WIND-VEHICLE-BRIDGE INTERACTION: FATIGUE ASSESSMENT AND RELIABILITY

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ABSTRACT

Many long-span suspension bridges have been built throughout the world in recent years but they are often subject to multiple types of dynamic loads, especially those located in wind-prone regions and carrying both trains and road vehicles. To ensure the safety and functionality of these long-span steel suspension bridges, fatigue assessment and reliability shall be performed from time to time during their service life. In this regard, structural health monitoring systems (SHMS) have been installed in a few long-span suspension bridges, but it is not clear how to make use of SHMS for fatigue assessment and reliability analysis. This study focuses on fatigue assessment and reliability analysis of long-span suspension bridges under multiple types of dynamic loads by integrating computer simulation with the measurement data from SHMS and by taking the Tsing Ma suspension bridge in Hong Kong as an example. This study leads to a powerful framework and an engineering approach for determining dynamic stress responses of long-span suspension bridges under combined highway, railway and wind loadings. This study also narrows down the gap currently existing between structural health monitoring technologies and structural condition assessment practices by developing a few approaches capable of performing fatigue assessment and reliability analysis with taking into account uncertainty and randomness inherent in both physical field and computer simulation.

Keywords: Long-span suspension bridges, multiple dynamic loads, dynamic stresses, fatigue, reliability, structural health monitoring systems

1. INTRODUCTION

To meet the economic and social needs of our communities, many long-span suspension bridges carrying both road and rail traffic have been built throughout the world in recent years, and some of them are located in wind-prone regions. These long-span suspension bridges are often made of steel, but 80-90% of failure in steel structures is related to fatigue and fracture (ASCE, 1982). Thus, fatigue is an important aspect of the functionality and safety of steel bridges. Given that fatigue

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damage accumulates with dynamic load-induced stresses over the service period of a bridge, an accurate estimation of the dynamic stress responses is essential in fatigue assessment. However, this is not an easy task, for the dynamic stress responses of a long-span suspension bridge are induced by multiple types of dynamic loads, such as railway, highway, and wind loads, and uncertainty and randomness are inherent in these dynamic loads. In this regard together with other considerations, structural health monitoring systems (SHMS) have been installed in a few long-span suspension bridges, but it is not clear how to make use of SHMS for fatigue assessment and reliability analysis.

This study therefore focuses on fatigue assessment and reliability analysis of long-span suspension bridges under multiple types of dynamic loads by integrating computer simulation with the measurement data from SHMS and by taking the Tsing Ma suspension bridge in Hong Kong as an example. A comprehensive framework based on the finite element method is proposed for the dynamic stress analysis of long-span suspension bridges under combined action of wind, railway, and highway loads. The proposed framework is then verified by using measurement data of both structural responses and load conditions recorded by SHMS installed in the Tsing Ma Bridge. To apply the framework for the fatigue assessment of multiloading suspension bridges, two major simplifications have to be made to produce an engineering approach for efficient computation of dynamic stress and fatigue damage accumulation. The computational accuracy and efficiency of the engineering approach are also verified through numerical simulations and field measurements. Subsequently, a general computational procedure is proposed for the fatigue analysis of a multiloading suspension bridge over its design life, which is used to compute the cumulative fatigue damage induced by either individual type of dynamic load or multiple types of dynamic loads. Finally, a framework for fatigue reliability analysis is developed to estimate fatigue failure probabilities at fatigue-critical locations of a multiloading suspension bridge for different time epochs.

2. DYNAMIC STRESS ANALYSIS

2.1. Framework

To undertake the fatigue analysis of multiloading long-span suspension bridges, a dynamic stress analysis of the bridge under multiple types of dynamic loads shall be first conducted. A comprehensive framework based on the finite element method is therefore developed to fulfil this task (Chen et al. 2011). In the framework developed, a long-span suspension bridge, trains, and road vehicles are regarded as three subsystems. A SHM-oriented finite element model (FEM) is established for the long-span suspension bridge such that dynamic stresses of major bridge components can be predicted directly. The trains and road vehicles are also modelled using the FE method. Given that a large number of degrees of freedom are involved in the finite element models of the three subsystems, the mode superposition method is adopted to make it manageable for the dynamic stress analysis of the bridge under multiple types of dynamic loads. The three subsystems are coupled through the contacts between the bridge and trains and between the bridge and road vehicles in terms of wheels-rails and tires-road surface. The nonlinear restoring forces and damping forces in the suspension units of the trains and road vehicles are treated as pseudo forces in the train and road vehicle subsystems. Wind forces may act on all three subsystems. The spatial distributions of both buffeting forces and self-excited forces over the bridge deck surface are considered for the dynamic stress analysis of the bridge. The aerodynamic wind forces acting on the car body of a train or road vehicle are determined using a quasi-steady approach. A stepwise explicit integration method is adopted to solve the coupled equations of motion for the wind-vehicle-bridge system. A set of computer programs coded in Fortran language and integrated with a commercial FE software package are developed to implement the framework for the dynamic stress analysis of a long-span suspension bridge under combined railway, highway and wind loading.

2.2. Verification

The accuracy of the proposed framework must be validated before it can be applied in practice. The Tsing Ma Bridge in Hong Kong is a suspension bridge that carries both trains and road vehicles, and it is also located in one of most active typhoon regions in the world (see Figure 1).

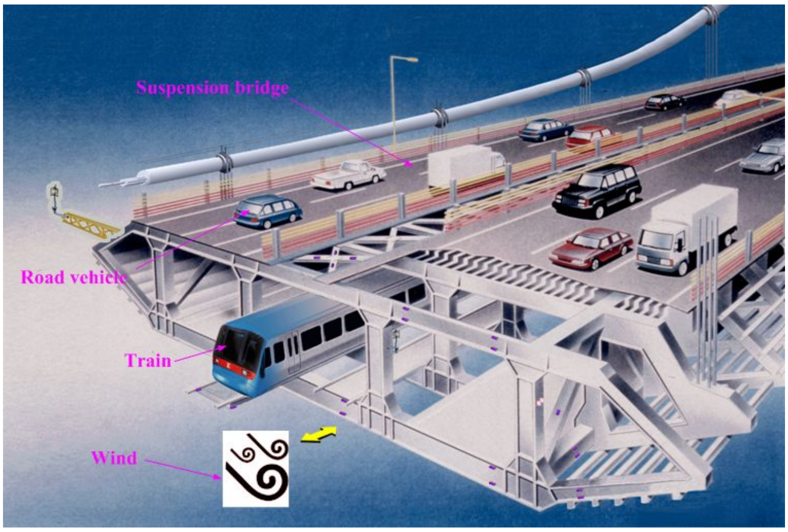


Figure 1: Tsing Ma Bridge under railway, highway, and wind loading

A structural health monitoring system (SHMS) with a total of about 300 sensors was installed in the bridge and started working since 1997. Figure 2 shows the distribution of dynamic strain gauges and anemometers in the Tsing Ma Bridge. The data recorded by the SHMS provide an excellent opportunity for validation. The SHMS provides not only the measurement data of different types of dynamic loads as input for computer simulation but also the measured local stress responses for comparison with the computed ones.

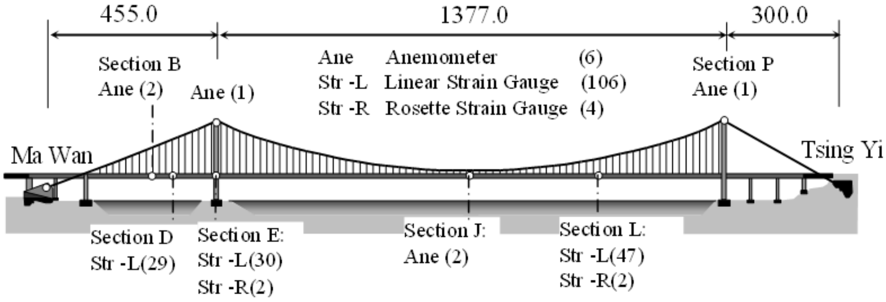


Figure 2: Distribution of dynamic strain gauges and anemometers in Tsing Ma Bridge

In consideration of the requirement of stress analysis of local bridge components, the structural health monitoring oriented FEM of the Tsing Ma Bridge was established (Liu et al. 2009) and shown in Figure 3. The finite element model contains 12898 nodes, 21946 elements (2906 plate elements and 19040 beam elements) and 4788 Multi-Point Connections.

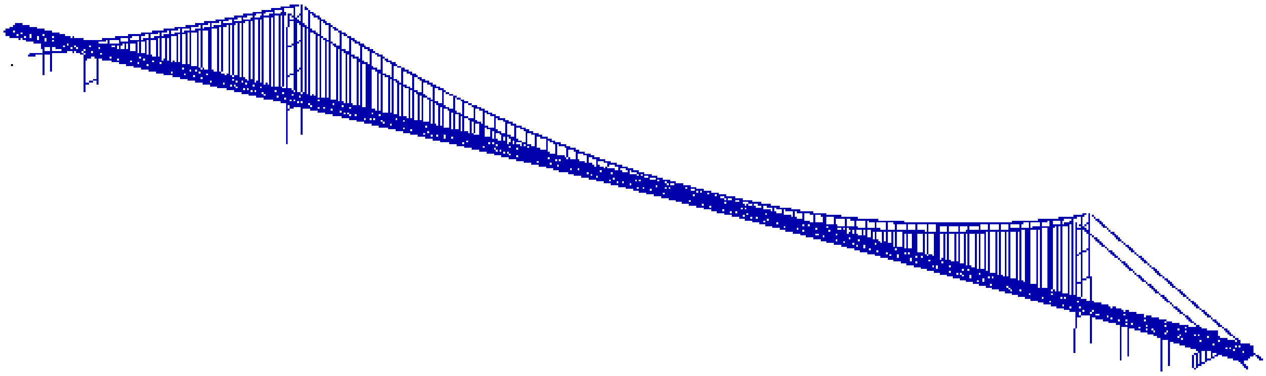


Figure 3: 3-D Finite element model of the Tsing Ma Bridge

The trains and road vehicles are also modelled using the FE method. Figure 4 displays the FEM of a railway vehicle while Figure 5 exhibits the FEM of a highway vehicle. The total degrees of freedom of the railway vehicle are 23. The total degrees of freedom of one road vehicle are 11.

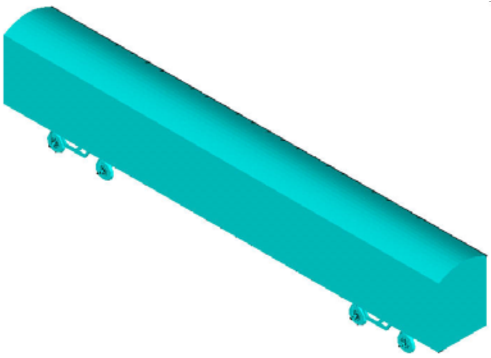


Figure 4: FEM of a railway vehicle

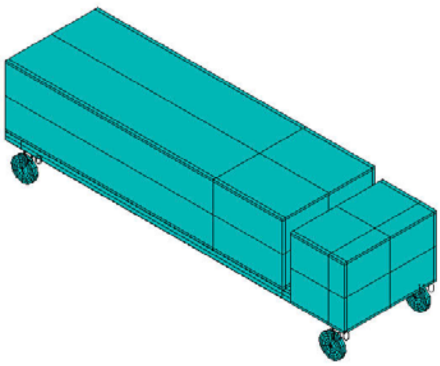


Figure 5: FEM of a road vehicle

To validate the framework in detail, three particular load cases are examined: (1) under strong wind only; (2) under strong wind and running trains; and (3) under strong wind, running trains, and running road vehicles. The selection and pre-processing of the measurement data for wind, trains, road vehicles and structural responses are performed. The selected data corresponding to the three load cases are then analyzed, respectively, to extract both input data for the computer simulation and output data for comparisons. Comparisons between the computed and measured dynamic stress responses are finally made for each load case in terms of time histories and amplitude spectra. Displayed in Figure 6 are the computed and measured 140 sec stress response time histories at the location of a strain gauge (SS-TLS-12) installed under a railway beam. During the time period concerned, one train, several heavy road vehicles, and strong wind act on the bridge. The normal hourly mean wind speed at the bridge deck level is 11.91 m/s. The measured stress responses are processed using a digital low-pass filter with an upper bound of 25 Hz for a reasonable comparison with the computed ones. It can be seen from Figure 6 that the time histories of the computed stress responses are close to those measured by the corresponding strain gauges, which indicates that the proposed framework can accurately predict the dynamic stress responses of the local components of a suspension bridge under combined railway, highway, and wind loading.

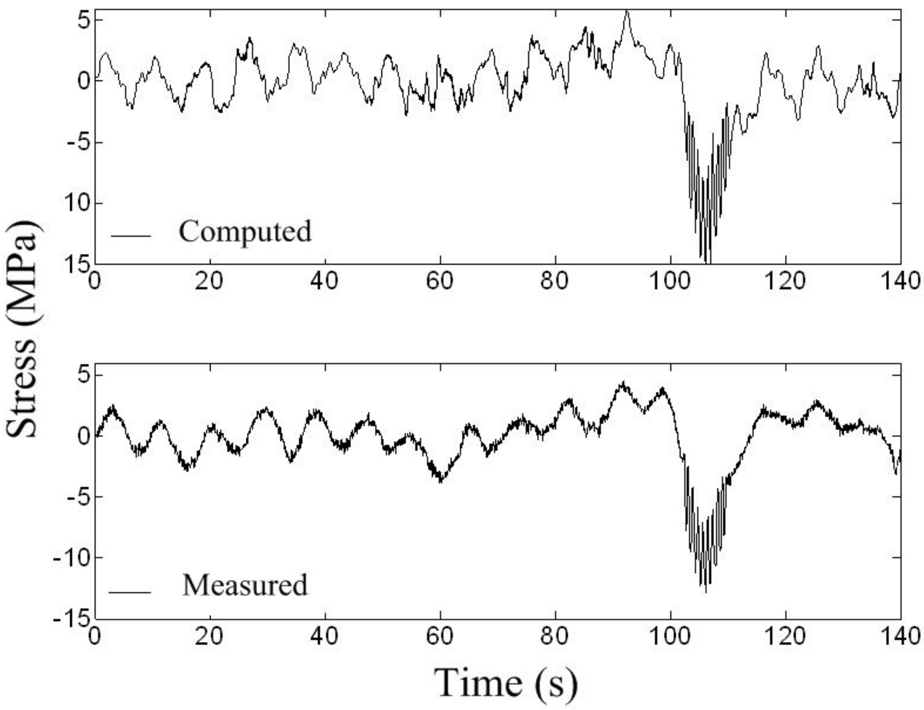


Figure 6: Comparison of stress responses under combined railway, highway and wind loading

3. ENGINEERING APPROACH

In addition to computational accuracy, computational efficiency is very important in calculating dynamic stress responses of a long-span suspension bridge because a great number of stress time histories at various locations of major bridge components shall be computed for fatigue assessment. However, the level of computational efficiency of the framework presented in Section 2 is very low, as several hours are required to compute the 140 sec stress response time histories. It is thus necessary to develop an engineering approach based on the framework mentioned above for computational efficiency while keeping computational accuracy to a certain extent. Two major assumptions are adopted to simplify the coupled dynamic stress analysis framework described above for long-span suspension bridges (Chen et al. 2011). As the dynamic response of a long-span suspension bridge rather than the safety of running vehicles is of interest in this study and also because a suspension bridge deck is massive and its fundamental frequencies are very low, trains and road vehicles running on the bridge deck can be simplified as moving loads, and the stress responses induced by trains and road vehicles are calculated based on the stress influence lines. Furthermore, in consideration of the low level of wind-induced stress response in normal wind conditions and the relatively low level of traffic-induced stress response in extreme wind conditions, it is reasonable to assume that the coupled effects of dynamic stresses induced by railway, highway and wind loading can be neglected. Based on this assumption, the bridge stress responses at given points induced by railway, highway, and wind loading can be computed separately. The three stress responses to the three individual types of dynamic loads are finally superposed to obtain the combined response to the multiple types of dynamic loads.

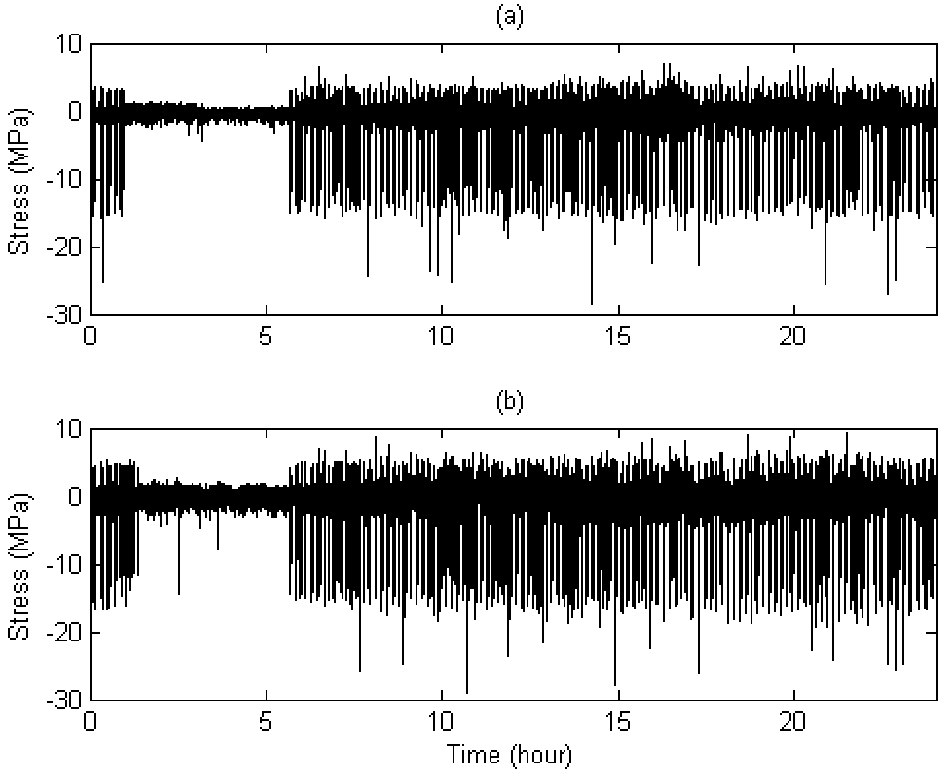


Figure 7: Daily stress time histories under multiple types of dynamic loads at the location of strain gauge SS-TLS-12: (a) computed; (b) measured

The Tsing Ma Bridge is employed to verify the feasibility of the proposed engineering approach. The computational accuracy is validated by comparing the stress responses computed by the engineering approach with those by the coupled dynamic analysis framework. The comparative results show that the differences between the stress responses computed by the two methods are small and the engineering approach is applicable to long-span suspension bridges. The computational accuracy and efficiency of the engineering approach are further verified by comparing the computed daily stress time histories with the measured ones. Figure 7 shows the multiple load-induced stress time histories at the location of strain gauge SS-TLS-12 on 19

November 2005. During this particular day, 440 trains and 16848 heavy road vehicles (weighing over 30 kN) run across the bridge, and the hourly mean wind speed perpendicular to the bridge axis ranges from 2 to 13 m/s. The measurement data of the trains, road vehicles, and wind by SHMS are utilized for the simulation. The results show that only several minutes are required for the engineering approach to compute the required stress time histories but the coupled dynamic approach is actually not applicable for the computation of the daily dynamic stress responses as it takes an intolerably long time. The relative differences between the computed and measured stress time histories are small, which indicates that the engineering approach has a high level of computational efficiency and acceptable level of computational accuracy. The engineering approach can be used for fatigue assessment and reliability analysis of multiloading suspension bridges.

4. FATIGUE ASSESSMENT

The deterministic approach based on the Miner's rule is widely applied in the fatigue assessment of bridge structures in practice. Here, a general computational procedure based on this rule is proposed for the fatigue assessment of a multiloading suspension bridge over its design life. The procedure is then applied to the Tsing Ma Bridge as a case study. There are thousands of structural members in the Tsing Ma Bridge. The fatigue-critical locations for fatigue assessment are first determined based on the maximum stress ranges in the stress time histories induced by a standard train running over the bridge. The results show that the fatigue-critical sections of the bridge deck are around the bridge towers, the pier on the Ma Wan side, and the quarter span of the main span on the Tsing Yi side (Chen et al. 2011). The fatigue-critical locations of the Tsing Ma Bridge, which are most sensitive to wind loading, are around the cross sections at the bridge towers (Xu et al. 2009). Therefore, the components around the bridge towers are fatigue-critical locations with respect to both traffic and wind loading, and six of them are chosen for fatigue analysis, that is, the elements E32123, E34415, E40056, E40906, E55406, and E39417.

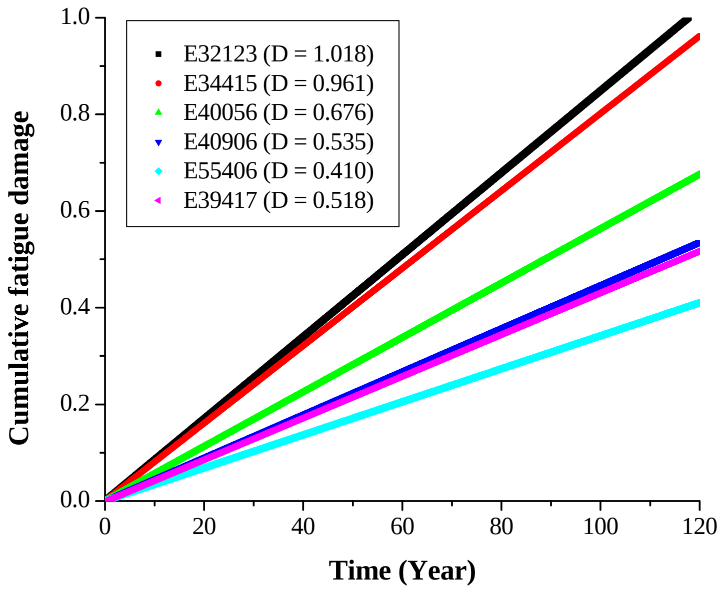
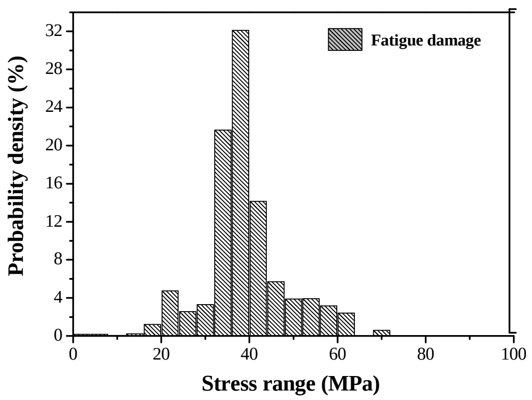


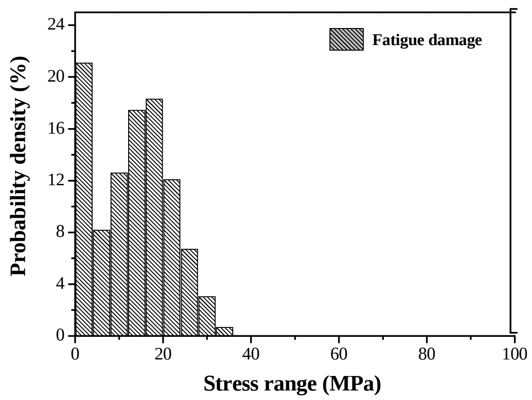
Figure 8: Cumulative fatigue damage curves at the fatigue-critical locations

Databases for the dynamic stress responses at the critical locations induced by wind, railway, and highway loading are established. The time histories of dynamic stresses of 120 years induced by railway, highway, and wind loading are then computed using the databases. The multiple load-induced stress time histories are finally generated. Fatigue analysis based on the stress time histories is performed to assess the cumulative fatigue damage over the bridge design life. Figure 8 shows the cumulative fatigue damage curves at the fatigue-critical locations within a design life of 120 years. The cumulative fatigue damage of 120 years at most critical locations of the Tsing Ma Bridge, except for the E32123, is smaller than one, which implies that health condition of the bridge regarding fatigue is satisfactory.

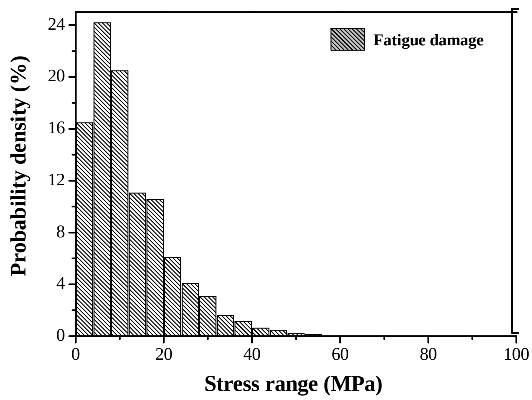
The cumulative fatigue damage induced by each type of dynamic load and the damage magnification due to the multiple types of dynamic loads are also investigated. It is found that railway loading plays the dominant role in the bridge fatigue. The fatigue damage induced by highway loading is greater than that by wind loading for some structural components, but there is a reversal for other components. It is also found that fatigue damage due to combined effects of railway, highway, and wind loading is larger than the sum of fatigue damage due to each of individual loadings, for fatigue damage is the function of m-power stress range (nonlinear relationship), and stress ranges induced by multiple loading are larger than those caused by individual loading. In addition, the fatigue damage spectra of railway, highway, and wind loading are investigated based on the 120-year time histories, and the results are shown in Figure 9 (a-c).



(a)



(b)



(c)

Figure 9: Fatigue damage spectra: (a) railway; (b) highway; (c) wind

Figure 9 shows that the spectra are quite different. For example, the greatest fatigue damage induced by railway loading is in the stress range of 32-40 MPa, that induced by highway loading is in the range of 0-4 and 8-24 MPa, and that induced by wind loading in the range of 0-12 MPa. To study the combined effect of multiple types of loading on fatigue damage, a multiple load magnification factor is defined as the ratio of the fatigue damage due to the combined effect of the three loadings to the sum of the damage due to each individual loading. The factors at the six fatigue-critical locations are computed and range from 1.06 and 1.35. The maximum factor is at critical locations E32123 and E34415, at which the fatigue damage induced by highway and wind loading is much closer to that induced by railway loading than at the other critical locations. The results indicate that the combined effect of multiple loads must be considered in a bridge subject to multiple types of loading, especially in the case in which the contributions of different loadings to fatigue damage are close.

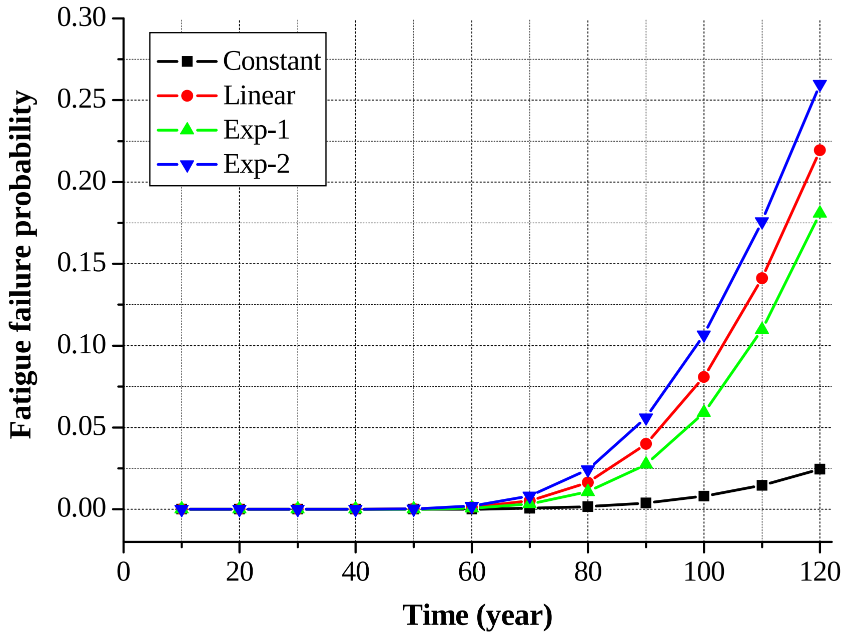


Figure 10: Evolution of fatigue failure probability over time

5. FATIGUE RELIABILITY

Deterministic fatigue analysis is unable to consider the effects of uncertainties arising from load and structural properties. A new framework for fatigue reliability analysis is therefore proposed and applied to the Tsing Ma Bridge (Chen et al. 2012). A limit state function is defined to describe the relationship between the fatigue resistance and the fatigue loading. Based on loading data acquired from SHMS, the probabilistic models of railway, highway, and wind loading are established to describe the uncertainties inherent in different loads. Using the probabilistic loading models, the dominant loading parameters are then generated using Monte Carlo Simulation (MCS), and the daily stochastic stress responses induced by railway, highway, and wind loading are simulated at the fatigue-critical locations using the FE stress analysis. The probability distribution of the daily sum of m-power stress ranges is estimated based on the daily stochastic stress responses. The probability distribution of the sum of m-power stress ranges over the period concerned is then estimated based on assumptions of future loading and traffic growth patterns. The future traffic loadings is assumed to be a 30% increase in both railway and highway loading compared with the current traffic loading. Different traffic growth patterns are assumed to estimate the probability distribution of the sum of m-power stress ranges within the period concerned, including no traffic growth pattern (Constant), and growth in a linear pattern (Linear) and in two exponential patterns (Exp-1 and Exp-2). Finally, the fatigue failure probabilities for different time epochs are solved at the fatigue-critical locations using the First-Order Reliability Method (FORM). The evolution of the fatigue failure reliability over time at the element E32123 is shown in Figure 10. The figure indicates that the fatigue failure probabilities increase with time, and that the failure probability without traffic growth is smaller than that of the three patterns with traffic growth. Among the three growth patterns, the failure probability is the largest for the Exp-2 pattern, followed by the linear pattern, and then the Exp-1 pattern. The results demonstrate that the health condition of the bridge at the end of its design life is satisfactory under current traffic conditions without growth, but attentions should be paid to future traffic growth because it may lead to a greater failure probability.

6. CONCLUSIONS

This paper has demonstrated how to make good use of SHMS for fatigue and reliability assessment of long span suspension bridges under railway, highway, and wind loading by integrating with computer simulations and by taking the Tsing Ma Bridge in Hong Kong as an example. The results indicate that it is necessary to consider the combined effect of loads in the fatigue analysis of multiloading suspension bridges, and the health condition of the Tsing Ma Bridge at the end of its design life is satisfactory under current traffic conditions without growth, but attentions should be paid to future traffic growth.

7. ACKNOWLEDGMENTS

The authors wish to acknowledge the financial supports from the Research Grants Council of the Hong Kong (PolyU 5327/08E and PolyU 5289/12E) and The Hong Kong Polytechnic University through a PhD scholarship to the second author. Sincere thanks should go to the Highways Department of Hong Kong for providing the authors with the field measurement data. Any opinions and concluding remarks presented in this paper are entirely those of the authors.

REFERENCES

ASCE (1982). Committee on fatigue and fracture reliability of the committee on structural safety and reliability of the structural division, fatigue reliability: 1-4. Journal of Structural Engineering, ASCE. 108, pp. 3-88.

Chen ZW, Xu YL, Li Q, and Wu DJ (2011). Dynamic stress analysis of long suspension bridges under wind, railway and highway loadings. Journal of Bridge Engineering, ASCE. 16(3), pp.383-391.

Chen ZW, Xu YL, Xia Y, Li Q, and Wong KY (2011). Fatigue analysis of long suspension bridges under multiple loading: Case study. Engineering Structures. 33(12),pp. 3246-3256.

Chen ZW, Xu YL and Wang XM (2012). SHMS-based fatigue reliability analysis of multi-loading suspension bridges. Journal of Structural Engineering, ASCE. 138(3), pp.299-307.

Liu TT, Xu YL, Zhang WS, Wong KY, Zhou HJ, and Chan KWY (2009). Buffeting-Induced stresses in a long suspension bridge: structural health monitoring orientated stress analysis. Wind and Structures. 12(6), pp.479-504.

Xu YL, Liu TT, Zhang WS, Wong KY, Zhou HJ, and Chan KWY (2009). Buffeting-induced fatigue damage assessment of a long suspension bridge. International Journal of Fatigue. 31(3), pp.575-586.