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Dynamic response and performance of cable-stayed bridges under blast load: Effects of pylon geometry

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ABSTRACT

The air blast that is generated by the explosion of bombs or fuel tankers on or adjacent to a bridge can cause severe structural damage, and may result in partial or full collapse of the bridge. The dynamic response and structural performance of buildings under blast has been the subject of several studies, with considerably less attention being paid to the assessment of bridges under extreme blast loading scenarios. To reduce the computational expense of conducting blast analyses on large or complex bridges, the numerical sub-structuring technique is used in current practice. However, the simplifying assumptions adopted in these sub-structuring methods can lead to erroneous results. Accordingly, this study attempts to simulate numerically the dynamic response of an entire cable-stayed bridge subjected to blast loading using the LS-DYNA explicit finite element code. Based on best practice available in the literature, the blast load estimation, material modelling and detailed numerical simulation are carried out and the response of a cable-stayed steel bridge (designed according to minimum requirements of the Australian Bridge Standard) under blast loads ranging from a small to large detonation at different positions above the deck and near pylon are obtained. Furthermore, the potential effects of blast loads on different structural components with a focus on the cross-sectional geometry of the pylons are investigated.

1. Introduction

Recent collapses of bridges under accidental or intentional extreme loads have raised an awareness amongst engineers regarding the safety of critical infrastructure. Extreme blast loads, such that resulting from a fuel tanker impact or terrorist attacks have a high magnitude and short duration, and can result in significant structural damage in bridges that have a crucial role within a transportation network. Accordingly, these blast loads can result in partial collapse of the bridge and significant loss of life and property, as well as causing social and economic devastation. The fiery crash of a gasoline tanker in 2007 resulted in the partial collapse of the Interstate 80/880 interchange bridges in Oakland, California and caused significant damage and disruption to traffic. A similar catastrophe occurred in Saudi Arabia in 2012 when a gas tanker hit a bridge, causing a gas leak followed by an explosion. An industrial building close to the bridge was almost entirely destroyed with significant loss of life and limb. More recently, the explosion of a fireworks-carrying truck brought down two spans of an expressway bridge in China. Since the events of September 11, 2001, there has been serious concern that major bridges may be targeted by terrorists.

Over the past couple of decades, significant efforts have been devoted to capturing the response and to assess the performance of important or critical buildings under blast load, and in developing guidelines to increase the resistance of buildings against such possible blast loads [1–4]. However, far less attention has been paid to the response and safety evaluation of bridges subjected to blast loading. In addition, the design provisions for blast-resistant bridges are limited due to inadequate knowledge of the local and global dynamic response of the bridge components when subjected to blast loading scenarios. Moreover, existing design guides for blast-resistant bridges are only limited to particular structural components [5].

Bridge structures are typically more vulnerable to extreme loading scenarios than are buildings, because bridges have less structural redundancy when compared to buildings. Hence, in the case of failure of any primary structural member in bridges, redistribution of the applied load through an alternative load path that prevents potential progressive collapse is almost impossible. For example, failure of a pylon in a cable-stayed bridge can potentially lead to the collapse of the entire bridge. Moreover, whilst providing limited vehicle access to buildings can dramatically reduce the threats of possible collapse due to blast and terrorist

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attacks, limiting general vehicle access is not feasible in bridges because the main function of a bridge is to provide a safe path for vehicles.

To design blast-resistant bridges, an understanding of the blast wave propagation and its effects on the bridge structures are required. Numerical methods can be used to simulate the explosion and so capture the interaction between the blast wave and structure, as well as the dynamic response of the structure itself. Recent advancements in numerical methods have made it possible to simulate complicated blast-structure interactions in a rather realistic, efficient and cost-effective way. As a result, computer simulations have been used by different researchers to capture the failure mode and dynamic response of cable-stayed bridges subjected to hypothetical blast scenarios and to also provide useful reference data for the safeguard-design of critical infrastructure.

To reduce the computational effort, studies of bridges subjected to blast impact typically take advantage of the sub-structuring technique, in which only part of the structure is modelled [6–10]. However, such oversimplifications can lead to erroneous results. Winget [6] employed the US army- developed software SPAn32 to perform an equivalent SDOF dynamic analysis of prestressed concrete girders, and developed an understanding of the required security measures for such a bridge structure. The blast load pressure was applied on the elements as an equivalent uniformly distributed load. The results of the analyses conducted by Winget [6] revealed that the bridge geometry can significantly affect the blast loads applied below the deck, and also that below the deck blasts may result in more damage than an explosion that takes place on top of the deck. The response of a fixed-base cable-stayed bridge under blast load was studied numerically by Tang and Hao [7,8] and, after predicting the extent and nature of the damage, possible retrofitting strategies were discussed. The FE models contained most of the important bridge components such as the piers, towers, back spans and the steel-concrete composite main span, which were investigated individually. The damage captured by Tang and Hao's FE models were localised, and they were associated with compressive crushing and spalling of the concrete. Despite the localised nature of the damage observed in different components, it was identified that this damage could have potentially triggered the progressive collapse of the entire bridge. However, the subsequent progressive collapse analysis (uncoupled with the blast load) of the bridge showed that failure of the main span and propagation of the damage from the back span through the entire deck was unlikely to occur. Moreover, the application of CFRP strengthening of the deck was found to be ineffective, even though strengthening does reduce the adverse response of the bridge to the blast.

The structural performance of a hollow steel box pylon and a concrete-filled composite pylon in a cable-stayed bridge subjected to blast loads has been studied using an Arbitrary Lagrangian Eulerian (ALE) finite element (FE) model developed in a MD Nastran FE package [9]. In this recent study, only part of the deck was modelled and instead of cables themselves, only the cable forces were applied to the model and were assumed to remain constant throughout the analysis. Furthermore, the initial condition for the explicit method was derived from an implicit solution scheme to reduce the simulation time. The results of the FE simulations showed that the blast resistance of the concrete-filled steel box pylon was much better than the single hollow steel box pylon. In the hollow steel box pylon, P-Δ effects can cause significant instability after the blast that can trigger the potential failure of the pylon. To capture the destabilizing effects of blast loads on the bridge, it was also recommended that the simulation time needs to be extended [9].

The interactions between the different structural components can significantly affect the structural response and performance of a bridge in the event of an explosion. Accordingly, investigating the vulnerability of individual structural elements irrespective of their interactions with other structural components cannot adequately capture the progressive collapse response and the vulnerability of the entire bridge, but it can be the first step towards understanding the extent of the damage in the particular structural components and the possible initiation of progressive collapse. In addition, designers need to consider the post-blast behaviour of the damaged structural components under gravity loads, particularly the possible instabilities and second order effects in the pylons that could trigger collapse of the entire structure.

The current study intends to simulate the dynamic response of an entire cable-stayed bridge subjected to blast loading using the LS-DYNA [11] explicit FE package. The capabilities of LS-DYNA for capturing blast loads and the response of structural components (including steel plates) subjected to air blast pressure have been widely studied in the literature [12–14]. Accordingly, based on best practice data obtained from a thorough review of the literature, blast load estimation, material modelling and detailed numerical simulation are conducted. The cable-stayed bridge under investigation complies with the minimum requirements of the Australian bridge Standard, AS5100 [15], and it is analysed under dead, traffic and blast loads with explosive sizes ranging from 1W to 10W (W being the TNT equivalent explosive weight index). The results of the FE models are used to assess the performance of different structural components (*i.e.* the deck and pylons). Furthermore, the values of the so-called demand-to-capacity ratio (*DCR*) at different cross-sections along the pylons are computed to establish a criterion for yielding or nonlinearity of material at the *section-level,* consistent with conventional design provisions. In addition to the *DCR* values, a maximum strain criterion is used at the *material level* to determine the extent of localised damage (material nonlinearity). The DCR and maximum strain criterion are employed to evaluate and compare the blast performance of the steel pylons with different cross-sections, *e.g.* rectangular, octagonal and the like. In the current study, *DCR* is defined as being

$$DCR = |\sigma_{max,eff}/\sigma_{yd}| \qquad (1)$$

where $\sigma_{max,eff}$ is the maximum effective stress (3D von-Mises stress) obtained from the LS-DYNA model in the cross-section under consideration and σ_{yd} is the yield strength of the steel including the strain rate effect. A *DCR* value greater than unity is indicative of the steel yielding or material nonlinearity at cross-section level. In the blast load cases, the effect of the strain rate on the yield strength of steel, σ_y, was taken into account by empirical models available in the literature.

2. Description of models and analysis techniques

2.1. Bridge details

For security reasons and to avoid publishing the vulnerabilities of a specific bridge, the hypothetical cable-stayed steel bridge shown in Fig. 1 was designed according to the minimum requirements of AS5100 [15]. The cable-stayed bridge adopted consists of three spans. The back spans are 227.5 m and the middle span is 580 m long.

The steel orthotropic box deck is 2.0 m deep and 28 m wide that provides 6 standard traffic lanes and 2 walkways and it was designed as a closed hexagon multi-cell box girder. A 25 mm thick steel plate was used for the top and bottom flanges of the deck. The longitudinal stiffeners on both flanges are 400 mm high and spaced 700 mm apart. Intermediate stiffeners are used for the 20 mm web plates which have a spacing of 4 m. To prevent premature excessive distortional deformation under torsional loads, the deck is