UNIVERSITI PUTRA MALAYSIA

IMPLEMENTING NUMERICAL SIMULATION FOR STATIC AND DYNAMIC LOADING OF CABLE-STAYED PENANG BRIDGE

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IMPLEMENTING NUMERICAL SIMULATION FOR STATIC AND DYNAMIC LOADING OF CABLE-STAYED PENANG BRIDGE

By

MOHAMMED IDRIS MOHAMMED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

November 2016

DEDICATION

My Parents

My wife

My children

Brothers and relatives

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

IMPLEMENTING NUMERICAL SIMULATION FOR STATIC AND DYNAMIC LOADING OF CABLE-STAYED PENANG BRIDGE

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November 2016

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Penang (I) bridge is classified as a Cable stayed bridge, which constructed globally for their long spans and aesthetics appealing. Factors such as high traffic volumes and geometrical movements cause increase in deflections and stresses on the bridge system, which at the end these defects possibly lead to degrade their service life cycle. Due to these reasons, Penang (I) bridge needs continuous monitoring i.e. a tool to resist any changes toward various loading conditions, such as sensors arrangement. Hence, the study aims to recommend sensors positions for Penang (I) bridge, by conducting modal analysis and simulation processes which introduced in the Finite Element Method (FEM). In addition, specific software called, 'Nastran & Patran' was used to compute the displacement, forces and stresses based on static symmetrical and unsymmetrical loading conditions, as well as mode shapes on dynamic loading condition. As a result, from these analyses, critical elements and their associated grids points of the bridge elements were identified, which eventually, sensors placement have been proposed. The results revealed there are 78 sensors can be placed at the entire structures, which are mainly located at the cables, towers and end side spans and main spans of the bridge. In term of contribution, the study noticed the complexity of Penang (I) bridge structures coupled with high traffic volumes might lead to damages at invisibles locations, which only can be identified using the finite element analysis. Therefore, the proposed sensors for the bridge probably can be used by the relevant authorities and perhaps as guidelines for future references.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

MELAKSANAKAN SIMULASI BERANGKA MENGGUNAKAN STATIK DAN DINAMIK UNTUK KABEL-PENAHAN JAMBATAN PULAU PINANG (I)

Oleh

MOHAMMED IDRIS MOHAMMED

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Jambatan Pulau Pinang (I), merupakan jambatan kabel-penahan yang dibina di peringkat global bagi jangka panjang dan mempunyai nilai estetika. Faktor-faktor seperti penambahan jumlah trafik dan peningkatan pergerakan geometri menyebabkan pesongan dan tekanan pada sistem jambatan, dan juga ia membawa kepada memendekkan kitaran hayat perkhidmatan mereka. Oleh kerana sebab-sebab ini, Jambatan Pulau Pinang (I) memerlukan pemantauan berterusan iaitu alat untuk menentang sebarang perubahan ke arah pelbagai keadaan beban muatan, seperti susunan sensor. Oleh itu, kajian ini bertujuan untuk mengesyorkan kedudukan sensor untuk jambatan Pulau Pinang (I), dengan menjalankan proses analisis dan simulasi modal yang diperkenalkan pada Kaedah Unsur Terhingga (FEM). Di samping itu, perisian yang dipanggil, 'Nastran & Patran' telah digunakan untuk mengira anjakan, daya dan tekanan berdasarkan keadaan bebanan simetri dan simetri statik, serta bentuk mod dengan bebanan dinamik. Hasil daripada analisis ini, unsur-unsur kritikal dan mata grid yang berkaitan dengan elemen jambatan telah dikenal pasti, yang akhirnya, penempatan sensor telah dicadangkan. Keputusan mendedahkan terdapat 76 sensor boleh diletakkan pada keseluruhan struktur, yang kebanyakannya terletak di kabel, menara dan rentang sampingan akhir dan rentang utama jambatan. Dari segi signifikan kajian, kajian mendapati struktur pembinaan Jambatan Pulau Pinang (I) yang agak kompleks dan ditambah pula dengan trafik yang tinggi mungkin membawa kepada kerosakan di lokasi yang sukar untuk dilihat, yang hanya boleh dikenal pasti dengan menggunakan analisis unsur terhingga (FEM). Oleh itu, sensor yang dicadangkan untuk jambatan mungkin boleh digunakan oleh pihak berkuasa yang berkaitan dan mungkin sebagai garis panduan untuk rujukan masa depan.

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I certify that a Thesis Examination Committee has met on 14 November 2016 to conduct the final examination of Mohammed Idris Mohammed on his thesis entitled "Implementing Numerical Simulation for Static and Dynamic Loading of Cable-Stayed Penang Bridge" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF SYMBOLS AND ABBREVIATIONS

1-D	One-Dimensional
2-D	Two-Dimensional
3-D	Three-Dimensional
CBAR	Connected Bar
CBEAM	Connected Beam
CELASi	Elastic Springs
CMASSi	Concentrate Mass
CQUAD4	Quadrilateral Plate Element Connection
CROD	Connecting Rod
CSHEA	Shear Panel Element Connection
CTETRA	Four-Sided Element Connection
DEFORM	Specified Strain In Structural Element
DL	Dead Load
LL	Life Load
ML	Moving Load
EIGRL	Real Eigenvalue Extraction Data
FEM	Finite Element Method
FORCE	Concentrated Forces
FORCE1	Concentrated Forces
GRAV	Gravity force Format
HA	Normal Load
HA-KEL	Normal Load-Knife Edge Load
HA-UDL	Normal Load-Uniform Distributed Load
HB	Abnormal Load
MAT1	Isotropic Material
DL	Dead Load
ML	Moving Load
LL	Live Load
MOMENT1	Concentrated Moments
PBAR	Property Bar

PLOAD	Pressure Load
PLOAD1	Ditributed Load
PROD	Rod Properties
SHM	Structural Health Monitoring
SPC	Single Point Constraint
Sec.	section
E	Modulus Of Elasticty
G	Shear Modulus
m	Mass (Inertia)
k	System Stiffness
p	Applied Load Vector
u	Grid Point Displacements
$\ddot{u}$	Acceleration of Mass
$\mathring{u}$	Velocity of Mass
v	Poission’s Ratio
ϕ	Eigenvector or Mode Shape
ω	Circular Natural Frequency
f	Natural Frequency

CHAPTER 1

INTRODUCTION

1.1 Research Background

Many countries have reflected substantial interest and / or concern toward their civil infrastructure, especially in cable stayed bridges. The bridges are elegant, efficient using material structure, excellent self-balancing structural system, superior overall stiffness, enhanced aerodynamic behavior, economical design and weight than suspension bridges. They comprise of principle components deck, one / more towers and Fan / Harp cables pattern. The incline cables are suspended from the high pylons and attached to the girder at grid points. The elasticity of stayed cables primarily grants the bridge longer spans without intermediate piers. Such that the dead load and live load effect at the girder-deck are transmitted to the towers through the cables (Wu and Wang, 2008; Lee, et al., 2008; Gimsing and Georgakis, 2011).

However, these large structures are experiencing inadequate and deterioration over its operating time. Hence, there is a necessity for continuous maintenance and rehabilitation scheduled services. In many engineering areas, monitoring techniques are employed to ensure the structure integrity and hence able to maintain its safety. The term, structural health monitoring actually deals with safety issue, which emphasizes on structural performance as well as contribute to saving cost of repairing. Hence, the application of continuous monitoring would delay or limit damage growth, as sufficient information of data related to damage rates exists (Zapico and Gonzalez, 2006). In addition, Deza (2004) stated bridges disposition demands for safety implication and clear economical so that the burden of repairing or replacing cost is refrained. Meanwhile, an accurate assessment of the present traffic load relevant to the bridge carrying capacity and anticipation of alteration in future loads or the structure capacity can cause deterioration in the applicable time span.

Despite experiencing deterioration over its operating time, the structures are also suffered from damage. It is described and characterized as the alteration in the designed components features of the infrastructure from geometry and material properties, which caused and involved unfavorable circumstance to structure integrity and its operative functionality (Farrar, et al., 2006). The damages of the bridge structure can be identified in two ways i.e. directly and/or indirectly. The first is identifying the damage type e.g. cracks due to corrosion / delamination, in which the appropriate inspection technique is used based on the physical phenomena and have local and direct application. While the latter is via global response characteristics of undamaged structure, where it compares the data before and after the damage. In both conditions, it requires reliable monitoring i.e. quantitative performance measures. The technique of monitoring previously was primarily based on pessimistic prediction and periodic inspection which was referring to the direct approach (Staszewski, et al., 2004).

Furthermore, the bridges are also encountered the structural material failure, which is known as defect or flaw, due to improved loading condition. For examples the bridge may operate at its optimal level which resulted to corrosion and fatigue damages. While, environmental hazards such as floods or earthquake are the examples of scenario that caused bridge structure failure, where it inflicts the structure to the level of non-adequate to perform effectively (Farrar and Worden, 2007). Hence, in dealing with these issues, Civil Structural Health Monitoring (CSHM) has been introduced in implementing measurable periodical procedure to recognize the identity of damage strategy in the complex civil structures. These measures are analyzed to predict the structure physical condition (Farrar, et al., 2006).

Structural Monitoring covers modeling and analysis that are utilized to assess the integrity of the bridge in the sense of operating, ageing, and the level of safety. The implementation of structure health monitoring systems for bridges is to determine the vital logical explanations, which can be described in 6 levels; (1) the existence of damage in the bridge; (2) the location of this or these damages; (3) the character or particular kind of damage present; (4) the degree of damage and its extent level; (5) the consequence effect and the influence of the damage on the structure at present and future;(6) the bridge persistence situation to run for longer period than anticipated include forecasting its future behavior and integrity (Stubbs et al., 2000). In relation to the current study, it concerns on the first 2 levels of the implementation of structure health monitoring systems for bridge i.e. the existence and location of these damages.

1.2 Problem Statement

The global challenge of civil and mechanical engineering community is monitoring the performance of bridge structures, which are operating beyond than their design expectation. Factors such as aging, natural phenomena, incremental traffic volume and fluctuations functionality are detrimental causes which inflict and degrading bridge members operate during their life cycle (Frangopol, 2011). Significantly, the demand for high bridge performance and/or aging may result in the vulnerability of constructed facilities (Tsompanakis, 2010).

According to Cohen et al. (2007); Belluck, (2007); Doyle, (2009), previous statistics have indicated that around 41% of the USA’S 577,710 bridges are either suffers from structural deficient or functional obsolete. One of such cases is the total collapse of I-35W Highway Bridge of four lanes in the state Minnesota- Minneapolis city which use to carry 140,000 vehicles/day in 2007, the image of such collapsed is illustrated in Figure 1.1. Furthermore, the outcome of the investigation revealed that it was due to; (I) the migration toward opportunity in big cities leading to increase in traffic volume; (II) the country economy declines; (III) lack of structural inspection which resulted in negligence of the corroded bridge members and become unsafe. Similarly, in China and India where bridges are essential to overcome river banks and/or passage overgrowing population area. Their bridges collapsed due aging, ineffective monitoring procedures, and overloading tracks. Meanwhile, in Queensland Australia alone, about 3000 bridges with an annual maintenance cost in excess of 20 million dollars and replacement value of two billion dollars (Tan et al., 2009).

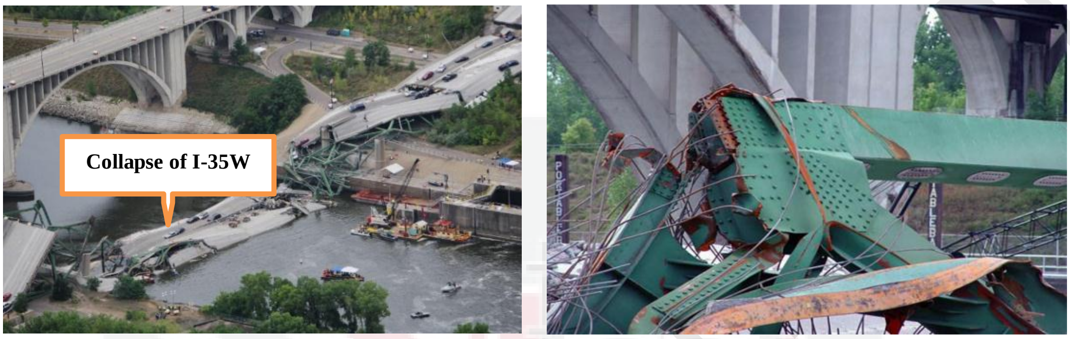

Figure 1.1 : I-35W highway bridge collapsed in Minneapolis Aug. 2007
(Source: Salam and Helmy, 2014).

As bridges need to operate in any environmental conditions, their infrastructures are required to be sensed to perform their task for safety and ensure long term services. In order to understand their reaction, the involvement of embedded sensing system make them intelligently response to any suffering due to strain-displacement, temperature, internal forces, stresses and vibration that result in deterioration and /or deformation from their natural characteristic.

In relation to cables stayed bridges, many of them are still in use today and were designed according to the old traffic code. Presently, their infrastructures are experiencing to faster, heavier weight tracks and growing moving traffic volume than before. In order to continue using these structures, it is necessary to continue evaluate their loading-bearing capacity for pursuing of ensuring safe performance (Spyrakos, et al., 1999; Deza, 2004).

Without exception in Malaysia, Penang (I) Bridge is also classified as old cables stayed bridge. This bridge is located at the North-West of Peninsular Malaysia, it is about 13.7km long concrete civil structure, harp cable stayed and 4 lanes opened to traffic in September 1985 (McCabe et al., 1990). Due to increase in traffic capacity, the approach spans were winded from 2-lane to 3-lane dual carriageway. The expansion had included additional lane for motorcycle (King, et al., 2009). Also, Two-lane at the viaduct approach spans and two single-lane approach ramps were added (Buckby, et al., 2009; Corbett, et al., 2010). However, at present, the traffic volume and the weight of vehicles are no longer the same as in the 1990's, these are due to the growth of industry and population at the mainland and Penang Island.

The highest traffic volumes recorded at rush hours between 6.00am to 8.00am, nearly thousand vehicles toward the island and similarly leaving the island at peak hour 4.00pm to 7.00pm[1]. It is interesting to note that, even though Penang (II) Bridge was officially opened to traffic in the year 2014, but still Penang (I) Bridge dominates high percentage of the traffic volume. In addition, the result from the interview also revealed it was about 5% to 10% certain class of vehicles were reduced, since Penang (II) Bridge operates. A survey conducted by the Public Transport Department in 2010 found out that 70% of daily users of the bridge were from the mainland-Butterworth side going to the industrial zones of Penang Island which is closer to Penang (I) Bridge.

With regard to Penang (I) bridge stayed cables, the history indicated since 1996 to 1999 the bridge had been vulnerable to cables overstress in short cables M1 and E1[2]. In 2000, new bearings positioned at the piers to limit the load on short cables. Simultaneously, two short cables coded M2 and E2[3] were replaced. In 2003, the bridge installed with acoustic system for monitoring cables but still uncertainty for health the rest of the other cables. The delay in response to embedding monitoring instrument may be due to change of authority body.

In December 2004, cable coded M9 was substituted as a result of unexpected breakage. Then, later 80 couplers were replaced after being found defected. In another event, in 2006, southwest side of the bridge breakage of cable code E9 has been detected by the present monitoring system. Corrosion was common result to replace the cables by consulting companies from United Kingdom Atkin. Co (Hendy and Sandberg, 2004) and Systra Co. (Lam, et al., 2012). Figure 1.2 below shows the crack which located between cable anchorage and the concrete attachment to the bridge girder. Figure 1.3 depicts the corrosion induced in the cable coupler.

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[1] Based on the survey interview with the PLUS officer on 13th March 2014

[2] Cable Codes for Penang (I) Bridge

[3] Cable Codes for Penang (I) Bridge

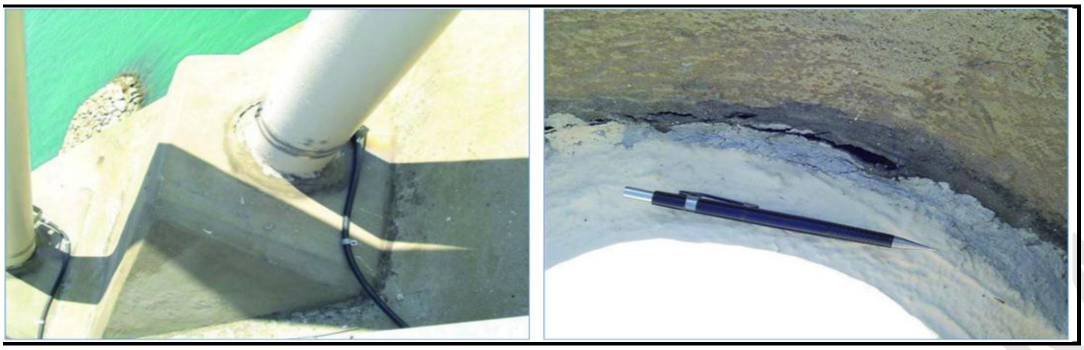

Figure 1.2 : Structural defect of cable Anchorage with bridge girder
(Source: Hendy and Sandberg-Atkins-2004)

Figure 1.3 : Illustrate the cable couplers before and after corrosion
(Source: Hendy and Sandberg-Atkins-2004)

As far as Penang (I) Bridge is concerned, it also suffered from common breakage of cables, hence, the bridge has been installed with an additional system known as advitam "load cells", which was placed at the cables. Its function is to determine loading magnitude and monitoring the capacity of cables, which at the end able to provide the data on attributing factors. The system revealed that Penang (I) Bridge is actually under deterioration as a result from trafficking loading and ageing factors. Despite cables, the other elements such as deck, pylon, piers, and piles are facing the same environmental conditions, which require for monitoring system to ensure its safety.

Based on the above discussion, there is a need of device to spot the damages. One of the solutions to detect damages is via sensors implementation. Sensors implementation globally is expected to detect damage and their reliability of the data collecting subject upon the sensor arrangements. Their average number relies upon the length of the infrastructure span. Additionally, limited sensor numbers and locations can constraint the measured data for only certain regions i.e. poor measurement performance (Ismail, 2011).

Traditionally, the global sensing techniques are more effective to assess the entire bridge performance. To implement global sensing device of various types, it requires identifying the hot spot stresses regions to position these sensors. Thus, in order to assist analysis alteration in properties and predict damages easily, Penang (I) Bridge needs to have quantitative global sensors placement for overall structure system, in addition to the existing local sensor locations. This is also supported by the result of the interview conducted earlier with PLUS officer, where it revealed that the bridge has minor defects at certain locations. Due to the issues highlighted above, the study is conducted based on several objectives.

1.3 Research Objectives (RO)

The aim of the research is to employ finite element analysis of Penang (I) Bridge to monitor the structure and install sensors. The bridge is assessed with real-time live traffic load effect conditions. The objectives of the study are explained in the following sequences:

i. To perform static analysis of symmetrical dead load case, additional live load case according to British Standard BS 5400 and identify bridge critical points for sensor placement.
ii. To conduct unsymmetrical analysis at the combine dead and live loads and investigate the bridge critical points for sensor placement.
iii. To carry out dynamic analysis at dead load stage and determine frequencies with relevant mode shapes.

1.4 Scope of Research Work

The present study focuses on evaluating the Penang (I) bridge structure using analytical modal data as to determine the weakness of its members. Factors such as location, size and cost of construction demanding the bridge to be assessed and it is also important to note that the structure itself is nearly 30years in service. Due to these facts, the bridge might be experience deterioration, damage, structural material failure and others. Therefore, the bridge needs a proper continuous monitoring tool i.e. sensors in detecting the failure of its members.

Hence, realizing the importance of having sensors arrangement for Penang (I) Bridge is the main goal of the research. Therefore, the current study applied nonintrusive approach by simulating the bridge model as proposed by (Ragland et al., 2011). In terms of modal analysis and simulation, in line with (Miao, et al., 2007; Li, et al., 2010), this research focusing on linear ‘symmetrical and unsymmetrical’ method of finite element and the logical outcome based of static and dynamic responses were used to propose locations of the sensors.

As for the analysis part, the finite element software program i.e. Nastran and Patran program has been selected in the current study, which was used by National Aeronautics and Space Administration (NASA) for general finite element solution instead of SAP2000[4] which is useful for elastic second order cable element response (Thai and Kim, 2008).

This is vital to identify the locations of highly stressed members i.e. its critical grid points, which eventually lead to sensors placements in the overall bridge infrastructure. In relation to this, the study considered the loading condition in the analysis. It used the standard to develop the symmetrical and unsymmetrical analysis which at the end, the results would indicate the proposed sensor locations.

The details of the research procedure are summarized and pursued as follows:

- To determine the objects and investigate the structure problem and to exploit the scope of the research.
- To review previous scholars works on bridge monitoring using finite element and identify their limitations.
- To employ modal analysis and simulation by adopting a static approach of dead load and to determine the critical areas of the bridge members.
- To include British Standards BS5400 as live traffic load to the infrastructure and evaluate the bridge elements for crucial spot of stresses.
- To establish unsymmetrical condition due to the previous combined static loads and assess the bridge behavior.
- To apply dynamic analysis at the dead load case and to determine the critical areas of the bridge members.
- To discuss the result and findings of analysis in each case of the analysis.
- To propose sensor locations at each step of the analysis to all bridge elements.
- To conclude and state objective achievement.

1.5 Thesis Organization

Basically, the thesis is orderly split up into five chapters in the following manner;
Chapter 1: begins its journey by addressing the background of the structural health monitoring to be proposed on bridge civil structure. It covers the background of the research, problem statement that triggers the interest of the study. Then it continues with the objectives of the research, scope of the research work and the importance of the investigation to Structural Monitoring application which is related to maintenance and rehabilitation activities for instance frequent visual inspection, repair, sensing monitor and managing bridge structures.

[4] Finite element software

Chapter 2: Past literatures on related topics have been covered at this chapter. Basically, it provides background the bridge structures, bridge monitoring, the concept of finite element concept which explains the static and dynamic analysis, bridge loading aspect as well as the sensor arrangements. Finally, the gap is highlighted at the end of the discussion.

Chapter 3: portrays the way the study is conducted. The use of finite element method and its contribution in structural analysis is explained. The model of Penang (I) Bridge is created with the aid of NASTRAN and PATRAN program.

Chapter 4: presents the modal analysis and simulation results and discussion. The discussion of the results is divided into 2 main parts i.e. a) Static loading analysis and b) dynamic loading analysis. For Static loading analysis, it further divided into 2 parts, which are symmetrical and unsymmetrical analysis. The discussion starts with symmetrical static loading aspect, where the results is sub-divided into 2 cases, a) static analysis of symmetrical dead load case and b) static analysis of symmetrical live traffic load case using British Standard 'BS 5400'. Later, for unsymmetrical Static Loading aspect, both scenario i.e. the dead load and live load case are considered during the analysis. While, Dynamic analysis is performed to derive the frequencies and mode shapes of the bridge at the dead load case. All the analysis is conducted in order to determine the critical grid points, which eventually lead to proposed location of sensors placements.

Chapter 5: Conclusion and recommendation for future works, this final chapter reveals prediction and predetermined summary of the three investigated objectives. Finally, it highlights the conclusion as a result from the findings, which include recommendations for future research.

REFERENCES

Abdul-Aziz, A., Baaklini, G. Y., Zagidulin, D., & Rauser, R. W. (2000, May). Challenges in integrating nondestructive evaluation and finite-element methods for realistic structural analysis. In SPIE's 5th Annual International Symposium on Nondestructive Evaluation and Health Monitoring of Aging Infrastructure (pp. 35-46). International Society for Optics and Photonics.

Aiqun, L., Changqing, M., & Zhaoxia, L. (2003). Health monitoring system for the Runyang Yangtse river bridge. Journal of Southeast University: Natural Science Edition, 33(5), 544-548.

Alomar (2009). Comparison Between Grillage and Finite Element Model. Master Thesis. University Technology Malaysia, Malaysia.

American Concrete Institution. Analysis and Design of Reinforced Concrete Bridge Structures: ACI 343r-95, American Concrete Institution (2003).

Akin, J. E. (2010). Finite element analysis concepts: via Solid Works. World Scientific Publishing.

Aktan, A. E., Catbas, F. N., Grimmelsman, K. A., & Tsikos, C. J. (2000). Issues in Infrastructure Health Monitoring for Management. *Journal of Engineering Mechanics*, 126(7), 711-724.

Aktan, E., Chase, S., Inman, D., & Pines, D. (2001, March). Monitoring and managing the health of infrastructure systems. In Proc. SPIE (Vol. 4337).

Atkin company 2004. Replacement of the stay cables on Penang Bridge.

Andersen, L., Nielsen, S. R., & Kirkegaard, P. H. (2001). Finite element modelling of infinite Euler beams on Kelvin foundations exposed to moving loads in convected co-ordinates. *Journal of Sound and Vibration*, 241(4), 587-604.

ASCE. (2003). Assessment of performance of vital long-span bridges in the United States. ASCE subcommittee on performance of bridges, R. J. Kratky, ed., ASCE, Reston, Va.

Armero, F. (2000). On the locking and stability of finite elements in finite deformation plane strain problems. *Journal of Computers & Structures*, 75(3), 261-290.

Armero, F., & Dvorkin, E. N. (2000). On finite elements for nonlinear solid mechanics. *Journal of Computers & Structures*, 75(3), 235.

Arshad, A.A. Bridge Design to JKR Specification. Civil & Structural Engineering Technical Division. The Institution of Engineering Malaysia (IEM), 29th May 2001

Arurkar, T. P. (2006). Accelerated Construction Decision Making Process. (Doctoral dissertation, University of Cincinnati).

Azar, R. S., & Shafri, Z. M. (2009). Mass structure deformation monitoring using low cost differential global positioning system device. American Journal of Applied Sciences, 6(1), 152.

Balageas, D., Fritzen, C. P., & Güemes, A. (Eds.). (2006). *Structural Health Monitoring* (Vol. 493). London: ISTE.

Belluck, P. (2007). Victims missing in bridge collapse identified. The New York Times, 5 August 2007

Bently, D.E. and C.T. Hatch, Fundamentals of Rotating Machinery Diagnostics. 2003, New York: ASME press. pp. 726.

Berger, H., Non-destructive Evaluation Techniques. Anti-Corrosion Methods and Materials -Emerald, 1982. 29(12): 11-13.

Bergmeister, K., & Santa, U. (2001). Global monitoring concepts for bridges. *Journal of Structural Concrete*, 2 (1), 29-39.

Brenner, B., Bell, E. S., Sanayei, M., Pheifer, E., Durack, W., Fay, S., & Thorndike, L. L. C. (2010). Structural modeling, instrumentation, and load testing of the Tobin Memorial Bridge in Boston, Massachusetts. In Proc., 2010 Structures Congress (pp. 729-740).

Brownjohn, J. M., Xia, P. Q., Hao, H., & Xia, Y. (2001). Civil structure condition assessment by FE model updating: methodology and case studies. Finite elements in analysis and design, 37(10), 761-775.

Brownjohn, J., Tjin, S. C., Tan, G. H., Tan, B. L., & Chakraboorty, S. (2004, June). A structural health monitoring paradigm for civil infrastructure. In *1st FIG International Symposium on Engineering Surveys for Construction Works and Structural Engineering, Nottingham, United Kingdom* (Vol. 28).

Buckby, R., Peng, C. W., Corbett, P., & Singh, M. (2009). Widening of the Penang Bridge, Malaysia. *Journal of Structural Engineering International*, 19(1), 41-45.

Budelmann, H., Hariri, K., Cho, H. N., Frangopol, D. M., & Ang, A. H. S. (2006). *A structural monitoring system for RC/PC structures* (pp. 3-17). London: Taylor and Francis.

Cao, D.Q., Song, M.T., Zhu, W.D., Tucker, R.W., Wang, C.H-T., (2012). Modeling and Analysis of in Plane Vibration of a Complex Cable-Stayed Bridge. *Journal of Sound and Vibration* 331(26): 5685-5714

Caprani, C. C., OBrien, E. J., & McLachlan, G. J. (2008). Characteristic traffic load effects from a mixture of loading events on short to medium span bridges. *Journal of Structural Safety*, 30(5), 394-404.

Chan, T. H., Guo, L., & Li, Z. X. (2003). Finite element modelling for fatigue stress analysis of large suspension bridges. *Journal of Sound and Vibration*,*261*(3), 443-464.

Chang, P. C., & Liu, S. C. (2003). Recent research in nondestructive evaluation of civil infrastructures. *Journal of Materials in Civil Engineering*, 15 (3), 298-304.

Chang, P.C., Flatau, A., and Liu, S.C. (2003). Review paper: Health monitoring of civil infrastructure, *Journal of Structural Health Monitoring*, 2(3): 257-67.

Chang, F. K. (Ed.). (2005). *Structural health monitoring 2005: advancements and challenges for implementation*. DEStech Publications, Inc.

Chin, F. K. (1988). The Penang bridge: planning, design and construction. Lembaga Lebuhraya Malaysia.

Chintalapudi, K., Fu, T., Paek, J., Kothari, N., Rangwala, S., Caffrey, J. & Masri, S. (2006). Monitoring civil structures with a wireless sensor network. *IEEE Internet Computing*, 10(2), 26-34.

Chen, S. R., & Wu, J. (2009). Dynamic performance simulation of long-span bridge under combined loads of stochastic traffic and wind. *Journal of Bridge Engineering*, *15*(3), 219-230.

Chong, K. P., Carino, N. J., & Washer, G. (2003). Health Monitoring of Civil Infrastructures. *Journal of Smart Materials and Structures*, 12 (3), 483.

Choi, M. and Sweetman, B. (2010). Efficient calculation of statistical moments for structural health monitoring, *Journal of Structural Health Monitoring*, 9 (1): 13-24.

Cohen, S., Bakst, B., Borenstein, S., Lohn, M., Foley, R., & Krawczynski, J. (2007). Minnesota bridge problems uncovered in 1990.

Collings, D. (2015, August). Planning, design and construction of the Second Penang Bridge. In Proceedings of the Institution of Civil Engineers-Bridge Engineering (Vol. 169, No. 4, pp. 260-270). Thomas Telford Ltd.

Corbett, P. W., Buckby, R. J., & Wee, E. L. (2010). Penang Bridge widening: design and construction challenges. *Proceedings of the ICE-Bridge Engineering*, 163(3), 125-135.

Das, P. C. (Ed.). (1997). Safety of Bridges. Thomas Telford.

Daniell, W. E., & Macdonald, J. H. (2007). Improved finite element modelling of a cable-stayed bridge through systematic manual tuning. *Journal of Engineering Structures*, 29(3), 358-371.

Davalos, E. (2000). Structural Behavioure of Cable Stayed Bridges. Master Thesis, Massachusetts Institute of Technology, USA.

Dawe, P. (2003). Research perspectives: Traffic loading on highway bridges. Thomas Telford.

Desai, A.K., Desai, J.A. and Patil, H.S., (2006). State of art review-Seismic Analysis of Cable Stayed Bridges, Proceedings, National Conference on Resent Advances in Structural Engineering, Kakinada, India, pp-144-147.

Deza, U. (2004). *Evaluation of the In-Service Performance of Bridge Decks Built with Fiber Reinforced Polymer (FRP) Composite Systems* (Doctoral dissertation, Master Thesis, University of Missouri–Rolla, Rolla, MO, USA).

Doebling, S.W., Farrar, C., Prime, M.B., and Shevitz, D.W (1996). "Damage Identification and Health Monitoring of Structure and Mechanical Systems from Changes in their Vibration Characteristics: A literature Review". Technical Report LA-13070-MS, Los Alamos National Laboratory, Los Alamose, New Mexico.

Doyle, J. (2009). A Model for Emergency Preparedness and Response in the 21st Century: A Closer Look at the I-35 W Bridge Collapse and the City of Minneapolis's Crisis Management System (Doctoral dissertation, Hubert H. Humphrey Institute of Public Affairs).

El Shenawy, E. A., & Schlaich, M. (2013, September). Stay Cable Forces under Dead Load for Cable-Stayed and Extradosed Bridges. In IABSE Symposium Report (Vol. 101, No. 13, pp. 1-8). *International Association for Bridge and Structural Engineering.*

El Araby El Shenawy. (2012). Form Finding for Cable-Stayed and Extradosed Bridges (Doctoral dissertation, Universitätsbibliothek der Technischen Universität Berlin).

Ellingwood, B. R. (2005). Risk-informed condition assessment of civil infrastructure: state of practice and research issues. *Journal of Structure and infrastructure engineering,* 1(1), 7-18.

Enckell, M. (2007). Structural health monitoring of bridges in Sweden. *Proceedings of the ISHMII-3, paper*, (117).

Estes, A.C., and Frangopol, D.M., (2001). Minimum Expected Cost-Oriented Optimal Maintenance Planning for Deteriorating Structures: Application to Concrete Bridge Decks. *Journal of Reliability Engineering & System Safety*, 73 (3): 281-291.

Fan, W., & Qiao, P. (2011). Vibration-based damage identification methods: a review and comparative study. *Journal of Structural Health Monitoring*, 10(1), 83-111.

Fang, I. K., Chen, C. R., & Chang, I. S. (2004). Field static load test on Kao-Ping-Hsi cable-stayed bridge. *Journal of Bridge Engineering*, 9(6), 531-540.

Farrar, C. R., Baker, W. E., Bell, T. M., Cone, K. M., Darling, T. W., Duffey, T. A., & Migliori, A. (1994). Dynamic characterization and damage detection in the I-40 bridge over the Rio Grande (No. LA--12767-MS). Los Alamos National Lab., NM (United States).

Farrar, C., & Jauregui, D. (1996). Damage detection algorithms applied to experimental modal data from the I-40 bridge (No. LA--13074-MS). Los Alamos National Lab., NM (United States).

Farrar, C.R., Doebling, S.W., and Nix, D.A. (2001). Vibration-Based Structural Damage Identification. Philosophical Transactions of royal Society: Mathematical, Physical & Engineering Sciences. 359 (1778):131-149.

Farrar, C. R., Park, G., Allen, D. W., & Todd, M. D. (2006). Sensor Network Paradigms for Structural Health Monitoring, *Journal of Structural control and health monitoring*, 13(1), 210-225.

Farrar, C. R., & Lieven, N. A. (2007). Damage prognosis: the future of structural health monitoring. Philosophical Transactions of the Royal Society A: *Journal of Mathematical, Physical and Engineering Sciences*, 365(1851), 623-632.

Farrar, C. R., & Worden, K. (2007). An Introduction to Structural Health Monitoring, Philosophical Transactions of the Royal Society A: *Journal of Mathematical, Physical and Engineering Sciences*, 365(1851), 303-315.

Fleming, J. F. (1979). Nonlinear Static Analysis of Cable-Stayed Bridge Structures. *Journal of Computers & Structures*, 10(4), 621-635.

Frangopol, D. M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges 1. *Journal of Structure and Infrastructure Engineering*, 7(6), 389-413.

Freire, A. M. S., Negrao, J. H. O., & Lopes, A. V. (2006). Geometrical nonlinearities on the static analysis of highly flexible steel cable-stayed bridges. *Journal of Computers & Structures*, 84(31), 2128-2140.

Galati, N., Casadei, P., & Nanni, A. (2005). *In-Situ Load Testing of Bridge A6102 Lexington, MO* (No. UTC R124-2).

Gimsing, N. J., & Georgakis, C. T. (2011). Cable supported bridges: concept and design. John Wiley & Sons.

Glisic, B., & Inaudi, D. (2008). Fiber optic methods for structural health monitoring. John Wiley & Sons.

Hanganu, A. D., Onate, E., & Barbat, A. H. (2002). A finite element methodology for local/global damage evaluation in civil engineering structures. *Journal of Computers & Structures*, 80(20), 1667-1687.

Hassan, M. K., Zain, M. F. M., Hannan, M. A., & Jamil, M. (2010). Sensor placement technique and GUI System for monitoring the bridge girder. International Journal of Civil and Structural Engineering, 1(3), 583.

Haque, M.E. Zain, M.F.M. Hannan, M.A. Jamil, M. and Johari, H. (2012). Recent Application of Structural Civil Health Monitoring Using WSN and FBG, *World Applied Sciences Journal*, 20 (4): 585-590.

Hendy, C. R., & Sandberg, J. Replacement of the Stay Cables on Penang Bridge 021.

He, X. H., Zhao, A. H., Scanlon, A., & Peng, L. P. (2010, January). Local Stress Analysis and Model Test of Arch Foot for a Steel Box Arch Bridge on High-Speed Railway. In *2010 Joint Rail Conference* (pp. 121-128). American Society of Mechanical Engineers.

Hu, J., Harik, I. E., Smith, S. W., Gagel, J., Campbell, J. E., & Graves, R. C. (2006). Baseline modeling of the Owensboro cable-stayed bridge over the Ohio River.

Ismail, Z., Ibrahim, Z., Ong, A. Z. C., and Rahman, A. G. A. (2011). Approach to Reduce the Limitations of Modal Identification in Damage Detection Using Limited Field Data for Nondestructive Structural Health Monitoring of a Cable-Stayed Concrete Bridge. *Journal of Bridge Engineering*. 17(6): 867-875.

Ismail, Z., Org, A.Z.C., Rahman, A. G.A., (2012). Serviceability of Concrete Bridges in Malaysia Focusing on Susceptibility to Atmospheric Chloride Corrosion. *International Journal of Physical Sciences*. 7 (4): 655-659.

Ito, M., Fujino, Y., Miyata, T., Narita, N., 1991. Cable-Stayed Bridges Recent Developments and Their Future. Proceeding of the seminar, Yokohama, Japan. Elsevier Science Publishers Company INC, 665 Avenue of the Americas, New York. N.Y.10010.USA.]

Kim, K. S., & Lee, H. S. (2001). Analysis of target configurations under dead loads for cable-supported bridges. *Journal of Computers & structures*, 79(29), 2681-2692.

Ko, J. M., Xue, S. D., & Xu, Y. L. (1998). Modal analysis of suspension bridge deck units in erection stage. *Journal of Engineering structures*, 20(12), 1102-1112.

Kumar, G. (2005). *Reliability analysis of prestressed concrete bridge girder beam*. Master Thesis. University Technology Malaysia.

Lam, H., Amami, H., Lemaire, A., Ketfi, M., & Montens, S. (2012, September). Penang Bridge Stay Cable Replacement. In IABSE Congress Report (Vol. 18, No. 7, pp. 1536-1543). *International Association for Bridge and Structural Engineering.*

Law, A. M., & Kelton, W. D. (1991). Simulation modeling and analysis (Vol. 2). New York: McGraw-Hill.

Lee, Y. S., Phares, B., & Wipf, T. (2007, August). Development of a Low-Cost, Continuous Structural Health Monitoring System for Bridges and Components. In Proceedings of the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Lee, Y.-S., Development of a Structural Health Monitoring System for Bridges and Components, in Dept. of Civil Engineering (Structural Engineering). 2007, Iowa State University: Ames, Iowa. p. pp.312.

Lee, T. Y., Kim, Y. H., & Kang, S. W. (2008). Optimization of tensioning strategy for asymmetric cable-stayed bridge and its effect on construction process. *Journal of Structural and Multidisciplinary Optimization*, 35(6), 623-629.

Li, Y., Xiang, Z., Masheng, Z., Cen, Z. (2010). Sensor Placement for Mode-Shape Based Damage Identification on Bridges, *Journal of Tsinghua University (Science and Technology)*, pp150-3.

Liu, T. T., Xu, Y. L., Zhang, W. S., Wong, K. Y., Zhou, H. J., & Chan, K. W. Y. (2009). Buffeting-induced stresses in a long suspension bridge: structural health monitoring oriented stress analysis. *Journal of Wind and Structures*, 12(6), 479-504.

Kim, H-K, Asce, M., Kim, K-T., Lee, H., Kim, S., (2013). Performance of Unpretensioned Wind Stabilizing Cables in the Construction of a Cable-Stayed Bridge *Journal of Bridge Engineering*, 18(8), 722-734.

King, M. W., Hassan, B., Rahman, A., Omar, B. W., & Zainuddin, W. (2009, January). Monitoring Structural Health of Penang Bridge Using Online System. In IABSE Symposium Report (Vol. 96, No. 20, pp. 30-39). *International Association for Bridge and Structural Engineering.*

Ko, J. M., & Ni, Y. Q. (2005). Technology developments in structural health monitoring of large-scale bridges. *Journal of Engineering structures*, *27*(12), 1715-1725.

Mandic, R., Hadzi-Nikovic, G., & Coric, S. (2011). Investigation of the behavior of the cable-stayed bridge under test load / Ispitivanje ponasanja ovjesenih mostova pod probnim opterecenjem. Geofizika, 28(1), 145-161.

Masri, S. F., Sheng, L. H., Caffrey, J. P., Nigbor, R. L., Wahbeh, M., & Abdel-Ghaffar, A. M. (2004). Application of a web-enabled real-time structural health monitoring system for civil infrastructure systems. *Journal of* I, 13(6), 1269.

McCabe, R., & Kee, C. F. (1990, August). PENANG BRIDGE PROJECT: SUPERSTRUCTURE-DESIGN AND CONSTRUCTION. In Institution of Civil Engineers, Proceedings, Pt 1 (Vol. 88).

Mechitov, K., Kim, W., Agha, G., Nagayama, T., High- frequency distributed sensing for structure monitoring, Proceedings of the 2nd international conference on Embedded Networked Sensing Systems, Tokyo, (2004).

Meng, J. Y., & Lui, E. M. (2000). Torsional effects on short-span highway bridges. *Journal of Computers & Structures*, 75(6), 619-629.

Miao, C., Hui-ting, H., Ai-qun, L., Xiong-fei, C., Ye-hua, F., (2007-11). Analysis on the Original SHM System of Jiangyin Bridge, *Journal of Highway and Transportation Research and Development*, pp85-90.

Miller, R., & Salem, S. (2006). Accelerated construction decision-making process for bridges.

Moses, F., Lebet, J.P. and Bez, R. (1994), Applications of Field Testing to Bridge Evaluation, *Journal of Structural Engineering*, ASCE, 120(6): 1745-1762.

Moss, R. M., and Matthews, S. L. (1995). In-Service Structural Monitoring. a State of the Art Review. *Journal of Structural Engineer*, 73(2).

Nagai, M., Fujino, Y., Yamaguchi, H., & Iwasaki, E. (2004). Feasibility of a 1,400 m span steel cable-stayed bridge. *Journal of Bridge Engineering*, 9(5), 444-452.

Nazmy, A. S., & Abdel-Ghaffar, A. M. (1990). Three-dimensional nonlinear static analysis of cable-stayed bridges. *Journal of Computers & structures*, 34(2), 257-271.

Niroumand, H., Zain, M. F. M., & Jamil, M. (2012). Bridge architecture in Malaysia. *International Journal of Environmental Science and Development*, 3(3), 311.

Norris, C. B. (1962). Strength of orthotropic materials subjected to combined stresses.

Oliveira Pedro, J. J., & Reis, A. J. (2010). Nonlinear analysis of composite steel–concrete cable-stayed bridges. *Journal of Engineering Structures*, *32*(9), 2702-2716.

Osterberg, E. (2004). Revealing of Age-related Deterioration of Prestressed Reinforced Concrete Containments in Nuclear Power Plants: Requirements and NDT methods. *Trita-BKN. Bulletin*, *79*, 1-80.

Pantaleón, M. J., Ramos, Ó. R., Ortega, G., Martínez, J. M., & Schanack, F. (2010). Dynamic analysis of a composite cable-stayed bridge: Escaleritas viaduct. *Journal of Bridge Engineering*, 15(6), 653-660.

Park, S., Stubbs, N., Bolton, R., Choi, S., & Sikorsky, C. (2001). Field Verification of the Damage Index Method in a Concrete Box-Girder Bridge via Visual Inspection. *Journal of Computer-Aided Civil and Infrastructure Engineering*, 16(1), 58-70.

Park, W., Kim, H. K., & Jongchil, P. (2012). Finite element model updating for a cable-stayed bridge using manual tuning and sensitivity-based optimization. *Journal of Structural Engineering International*, 22(1), 14-19.

Peng, Z. K., & Chu, F. L. (2004). Application of the wavelet transform in machine condition monitoring and fault diagnostics: a review with bibliography. *Journal of Mechanical systems and signal processing*, 18(2), 199-221.

Phares, B. M., Wipf, T. J., Greimann, L. F., & Lee, Y. S. (2005). *Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology. Volume I* (No. WHRP 05-03).

Penang Transport Master Plan Study. Retrieved from http://eps.mbpj.gov.my/urbantransport/paper2.pdf

Pines, D., & Aktan, A. E. (2002). Status of structural health monitoring of long-span bridges in the United States. Progress in Structural Engineering and materials, 4(4), 372-380.

Public-Transport user survey. Retrieved 25 Oct 2010 from http://anilnetto.com/society/public-transport/best-idea-bridge-express-shuttle-transit/25

Rafiq, M.I., Chryssanthopoulos, M.K., Onoufriou, T., (2004). Performance Updating of Concrete Bridges Using Proactive Health Monitoring Methods. *Journal of Reliability Engineering & System Safety*. 86 (3): 247-256.

Raghu, S. (2010). Finite Element Modelling Techniques in MSC. NASTRAN and LS/DYNA.

Ragland, W. S., Penumadu, D., and Williams, R. T. (2011). Finite Element Modeling of a Full-Scale Five-Girder Bridge for Structural Health Monitoring. *Journal of Structure Health Monitoring*, 10 (5): 449-465.

Raich, A., & Cinar, A. (1996). Statistical Process Monitoring and Disturbance Diagnosis in Multivariable Continuous Processes. AIChE Journal, 42(4), 995-1009.

Ren, W. X. (1999). Ultimate Behavior of Long-Span Cable-Stayed Bridges. *Journal of Bridge Engineering*, *4*(1), 30-37.

Ren, W. X., & Peng, X. L. (2005). Baseline finite element modeling of a large span cable-stayed bridge through field ambient vibration tests. *Journal of Computers & structures*, 83(8), 536-550.

Richard, B., Epaillard, S., Cremona, C., Elfgren, L., & Adelaide, L. (2010). Nonlinear finite element analysis of a 50 years old reinforced concrete trough bridge. *Journal of Engineering Structures*, 32(12), 3899-3910.

Ridge, G. T., & Stephan, C. R. B. Preparing For 21st Century Risks.

Roach, D., Rackow, K., & DeLong, T. (2007). "8.0 LIVING INFRASTRUCTURE CONCEPTS PART II: SMART STRUCTURES–IN-SITU, DISTRIBUTED HEALTH MONITORING SENSORS". *Use of Composite Materials, Health Monitoring and Self-Healing Concepts to Refurbish Our Civil and Military Infrastructure*, 223.

Roach, D., Rackow, K., & DeLong, W. (2008). 10.0 FIELD APPLICATION: REPAIR OF INTERSTATE 10 HIGHWAY BRIDGE. *Use of Composite Materials, Health Monitoring and Self-Healing Concepts to Refurbish Our Civil and Military Infrastructure*, 301.

Ruiz-Teran, A.M. and Aparicio, A.C. (2009). Response of under-deck cable–stayed bridges to the accidental breakage of stayed cables. *Journal of Engineering Structures*, 31 (7): 1425-1434.

Rytter, A., & Kirkegaard, P. H. (1994). Vibration Based Inspection of Civil Engineering Structures. Aallborg, Aalborg Universitetsforlag.

Rytter, A. (1993). "Vibrational Based Inspection of Civil Engineering Structures." PhD thesis, Department of Building Technology and Structural Engineering, Aalborg University, Denmark.

Salem, H. M., & Helmy, H. M. (2014). Numerical investigation of collapse of the Minnesota I-35W bridge. *Journal of Engineering Structures*, 59, 635-645.

Salem, S., & Miller, R. A. (2006). Accelerated Construction Decision-Making Process for Bridges (No. MRUTC 05-04). Midwestern Regional University Transportation Center, College of Engineering, Department of Civil and Environmental Engineering, University of Wisconsin, Madison.

Schlune, H., Plos, M., & Gylltoft, K. (2009). Improved bridge evaluation through finite element model updating using static and dynamic measurements. *Journal of Engineering Structures*, 31(7), 1477-1485.

Sakran, M., & Rao, D. P. (2010). Cable stayed bridges for elegance and economy. *The University of the West Indies, Trinidad and Tobago*.

Sih, G. C., Tang, X. S., Li, Z. X., Li, A. Q., & Tang, K. K. (2008). Fatigue crack growth behavior of cables and steel wires for the cable-stayed portion of Runyang bridge: disproportionate loosening and/or tightening of cables. *Journal of Theoretical and Applied Fracture Mechanics*, 49(1), 1-25.

Sikorsky, C., Stubbs, N., & Karbhari, V. (2003, January). Automation of Damage Index Method to Evaluate Structural Safety. *In Proceedings of the thirteenth international offshore and polar engineering conference*, Honolulu, Hawaii.

Sikorsky, C. (2005). A Strategy to Implement Structural Health Monitoring on Bridges. In Sensing Issues in Civil Structural Health Monitoring (pp.43-53). Springer Netherlands.

Simões, L. M. C., & Negrão, J. H. J. O. (2000). Optimization of cable-stayed bridges with box-girder decks. *Journal of Advances in Engineering Software*, 31(6), 417-423.

Sohn, H., & Farrar, C. R. (2001). Damage diagnosis using time series analysis of vibration signals. *Journal of Smart Materials and Structures*, 10(3), 446.

Sohn, H., Farrar, C. R., Hemez, F. M., & Czarnecki, J. J. (2002). A Review of Structural Health Review of Structural Health Monitoring Literature 1996-2001(No. LA-UR-02-2095). Los Alamos National Laboratory.

Sohn, H., Park, G., Wait, J. R., Limback, N. P., & Farrar, C. R. (2003). Wavelet-based active sensing for delamination detection in composite structures. *Journal of Smart Materials and structures*, 13(1), 153.

Song, X. D., Wu, D. J., & Li, Q. (2013). Dynamic impact analysis of double-tower cable-stayed maglev bridges using a simple model. *Journal of Bridge Engineering*, 19(1), 34-43.

Spyrakos, C. C., Kemp, E. L., & Venkatareddy, R. (1999). Validated analysis of wheeling suspension bridge. *Journal of Bridge Engineering*, 4(1), 1-7.

Staszewski, W., Boller, C., and Tomlinson, G.R., (2004). Health Monitoring of Aerospace Structure; Smart Sensor Technologies and Signal Processing. John Wiley & Sons, Ltd.

Stubbs, N., Kim, J. T., & Farrar, C. R. (1995, February). Field verification of a nondestructive damage localization and severity estimation algorithm. *In Proceedings-Spie the International Society for Optical Engineering* (pp. 210-210). Spie International Society for Optical.

Stubbs, N., Park, S., Sikorsky, C., & Choi, S. (2000). A Global Non-destructive Damage Assessment Methodology for Civil Engineering Structures. *International Journal of Systems Science*, 31(11), 1361-1373.

Sullivan, B. J. (2010). The finite element method and earthquake engineering: The 2006 Benjamin Franklin Medal in civil engineering presented to Ray W. Clough. *Journal of the Franklin Institute*, 347(4), 672-680.

Taib I. M., Jambatan Kedua Sdn Bhd. Retrieved 20 FEB 2011 from http://www.jambatankedua.com.my/webv1/images/stories/papers/utm_presentation-20.02.11.pdf

Taib, I. M., (2012). The Second Penang Bridge. Sustainable Design & Construction. Project Briefing & Industrial Training Placement. University Technology Malaysia (UTM). [7th March 2012]

Tan, CC. A., Kaphle, M., Thamberatnam, D. (2009). Structural Health Monitoring of Bridges Using Acoustic Emission Technology. IEEE.

Teughels, A., & De Roeck, G. (2003). Damage assessment of the Z24 bridge by FE model updating. In *Key engineering materials* (Vol. 245, pp. 19-26). Trans Tech Publications.

Teughels, A., & De Roeck, G. (2004). Structural damage identification of the highway bridge Z24 by FE model updating. *Journal of Sound and Vibration*, Vol.278 (Iss.3), pp.589-610.

Thai, H. T., & Kim, S. E. (2008). Second-order Inelastic Dynamic Analysis of Three-Dimensional Cable-Stayed Bridges. *International Journal of Steel Structure*, 8(3), 205-214.

Troitsky, M. S., 1988.Cable stayed bridges, an approach to modern bridge design, Van Nostrand Reinhold Company, New York.

Troitsky, M. S. (1977). Cable-stayed Bridges. Theory and Design (No. Monograph).

Tsompanakis, Y. (2010). Vulnerability Assessment of Structures and Infrastructures.

Virlogeux, M. (1999). Recent evolution of cable-stayed bridges. *Journal of Engineering Structures*, 21(8), 737-755.

Vurpillot, S., Krueger, G., Benouaich, D., Clement, D., & Inaudi, D. (1998). Vertical deflection of a pre-stressed concrete bridge obtained using deformation sensors and inclinometer measurements. *ACI Structural Journal*, 95(5).

Walther, R., 1988. Cable Stayed Bridges, Thomas Telford Ltd, London, p.230.

Wang, P. H., Tseng, T. C., & Yang, C. G. (1993). Initial shape of cable-stayed bridges. *Journal of Computers & Structures*, 46(6), 1095-1106.

Wang, F., Li, Y., Han, K., & Feng, Y. T. (2006). A general finite element model for numerical simulation of structure dynamics. Science in China series G: *Journal of Physics, Mechanics and astronomy*, 49(4), 440-450.

Wang, Y., Li, Z., WU, B., (2008). Fatigue Stress Monitoring and Analysis for Steel Box Girder of Runyang Suspension Bridge. *Journal Frontiers of Architectural and Civil Engineering China*, 2(3):197-204.

Wei, L., Cheng, H., & Li, J. (2012). Modal Analysis of a Cable-Stayed Bridge. *Journal* of *Procedia engineering*, vol.31, pp.481-486.

Wilson, J. C., & Gravelle, W. (1991). Modelling of a cable stayed bridge for dynamic analysis. *Journal of Earthquake engineering & structural dynamics*, 20(8), 707-721.

Worden, K., & Dulieu-Barton, J. M. (2004). An overview of intelligent fault detection in systems and structures. *Journal of Structural Health Monitoring*, 3(1), 85-98.

Wenzel, H. (2008). Health Monitoring of Bridges. John Wiley & Sons.

Wu, Z. S., & Wang, X. (2008, July). Investigation on a thousand-meter scale cable-stayed bridge with fibre composite cables. *In Proceedings of the 4th International Conference on FRP Composites in Civil Engineering*, Zurich, Switzerland (Vol. 2224).

Xiao, X., Xu, Y. L., & Zhu, Q. (2014). Multiscale modeling and model updating of a cable-stayed bridge. II: Model updating using modal frequencies and influence lines. *Journal of Bridge Engineering*, 20(10), p 04014113.

Xie, X., Li, X., & Shen, Y. (2014). Static and dynamic characteristics of a long-span cable-stayed bridge with CFRP cables. *Journal of Materials*, 7(6), 4854-4877.

Yang, C., Wu, Z., & Zhang, Y. (2008). Structural health monitoring of an existing PC box girder bridge with distributed HCFRP sensors in a destructive test. *Journal of Smart Materials and Structures*, *17*(3), 035032.

Yaralioglu, G. G., Ergun, S. A., & Khuri-Yakub, B. T. (2005). Finite-element analysis of capacitive micromachined ultrasonic transducers. IEEE *Journal* of transactions on ultrasonics, ferroelectrics, and frequency control, 52(12), 2185-2198.

Yu, L., Giurgiutiu, V., Ziehl, P., Ozevin, D., & Pollock, P. (2010, March). Steel bridge fatigue crack detection with piezoelectric wafer active sensors. In *SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring* (pp. 76471Y-76471Y). *International Journal of Society for Optics and Photonics*.

Zadeh, O. S. (2012). Comparison Between Three Types of Cable Stayed Bridges Using Structural Optimization. Master thesis of Civil and Environmental Engineering. University of Western Ontario London, Ontario, Canada

Zapico, J. L., & González, M. P. (2006). Numerical simulation of a method for seismic damage identification in buildings. *Journal of Engineering structures*, 28(2), 255-263.

Zhaoxia, L., Aiqun, L., & Hongtian, C. (2003). Finite element modeling for health monitoring and condition assessment of long-span bridges. *Journal of Southeast University (Natural Science Edition)*, *33*(5), 562-572.

Zingoni, A. (2005). Structural Health Monitoring, Damage Detection and Long-term Performance. *Journal of Engineering structures*, 27(12), 1713-1714.

Zhu, Q., Xu, Y. L., & Xiao, X. (2014). Multiscale modeling and model updating of a cable-stayed bridge. I: Modeling and influence line analysis. *Journal of Bridge Engineering*, 20(10), 04014112.

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