International Journal of Crashworthiness

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t778188386

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Online publication date: 29 April 2011

To cite this Article Seo, Junwon , Linzell, Daniel G. and Rado, Zoltan(2011) 'Computational and experimental modification of portable sign structure design following NCHRP 350 criteria', International Journal of Crashworthiness, 16: 2, 111 — 116

To link to this Article: DOI: 10.1080/13588265.2010.514771

URL: http://dx.doi.org/10.1080/13588265.2010.514771

International Journal of Crashworthiness
Vol. 16, No. 2, April 2011, 111–116

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Computational and experimental modification of portable sign structure design following NCHRP 350 criteria

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(*Received 27 February 2010; final version received 9 August 2010*)

As a follow-up to a study published in 2008 [J.-W. Seo, D.G. Linzell, and Z. Rado, *Crash performance of x-shaped support base work zone temporary sign structures*, Int. J. Crashworthiness 13 (2008), pp. 437–450], research discussed herein examines effective methods for selecting and modifying portable sign structure designs so that they are deemed acceptable according to National Cooperative Highway Research Program (NCHRP) Report 350 [H.E. Ross, Jr., D.L. Sicking, J.D. Zimmer, and R.A. Michle, *Recommended procedures for the safety performance evaluation of highway features*, National Cooperative Highway Research Program Rep. 350, Publication Project 22–7 FY'89, Texas Transportation Institute, Austin, TX, 1993] criteria. Portable sign structures, often used as signage for work zones, are frequently susceptible to vehicular impact. If an impact occurs, a possible safety threat to occupants in the vehicle exists due to sign panel penetration. In this study, the methodology used to select a portable sign structure design from two alternatives, one of which was summarised in the 2008 publication [J.-W. Seo, D.G. Linzell, and Z. Rado, *Crash performance of x-shaped support base work zone temporary sign structures*, Int. J. Crashworthiness 13 (2008), pp. 437–450], is presented along with the procedure used to optimise the selected design so that it performed acceptably according to the NCHRP 350 standards. The selected design, one having an H-base, was modified to meet the NCHRP 350 criteria by strategically replacing traditional metallic fasteners with nylon fasteners. Procedures used to simulate the impact tests, select the appropriate base design and modify that design to meet the NCHRP criteria are presented.

Keywords: portable sign structure; penetration; impact; numerical simulations; full-scale impact testing

Introduction

A portable sign structure can be defined as any sign not permanently attached to the ground or other permanent structure and is a primary form of traffic control used in roadway work zones in the United States. The portable sign structures often are implemented to make oncoming traffic stop or decelerate when approaching the work zone. When a vehicle approaching the work zone loses control and impacts a portable structure, the sign panel and support structure may become a safety threat, especially to vehicle occupants if the panel penetrates their compartment. This safety problem is not new, and many research efforts have been undertaken that attempt to address panel penetration. Numerous full-scale impact studies on portable sign structures have been performed, including those by Olson [12], Breaux et al. [2], Ross et al. [13], Brewer et al. [3], and Mak et al. [6]. They generally summarised full-scale automobile crash tests that evaluated the crashworthiness for a specific portable sign support system. Other portable work zone sign support systems have been impact tested by Kapoor et al. [4], Sturt and Fell [16], Anghileri et al. [1] and Naing et al. [9].

The most extensive publication for evaluating and assessing transportation structure performance under a vehicular impact is National Cooperative Highway Research Program (NCHRP) Report 350 [14]. The primary purpose of this report is to form the basis for establishing crashworthiness levels for all transportation structures and evaluating occupant risk in the event of a vehicular impact.

As presented in a companion publication [15], Seo et al. summarised crash tests completed on two X-base sign structures. Numerical simulations using LS-DYNA [5] were developed to mimic the impact behaviour of actual crash tests and the accuracy of those models was validated. However, as discussed in that publication, the X-base structures that were studied did not perform adequately according to the NCHRP Report 350 because of sign panel penetration into the occupant compartment.

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ISSN: 1358-8265 print / ISSN: 1754-2111 online

DOI: 10.1080/13588265.2010.514771
http://www.informaworld.com

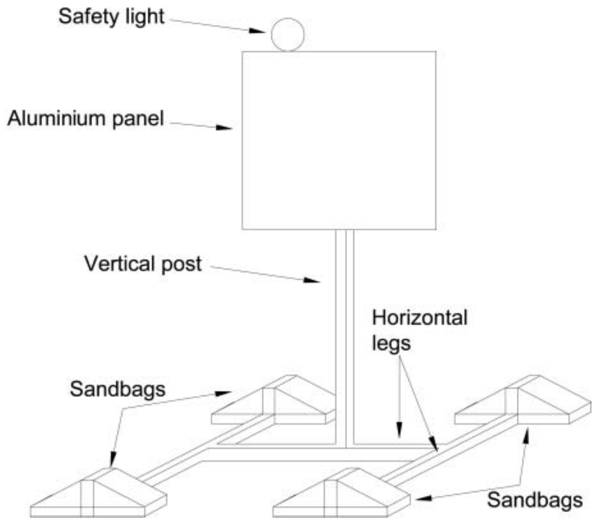

Figure 1. H-base portable sign structure configuration.

Summarised within the current manuscript are tests and analyses performed on another support design, termed an H-base structure, and subsequent assessment of its adequacy following the NCHRP 350 criteria. In addition to these studies, subsequent optimisation of the selected portable sign design, which was the H-base structure, to ultimately meet the NCHRP criteria with respect to occupant compartment penetration, is also presented. These modifications involved replacing traditional metallic fasteners between the sign and supports with nylon fasteners.

H- and X-base structure description

A typical H-base portable sign consists of an aluminum sign panel supported by a steel vertical upright post and resting on legs as shown in Figure 1. Typically, these structures have sandbags placed onto their legs to provide stability and a safety light mounted at the top of sign panel. A representative sketch of a typical H-base structure, including schematics representing the sandbags and safety light, is shown in Figure 1.

Differences between the H- and X-base structures relate to the size and orientation of the support legs. H-base structures have three leg components, two 914.4-mm (36-in.) long parallel legs connected by a 609.6-mm (24-in.) cross piece, as shown in Figure 2. X-base structures [15] are composed of 1111.3-mm (43.8-in.) long legs that cross at a 90° angle.

Numerical impact testing behaviour

Similar to modelling that was completed for the X-base signs [15], numerical models of H-base collision tests were developed using LS-DYNA to assist with design selection and optimisation. Each sign structure was subjected to virtual impact tests using a standard NCHRP 350 820C vehicle (Geo Metro) with the sign-oriented facing and at 90° with respect to the vehicle's direction of travel and with the top of the sign 2438 mm (96 in.) above the ground. Model construction and discretisation for the finite element analyses (FEA) that were performed followed what was used for the X-base signs [15]. LS-DYNA models, which were validated using actual testing results [15], were used to evaluate the behaviour of H-base signs and improve their design before additional, and more expensive, tests on such sign structures were carried out.

Results for numerical vehicular impact tests of H-base sign structure, which originally used metallic fasteners, are shown in Figure 3 for the panel rotated at 90°. The figure details sequential snapshots of the impact behaviour from LS-DYNA. Similar to behaviour presented for the X-base sign [15], the lower bolted connection for the H-base sign failed at impact (0.03 sec), while the upper bolt did not fail until 0.13 sec later, an unbalanced connection failure sequence that rotated the sign panel clockwise and caused

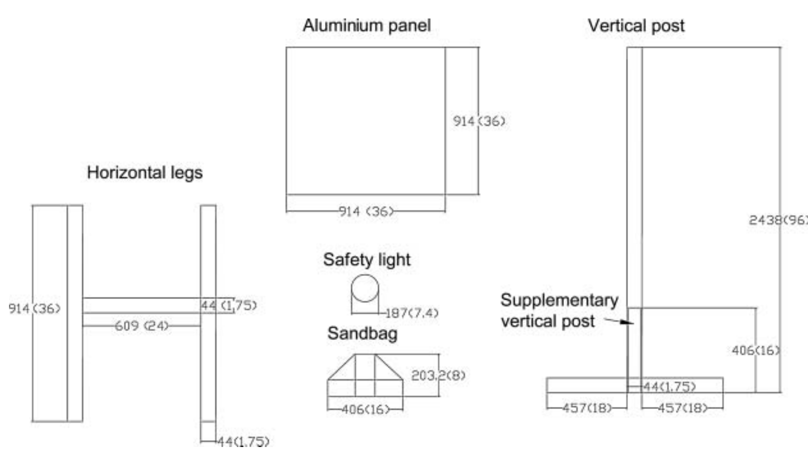

Figure 2. Sign component details (in mm (in.)).

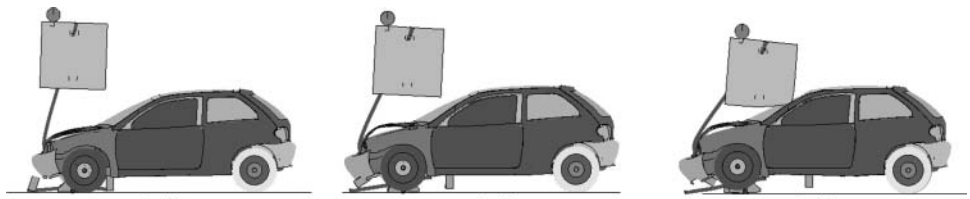

Figure 3. LS-DYNA snapshots for H-base sign structures with aluminium fasteners.

it to impact the windshield and vehicle roof, resulting in occupant compartment penetration. As a result of this penetration, the numerical results appeared to indicate that, similar to X-base [15], the H-base design using metal fasteners did not meet NCHRP 350 criteria.

Based upon numerical simulations, a design modification was explored that would theoretically allow for acceptable impact testing performance according to NCHRP 350 criteria. The modification focused on avoiding penetration into the occupant compartment of the 820C vehicle and focused on the fasteners between the sign and H-base to accomplish this. The basic premise was that the sign panel would have sufficient inertial properties upon a high-speed impact to shear off its fasteners to the support post. As a result, the 820C vehicle would pass under the separated sign panel with the occupants unharmed and the remainder of the structure would travel with the vehicle and would not enter the occupant compartment.

In order to achieve these desired effects, a number of fasteners were examined. Nylon fasteners were identified and selected because of the material's low shear capacity, good corrosive resistance, improved tensile strength, superior performance in adverse temperatures and wider acceptable temperature utilisation range when compared to other fastener types. Relevant properties for the nylon fasteners that were selected are shown in Table 1.

In an attempt to avoid panel penetration into the test vehicle compartment, the metallic fasteners in the LS-DYNA model were replaced with the aforementioned nylon fasteners and the H-base impact test simulations were re-analysed. The nylon fasteners that connected the sign and support structure components were modelled using what are termed as Constrained Spot Welds in LS-DYNA. Constrained spot welds couple nodes together using additional nodal forces imposed at the coupled nodes to represent the capacity of the nylon fasteners with fastener failure criteria being based on a least squares algorithm [5,15]. Specified maximum normal and shear forces at the coupled nodes simulated the fastener capacity and these limits were found from literature published by the fastener manufacturer [7]. LS-DYNA snapshots of these analyses are shown in Figure 4. The figure indicates that the nylon fasteners simultaneously failed and no sign penetration into the vehicle compartment occurred, a satisfactory performance according to NCHRP 350.

Full-scale impact testing

Full-scale impact tests were performed to evaluate the performance of the numerically redesigned H-base sign structures. In addition, the accuracy of the modelling approach that was used for the sign structures and, more specifically, the nylon fasteners was examined. NCHRP 350 Level 3 approval, which was necessary for these structures [14], required successful testing at 100 km/hr (62.1 mph) as a minimum for Category 2 work zone traffic control devices [10,11]. As had occurred for the X-base structures, the 820C vehicle impacted the H-base signs with the sign panel parallel and at 90° to the direction of the vehicle. The collision test was set up to impact the two sign orientations with one vehicle run. One structure was placed at the left quarter point of the approaching vehicle at a 90° angle relative to the vehicle direction while the second was placed one vehicle length behind the first at 0° with impact occurring at the right quarter point of the front of the vehicle (Figure 5). The impact testing facility and procedure were similar to that discussed in the previous publication [15].

Table 1. LS-DYNA nylon fastener material properties [7].

Material properties for nylon fastener				
Tensile strength, MPa (psi)	Elongation at yield (%)	Elongation at fail (%)	Temperature range, °C (°F)	Rockwell hardness
62 (9000)	20	200	−40 (−40) to 85 (185)	R105

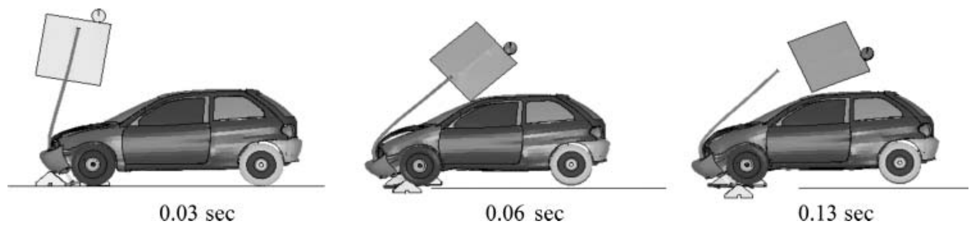

Figure 4. LS-DYNA snapshots for H-base sign structures with nylon fasteners.

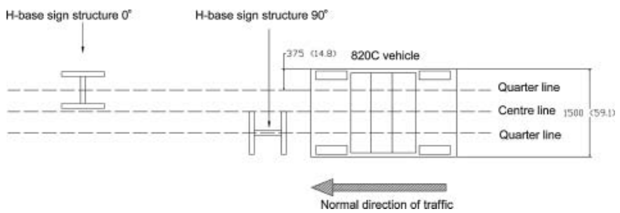

Figure 5. Impact test plan view (in mm (in.)).

Similar to the numerical predictions, results from the full-scale impact testing indicated that the lower and upper nylon fastener connections simultaneously failed on impact for both 0° and 90° H-base sign orientations (Figure 6). As a result of this failure mode, H-base sign panels did not enter the occupant compartment as had occurred for X-base signs with the original metallic fasteners as reported in the previous publication [15]. In both cases, the H-base signs flew over the vehicle and the supports posts buckled on impact (Figures 7 and 8).

Post-impact performance

Figure 9 contains photographs detailing the post-impact performance for the H-base structures with the nylon fasteners. As predicted using the LS-DYNA simulations, both the 0° and 90° H-base supports were completely separated from sign panels. In addition, the supports were deformed similarly to those discussed in the previous manuscript [15], having severe deformation of approximately 43 cm (17 in.) in height above the ground, which was approximately equal to the front bumper height. The support legs were also severely deformed at their connection points in similar fashion to the X-base supports. Figure 9 shows that the 820C

Figure 6. H-base sign panel separation due to vehicle impact.

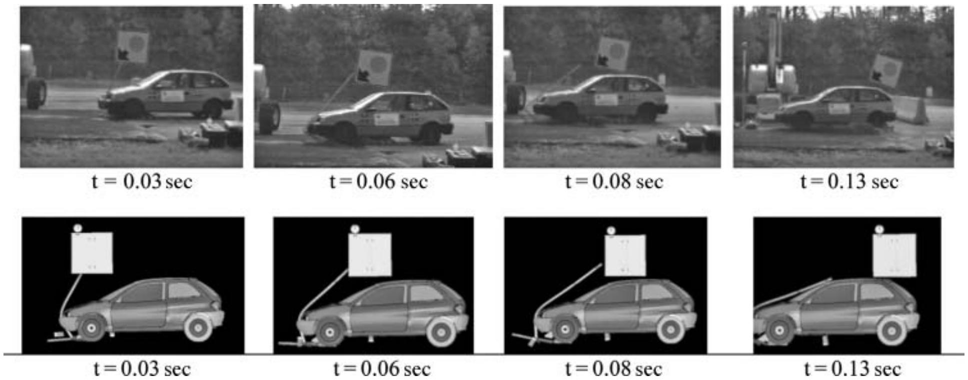

Figure 7. Impact test and LS-DYNA simulation snapshots, H-base at 90°.

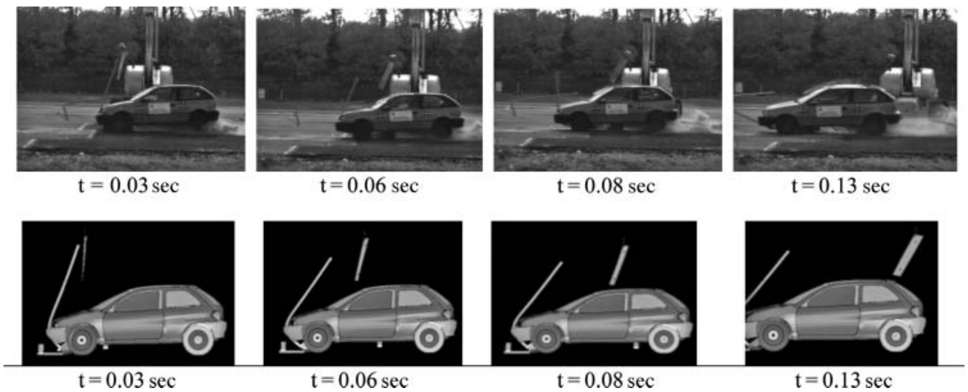

Figure 8. Impact test and LS-DYNA simulation snapshots, H-base at 0°.

(a) 0° H-base **(b) 90° H-base** **(c) Testing vehicle**

Figure 9. Post-impact performance.

vehicle was mildly damaged with the front bumper and vehicle hood having small permanent deformations. It was also observed that the windshield suffered slight damage, but no penetration occurred.

The H-base sign impact performance was examined following NCHRP 350 criteria in similar fashion to the X-base [15]. Table 2 summarises the occupant risk factors [8] and corresponding limitations from NCHRP 350

Table 2. Aggregate occupant risk factors for H- and X-base structure impact testing.

Sign structure	Impact angle	Impact speed, km/hr (mph)	Aggregate occupant impact velocity, m/sec (ft/sec)	Occupant ridedown acceleration, m/sec^2 (ft/sec^2)
H-base structure	0°	100.4 (62.4)	1.93 (6.33)	6.72 (22.05)
	90°	100.4 (62.4)	2.15 (7.05)	7.56 (24.8)
X-base structure [15]	0°	100.4 (62.4)	1.77 (5.80)	3.30 (10.8)
	90°	100.4 (62.4)	1.79 (5.87)	3.61 (11.8)

along with the 0° and 90° H- and X-base sign structure test performance. As presented in Table 2, the H-base sign had slightly higher occupant impact velocities and ridedown accelerations than the X-base sign because of the connection failure that occurred. It can be observed from the table that the H-base sign structures had aggregate occupant impact velocities that were within preferred NCHRP 350 limitations [14] and occupant ridedown accelerations that were slightly above preferred limitations [14], but still acceptable. These values differed slightly from those for the X-base signs that were tested [15].

Conclusions

This manuscript is the second that summarises a study used to determine an optimal portable sign design configuration in Pennsylvania. Detailed in the previous manuscript were tests of an X-base sign structure and corresponding LS-DYNA models [15]. Discussed herein is the performance of two configurations of H-base sign structure as predicted using validated LS-DYNA models and tested under vehicular impact.

The two designs that were studied involved H-base structures that originally used metallic fasteners between the sign panel and support post and another that utilised nylon fastener replacements. Decisions to replace the fasteners were purely based on the LS-DYNA model predictions. The revised models indicated that the H-base sign panels would not enter the occupant compartment as had occurred for the original metallic fasteners and these predictions were verified using additional vehicular impact tests. The H-base sign performance acceptability was also assessed according to other NCHRP 350 criteria and found to be acceptable.

Therefore, in addition to assisting with the portable sign structure selection process, this study also helped substantiate the effectiveness of using numerical simulations for predicting vehicular portable sign structure impact response and additional, expensive crash tests were eliminated. The use of constrained spot welds to represent fasteners between the sign and support posts was also validated via accurate crash performance prediction for the H-base structures. This study indicates that representing critical connections in sign structures could be adequately accomplished using the constrained spot welds in applications where high strain rates are anticipated, such as in the vehicular impact scenarios that were studied.

Acknowledgements

The authors would like to acknowledge the Pennsylvania Department of Transportation for funding this work.

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