Analysis of the Performance of Cable-Stayed Bridges under Extreme Events

Thesis by

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRUCT

In bridge structures, loss of critical members (e.g. cables or piers) and associated collapse may occur due to several reasons, such as wind (e.g. Tacoma narrow bridge), earthquakes (e.g. Hanshin highway) traffic loads (e.g. I-35W Mississippi River Bridge) and potentially some blast loadings. One of the most infamous bridge collapses is the Tacoma Narrow Bridge in United States. This suspension bridge collapsed into the Tacoma Narrow due to excessive vibration of the deck induced by the wind. The collapse mechanism of this bridge is called "zipper-type collapse", in which the first stay snapped due excessive wind-induced distortional vibration of the deck and subsequently the entire girder peeled off from the stays and suspension cables. The zipper-type collapse initiated by rupture of cable(s) also may occur in cable-stayed bridges and accordingly guideline, such as PTI, recommends considering the probable cable loss scenarios during design phase. Moreover, the possible extreme scenario which can trigger the progressive collapse of a cable-stayed bridge should be studied. Thus, there are three main objectives for this research, which are the effect of sudden loss of critical cable(s), cable loss due to blast loadings and progressive collapse triggered by the earthquake. A finite element (FE) model for a cable-stayed bridge designed according to Australian standards is developed and analysed statically and dynamically for this research purpose. It is noted that an existing bridge drawing in Australia cannot be used due to a confidential reason. The bridge model has steel deck which is supported by total of 120 stays. Total length of this bridge is 1070m with 600m mid-span.

This thesis contains 8 chapters starting with the introduction as chapter 1.

In chapter 2, comprehensive literature review is presented regarding three main objectives.

In chapter 3 to 5, results of the cable loss analyses are presented. In chapter 3, the dynamic amplification factor (*DAF*) for sudden loss of cable and demand-to-capacity ratio (*DCR*), which indicate the potential progressive collapse, in different structural components including cables, towers and the deck are calculated corresponding with the most critical cable. The 2D linear-elastic FE model with/without geometrical nonlinearity is used for this analysis. It is shown that *DCR* usually remains below one (no material nonlinearity occurs) in the scenarios studied for the bridge under investigation, however, *DAF* can take values larger than 2 which is higher than the values recommended in several standards. Moreover, effects of location, duration and number of cable(s) loss as well as effect of damping level on the progressive collapse resistance of the bridge are studied and importance of each factor on the potential progressive collapse response of the bridges investigated.

As it was shown in chapter 3, a 2D linear-elastic model is used commonly to determine the loss of cable. However, there is a need to study the accuracy and reliability of commonly-used linear elastic models compared with detailed nonlinear finite element (FE) models, since cable loss scenarios are associated with material as well as geometrical nonlinearities which may trigger progressive collapse of the entire bridge. In chapter 4, 2D and 3D finite element models of a cable-stayed bridge with and without considering material and geometrical nonlinearities are developed and analysed. The progressive collapse response of the bridge subjected to two different cable loss scenarios at global and local levels are investigated. It is shown that the linear elastic 2D FE models can adequately predict the dynamic response (i.e. deflections and main stresses within the deck, tower and cables) of the bridge subject to cable loss. Material nonlinearities, which occurred at different locations, were found to be localized and did not trigger progressive collapse of the entire bridge.

In chapter 5, using a detailed 3D model developed in the previous chapter, a parametric study is undertaken and effect of cable loss scenarios (symmetric and un-symmetric) and two different deck configurations, i.e. steel box girder and open orthotropic deck on the progressive collapse response of the bridge at global and local level is investigated. With regard to the results of FE analysis, it is concluded that deck configuration can affect the potential progressive collapse response of cable-stayed bridges and the stress levels in orthotropic open decks are higher than box girders. Material nonlinearities occurred at different locations were found to be localized and therefore cannot trigger progressive collapse of the entire bridge. Furthermore, effect of geometrical nonlinearities within cables (partly reflected in Ernst's modulus) is demonstrated to have some effect on the progressive collapse response of the cable-stayed bridges and accordingly should be considered.

In chapter 6, the blast loads are applied on the bridge model and determined the bridge responses, since the blast load is one of the most concerned situations after 911 terrorist attacks. The effect of blast loadings with different amount of explosive materials and locations along the deck is investigated to determine the local deck damage corresponding to the number of cable loss. Moreover, the results obtained from the cable loss due to blast loadings are compared with simple cable loss scenarios (which are shown in chapter 3 to 5). In addition, the potential of the progressive collapse response of the bridge at global and local level is investigated. With regard to the results of FE analysis, it is concluded that the maximum 3 cables would be lost by the large amount of TNT equivalent material due to damage of the anchorage zone. Simple cable loss analysis can capture the results of loss of cable due to blast loadings including with local damages adequately. Short cables near the tower are affected by blast loadings, while they are not sensitive for the loss of cables. Furthermore, loss of three cables with damaged area did not lead progressive collapses.

Finally, in chapter 7, dynamic behaviour of cable-stayed bridges subjected to seismic loadings is researched using 3D finite element models, because large earthquakes can lead to significant damages or even fully collapse of the bridge structures. Effects of the type (far- or near-field) and directions of seismic loadings are studied in several scenarios on the potential progressive collapse response of the bridge at global and local level. According to the case studies in this chapter, it is shown that near filed earthquakes applied along the bridge affected to deck and cables significantly. Moreover, the mechanism of bridge collapsed due to longitudinal excitation is analysed by an explicit analysis, which showed the high plastic strain occurring around the pin support created the permanent damage.

The summary and suggestions for this research are shown in final chapter 8.

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List of Symbols

A	Cross-sectional area
b	Width of the deck
$CLDF$	Cable loss dynamic forces
DC	Dead load of structural components and non-structural attachments
DW	Dead load of wearing surfaces and utilities
E	Modulus of elasticity
$\overline{E}$	Equivalent modulus of elasticity
E_{sh}	Hardening modulus of steel
EV	Extreme event load
I	Moment of inertia of the section
IM	Vehicular dynamic load allowance taken
l	Horizontal span
LL	Full vehicular live load placed in actual stripped lanes
M	Bending moment
M_y	Yield moment
N	Axial force
N_y	Yield Force
R	Distance between contact surface and the denote centre
t	Thickness of the steel plate
W	Equivalent TNT amount
y	Distance from the neutral axis moment of inertia of the section
Z	Scaled distance (in $m/kg^{1/3}$),
$\varepsilon_{i\text{-}PT}$	Initial post-tensioning strain in cables
γ	Density
σ	Existing stress from dynamic analysis
σ_u	Ultimate stress
σ_y	Yield stress
λ_{ey}	Yield limit slenderness ratio