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An efficient FE model of slender members for crash analysis of cable barriers

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ABSTRACT

Slender members such as cables and hook–bolts are largely seen in highway cable barriers. These members raise a significant challenge to crash simulations that involve a large number of contact analyses. In this paper, a beam-element model was presented and evaluated for slender members used in the crash analysis of traffic barriers. A numerical study was performed to investigate different modeling options, including various types of elements and contacts, and to compare the beam-element model with conventionally used shell- and solid-element models on stability, accuracy and efficiency. Advantages and disadvantages of the models were discussed. To verify the quality of the beam-element model, numerical simulations of hook–bolt pullout tests were performed under quasi-static and dynamic loading conditions. The accuracy of simulation results was evaluated by comparisons to experimental data available in the literature. Full-scale crash simulations of a cable barrier under vehicular impacts were also included to demonstrate the applicability and efficiency of the beam-element model.

1. Introduction

In the past two decades, the dramatic increase of traffic volume on US highways continues to raise public concerns about transportation safety. Despite the increase of traffic volume, the crash fatality rate has mostly remained constant and shows a decreasing trend since 2005. According to the National Highway Traffic Safety Administration (NHTSA), the number of crash deaths ranged from 40,716 to 43,510 between 1994 and 2005 and decreased to 33,808 in 2009. This relatively stable fatality rate is largely attributed to the use of roadside barrier systems. Among the commonly used barrier systems, cable barriers are flexible systems that cause less impact forces than (rigid) concrete barriers and are easier to maintain than the (semi-rigid) W-beam guardrails. For these reasons, cable barriers have been increasingly used during the past decade and were shown to be effective as median barriers to prevent cross-median head-on collisions. However, most of the safety studies on cable median barriers are empirical; further research is needed on the design, installation, and retrofit options of these barriers. This research involves a large number of evaluations of cable barriers under vehicular impacts; a viable means for performing these evaluations is required.

Full-scale physical tests of vehicular crashes provide valuable information on the vehicles' crash behavior and provide a basis for numerical simulation and design evaluation. However, they are in general very expensive and time consuming. Due to the destructive nature of crash testing and limitations of data-acquisition techniques, many parameters related to crashworthiness cannot be directly measured in an experiment. To this end, physical crash testing is only affordable in small numbers and is primarily used for validation purposes. Since the late 1990s, the rapid evolution of computer hardware and super computers has promoted the usage of explicit finite element (FE) codes in crash analysis as well as the development of vehicle models, from the early highly simplified 259-node model [1] to more detailed and refined models [2–6]. Although there are initial costs to develop and validate an FE model, the subsequent simulation work provides a fast, cost effective, and powerful means for crashworthiness analysis and designs.

In recent years, more and more researchers have adopted crash simulations to aid the design and safety evaluations of modern vehicles. There is a plethora of literature on crashworthiness designs of vehicle components or partial structures [7–12]. Additionally, Williams et al. [13] investigated the overall vehicle responses

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and component interactions using nonlinear FE simulations. They used component-level experimental data to guide vehicle modeling work. Full-scale FE simulations were also used in different crash scenarios such as side and rear impacts and rollovers, as seen in the work of Fang et al. [14], Mao et al. [15], and Gursel and Nane [16]. Using results of full-scale simulations of an offset-frontal and side impacts, Fang et al. [14] performed optimization of 21 components in the vehicle to maximize energy absorption while minimizing weight. In the work of Mao et al. [15], full-scale FE models were used to simulate dynamic roof crush tests. The study revealed useful results that were otherwise difficult to obtain (e.g., 30% of the roof strength came from the bonded windshield and the roof strength was a function of the roll and pitch angles). Gursel and Nane [16] simulated the frontal, offset-frontal and side impacts of a Ford Taurus and a Dodge Intrepid and showed good agreement between the experimentally recorded accelerations and FE simulation results.

In addition to their applications to crashworthiness design of modern vehicles [17–21], crash tests and simulations are also used for highway infrastructure safety evaluation and validations [22–30]. For example, in the work of Borovinsek et al. [28], the results of FE crash simulations were used in the evaluation of different safety barrier reinforcements to determine the best barrier design. This work was also validated using data available from physical crash tests. Ulker and Rahman [30] utilized FE simulations to develop design guidelines for a portable concrete barrier system. In their sensitivity analysis of pavement types, impact speeds and angles, and barrier lengths, they showed that the barrier had less transverse displacement on concrete pavement and that the total barrier length needed to be at least 61 m to stabilize the transverse displacement.

In FE crash simulations, particularly those using full-scale models, appropriate modeling of structural components is critical to the accuracy and numerical stability of the simulations that involve large, nonlinear deformations and a large number of contacts. Slender members such as cables and hook–bolts are largely used in highway cable median barriers, as illustrated in Fig. 1. These members raise a significant challenge when used in crash

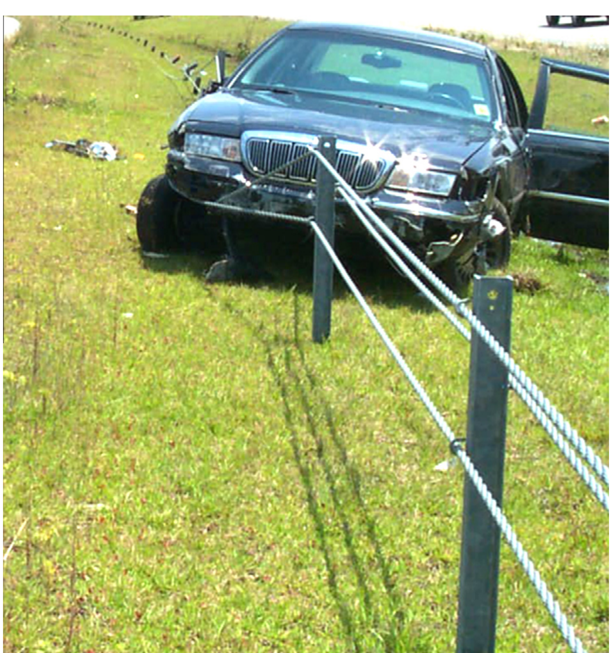

Fig. 1. Cables and hook–bolts in a cable barrier system.

simulations that require the exterior surfaces of these members to be explicitly represented in the models for contact analysis. For instance, the small cross-sectional geometry of the cable requires relatively small mesh sizes, which results in a large simulation model due to the large longitudinal dimension of the cable, typically around 122 m (400 ft). Furthermore, this small mesh size may not match those of other components on the barrier and the impacting vehicle, causing undetected penetrations in a contact analysis. When nodes-to-surface or surface-to-surface contacts are used, if the mesh of the master segment is finer than the slave segment, undetected penetration may occur.

There are currently two types of cable or hook–bolt models available in the literature for crash analysis: one uses solid elements and the other uses a combination of beam and shell elements. In the second model, the beam elements are used to give the stiffness of the slender member and the shell elements are used to approximate the exterior surface for contact purposes. These shell elements have null materials (therefore called null shells) and are connected to the beams via nodal rigid links. Reid and Coon [31] evaluated the solid FE models of a hook–bolt using dynamic and quasi-static pullout tests. In their study, simulations using various element sizes were carried out and it was observed that at least 32 elements on the cross-section were required to have satisfactory accuracy compared to experimental data. However, the simulation cost of the solid-element model was generally high. Most importantly, when used on cables in a full-scale model, the solid-element model was found to cause severe, unrealistic twisting of the cables. The null-shell based cable and hook–bolt models were first developed by Mohan et al. [32] at the National Crash Analysis Center (NCAC). In this model, the circular cross-section of a cable or hook–bolt was approximated by a hexagon, formed by six shell elements. The NCAC cable and hook–bolt models were found to be computational more efficient and stable than the solid-element model and could be used in full-scale crash simulations. However, undetected penetrations were frequently seen in full-scale simulations due to edge contacts and mismatch of element sizes with other components.

This literature overview illustrates that, although slender members such as cables and hook–bolts have been studied before, most efforts have been focused on solid-element and shell-element based models. There is a need to develop and study more stable and efficient FE models for practical full-scale crash simulations. Limited work has been done to compare and evaluate the relative merits of different models for accuracy, stability, and computational efficiency. The present work was intended to fill this gap, and focused on investigating an efficient FE model for slender members used in crash simulations. In the remaining sections of this paper, the beam-element model of slender members for contact analyses is first introduced along with a brief overview of contact analysis methods. The solid-element model and the shell-element model are also introduced. The hook–bolt pullout tests from the literature are then presented for evaluating the simulation results. The three FE models are then compared and analyzed to determine their advantages and disadvantages. Finally, the results of practical full-scale crash simulations are presented to compare the shell-element and beam-element models; this is followed by some concluding remarks.

The present work differs from the literature in the following important ways: (1) a stable, accurate and efficient beam-element model for cables, hook–bolts, and other slender members used in crash simulations was investigated; (2) the beam-element model, the solid-element model, and the shell-element model were compared and evaluated and advantages and disadvantages of these models were delineated; and (3) application of the beam-element model for practical full-scale crash simulations of cable barriers was studied.