Advances in Engineering Software 82 (2015) 1–13

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

Crash analysis and evaluation of cable median barriers on sloped medians using an efficient finite element model

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ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 13 November 2014
Accepted 21 December 2014
Available online 9 January 2015

Keywords:
Crash analysis and design
Finite element analysis
Cable barrier
Vehicular crash
Transportation safety
Sloped median

ABSTRACT

Perpetual high traffic volumes on U.S. highways have raised more public concern than ever about transportation safety. Over the years, various traffic barrier systems, including cable median barriers (CMBs), have been developed to reduce the number and severity of vehicle crashes. Despite their general effectiveness, there remains room for improvement, especially when CMBs are installed on unlevelled terrains such as sloped medians. The destructive nature of crashes imposes significant challenges to barrier design using full-scale physical testing; numerical simulations thus become a viable means to support crash analysis, performance evaluation, and barrier designs. In this study, validated vehicle and CMB models were used to perform full-scale simulations of vehicle-CMB impacts. Several CMB designs, including the currently used one, were evaluated under vehicular impacts at different velocities and angles. To address the challenge of modeling slender members such as cables and hook-bolts in contact analyses, an efficient beam-element contact model was employed in the analysis. Different design options of cable height and spacing under various impact velocities and angles were investigated in this study.

1. Introduction

Transportation safety has received wide attention in recent years due to the perpetual high traffic volumes on U.S. highways. One of the major concerns about highway safety is the prevention of cross-median crashes, which are caused by run-out-of-way vehicles crossing the median and colliding with oncoming vehicles. Due to the high relative velocity of the two colliding vehicles, cross-median crashes have very high fatality rates and result in severe damage. Median barriers are designed to prevent such events by safely redirecting the run-out-of-way vehicles. Different types of barriers have been developed over the years including rigid, semi-rigid, and flexible systems. All barriers used on U.S. highways are designed following the guidelines of the American Association of State Highway and Transportation Officials (AASHTO) [1,2] and must be tested to satisfy the safety requirements specified by the Manual for Assessing Safety Hardware (MASH) [3], which is a replacement of National Cooperative Highway Research Program (NCHRP) Report 350 [4]. The evaluation of safety devices was facilitated through three main criteria: structural adequacy, occupant risk and post-impact trajectory. With respect to cross-median crashes, MASH specifies the standard testing conditions for median barriers. All barrier systems on U.S. highways must be tested to satisfy the requirements specified by MASH. However, it should be noted that the standard safety tests specified in MASH are all conducted on flat terrain, while most in-service barriers are installed on sloped medians. To this end, evaluation of in-service performance of median barriers has been one of the important and challenging efforts in transportation safety research [5–16].

Cable barriers are cost-effective, flexible systems that are ideal for retrofit designs to prevent cross-median crashes in existing, relatively wide medians. Although they are tested on flat terrain and pass the MASH requirements, cable barriers are shown to be generally effective on medians with 6H:1V slopes. Cable median barriers (CMBs) are more forgiving than concrete barriers and W-beam guardrails when struck by an errant vehicle, because the cables deflect laterally and reduce the impact forces transmitted to the vehicle and occupants. The high flexibility of cable barriers, however, requires that the medians have sufficient widths to allow for lateral cable deflections. For the single-run, low-tension CMB shown in Fig. 1, the median is required to have a minimum width of 24 ft. (7 m), with 12 ft. (3.5 m) on each side of the CMB [1,2]. Although all of the CMBs satisfied the safety requirements of AASHTO MASH, penetrations of CMBs were still found in certain

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http://dx.doi.org/10.1016/j.advengsoft.2014.12.009
0965-9978/

situations. For example, the crash data analysis performed by research engineers in the North Carolina Department of Transportation (NCDOT) showed that there was approximately a 3.6 percent penetration occurrence for CMBs, with the majority of penetrations being vehicle under-riding [17]. Although these CMBs had a very good safety performance (less than five percent penetrations), it is desired that CMB performance be improved.

Full-scale crash tests have been adopted by researchers and engineers to evaluate the safety performance of vehicles and roadside hardware systems for a long time, for their good representation of real crash scenarios. Fig. 2 shows an example of a crash test in which a sedan was on its way to under-riding and penetrating a CMB [11]. Despite its usefulness in understanding the crash mechanism and evaluating safety performance, full-scale crash testing is typically time consuming and uneconomical, especially in evaluating large test matrices of designs. With the rapid development of computer technology and parallel computing algorithms, it is now possible to perform full-scale finite element (FE) simulations of vehicular crashes using commercial software packages such as LS-DYNA [18,19]. Computer simulations have become a viable alternative for crashworthiness analysis of vehicular components [20–25] and the entire vehicular structure under different crash scenarios such as front, side, and rear impacts [26–34]. In addition to their applications to crashworthiness design of modern vehicles, crash simulations are also used for safety evaluation and validations of highway infrastructure [35–46] as well as for the failure analysis of security barriers [47]. The use of simulations has progressed from modeling crash tests to supporting hardware design decisions and to providing guidance for roadside hardware placement. Effective use of simulations permits design optimization, as exemplified in the work of Hou et al. [48], and minimizes the number of crash tests required to achieve acceptable safety performance, thus reducing the costs of development, installation, and retrofit of roadside safety devices. Additionally, simulations provide a tool for assessing the performance limits of roadside hardware devices under conditions that full-scale crash testing cannot readily accommodate.

By integrating the vehicle and barrier models, researchers have successfully evaluated the performance of existing barrier systems [12] and developed a new cable barrier that was finally crash tested [13]. Since most actual medians have slopes and horizontal curves, the in-service conditions of a barrier system are different from the testing conditions specified in MASH and may cause the in-service performance of a barrier to be unsatisfactory under certain impact conditions. Therefore, cross-median simulations with in-service conditions need to be studied and verified with testing to ensure that correct dynamic crash responses can be obtained in numerical simulations. Although the current MASH standards only require assessing barriers on flat terrain, extensive research has been carried out for barriers on sloped terrains [49–52]. Recent and ongoing research seeks to develop a test matrix to specifically assess the safety performance of barriers placed close to or within slopes, including the NCHRP 22-22 project. Currently, little work exists in the literature that deals with crash simulations on sloped medians; most of the safety studies on CMBs are empirical.

Fig. 1. Three-strand CMB. (http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/resource_charts/cable.pdf).

In this study, nonlinear FE simulations were employed to investigate several CMB designs under vehicular impacts to assist with design improvement and retrofit options of in-service CMBs. Since under-riding CMB penetrations were the focus of this study, the FE model of a small vehicle (i.e., a 1996 Dodge Neon) was used to evaluate the performance of different CMB designs under vehicular impacts from both sides of the CMB. All available numerical data obtained from FE analyses were summarized in order to evaluate the performance of various CMB designs. The major research objectives were to: (1) develop the relationship between cable height and cable-vehicle engagement, so as to determine the recommended height of the cables in the three-cable system; and (2) investigate the cable and vehicle interaction behavior corresponding to different impact scenarios, such as a range of impact velocities and angles. In addition, CMBs with four cables were also studied in comparison to the traditionally used three-cable CMBs. Based on the literature review and crash data analysis, eight different CMB design cases were first generated for impacts at different vehicle velocities and impact angles. The simulation results were then analyzed and showed that cable-vehicle engagement was related to the cable heights, impact velocities, and impact angles. The use of FE simulations in the exploration of new designs was shown to be both effective and efficient. Based on FE simulation results, full-scale crash tests can be conducted to further validate

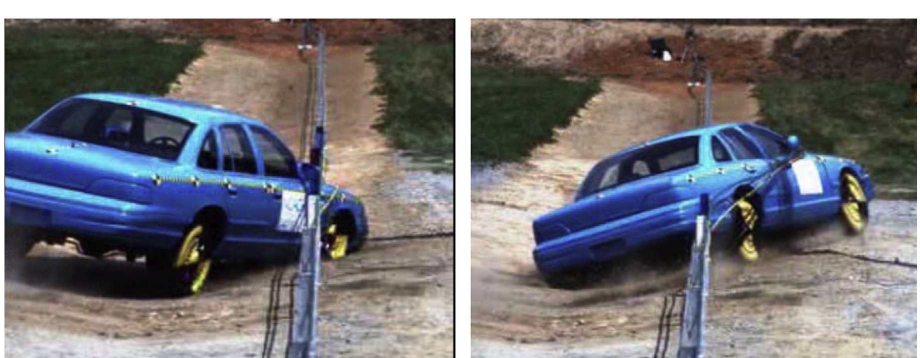

Fig. 2. A sedan on its way to under-riding a cable barrier in a crash test [11].