I) Bridge Finite Element Model

A 2D one section mathematical model is provided by the Malaysian highway authority as depicted in Figure 3 (Chin,1988). Using Nastran program, the 3D Finite element model was tuned manually to reduce the errors and discrepancy of modelling (Schlune, et al., 2009). The bridge global coordinate was set at the left end side support and the tower's footages are modelled as fixed boundary conditions since spread on stiff rocks (Cho, et al.,2010). The model of structural members was comprised of 555 grid points, 671 CBAR elements, 144 CROD elements and 192 CQUAD4 elements. Figure 4 portrays the configuration of Penang (I) bridge with the geometrical and the material properties obtained [37]. The analytical modal analysis adopted small displacement theory where the Bernoulli-Euler beam theory applied as well as the Mindlin plate theory. The cable was modeled as a rod where only axial forces were considered in the analysis. Upon Using Patran program the model was simulated to determine the structural natural frequencies which resulted certain grid points to be stressed due to vibration. Hence, critical spots at the bridge's members were identified and sensors locations were proposed.

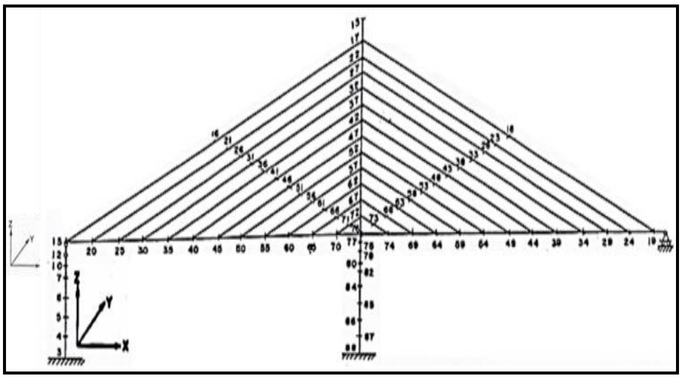

Fig – 3: One section of bridge (I) model (source: Chin, 1988)

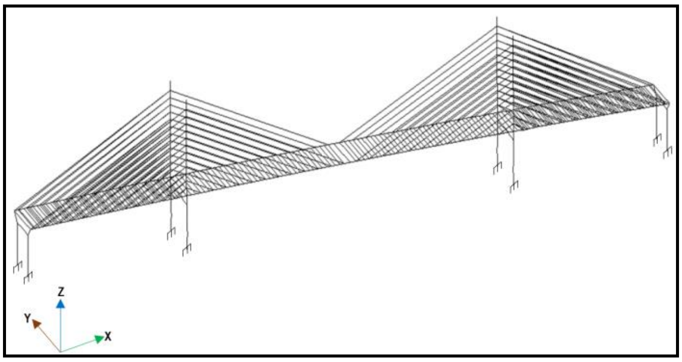

Fig – 4: Developed 3D finite element bridge model

2. Result and Discussion

2.1 Dynamic modeling and structural responses

The analytical model analysis was performed on 3D finite element model of Penang (I) bridge to determine the structural dynamic behavior. The bridge response was based upon its dead load. The self-weight of cable stayed bridges is essential position to verify the bridge responses in achieve dynamic analysis of vehicles and environmental loadings. It contributes toward the structural loads, where such load eventually effects the stiffness of the bridge. This effect was included when modal analysis was conducted from the static initial equilibrium state as a result of the bridge self-weight and 'pre-stress modal analysis'.

Thus, modal analysis of this type of bridges is regard as 'pre-stress modal analysis' which involves two stages: firstly, static analysis carried out at dead load and pre-tension of cable; secondly, from the modal 'free vibration' analysis which was started from the deformed equilibrium configuration caused by the dead load and the pretension of cable (Ren, et al., 2005). The study performed 15 frequencies and correlated mode shapes from the modal analysis of the bridge. Figure 5 depicts the first eight frequencies and the related mode shapes. The configurations show gradual increase in the frequencies as a result of the pre-stressed modal analysis despite that the such analysis might have a minimum impact upon the natural frequencies of the bridge in concern (Ren, et al., 2005).

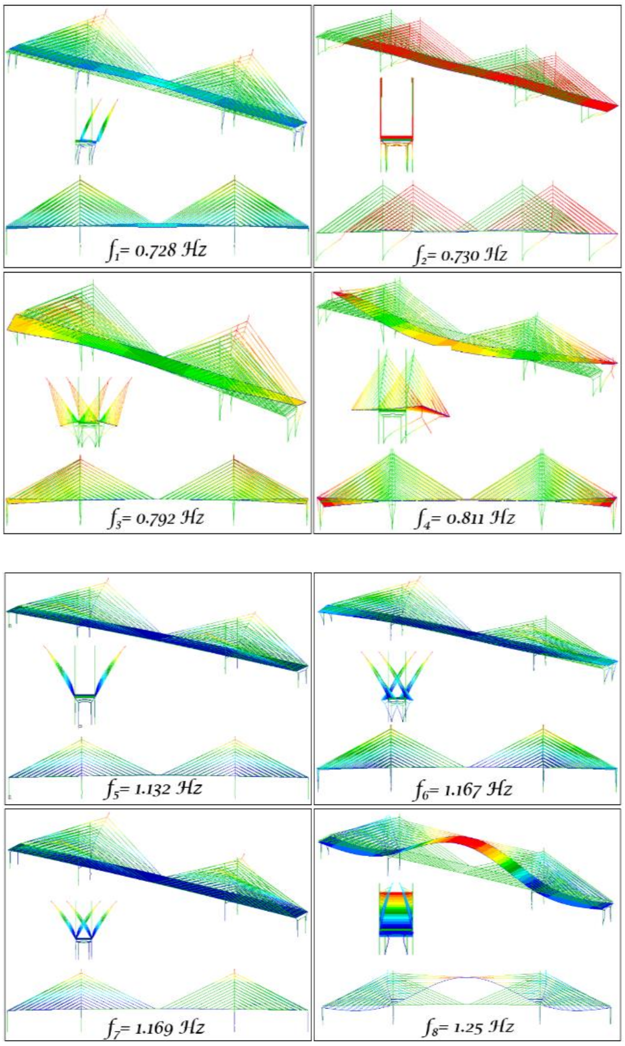

Fig - 5. Eight Penang (I) bridge mode shapes

Table 1 presents the nature of mode shapes obtained from the finite element analysis. The common modes were Lateral bending, vertical bending and torsion of the spans. In addition, another two modes were found which were deck longitudinal drift. In few modes, the bridge pylons / towers were coupled with the bending of the spans. The free vibration of the bridge model provided the critical grid points which lead to propose sensors placements to monitor the bridge members. Figure 6 demonstrates the most likely proposed positions where sensors would be placed at the bridge members. Table 2 presents the proposed locations of the sensors at the Penang (I) bridge structure. Overall, the objective of proposing sensors placements due to the dead load of the bridge is achieved from the analytical modal analysis.

Table - 1: 15 Frequencies and shape mode features

Frequencies	Mode shape no.	Mode shape features : finite element analysis
f_1: 0.728Hz	Mode Shape I	Symmetrical lateral bending of deck with same bending of towers
f_2: 0.730Hz	Mode Shape II	Longitudinal drift of deck
f_3: 0.792Hz	Mode Shape III	Vertical bending of end side spans
f_4: 0.810Hz	Mode Shape IV	Lateral bending sideway main span and vertical sideway bending of end spans
f_5: 1.132Hz	Mode Shape V	Vertical bending of main span
f_6: 1.163Hz	Mode Shape VI	Unsymmetrical bending of end side spans with opposite bending of pylons
f_7: 1.167Hz	Mode Shape VII	Bending sideway of pylons
f_8: 1.25 Hz	Mode Shape VIII	Vertical bending of main span
f_9: 1.29Hz	Mode Shape IX	Lateral bending of deck with same direction bending pylon
f_{10}: 1.56Hz	Mode Shape X	Torsion of deck
f_{11}: 1.96Hz.	Mode Shape XI	Symmetrical lateral bending of deck with opposite direction bending of towers
f_{12}: 2.70Hz	Mode Shape XII	Symmetrical lateral bending of deck with same direction bending of towers
f_{13}: 2.87Hz	Mode Shape XIII	Longitudinal drift of deck with opposite direction bending of towers
f_{14}: 2.93Hz	Mode Shape XIV	Symmetrical vertical bending of deck with same direction bending of towers
f_{15}: 3.0 Hz	Mode Shape XV	Torsion of deck

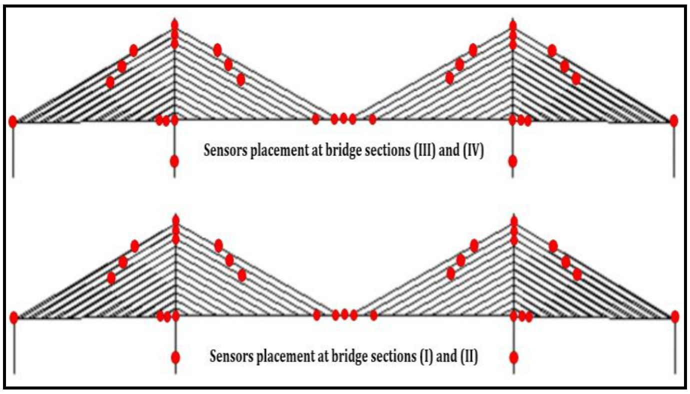

Fig - 6: Sensors positions at bridge structure owing to natural vibration

Table 2: Sensors locations at the Penang (I) bridge model

Sensors locations due to modes of vibration		
Deck grid points	Towers grid points	Cables at End side and Main spans
220.0 m / End side span	86.4 m	E12 , E 11, E10 / End side spans
144.5 m / End side span - cable	82.2 m	M12, M11, M10 / Main spans
121.5 m / End side span - cable	78.0 m	
119.9 m / End side span - cable	35.6 m	
112.5 m / deck - tower	21.6 m	
16.0 m / Main span - cable		
4.0 m / Main span		
0.0 m / Main span - Middle grid point		

3. CONCLUSION

Non-destructive monitoring technologies are essential method to evaluate bridges structures. The study adopted finite element analysis to assess the dynamic behavior of

Penang (I) bridge. The analytical modal analysis was carried out to determine 15 frequencies and the associated mode shapes of the structure at dead load state. The results show the dominated modes were lateral and vertical bending modes, in addition to the longitudinal and torsion modes due to natural vibration. From the nature of modes vibration, critical grid points were identified at the bridge members. In corresponding to these grid points locations, sensor placements were proposed accordingly.

These locations were at 220.0m, 144.5m, 121.5m, 119.9m grid points at the end side spans; 112.5m grid point at towers areas; 16.0m, 4.0m at main span and 0.0 m middle main span of each side of the bridge. Meanwhile, at the towers member, grid points of 86m, 82.2m, 78.0m at the pylons and 35.6m, 21.6 m at the piers. Finally, the grid points influenced by the vibration were at end side spans cables coded as E12, E11, E10 and M12, M11, M10 at the main spans. Thus, based on the analysis conducted and discussion of the findings above, the study recommends 66 locations of sensors for Penang (I) bridge.

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