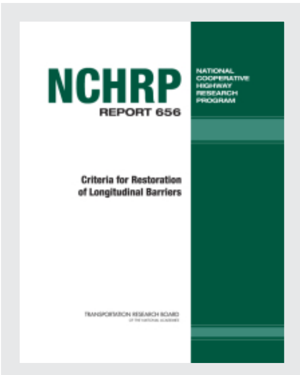

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Criteria for Restoration of Longitudinal Barriers

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The project that is the subject of this report was a part of the National Cooperative Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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FOREWORD

By Charles W. Niessner
Staff Officer
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This report provides guidance to assist maintenance personnel in identifying levels of damage and deterioration to longitudinal barriers that require repairs to restore operational performance. Using pendulum testing, full-scale crash testing, and finite element simulations, the research team developed a "Field Guide for Criteria for Restoration of Longitudinal Barriers." The report will be of particular interest to maintenance personnel responsible for the maintenance and repair of damaged longitudinal barriers.

Transportation agencies expend resources to ensure that all longitudinal barriers meet the safety performance guidelines to which they were constructed. Barrier systems are damaged by a wide variety of activities and factors, including minor crashes, snow plowing, mowing operations, and deterioration due to environmental conditions. Such damage may or may not be repaired by maintenance forces. For example, snowplows often bend W-beam guardrails and sometimes bend or break the posts. Even seemingly insignificant barrier damage or deterioration may compromise a barrier's safety performance.

With limited maintenance budgets, state highway agencies often have large backlogs of needed safety-feature repairs. These agencies cannot afford to repair damage that does not alter a barrier's safety performance, but significant barrier damage must be repaired to provide adequate protection for the motoring public. Unfortunately, in the absence of objective criteria for determining when repair is not required, highway agencies may be held to the unachievable standard of maintaining all safety features in as-built condition to avoid tort liability. Therefore, there is a need for objective, quantitative criteria in the form of guidelines for assessing damage and deterioration and determining when a longitudinal barrier requires repair or can remain in service.

Under NCHRP Project 22-23, "Criteria for Restoration of Longitudinal Barriers," Virginia Polytechnic Institute and State University reviewed the current criteria for repair of longitudinal barriers and evaluated the crash performance of barriers with minor damage using pendulum testing, full-scale crash testing, and finite element simulations. Based on these evaluations, recommended repair guidelines were developed.

The guidelines are presented in a format designed for use in the field by highway maintenance personnel. The guidelines include the damage mode, quantitative repair thresholds, the relative priority of making the repair, and a sketch of the damage mode.

CONTENTS

ACKNOWLEDGMENTS

This research project was sponsored by the National Academy of Sciences under the NCHRP Project 22-23, "Criteria for Restoration of Longitudinal Barriers." The authors wish to acknowledge the guidance of Charles W. Niessner, Program Office for NCHRP Project 22-23. We owe a special debt to the members of the NCHRP Project 22-23 Panel who were active participants throughout the research effort. The Project Panel provided the research team with many of the barrier damage photographs in this report, gave invaluable feedback on our project findings, and helped us develop and fine-tune our strategy for making this a project which could be readily implemented by the highway maintenance community.

We thank Ken Opiela and the FHWA for making the FOIL facility available for the pendulum testing at no cost to the project. We gratefully acknowledge Trinity Industries, Inc., and Gregory Industries, Inc., for contributing the guardrail materials for the pendulum and full-scale crash tests at no cost. We also wish to thank Dhafer Marzougui, Pradeep K. Mohan, Chris Story, Scott Mosser, and Eduardo Arispe, the contract staff of the National Crash Analysis Center (NCAC) from George Washington University, for their assistance in the setup and execution of the tests.

We wish to thank David Little and the Iowa DOT for hosting a workshop in Mason City, IA, in May 2009 on the proposed guidelines. The workshop allowed the research team to obtain invaluable feedback from actual maintenance practitioners which we have used to fine-tune the guidelines for improved readability and practicality.

We wish to acknowledge Virginia Tech graduate students Craig Thor, Greg Webster, and Kristofer Kusano for assisting with the pendulum experiments; Qian Wang, graduate student, for his contribution to the weak-post analysis; and Weijia Wu, post-doctoral fellow, for his development of the preliminary finite element models for this project. The majority of the finite element analysis in this project was conducted by Carolyn Hampton and reported in her M.S. thesis, "Limits of Permissible Damage in Strong-Post W-Beam Guardrail."

The authors wish to thank Roger Bligh for providing TTI crash test data and Karla Polivka-Lechtenberg for providing the test reports and data for the UNL long-span crash tests. We also gratefully acknowledge LSTC and Altair Engineering for providing the academic software licenses used to develop the models.

CHAPTER 1

Introduction

Longitudinal barriers, such as guardrails, are installed along a roadway or in the roadway median to prevent an errant vehicle from traversing a steep slope, impacting a more dangerous roadside object, or entering opposing vehicle travel lanes. Full scale crash testing is used to evaluate the performance of these barriers prior to their installation along a highway (Ray and McGinnis, 1997; Ross et al, 1993). Based on an evaluation using real-world crash data, these barriers have consistently been shown to be effective (Short and Robertson, 1998; Michie and Bronstad, 1994; Elvik, 1995). Very little is known, however, with respect to how these barriers perform after they have been damaged.

Highway agencies expend considerable resources to repair damaged longitudinal barriers. Limited funds prevent highway agencies from maintaining all field-installed systems in an ideal as-built condition. Instead, these agencies focus on repairing only damage that is perceived to have a detrimental effect on the safety performance of the barrier. The distinction between minor damage and more severe performance-altering damage, however, is not always clear. In the case of a high severity crash involving rail penetration (left image in Figure 1), the need for barrier repair is obvious. Much more common, though, is minor barrier damage, e.g., a shallow dent which occurs in a low-speed collision or a sideswipe (right image in Figure 1). Minor damage to barriers may also result from routine highway maintenance operations, including snowplowing, mowing or paving, and exposure to the environment, which may result in corrosion or termite damage.

Regardless of the cause, damage of this type poses a challenge to highway agencies. A failure to repair damage that affects barrier performance may lead to fatal consequences for passing motorists as well as potential exposure of the agency to a tort liability claim. Crash testing of undamaged barriers has consistently demonstrated that seemingly insignificant alterations to a barrier, such as using a rectangular washer on the post-rail connection, may result in catastrophic consequences for an impacting vehicle. This underscores the importance of the ability of agencies to identify seemingly minor damage that has serious implications on crash performance.

1.1 Research Problem Statement

The research problem statement for the project is quoted below:

> Transportation agencies expend resources to ensure that all longitudinal barriers meet the safety performance guidelines to which they were constructed. Barrier systems are damaged by a wide variety of activities and factors, including minor crashes, snow plowing, mowing operations, and deterioration due to environmental conditions. Such damage may or may not be repaired by maintenance forces. For example, snowplows often bend W-beam guardrails and sometimes bend or break the posts. Even seemingly insignificant barrier damage or deterioration may compromise a barrier's safety performance.
>
> With limited maintenance budgets, state highway agencies often have large backlogs of needed safety-feature repairs. These agencies cannot afford to repair damage that does not alter a barrier's safety performance, but significant barrier damage must be repaired to provide adequate protection for the motoring public. Unfortunately, in the absence of objective criteria for determining when a repair is not required, highway agencies may be held to the unachievable standard of maintaining all safety features in as-built condition to avoid tort liability. Therefore, there is a need for objective, quantitative criteria in the form of guidelines for assessing damage and deterioration and determining when a longitudinal barrier requires repair or can remain in service.

1.2 Objectives and Scope

The objective of this project was to develop guidelines to assist maintenance personnel in identifying the levels of damage and deterioration to longitudinal barriers that require repairs to restore operational performance. The scope of this project was limited to w-beam barriers, which are by far the most common barrier in use in the United States. The primary focus was on the barrier length of need sections. Although specific end terminals were not in the scope of this project, generic guidance applicable to all end terminals was included in the recommended guidelines but was not quantitatively evaluated.

It is also important to note what was not covered under the scope of this project. The guidelines pertained only to the

Figure 1. Catastrophic vs. minor guardrail damage.

repair of damaged or deteriorated barriers and were not intended to cover installation issues such as improper installation height. The project scope did not include guidelines for maintenance of cable barrier systems. Maintenance of cable systems was expected to be covered under NCHRP Project 22-25, "Development of Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems." Rigid barriers such as the New Jersey shape concrete barrier were not in the scope of this project. Proprietary systems were also not in the scope of the project.

To accomplish these objectives, the study was delineated into the following seven tasks:

1. Identify and review completed and ongoing research and activities, including international sources, related to the project objective.
2. Conduct a survey of state and Canadian provincial transportation agencies to gather existing policies and guidelines governing inspection and repair of longitudinal barriers. The survey should be used to identify the barrier systems and the types of damage and deterioration that should be considered in this project.
3. Submit an interim report that, as a minimum, includes the following:
   - The results of Tasks 1 and 2 with a discussion of the critical findings.
   - A discussion of the objective criteria, to be developed, for quantifying damage and deterioration related to barrier performance.
   - An updated, detailed work plan, including the research approach and costs to evaluate each damage and deterioration type identified in Task 2.
   - A preliminary draft outline of the proposed guidelines.
4. Meet in Washington, DC, with the NCHRP panel to review the Task 3 interim report approximately 1 month after its submittal. After the meeting, submit a revised interim report addressing the review comments and decisions at the meeting.
5. Execute the approved work plan.
6. Submit the preliminary draft guidelines for review by the panel. Revise the guidelines addressing the review comments.
7. Submit a final report documenting the entire research effort. The final report shall describe how the project was conducted and include an appendix with the guidelines.

1.3 Organization of Report

The first chapter presents the critical need to establish quantitative guidelines and criteria for the repair of longitudinal barriers and the research statement for NCHRP Project 22-23. Chapter 2 first presents a synthesis of the current repair criteria for longitudinal barriers with crash damage or environmental deterioration. Chapter 3 presents the research team's approach to evaluating the crash performance of longitudinal barrier with minor damage modes. This chapter describes each of the three evaluation approaches, i.e., pendulum testing, full scale crash testing, and computational modeling. Chapters 4–14 present the results of the evaluation of the crash performance of longitudinal barriers with minor damage and the recommended repair criteria and the rationale for each criterion. Chapter 15 presents a summary of the recommended repair guidelines. Finally, Chapter 16 presents the final product—a "Field Guide for Criteria for Restoration of Longitudinal Barriers." A comprehensive set of appendices are provided which include all test reports and a detailed report on the finite element simulations.

CHAPTER 2

Synthesis of Current Repair Criteria for Longitudinal Barriers with Crash Damage

2.1 Objective

The purpose of this chapter is to synthesize current U.S. and Canadian criteria for repair of damaged flexible or semi-rigid longitudinal barriers.

2.2 Methodology

The general methodology for this study was to both examine the available literature and conduct a survey of transportation agencies to ascertain current damaged barrier repair thresholds among transportation agencies in the U.S. and Canada. The literature review focused on available national guardrail repair guidance and individual agency guidelines for the repair and maintenance of semi-rigid and flexible longitudinal barriers. These individual agency guidelines generally fell into two categories: (1) maintenance manuals that describe conditions that warrant repairs on a particular barrier and (2) maintenance assessment criteria that are used to assess the barrier condition against a reference condition. Maintenance assessment criteria typically evaluate barrier functionality but can also include other factors such as aesthetics. Although maintenance assessment criteria may not be directly linked to barrier repair, they have been included as they are a gauge of barrier condition.

Using the findings from the literature survey, a survey instrument was developed for distribution to U.S. and Canadian transportation agencies. The 22 question survey was organized into the following five sections:

- Inventory of Guardrail and Median Barriers;
- Repair Policies;
- Non-Crash Related Damage/Deterioration;
- Notification and Repair Responsibilities; and
- Inspection Policies and Procedures.

The purpose of the barrier inventory section was to understand the types of barriers most used within a particular agency's jurisdiction. The repair policies section, the crux of the survey, was intended to provide insight into what thresholds are currently used to determine barrier repair needs, how damaged sites are prioritized, timelines for repairs, documented cases of impacts into damaged barriers, and whether the agency would benefit from more quantitative barrier repair guidelines. This chapter presents a summary of the survey results on the guardrail inventory and repair policies sections.

2.3 Results

2.3.1 National Guardrail Repair Guidance

National guidance regarding the repair of w-beam barriers is provided by the FHWA's "W-Beam Guardrail Repair: A Guide for Highway and Street Maintenance" (2008). This document provides highway maintenance personnel with a comprehensive overview of the importance and logistics of w-beam barrier repair. Guidance is provided on determining whether repair is necessary, based on a site visit and a classification of the damage severity. A damaged barrier is classified into one of three categories, as summarized in Table 1.

According to the FHWA guidelines, each transportation agency should develop guidelines for the timing of repair for each damage category. The FHWA report recommends that timing be based upon the expected frequency with which the damaged section will be struck, the severity of impact to the damaged section, and agency resources. Despite the relatively quantitative description of the damage categories shown in Table 1, the guidelines appear to have been developed based on previous state experience with w-beam barrier and engineering judgment. The report does not reference either tests or quantitative analysis as the basis for the guidelines.

The American Association of State Highway and Transportation Officials (AASHTO) also provide guidelines on longitudinal barrier maintenance in their Maintenance Manual (AASHTO, 2007). Although comprehensive in terms of what types of damage requires repair, little is provided in terms

Table 1. Guardrail damage classification details (FHWA, 2008).

Damage Category	Damage Attributes
(1) Non-Functional	Rail element is no longer continuous 3 or more posts broken off or no longer attached to rail Deflection of rail element more than 18 in. Rail element torn Top of rail less than 24 in.
(2) Damaged but should function adequately under majority of impacts	Rail element is continuous (can be bent or crushed significantly) 2 or fewer posts are broken or separated from the rail element Deflection of the rail element is less than 12 in.
(3) Damaged but should not impair the guardrail's ability to perform	Rail element is continuous (can be crushed or flattened) No posts are broken off or separated from the rail element Deflection of the rail element is less than 6 in.

of quantitative guidelines. For instance, w-beam guardrail repair is recommended when a "deep pocket in the rail line" exists, with no mention of a length or depth threshold. Other examples of guardrail damage requiring repair include "sections torn loose from posts," "rail section flattened," or an "anchor at either end of a run broken loose."

2.3.2 Published State Transportation Agency Guidelines for Damaged Barrier Repair

The literature review included published guidelines from 26 U.S. state transportation agencies relating to the maintenance and/or performance assessment of longitudinal barrier. Of these 26 agencies, only 9 were found to have quantitative longitudinal barrier repair criteria (6 maintenance assessment criteria and 3 maintenance manual criteria). For the purpose of this study, "quantitative" was defined as both objective and measurable. A guideline indicating that posts out of alignment more than 305 mm (12 inches) horizontally require repair, for instance, would be considered "quantitative." However, a guideline indicating that barriers need to be repaired if 5% of the barrier is not functional would not be classified as "quantitative" as there is no measurable definition of "not functional." For transportation agencies, quantitative barrier repair criteria are important for consistently and objectively identifying barrier damage that requires repair.

As additional quantitative barrier repair criteria were identified via the survey responses, all quantitative criteria were combined and discussed further in the survey results section. Table 2 summarizes selected agency barrier repair thresholds

Table 2. Selected state transportation agencies with non-quantitative guardrail repair guidelines.

Agency	Type*	Criteria Description/Excerpt (Reference)
Alabama DOT	MM	Repair or replacement of guardrail sections, posts and hardware due to crash damage or normal deterioration. (AL DOT, 2005)
Idaho Transportation Department	MM	Any guardrail that is damaged. Most guidance is with respect to upgrading non-standard guardrail to standard hardware if it is damaged. (ID TD, 2008)
Indiana DOT	MM	Maintain guardrail to assure that it will function as designed. Repairs of non-functional barrier should be performed within 5 working days. (IN DOT, 2001)
Kentucky Transportation Cabinet (TC)	MA	Measure and record the total linear feet of guardrail that is damaged to the extent that structural integrity or functionality is lost. (KY TC, 2000)
Michigan DOT	MM	Only a description of how repair work should be completed. No criteria for when guardrail is considered deficient or should be repaired. (MI DOT, 2004)
Montana DOT	MM	"Guardrails are repaired and replaced in order to maintain its structural integrity" (MT DOT, 2002a)
North Carolina DOT	MA	Threshold condition is "Guardrail damaged or not functioning as designed." (NC DOT, 1998; NC DOT, 2004)
Oregon DOT	MM	Description only of the work involved. Maintain, repair, realign, or replace guardrail to preserve or restore the installation to its designed condition. (OR DOT, 2004)
South Carolina DOT	MA	Threshold condition: "Guardrail damaged or not functioning as designed." (SC DOT, 2004)
Utah DOT	MA	Each guardrail run should function as intended - all posts, blockouts, panels, and connection hardware shall be in place. (UT DOT, 2004)

* MM denotes criteria present in a maintenance manual; MA denotes maintenance assessment criteria.

that were not classified as quantitative. The prevailing maintenance manual and maintenance assessment damage threshold is stated as "damage that affects the structural integrity of the barrier." For maintenance assessment criteria, several agencies even rate barriers in terms of a percentage that is "functional" without specifically defining damage that impairs barrier functionality. Without an objective definition of the damage that affects barrier integrity, maintenance personnel tasked with evaluating barrier repair need may have significantly different interpretations of what damage impairs barrier functionality. The fact that the majority of state agencies employ this blanket statement without accompanying quantitative guidelines underscores the importance of developing a better understanding of how quantifiable barrier damage correlates to subsequent impact barrier performance.

Also evident from this literature review is the variation between maintenance manuals and maintenance assessment criteria even within the same jurisdiction. For instance, North Carolina had quantitative barrier repair guidelines in the maintenance manual but no quantitative guidelines for maintenance assessment (see Table 2). It should be noted that these criteria for a given agency are not required to coincide as these manuals are typically developed independently. In addition, maintenance assessment criteria are not necessarily used by maintenance personnel to justify barrier repair and may include factors other than the safety performance of the barrier in their scope. For all the published maintenance assessment manuals found in this study, however, functionality was a main component of barrier condition. Another observation from these published guidelines was that there was little distinction between the repair thresholds based on barrier application, e.g., on the roadside or in the median.

2.3.3 Analysis of Survey Responses

A total of 39 transportation agencies responded to the survey. From the United States, there were responses from 29 transportation agencies from the continental states as well as Hawaii and Puerto Rico. From Canada, there were responses from a total of 8 Canadian Provinces: Alberta, British Columbia, Manitoba, New Brunswick, Nova Scotia, Ontario, Prince Edward Island, and Quebec. Approximately 38 percent of the respondents (15 agencies: 11 U.S. States, 3 Provinces, and Puerto Rico) provided detailed information for guardrails within their respective jurisdictions. In total, these agencies provided an inventory in excess of 37,000 miles of longitudinal barrier (no distinction was made between roadside and median barriers). The strong-post w-beam barrier was the most frequent barrier type, accounting for roughly 60 percent of total barrier length by the responding state agencies. Excluding the two agencies that reported no use of strong-post w-beam (South Carolina and British Columbia), the average use of strong-post w-beam barriers was approximately 75 percent. Concrete, cable barrier, strong post thrie beam, and the weak post w-beam were ranked second through fifth, respectively, based on the responding agencies providing detailed barrier information. The distribution of barriers identified in this survey appears similar to that reported by Ray and McGinnis (1997). Note, however, that the Ray and McGinnis study did not request agencies to report barrier mileage.

Approximately 60 percent of responding agencies (23 of 39) indicated the presence of specific guidelines for determining when a guardrail needs to be repaired. Of these 23 agencies, however, only 7 were classified as "quantitative" with 2 of these agencies previously identified through the literature review. In general, the quantitative guidelines resulting from the survey were similar to those found through the literature review. For the purpose of this study, the quantitative criteria found via the survey and literature review have been combined and shown in Tables 3–6. Tables 3–5 summarize the metal beam barrier criteria while Table 6 summarizes the criteria for cable barriers. Each criterion was classified based on the barrier component to which it refers, i.e., the rail element, the posts/blockouts, or the connections. For the rail element and post/blockout categories, the criteria have been further classified into 3 general damage types: (1) deflection, (2) tearing/breaks and/or punctures, or (3) deterioration. The transportation agencies using each of these criteria are listed on the right hand side of the table and grouped into one of two categories: maintenance or maintenance assessment. Again, note that for the same agency, maintenance manual-based criteria and maintenance assessment criteria are not necessarily the same. The Ohio DOT, for instance, has quantitative criteria for both barrier maintenance and maintenance assessment; however, as indicated in the table, these criteria are not the same. Another example is the Indiana DOT that has quantitative maintenance assessment criteria, but the maintenance manual uses only a non-quantitative "functional/non-functional" criterion and thus was not included in the tables. Note that references for each agency's barrier repair criteria appear next to the agency name.

Current FHWA guidelines for metal beam barriers have been provided for reference and are the thresholds to distinguish between the "minor damage" and "damaged but should function adequately under majority of impacts" categories. No FHWA guidelines were found for cable barriers. The majority of the criteria listed in the table are those used to distinguish between minor damage and damage that needs to be repaired (or results in a "deficient" rating in terms of maintenance assessments). Some agencies also have (or only have) criteria for severely damaged barriers; these criterion are marked with an asterisk.

For metal beam barrier rail elements, the most prevalent quantitative criterion for repair was barrier deflection with a majority of agencies using the FHWA-endorsed 152 mm (6 inches) threshold. Maintenance assessment procedures

Table 3. Summary of quantitative damaged barrier criteria: metal beam barrier rail elements.

Category	Type	Criteria Description		Maintenance				Maintenance Assessment										
			FHWA (2008)	California (2006)	Ohio (2005)	North Carolina (2000)	Quebec (2004)	Iowa (2004)	Montana (2002b)	Ohio (2004)	Washington State (2006)	Wisconsin (2004)	Pennsylvania (2006)	Missouri (2003)	Indiana (2006)	Wyoming (2006)	Nova Scotia (2006)	Florida (2007)
Rail Element	Deflection	Deflection > 76 mm (3 in.)												X				
		Deflection > 152 mm (6 in.)	X	X				X									X	
		Deflection > 152 mm at any point in 3.6 m section							X		X	X				X		
		* Deflection > 305 mm (12 in.)		X														
		* Deflection > 457 mm (18 in.)				X												
		Rail flattening > 50% thickness					X	X										
		Rail flattening > 30% height						X										
		> 50% crushed								X					X			
		> 50% torn								X					X			
		Rail distortion > 25% of rail section length					X											
		Any rail flattening (even if <152 mm deflection)							X		X					X	X	
		Rail height varies > +/- 51 mm (2 in.) from 706 mm (27 in.) standard height						X										
		Rail height varies > +/- 76 mm (3 in.) from 706 mm (27 in.) standard height												X				
		Rail height < 610 mm (ground to top of rail)											X			X		
		Rail height > 762 mm (ground to top of rail)														X		
	Tearing/Breaks & Punctures	Horizontal tear > 25 mm wide and 305 mm long						X										
		Any length vertical tear						X										
		* Any splits or tearing	X	X														
		> 50% torn													X			
		Non-manufacturer hole in rail > 25 mm diameter						X										
		> 3 Non-manufacturer holes in rail						X										
	Deterioration	Any structural corrosion						X					X				X	

* Maintenance criteria is used to indicate a threshold for severe barrier damage (e.g., immediate repair).
X → Agency uses the criteria to determine barrier repair need (maintenance column only) or barrier deficiency (maintenance assessment column only).

in Missouri, however, allow only a 76 mm (3 inches) deflection threshold for guardrails. Even with severe metal beam barrier damage, there are variations; the California maintenance manual specifies 305 mm (12 inches) of rail deflection while the North Carolina maintenance manual specifies 457 mm (18 inches). With respect to rail flattening, two states (Montana and Washington State) specify guardrail deficient if rail flattening is present even if the barrier was not deflected more than 152 mm (6 inches). The maintenance assessment procedures in Iowa were the only guidelines that prescribed specific thresholds for rail flattening: 50 and 30 percent of the cross-section thickness and height, respectively. For damage to posts, a majority of the agencies used a threshold of one or more broken or cracked posts. Two exceptions were Ohio and Indiana maintenance assessment procedures which prescribed two or more broken or cracked posts. For post deflection, a majority of the agencies used horizontal distance out of alignment; a notable exception was Pennsylvania and Nova Scotia which use post angle. For metal beam barrier connections, most maintenance assessment criteria rate a barrier as deficient if one or more bolts are missing while maintenance assessment in Wyoming specified 4 or more missing bolts. Interestingly, none of the quantitative maintenance criteria used a threshold for missing bolts.

Similar variations can be found with respect to cable barrier repair/assessment criteria. The overall number of criteria pertaining to cable barriers, however, was substantially less than that of metal beam barriers. Notable differences include criteria for cable sag which varies from 38 mm (1.5 inches, Iowa maintenance assessment) to 51 mm (2 inches, Ontario maintenance manual) up to 152 mm (6 inches, Pennsylvania maintenance assessment). For broken posts, a majority of agencies used a threshold of one or more (Ohio, Quebec, and Montana) while Ontario uses 3 or more consecutive posts. In general, maintenance assessment criteria employed by Iowa were found to be the most quantitative and comprehensive with respect to both flexible and semi-rigid longitudinal barrier assessment.

Table 4. Summary of quantitative damaged barrier criteria: metal beam barrier post and blockouts.

				Maintenance				Maintenance Assessment										
Category	**Type**	**Criteria Description**	**FHWA (2008)**	**California (2006)**	**Ohio (2005)**	**North Carolina (2000)**	**Quebec (2004)**	**Iowa (2004)**	**Montana (2002b)**	**Ohio (2004)**	**Washington State (2006)**	**Wisconsin (2004)**	**Pennsylvania (2006)**	**Missouri (2003)**	**Indiana (2006)**	**Wyoming (2006)**	**Nova Scotia (2006)**	**Florida (2007)**
Posts & Blockouts	Deflection	Deflection > 76 mm (3 in.)												X				
		Deflection > 152 mm (6 in.)	X	X				X									X	
		Post angle > 15° angle from vertical											X					
		Post angle > 20° angle from vertical															X	
		* Deflection > 305 mm (12 in.)		X														
		* Deflection > 457 mm (18 in.)				X												
		1 or more twisted/misaligned blockouts						X			X							
		3 or more continuous twisted/misaligned blockouts								X					X			
		> 10% of blockouts twisted																X
	Tearing/Breaks	1 or more broken/cracked posts	X		X		X	X	X		X	X				X	X	
		2 or more broken/cracked posts								X					X			
		*3 or more broken posts				X												
		1 or more missing blockouts						X						X		X		X
		3 or more continuous missing blockouts			X					X					X			
	Deterioration	1 or more rotten posts			X													
		2 or more continuous rotten posts			X					X					X			
		Rotten post (> 50% cross section)													X			
		> 10% of posts/blockouts deteriorated or rotten																X
		Any structural corrosion						X					X					

* Maintenance criteria is used to indicate a threshold for severe barrier damage (e.g., immediate repair).
X → Agency uses the criteria to determine barrier repair need (maintenance column only) or barrier deficiency (maintenance assessment column only).

Table 5. Summary of quantitative damaged barrier criteria: metal beam barrier connections.

				Maintenance				Maintenance Assessment										
Category	**Type**	**Criteria Description**	**FHWA (2008)**	**California (2006)**	**Ohio (2005)**	**North Carolina (2000)**	**Quebec (2004)**	**Iowa (2004)**	**Montana (2002b)**	**Ohio (2004)**	**Washington State (2006)**	**Wisconsin (2004)**	**Pennsylvania (2006)**	**Missouri (2003)**	**Indiana (2006)**	**Wyoming (2006)**	**Nova Scotia (2006)**	**Florida (2007)**
Connections	Integrity Loss	Splice damage (< 32 mm of rail material left at any point around the bolt)						X										
		1 or more missing/loose/damaged splice bolts						X										
		Loose/missing or damaged hardware											X					
		1 or more missing bolts							X		X	X		X			X	X
		1 or more posts separated from rail	X					X										
		4 or more missing/loose bolts in single section														X		
		*Bolts are missing or torn through rail element		X														

* Maintenance criteria is used to indicate a threshold for severe barrier damage (e.g., immediate repair).
X → Agency uses the criteria to determine barrier repair need (maintenance column only) or barrier deficiency (maintenance assessment column only).

Table 6. Summary of quantitative damaged barrier criteria: cable barrier.

Category	Type	Criteria Description	Maintenance					Maintenance Assessment							
			California (2006)	Ohio (2005)	North Carolina (2000)	Quebec (2004)	Ontario (2003)	Iowa (2004)	Montana (2002b)	Ohio (2004)	Washington (2006)	Wisconsin (2004)	Pennsylvania (2006)	Missouri (2003)	Indiana (2006)
Rail Element	Deflection	*Cable is on the ground	X							X					X
		Top cable height varies > +/- 51 mm (2 in.) from 762 mm (30 in.) standard height				X		X							
		Spacing between cables > 76 mm (3 in.)						X							
		Horizontal deflection > 76 mm (roadside cable barrier)												X	
		Horizontal deflection > 25 mm (median cable barrier)												X	
		Horizontal deflection > 152 mm (6 in.)							X						
	Tearing/Breaks	Any broken cable strands						X							
		Frayed cable					X								
		* Broken cable			X	X					X				
	Deterioration	Any structural rust						X							
		Cable sag > 38 mm (1.5 in.) between posts						X							
		Cable sag > 51 mm (2 in.)					X								
		Cable sag > 152 mm (6 in.)											X		
Posts	Deflection	Post angle > 15° angle from vertical											X		
	Tearing/Breaks	1 or more broken posts		X		X			X						
		3 or more consecutive posts missing/broken					X								
		Missing first 2 posts adjacent to anchor(s)					X								
		* 4 or more posts knocked down			X										
	Deterioration	Any structural rust						X							
Connections	Integrity Loss	Missing cable hooks (unsecured cables)					X	X							
		Damaged cable hooks										X			
		Corroded cable hooks (unsecured cables)				X									

* Maintenance criteria is used to indicate a threshold for severe barrier damage (e.g., immediate repair).
X → Agency uses the criteria to determine barrier repair need (maintenance column only) or barrier deficiency (maintenance assessment column only).

For 27 different minor barrier damage types, respondents were asked to indicate whether the damage type would be repaired and the corresponding repair priority. A total of 33 respondents filled in this information in whole or in part; the remaining 6 agencies did not provide any information. Table 7 summarizes the responses by indicating the percentage of agencies that would repair the particular guardrail damage. For each damage type, the number of respondents for which it is based has also been listed. Note that not every agency provided a repair indication for each damage type; in most cases, the agency did not provide a response or, in fewer instances, provided alternate responses (other than the yes/no specified by the survey instructions). There appears to be a consensus among respondents that post/rail deflection in excess of 152 mm (6 inches) and vertical rail tears need to be repaired. Splice damage, cable tension loss, damage to cables, soil erosion around posts, and bent or missing cable hooks had repair percentages in excess of 90 percent. There appears to be no particular consensus on what damage type does not need to be repaired. Rail deflection only and post/rail defection less than 6 inches appear to be the least likely to be repaired with 50 and 27 percent repair percentages, respectively.

A total of 34 agencies provided repair priority information for each damage type. Respondents were asked to categorize repair priority into one of 4 categories: (1) repair immediately, (2) repair as part of scheduled maintenance, (3) do not repair, and (4) at the discretion of maintenance personnel. Again, not all 34 agencies indicated repair priority for all damage types. On average, however, there were 27 respondents for each damage type. Figure 2 is a summary of the top 10 damage categories based on the percentage of respondents indicating the damage should be repaired as soon as possible. Not surprisingly, post and rail deflections in excess of 152 mm (6 inches), rail tears, and damage to cables ranked as high-priority repairs. With the exception of erosion of soil around posts, there is very good agreement between these top 10 and the top 10 presented in Table 7.

Table 7. Agency guardrail repair priorities by damage type.

Damage Type / Description	% Agencies that would Repair	# of Respondents
Post/rail deflection > 6 in. (152 mm)	100	30
Rail tear (vertical)	100	28
Loss of tension (cable barrier)	96	25
Damage to cable	96	24
Erosion of soil around posts	96	23
Bent or missing hooks (cable)	95	22
Snowplow damage	95	19
Splice damage	92	26
Missing bolts/hardware	92	25
Cable sag	91	22
Rail tear (horizontal)	89	28
Missing blockout	89	28
Loose bolts/hardware	87	23
Mowing damage	83	18
Rail flattening	81	27
Post wood rot	81	21
Slope-related barrier lean	79	24
Tear in steel post	78	27
Bolt pulled-through rail	77	26
Twisted blockout	77	26
Insect damage	68	19
Rail/post corrosion or rust	67	18
Cracked wood post	64	22
Holes > 1 in. (25 mm) in rail	58	24
Rail deflection only	50	22
Post/rail deflection < 6 in. (152 mm)	27	22

With respect to known cases of a vehicle impacting a previously damaged barrier, 32 of 39 respondents indicated no documented cases. Three other responding agencies did not provide an answer to the question while two agencies answered "unknown." Only two agencies (Oklahoma and New Hampshire) indicated documented cases of a vehicle impacting a damaged barrier. In Oklahoma, the single case identified a vehicle impacting a Truck Mounted Attenuator (TMA) that was in place (presumably in front of the damage section). In New Hampshire, the only details provided were that second impacts do not happen often.

Two-thirds of responding agencies (26 of 39) indicated that more quantitative guidelines for the repair of guardrail would be beneficial. Eleven agencies (28 percent) indicated that more quantitative guidelines would not be beneficial to their organization; however, only two (California DOT and Florida DOT) of these agencies reported quantitative barrier repair guidelines. Of the remaining two agencies, one indicated that more

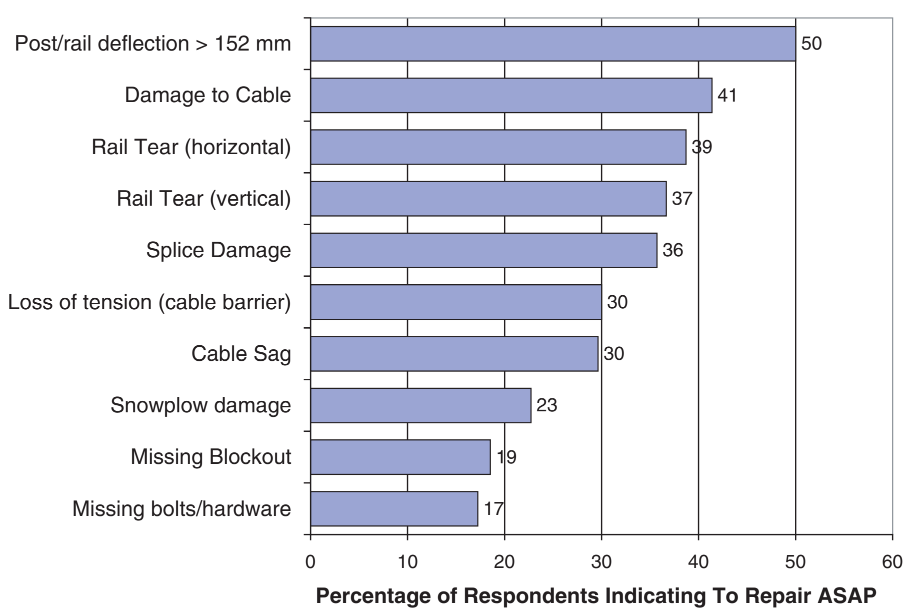


Figure 2. Damage type ranked by ASAP repair priority.

quantitative guidelines may be beneficial while the other indicated only if sufficient resources were available to comply with the more quantitative guidelines. The second agency expressed concern about the increased liability the agency would incur if unable to comply completely with the quantitative guidelines.

2.4 Discussion

A review of the available literature and a survey of U.S. and Canadian transportation agencies support several important notions regarding the current longitudinal barrier repair practices and priorities amongst transportation agencies. First is the general lack of quantitative guidelines to assess the longitudinal barrier damage level and the associated need for repair. Combining the literature review and survey results, data was obtained from a total of 40 of 50 U.S. states and 8 of 10 Canadian Provinces (approximately 80 percent of the U.S. and Canadian transportation agencies). Only 13 States and 2 Canadian Provinces, less than one-third of the 48 transportation agencies, had either quantitative barrier repair criteria or quantitative maintenance assessment guidelines for longitudinal barrier. For the remaining two-thirds of agencies, barrier repair and barrier assessment criteria usually required a determination of whether the barrier was "functional," with no specific guidelines for making that assessment. The current FHWA guidelines, published in 2008, do provide some loosely quantitative guidelines for barrier repair; however, the guidelines appear to be founded on engineering judgment instead of a strong analytic foundation. In addition, the survey responses suggest that transportation agencies would see a benefit in more quantitative barrier repair guidelines.

Second is the apparent variation between barrier assessment criteria, as present in maintenance assessment procedures, and those criteria used to determine the need for barrier repair, as prescribed in the maintenance manual. For thirteen agencies, information from both maintenance assessment procedures and corresponding agency maintenance manuals was available. Six agencies (Indiana, Iowa, Montana, Pennsylvania, Florida, and Washington State) had quantitative maintenance assessment criteria but lacked quantitative barrier repair criteria in the maintenance manual. Two agencies (California and North Carolina) had quantitative barrier repair criteria in the maintenance manual but lacked quantitative barrier assessment criteria. Ohio was the only agency that had both quantitative barrier repair criteria and quantitative maintenance assessment criteria while the remaining four agencies (Texas, Tennessee, Virginia, and Kansas) had neither quantitative barrier repair nor quantitative maintenance assessment criteria. Although these criteria are not required to coincide, all of the maintenance assessment criteria found in this study were either largely or solely based on barrier functionality. At a minimum, the variations noted in maintenance criteria and maintenance assessment criteria warrant further investigation.

Third, failure to promptly repair a damaged barrier may increase a transportation agencies legal liability. Crashes involving vehicles impacting previously damaged barriers are found to occur in the field. A review of the available tort liability cases in the U.S. revealed that impacts into previously damaged barriers have occurred and have been litigated (*Keller v. State of Illinois,* 1982; *Leonard Paxton v. Department of Highways,* 1999; *McDonald v. State of New York,* 2002; *Rosemary F. Woody v. Department of Highways,* 1989; *Volpe v. State of New York,* 2000). Many of these cases, such as *McDonald v. State of New York,* were dismissed. However, it would seem advantageous, at least from a legal perspective, to have more quantitative guidelines for when to repair damaged barrier and prioritize damaged barrier sections. Interestingly, the survey respondents could provide almost no documented cases of vehicles impacting previously damaged barriers.

All of these notions seem to point to the need for a better understanding of the effects of barrier damage on barrier performance.

2.5 Conclusions

Based on the findings of the literature review and analysis of the survey responses, the following conclusions are drawn:

1. A majority of the current U.S. and Canadian transportation agency guidelines for longitudinal barrier repair lack quantitative measures to evaluate the need for barrier repair. In most of these cases, the practice is to repair barriers if it is "non-functional" with no specific guidance on making that assessment.
2. There is a need for the development of more quantitative guidelines for longitudinal barrier repair that are based on a strong analytical foundation. This analytical foundation should include full-scale crash testing of damaged barrier, pendulum testing of damaged barrier sections, and finite element modeling of damaged barrier impacts.
3. Several state transportation agencies, including California, Iowa, Montana, Ohio, Washington State, North Carolina, Pennsylvania, Missouri, and Wisconsin, were found to have quantitative measures to rate or provide guidance on the repair of flexible and semi-rigid barriers. Even in these cases, however, there appears to be little connection between the criteria used to evaluate the condition of longitudinal barriers for the purpose of maintenance assessment and the criteria used by maintenance personnel to determine the need for barrier repair. As both criteria are based heavily on barrier functionality, these variations warrant further investigation.

CHAPTER 3

Research Approach

3.1 Research Plan

The goal of this research program is to develop guidelines to assist highway personnel in identifying levels of minor barrier damage and deterioration that require repairs to restore operational performance. The guidelines are to be based upon objective and quantitative threshold values for which barrier repair is recommended. This chapter describes the research approach used to develop these quantitative underpinnings. The research team's approach was to evaluate the more common damage types with a combination of controlled experiments and computational modeling to develop the repair guidelines. The experiments were used both to directly evaluate barrier performance and to validate the computational models.

The research program was conducted in the following three phases:

- Phase I: Candidate Repair Guidelines
- Phase II: Evaluation of Candidate Repair Guidelines
- Phase III: Recommendations for Improved Repair Guidelines.

3.1.1 Phase I: Candidate Repair Guidelines

The first phase of the research program was to develop a candidate set of repair guidelines needed to address commonly observed modes of minor damage. Selection of the damage modes for which guidelines were needed was conducted based upon a survey of U.S. and Canadian transportation agencies presented in Chapter 2. Additional damage modes were added as needed based upon analysis of a photographic catalog of minor barrier damage categories developed through field inspection of damaged barrier sites, and consultation with the project panel.

The next step was to propose objective and quantifiable repair criteria for each damage mode. The guidelines must further be based upon straightforward metrics which are practical for maintenance crews to use for quantifying minor barrier damage. The candidate set of guidelines and quantitative criteria to gauge minor barrier damage were based on current metrics employed by transportation agencies and supplemented as needed to address specific damage modes. The final set of candidate repair guidelines to be evaluated was presented to and approved by the project Panel prior to commencement of Phase II: Evaluation of Candidate Repair Guidelines.

Table 8 presents the candidate list of damage modes for non-proprietary w-beam barriers, including strong and weak post w-beam barriers which were to be evaluated in this program. Table 8 also presents the objective repair criteria which were sought for each damage mode. The objective of Phase II was to analytically determine these repair criteria.

The Project Panel also requested that the final report specify repair criteria for generic end terminals. The intent was to specify guidance which was applicable to all end terminal types (except as noted). Manufacturers of proprietary end terminal systems may recommend additional repair thresholds specific to an individual terminal. Note that this guidance was based solely on engineering judgment; no finite element simulations or pendulum tests evaluating these end terminal damage modes were conducted. These guidelines, shown in Table 9, were based primarily on an End Terminal Routine Maintenance Checklist developed for use by the Ohio DOT.

3.1.2 Phase II: Evaluation of Candidate Repair Guidelines

The candidate guidelines were evaluated through a combination of controlled experiments and computational modeling. Both pendulum tests and full scale barrier crash tests were conducted on longitudinal barrier into which a flaw, e.g., a vertical tear, had been purposely introduced. The tests were supplemented by a suite of computational simulations to further evaluate the crash performance of longitudinal barrier

Table 8. Repair thresholds to be determined for w-beam barriers.

Component	Damage Type	Damage Description	Quantitative Repair Criterion (to be determined)
Rail Element	Deflection	Rail Deflection	Deflection from as-built
		Rail Flattening (thickness)	Percent Flattened
		Rail Flattening (height)	Percent Flattened
	Tearing/Breaks / Punctures	Non-Manufacturer hole in Rail	Diameter of hole
		Non-Manufacturer holes in Rail	Number of holes in single section
		Vertical Tear	Length of tear
		Horizontal Tearing	Length of tear
	Deterioration	Any structural corrosion	Amount of Section Loss
Posts	Deflection	Post/Rail Deflection	Deflection from as-built
		Steel Post torsion	Number of damaged posts
	Tearing/Breaks	Broken Posts	Number of broken posts
	Deterioration	Rotten Wood Posts (any visible rotting)	Number of rotted posts
		Any Structural Corrosion (hole or section loss)	Amount of section loss
Blockouts	Deflection	Twisted/Misaligned Blockouts	Number of affected blockouts
	Missing	Missing Blockouts	Number of missing blockouts
	Deterioration	Rotten Wood Blockouts (any visible rotting)	Number of rotted blockouts
Connections	Integrity Loss	Splice Damage	Amount of rail material left between splice and bolt hole
		Missing, Loose, or Damaged Splice Bolts	Number of affected bolts
		Post Separated from Rail (any)	Number of posts separated from rail

with minor damage. The physical experiments were used both to directly evaluate barrier performance and to validate the computational models.

The results of each damaged barrier impact experiment or simulation were evaluated using criteria based heavily on *NCHRP Report 350.* Pendulum tests were evaluated based on the ability of the barrier to contain the pendulum, i.e., no pendulum penetration, underride, or override. For the full-scale crash tests and computational simulations of full-scale crash tests, the criteria shown in Table 10 were used to evaluate crash performance. The full-scale crash tests and simulations were also assessed for vehicle instability resulting from impact including roll, pitch and yaw, wheel snagging, and the presence/absence of vaulting. In these cases, the baseline case (for the qualitative comparison) was the respective vehicle impacting an undamaged barrier. The results of each evaluation were used to set the threshold for repair.

Repair priorities were assigned to the barrier damage evaluated to provide maintenance personnel with guidance regarding the relative importance of barrier damage types. This was accomplished by qualitatively ranking each damage type based on the scheme presented in Table 11. The priority rankings were based on the results of the finite element simulations and pendulum tests.

Table 9. Preliminary proposed repair thresholds for generic end terminals.

Component	Damage Description
Rail Element	Rail Element not Aligned Properly in Impactor Head*
Posts	Post Number 1 is Broken or Missing
Blockouts	Any Twisted / Misaligned Blockouts
Connections	> 1 in. of Slack in Anchor Cable or Missing Anchor Cable
	Bearing Plate Rotated or Missing
	Any Failed Lag Screws Securing Impactor Head *

* Applies only to Energy Absorbing End Terminals

Table 10. Barrier crash performance requirements.

Criterion	Required Performance
Structural Adequacy	1. Barrier contains and redirects the vehicle
	2. No vehicle penetration, underride, or override
Occupant Risk	3. Vehicle should remain upright during and after the collision; moderate pitch and roll are acceptable
	4. Lateral and longitudinal occupant impact velocity < 12 m/s (as computed by the flail space model)
	5. Lateral and longitudinal occupant ridedown acceleration < 20 G (as computed by the flail space model)
Vehicle Trajectory	6. Vehicle intrusion into adjacent traffic lanes is limited or does not occur
	7. Vehicle exit angle should preferably be less than 60 percent of the impact angle

3.1.3 Phase III: Recommendations for Improved Repair Guidelines

In the third and final phase of the project, the results of the impact tests and simulations were used to develop a recommended set of repair guidelines in a form suitable for maintenance personnel in the field. The end customer for these repair guidelines are highway maintenance personnel. In addition to being based upon a strong analytical foundation, the guidelines must be easily understood and implemented. The repair threshold guidelines were presented in a graphical format that clarified how damage to w-beam barriers should be measured and repair priority assessed.

A workshop on the new guidelines was presented to an Iowa DOT maintenance group to obtain the feedback from actual maintenance practitioners in Mason City, IA, in May 2009. Comments from the workshop participants were invaluable and were used to fine-tune the guidelines for improved readability and practicality.

3.1.4 Damage Evaluation Techniques

The remainder of this chapter describes the methods used to evaluate the crash performance of longitudinal barrier with each damage mode. The following sections describe the following techniques:

- Pendulum Testing Plan
- Full Systems Crash Test Plan
- Finite Element Modeling Plan
- Validation of Finite Elements Models

Table 11. Preliminary proposed repair priority scheme.

Priority Level	Description
High	A second impact results in unacceptable safety performance including barrier penetration and/or vehicle rollover.
Medium	A second impact results in degraded but not unacceptable safety performance.
Low	A second impact results in no discernible difference in performance from an undamaged barrier.

3.2 Pendulum Testing Plan

Pendulum tests were used in this research program for two purposes: (1) as tests of structural integrity and (2) to provide test data for validation of computational models. Pendulum tests are a better method than finite element modeling to check for structural integrity under impact conditions which might result in tearing or fracture. Finite element modeling using the LS-DYNA code is a less than ideal method of modeling this type of damage. Examples would include vertical tears, horizontal tears, holes, and splice damage. The pendulum tests were conducted at the Federal Outdoor Impact Laboratory (FOIL) in conjunction with the FHWA.

3.2.1 Experimental Design Development and Test Methodology

Pendulum Apparatus and Impactor Face. The pendulum tests used the pendulum device currently located at the FHWA FOIL in McLean, VA. The FOIL pendulum consists of a support structure, a 2000-kg (4500 lb) pendulum mass (center image in Figure 3), and two rigid posts (left image in Figure 3) located on either side of the suspended pendulum mass. A rounded triangular pendulum impactor face was fabricated for the tests (right image in Figure 3). The radius of chamfer at the impactor face center was 152 mm (6 inches), which was based on measurements of a 2006 Chevrolet 1500 pickup truck. The impactor face is 420 mm (16.5 inches) tall and is capable of

Figure 3. Existing rigid posts (left), FOIL pendulum mass (center), and new impactor face (right).

engaging the full w-beam cross section. The combined mass of pendulum and the impactor face was 2061.5 kg (4,545 lbs) to represent the mass of the *NCHRP Report 350* 2000-kg pickup truck (2000P) test vehicle. Note that the pendulum mass is slightly higher than the 2045 kg recommended mass limit specified by *NCHRP Report 350* for the 2000P test vehicle.

W-Beam Test Section, Anchorage, and Embedment. A two-post section of modified G4(1S) strong-post w-beam barrier with wood blockouts was selected for testing. The barrier test section length was constrained by the available span (approximately 5.5 meters) between the existing rigid posts on either side of the FOIL pendulum. Using standard 1905 mm (6.25 feet) post spacing and 3810 mm (12.5 feet) rail lengths, this allowed for one post to be located at a rail splice and the other post a non-splice location. As this section represents the smallest repeating unit for the strong-post w-beam barrier, this configuration was thought to be most representative of a typical full-length installation. Note that this two post section is roughly one tenth the length of a barrier in a full-scale crash test, which typically has 29 posts. The w-beam section was oriented such that the impact was mid-span between the two posts. Figure 4 is a schematic of the overall test setup. The overall rail length is approximately 5 meters (198 inches) and the posts were W150 × 13.5 steel posts, 1830 mm (6 feet) in total length.

Developing an appropriate method to anchor each end of the test section to the rigid posts proved to be the most challenging portion of the test setup. The goal was to replicate a two post section as if it was within a full length barrier section, which requires each end of the test section some freedom to both translate and rotate. Due to the close proximity of the rigid posts on either side of the pendulum, the primary focus was on designing the end fixture to allow rotation of each end of the w-beam test section. Also, an effort was made to use as much standard guardrail hardware as possible in the end fixture design. The original end fixture design selected consisted of 3 standard cable anchor brackets and a 910 mm (3 feet) version of the standard 1830 mm (6 feet) swaged cable typically used to anchor w-beam terminals (left image of Figure 5). This configuration was originally selected to ensure w-beam rail rupture would occur before failure of the anchorage.

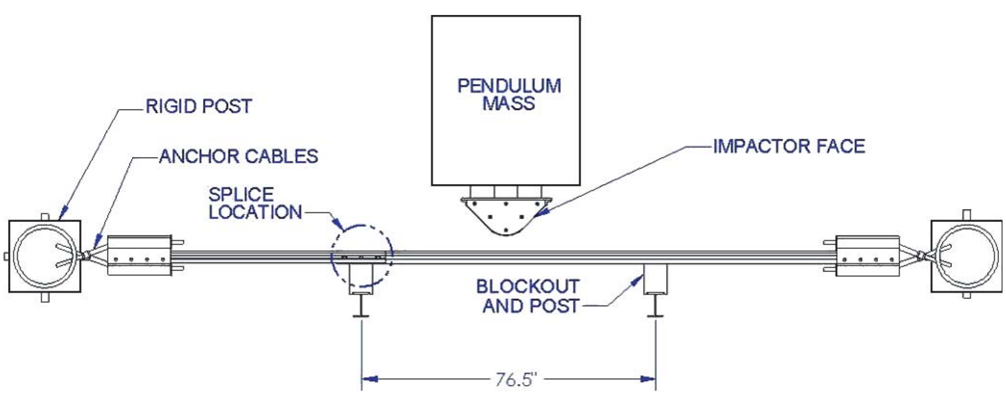


Figure 4. Overall pendulum test setup for an undamaged section.

Figure 5. Three cable (left) and two cable (center) w-beam end fixture and soil box (right).

Later, an alternative 2-cable end fixture design was developed (center image in Figure 5). A comparison of two undamaged section pendulum tests showed no discernable difference in deflection. The 2-cable end fixture proved to be robust and was used in the remainder of the tests to simplify the test setup and reduce costs. As experience was gained in conducting these tests, several minor modifications were made to the 2-cable end fixture, primarily to prevent tearing and bending failures within the fixture. Larger 82.6 mm (3.25 inches) outside diameter washers were used inside the rigid posts to prevent pullout of the cables from the rigid posts. The length of swaged cables was increased by 102 mm (4 inches) so the cable would bend instead of the swage. To prevent tearing in the fixture, the typical washers used in conjunction with the anchor brackets were replaced by an anchor plate. Results from pendulum tests conducted using both the 2-cable and 3-cable end fixture schemes will be presented later in this report.

As the anchor points on the existing rigid posts were higher than the standard w-beam rail height, a soil box was used to raise the ground level around the posts by 7 inches (178 mm) as shown in the right image in Figure 5. The soil box was constructed of four 38 mm × 235 mm × 2.44 m (2 in. × 10 in. × 8 in. long) pine boards and supported on each side by steel rebar to provide the soil restraining force such that proper compaction could be attained. As specified by *NCHRP Report 350*, the soil used in the test conformed to AASHTO M-147-65. A mechanical tamper was used to compact the soil surrounding each W150 × 13.5 steel post in 6-inch lifts. A nuclear density gauge (Troxler Model 3440) was used to determine the compaction and soil properties of each soil lift for each post. For each lift, the preferred compaction level was 95 percent.

Instrumentation. Instrumentation for all tests included two accelerometers located at the rear of the pendulum mass. Both accelerometers were in-line with the pendulum center of gravity and were aligned in the pendulum direction of travel. Tri-axial accelerometers were placed on each rigid post to quantify the motion of the rigid posts during the pendulum impact. Four high speed cameras were used in all tests to capture the behavior of the w-beam section during the impact. Each test had a minimum of two common camera views: (1) a top view of the middle of the w-beam section and (2) a perpendicular rear view of the entire w-beam section. The other two high speed camera views varied between tests depending on the location of the minor damage. In addition to the high speed cameras, one real time camera was used to capture a perspective view of the test in real time.

Impact Conditions and Relevance to Full-Scale Crash Testing. As the FOIL pendulum is not capable of reproducing an oblique impact characteristic of *NCHRP Report 350* longitudinal barrier test procedures, the tests were designed to mimic the lateral forces experienced in a *NCHRP Report 350* redirectional test (Figure 6).

Pendulum tests were conducted at two impact speeds: 32.2 km/hr (20 mph) and 28.2 km/hr (17.5 mph). A 32.2 km/hr (20 mph) impact speed was originally selected to approximate the lateral forces that would result from a 2000 kg test vehicle impacting at 100 km/hr (62 mph) and 20 degrees. Assuming that all the impact energy is absorbed in a two post section of a full-scale test barrier, these conditions represent a lateral impact speed approximately 75 percent that of an *NCHRP*

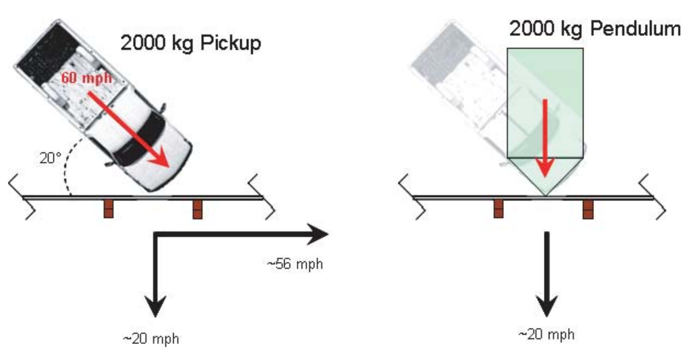


Figure 6. Analogous* NCHRP Report 350 *and pendulum impact scenarios.

Report 350 Test 3-11 impact (100 km/hr and 25 degrees). The constraining factor was the maximum speed of the FOIL pendulum, which is 32.2 km/hr (20 mph). The speed is limited by the maximum height to which the pendulum can be raised.

The pendulum impacts, however, are more severe than a full-scale crash test for two primary reasons: (1) the pendulum test section is a more rigid system and (2) the impact energy is distributed over a smaller area. The end fixtures attaching each end of the w-beam test section to the rigid posts allow only minimal longitudinal translation of the rail section in contrast to the full-scale test where the posts surrounding the impact area deflect, reducing the tension in the rail and splices. Second, in the pendulum test, all the impact energy is absorbed by a single two post (1,905 mm) barrier section. In full-scale tests, however, the lateral energy is primarily distributed over two to four of these 1,905 mm (6 foot) barrier sections. To account for this distributed loading, the pendulum impact speed was reduced to 28.2 km/hr. This impact speed conservatively assumes that the lateral impact energy in a full-scale test is absorbed by two 1,905 mm barrier sections, with each section absorbing half the vehicle lateral kinetic energy.

The pendulum tests were primarily intended to test the structural adequacy of barrier and damaged barrier sections based on representative lateral forces induced by a perpendicular impact to the barrier section. Other relevant barrier performance factors, such as wheel snagging, vehicle rollover, and occupant risk, cannot be evaluated using this test methodology.

3.2.2 Test Plan and Barrier Damage Modes

A total of 3 pendulum tests were conducted of undamaged two-post barrier section to serve as a baseline against which to compare the impact performance test sections with minor damage. Eleven tests of damaged barriers were conducted to test five different barrier damage modes. In each test, a flaw was artificially introduced into the test article prior to the pendulum impact. Table 12 presents a field example of each damage mode and the analogous pendulum test setup. Pendulum tests were conducted either at 32.2 km/hr (20 mph) or 28.2 km/hr (17.5 mph).

3.3 Full-Scale Crash Test Plan

This section describes the configuration of a crash test series to evaluate the crash performance of a damaged longitudinal barrier. The crash performance of the deflected post/rail, the most common damage mode, was evaluated in a full-scale crash test. The plan was to conduct a full-scale crash test of a large pickup truck (2000P) into a damaged strong-post w-beam barrier at *NCHRP Report 350* test level 3 conditions (Test 3-11). Both tests were conducted by MGA Research in Burlington, WI.

As shown in Figure 7, this task actually conducted two crash tests. In the first test, a length of guard rail was purposefully damaged in a low-severity crash, i.e., a low-speed angled impact. This test produced a realistic profile of minor damage to the barrier before the second test. Finite element modeling predicted that minor deflection could be produced through an impact speed of 47 km/hr (30 mph). In the second test, a Chevy C-2500 pickup truck was impacted into the damaged section of the barrier at *NCHRP Report 350* conditions (100 km/hr and an impact angle of 25 degrees). The result of the crash performance was a laboratory assessment of the performance of a barrier with minor post rail deflection damage.

Instrumentation for these tests included a tri-axial accelerometer at the vehicle center of gravity, yaw, roll, and pitch sensors, as well as high-speed photography of the tests. Detailed pre-test and post-test photographs were taken of both the guardrail system and the pickup trucks (Figures 8 and 9). The first lower severity test was documented by a total of six high-speed cameras recording at 500 frames per second and one real-time camera. High-speed cameras were placed alongside the guardrail to obtain both a front and rear overall view and a single camera was suspended over the impact site to collect an overhead overall view. There were also three high-speed cameras mounted behind the right side of the guardrail at varying distance to record the guardrail behavior. The final real-time camera was located behind the left side of the guardrail and panned to capture the full impact. The second full-scale test was documented with an almost identical setup, except that the front overall high-speed camera was removed. The remaining high-speed cameras and the real-time camera were placed in the same location and recorded at the same rates as for the first crash.

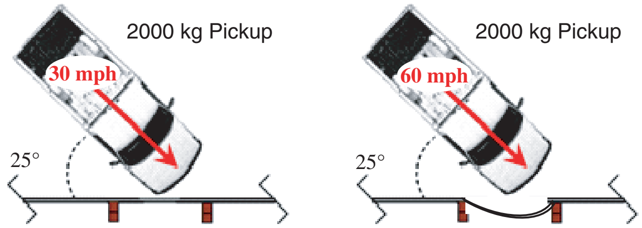
This test also served as a validation case for the finite element model of vehicle-to-guardrail impact. An LS-DYNA simulation of both crash tests was conducted of both tests prior to the tests themselves. The accuracy of the LS-DYNA model was assessed by comparing the results of the simulation with the results of the crash tests. Parameters which were compared included vehicle acceleration at the vehicle center of gravity (x, y, and z-axes), vehicle yaw rate, vehicle departure angle from the barrier, and vehicle stability.

3.4 Finite Element Modeling Approach

The ideal method to test the safety of strong-post w-beam guardrail with minor damage would be to perform crash tests. However, the cost of evaluating large numbers of different damage modes would be prohibitive. As an alternative approach, finite element modeling was used to evaluate the

Table 12. Barrier damage modes evaluated in pendulum tests.

Damage Mode	Field Example	Pendulum Test Setup
Vertical Tear		 
Horizontal Tear		
Splice Damage		
Twisted Blockout		
Missing Blockout		
Hole in Rail		



Crash Test 1 (30 mph) "dents" the rail

Crash Test 2 (62 mph) - second impact to the "dent"

Figure 7. Full-scale crash testing plan of minor post/rail deflection.

crashworthiness of damaged guardrail. Four damage modes were evaluated using finite element modeling: (1) post and rail deflection, (2) missing or damaged posts, (3) post and rail separation, and (4) rail flattening. This chapter describes the development and validation of the model used to evaluate each of these damage modes.

The LS-DYNA code was used to develop a finite element model of the damaged longitudinal barrier systems. LS-DYNA is used extensively by the roadside safety community to study the impact performance of roadside safety features, and by the automotive industry to study the crashworthiness of passenger vehicles. LS-DYNA is well suited to model the large deformations and high strain rates which are characteristic of vehicle crashes into roadside features. It is a general-purpose, explicit finite element program used to analyze the nonlinear dynamic response of three-dimensional structures (LSTC, 2003).

All of the LS-DYNA finite element models were run on a SGI Altix parallel system with 120 processors and 512 GB of memory. Each simulation was run using four processors, with multiple simulations being run in parallel to decrease the time needed to complete the study. Each of the finite element

Figure 8. Vehicle orientation prior to first MGA crash test.

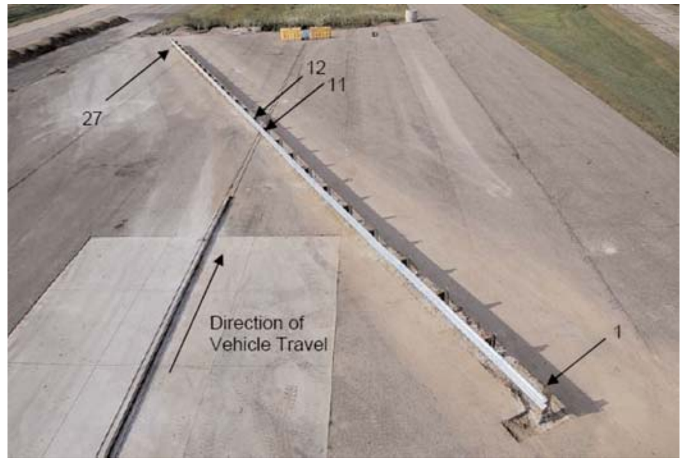


Figure 9. Guardrail for MGA crash tests.

models was built using roughly 172,000 elements. Running the simulations on the system described previously, each simulation took approximately one day of real time to calculate 1,000 ms of simulated time.

3.4.1 The Vehicle-Guardrail Model

A full-scale finite element model was created from two parts: (1) a model of a 175.8-foot (53.6 meters) length of strong-post w-beam guardrail and (2) a model of a Chevrolet 2500 pickup truck. Each model is described in more detail below. All of the initial conditions for the full scale model were adjusted to match the values specified by *NCHRP Report 350,* i.e., the vehicle was given an initial velocity of 62.1 mph (100 km/hr) and angle of impact was set to 25 degrees. An example of a completed full-scale model with 6 inches of rail and post deflection is shown in Figure 10.

3.4.2 Strong-Post W-Beam Guardrail Model

This research program focused on the modified G4 (1S) strong-post w-beam guardrail that uses steel posts with plastic

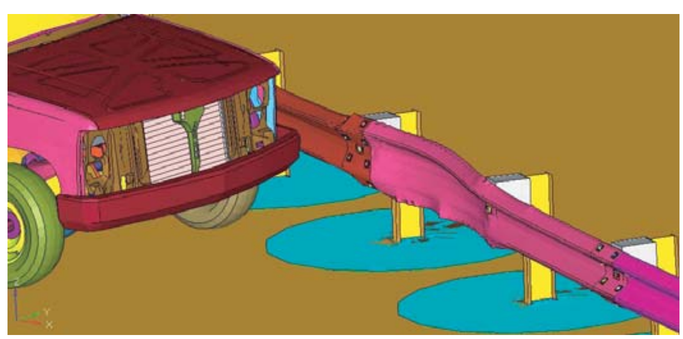


Figure 10. Simulated guardrail with rail and post deflection.

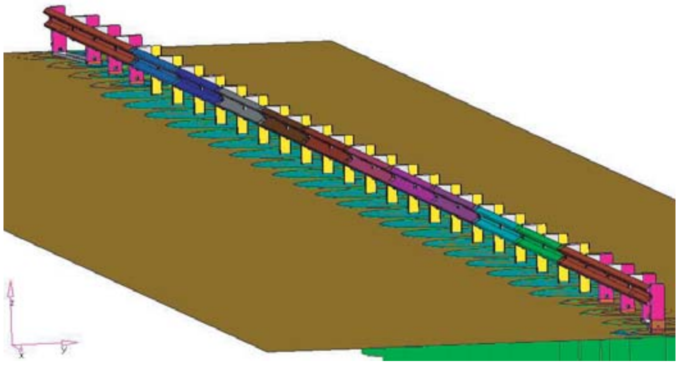


Figure 11. The NCAC strong-post w-beam guardrail model.

blockouts. A guardrail model with steel posts was selected because the steel posts represent the worst case scenario for both snagging of the vehicle tires during impact and the development of localized stress concentrations on the edges of the post flanges. While the results using a steel post system will be conservative, it was felt better to err on the side of caution than to allow a borderline hazardous condition to be considered an acceptable amount of damage.

The basic modified steel strong-post w-beam guardrail model was a publicly available model from the National Crash Analysis Center (NCAC) finite element library (NCAC, 2009a). The basic guardrail model used for this study is shown in Figure 11. The model was designed to be used with the LS-DYNA finite element simulation software (LSTC, 2003). The guardrail system was 53.6 meters (175.8 feet) in length from end to end with 29 posts. Routed plastic blockouts were used instead of wood blockouts. The soil supporting the guardrail system was modeled as individual buckets around each post, rather than as a continuum body. Each steel post was embedded in a cylindrical volume of soil 2.1 meters (6.9 feet) deep and 1.6 meters (5.25 feet) in diameter.

Since the vehicle and guardrail models selected for use in this research were validated against test data, there was little need to make changes to the models. The only alteration to the guardrail model was an increase in the stiffness of the springs holding the splice bolts together. The increase in stiffness from 66.5 to 2,400 kN (15 to 540 kip) was needed to keep the splice bolts from unrealistically separating during impact. The increase in stiffness reflected the bolt strength used in a model developed for a study on guardrails encased in paved strips (Bligh et al., 2004).

3.4.3 Pickup Truck Model

As a test vehicle, the finite element simulations used the detailed model of a 1994 Chevrolet 2500 pickup truck available from the NCAC library. Specifically, the simulations

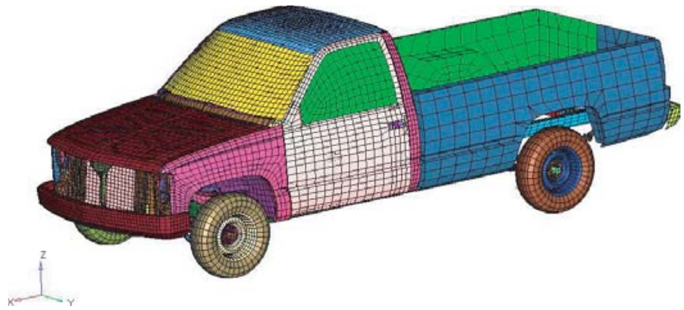


Figure 12. The NCAC finite element model of a 1994 Chevrolet 2500 pickup truck.

used Version 0.7, published by the NCAC finite element library on November 3, 2008 (NCAC, 2009b). Like the guardrail model, this vehicle model was designed to be used with the LS-DYNA finite element solver. The vehicle is shown below in Figure 12.

The detailed Chevrolet 2500 pickup model was selected for a number of reasons. First, the model was already subjected to a thorough validation effort to ensure the fidelity of the suspension of structural stiffness (NCAC, 2009a). The detailed model also incorporates many interior parts that would not be present in a reduced model, such as the seating, steering column, bearings, fuel tank, and battery. The higher mesh density for the detailed pickup model also improved the accuracy and contact stability during simulation.

A limitation of the finite element model of the Chevrolet 2500 was that the dimensions of the vehicle were fixed. Most real pickup trucks have adjustable suspensions, which allow the front and rear bumper height of the vehicle to vary by as much as 100 mm (3.9 inches). However, even changes of a few centimeters in the relative height of the vehicle and guardrail have had been shown to have dramatic effects on the crash test results (Marzougui et al., 2007).

The success or failure of a crash test can depend greatly on the relative height of the vehicle and guardrail (Marzougui et al., 2007). It was critical that the finite element vehicle model match the recorded dimensions of the real test vehicles as closely as possible. The three crash tests that were used for this study had drastically different bumper heights, as shown in Table 13. A modified version of the original finite element vehicle was developed to match these alternate dimensions. The majority of the simulations in this study were performed with the vehicle matching the dimensions for the Texas Transportation Institute (TTI) crash test.

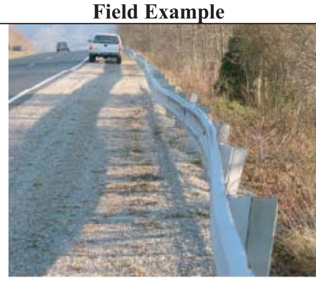
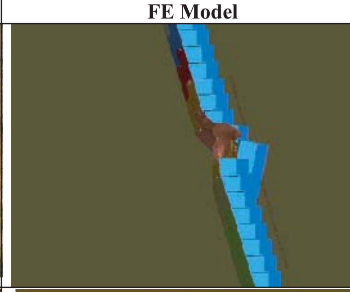
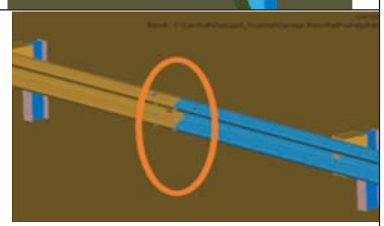
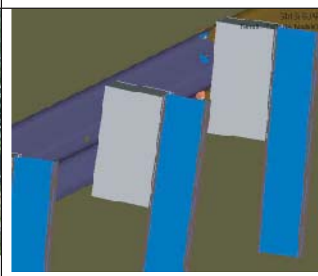
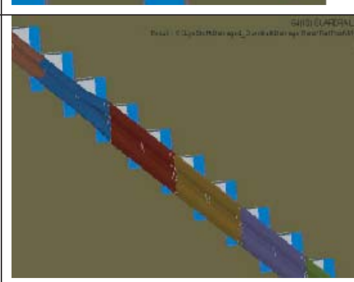
3.4.4 Matrix of Finite Element Simulations

Table 14 shows the finite element simulation matrix. In each case, a flaw was artificially introduced into the basic guardrail model prior to impact.

Table 13. Dimensions of finite element models of the Chevrolet 2500 pickup truck.

Dimension	Original Chevrolet 2500 for TTI Test	Chevrolet 2500 for UNL Test	Chevrolet 2500 for MGA Test
Width	195.4 cm	195.4 cm	195.5 cm
Length	565.5 cm	565.4 cm	565.5 cm
Height	179.2 cm	182.9 cm	185.4 cm
Front Bumper height	63.6 cm	60.3 cm	68.1 cm
Rear Bumper height	70.6 cm	79.9 cm	76.5 cm
Tire Diameter	73.0 cm	73.0 cm	73.0 cm
Weight	2013 kg	2011 kg	2014 kg

Table 14. Barrier damage modes evaluated through finite element modeling.

Damage Mode	Field Example	FE Model
Rail and Post Deflection		
Missing Post		
Separated Rail / Post		
Rail Flattening		

3.5 Validation of the Finite Element Models

Proper validation of the finite element models is crucial to the accuracy of the simulations. The validation plan for the finite element simulations was as follows: (1) validation of coupled vehicle-roadside hardware models, (2) validation against full-scale crash tests involving damaged barrier, and (3) validation against component tests conducted with a pendulum impact rig. In each case, the finite element models were able to faithfully reproduce the corresponding impact experiment. Details of the validation studies are provided in the appendices.

3.5.1 Undamaged Barrier Full-Scale Crash Test Validation

The most crucial form of validation was the validation of LS-DYNA models of the coupled vehicle-longitudinal barrier systems. To validate the model, the research team constructed an LS-DYNA model of an *NCHRP Report 350* crash test of the subject barrier under impact loading. The crash test that was selected for this purpose was a test performed by the TTI to demonstrate the crash performance of the modified G4 (1S) guardrail. The crash test was a success, with the vehicle being redirected away from the guardrail. The occupant impact velocity and ridedown acceleration were well below the recommended values of 9 m/s (20.1 mph) and 15 G, respectively. The damage to the guardrail was considered to be moderate, with approximately 1 meter (3.3 feet) of dynamic deflection and 0.7 meters (2.3 feet) of static deflection recorded.

Because this was a validation simulation, there was no need to induce any pre-existing damage in the guardrail. Thus, the finite element model of the vehicle and guardrail was unmodified. The finite element vehicle was given initial conditions to match the test level 3 criteria i.e., an initial velocity of 100 kph (62.1 mph) and an impact angle of 25 degrees. This varied slightly from the real test, for which the initial speed was 101.5 kph (63 mph) at 25.5 degrees. The model was run as is for 1,000 ms and compared to the documented crash test results.

The crash test results were compared with the structural impact response of the simulated vehicle-barrier system. The model was able to reproduce maximum dynamic and permanent rail deflection, vehicle exit conditions (exit speed and angle of the test vehicle), and the occupant injury parameter response (impact velocity and occupant ridedown acceleration as prescribed by *NCHRP Report 350*). Figure 13 shows the good qualitative comparison between the crash test and simulation. Detailed validation results are contained in the appendices.

3.5.2 Damaged Barrier Full-Scale Crash Test Validation

This research program also conducted an *NCHRP Report 350*-type crash test of a vehicle colliding with a damaged section of strong-post w-beam barrier. In parallel, an LS-DYNA model of this scenario was constructed and executed. The experimentally measured structural impact response of the vehicle/barrier was compared with the corresponding response from the simulation using the validation methodology used to validate the models against standard *NCHRP Report 350* crash tests involving undamaged barrier sections. In each case, the finite element models were able to faithfully reproduce the corresponding impact experiment.

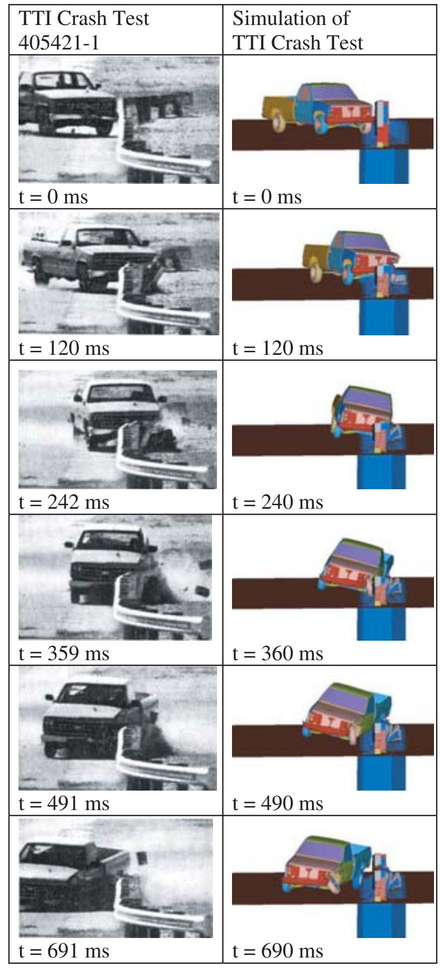


Figure 13. Comparison of undamaged guardrail crash test and simulation.

3.5.3 Pendulum Component Test Validation

Pendulum tests were conducted to provide additional validation data for the finite element longitudinal barrier models. Damaged two-post sections of barrier were impacted with a 2000 kg concrete impactor. The presumption is that if the finite element model can replicate a pendulum test, this is a necessary (but not necessarily sufficient) test of a 100-foot long rail section. The models were able to reproduce barrier response (maximum dynamic deflection and post position vs. time) and pendulum acceleration response.

3.6 Extensions to Other Damage Modes and Barrier Types

Comparison of the minor damage catalog in the appendices with the proposed repair guidelines also shows that it was not possible to test all proposed repair guidelines. However, the tests and simulations that were conducted allow us to infer the performance of several other damage modes under crash loading.

The following paragraphs provide a summary of those damage modes:

- **Rotten Wood Posts/Blockouts**—The proposed guidelines recommended replacement of rotted wood posts or blockouts. Although the research team did not simulate or test this directly, the effect of a rotted post or blockout would be the same as a missing post or blockout—a condition which was evaluated.
- **Steel Post Torsion**—The proposed guidelines recommend repair of barrier systems with posts that have been severely twisted. Although the research team did not simulate or test this directly, the effect of a severely twisted steel post would be similar to a missing post—a condition which was evaluated.
- **Any Structural Corrosion (hole or section loss)**—The proposed guidelines recommend repair of barrier systems which have suffered structural corrosion as opposed to surface corrosion of the galvanizing treatment. Although the research team did not simulate or test the effect of structural corrosion directly, the response of a seriously corroded rail was expected to be similar to a rail hole or tear—a condition which was evaluated.
- **Rail Flattening (vertical dent)**—The matrix evaluated length-wise flattening of the rail. This was observed to be a more common occurrence than height-wise flattening or vertical denting of rail. The research team's recommendation was based upon the consensus of current state guidelines. No simulations or tests were planned.
- **Missing or Loose Bolts**—The guidelines proposed that problems with bolts should be corrected. No simulations or tests were planned.
- **Weak Post W-Beam Systems**—Weak post w-beam guidelines were not evaluated independently of strong-post w-beam guidelines. Crash tests have shown that a primary failure mechanism of weak post w-beam barrier is rail rupture (Ray et al., 2001a; 2001b). The results of strong post pendulum tests of vertical tears, horizontal tears, and holes were assumed to apply to weak post systems. Because of the crucial function of the splice in weak-post systems, the proposed guidelines do not allow any splice damage or absence of splice bolts.

CHAPTER 4

Evaluation of Vertical Tear Damage

The objective of this evaluation was to determine the effect of a vertical tear on barrier crash performance (Figure 14). The approach was to subject a barrier test section with an artificially introduced vertical tear to a pendulum test. The performance of the barrier section with the flaw was compared to the performance of a similar barrier section with no flaw. This chapter presents the pendulum test results of both the baseline undamaged section and the section with the vertical tear. The pendulum test setup was described in an earlier chapter on the research approach.

4.1 Baseline Tests

Pendulum tests were conducted at two impact speeds: 32.2 km/hr (20 mph) and 28.2 km/hr (17.5 mph). In Test 03-2, the undamaged barrier contained the pendulum mass impacting at 30.9 km/hr (19.2 mph). The impact speed was calculated using the data from the pendulum-mounted accelerometers. The maximum dynamic deflection of the test section was 739 mm (29.1 inches) at 140 ms after the initial impact, computed from the pendulum acceleration data. The maximum static crush at the center of the w-beam was 356 mm (14 inches). The overall damage and individual post damage is shown in Figures 15 and 16. The post at the splice location (center in Figure 15) experienced more torsion than the non-splice post and had some minor cracking at the flange. The post at the splice location also remained connected to the rail while the post bolt at the non-splice location pulled through the slot in the rail. There were no failures in the anchor cables in this test, and there was no visible separation of the cable from the swaged portion of the anchor cable assembly. At the splice location, there was approximately 19 mm (0.75 inches) of relative movement between the two w-beam rail sections. No tears were evident in the guardrail and no bolt failure was observed. The left portion of Figure 17 shows time sequence snapshots of Test 03-2 obtained from the high speed camera positioned overhead.

In general, the remaining two undamaged barrier tests (not shown) had similar results to Test 03-2. Tests 01-2 and 07-1 both had successful containment of the pendulum mass. In both tests, the post-rail connection at the splice remained intact and post-rail bolt pullout was evident at the non-splice location. The separation at the splice was also approximately 19 mm (0.75 inches) in both tests. For Test 01-2, both the impact speed and maximum deflection were slightly higher compared to the analogous 2-cable test (Test 03-2, Table 15).

In all three baseline tests, the undamaged barrier section demonstrated satisfactory impact performance by containing the pendulum mass. The cable end fixture designs provided adequate connection of the w-beam section to the existing rigid posts on either side of the pendulum. With the exception of the shorter swaged cables, the end fixtures were constructed with standard barrier hardware. The cable end fixtures provide a very rigid connection of the w-beam to the essentially rigid posts on either side of the pendulum. Based on an analysis of data from the rigid post mounted accelerometers, the maximum motion of each rigid post was approximately 1 inch (data not shown) toward the pendulum mass, which would have a tendency to slightly reduce the tension in the w-beam rail. This rigid connection coupled with the 32.2 km/hr (20 mph) pendulum impact speed, though, provides a very severe impact to the barrier section, which approaches the limit of the strong post barrier section. The ability of the w-beam barrier to withstand an impact of this severity is a testament to its structural robustness.

The pendulum tests appear to be an appropriate surrogate for determining the structural adequacy of w-beam barriers. A limitation of this test methodology is an inability to evaluate vehicle trajectory/stability as well as occupant risk. Most importantly, these tests provide insight into the crash performance of modified G4 (1S) strong-post w-beam barriers

Field Example

Pendulum Test Setup – 4-in. Tear

Pendulum Test Setup – ½-in. Tear

Figure 14. Vertical tear evaluated in pendulum tests.

Figure 15. Test 03-2: overall damage (right) and post damage at splice (center) and non-splice location (right).

Figure 16. Test 03-5: overall damage.

that have sustained minor damage. Several of these damage modes have been tested with repeated tests, albeit with slightly different impact speeds.

4.2 Method of Introducing the Vertical Tear

A vertical tear was simulated by cutting a "V" shaped notch in the w-beam using a reciprocating saw. The point at the end of the notch was intended to provide a stress concentrator similar to those observed in the field in a crash-induced vertical tear. In all vertical tear tests, the location of the tear corresponded to the pendulum mass impact location, as this was believed to have the largest risk for rail rupture. Two different length tears were tested: a 4-inch (102 mm) tear and a 0.5-inch (13 mm) tear. All tears started from the top of the

Table 15. Pendulum testing summary for vertical tears.

Damage Mode	Test #	End Fixture	Impact Speed (km/hr)	Maximum Deflection* (mm)	Time of Max Deflection (ms)	Crash Performance
Undamaged	01-2	3-Cable	32.7	767	136	Containment
	03-2	2-Cable	30.9	739	140	Containment
	07-1	2-Cable	28.3	610	140	Containment
Vertical Tear (4 in.)	01-3	3-Cable	32.0	592*	84	Penetration, Tear at center
	03-5	2-Cable	32.8	533*	90	Penetration, Tear at center
Vertical Tear (0.5 inch)	08-2	2-Cable	32.9	711	144	Containment, Tear at center

w-beam section. For the 4-inch tear, the width of the tear was 0.5 inches at the w-beam edge and tapered to a point. For the 0.5-in (13 mm) tear, the width of the tear was approximately 4 mm (0.15 inches).

4.3 Results

In Test 03-5, the barrier section with a 4-inch (102 mm) vertical tear was unable to contain the pendulum mass impacting at 20.4 mph (32.8 km/hr) (see Table 15). Impact speed was computed by analysis of the high-speed overhead video footage. A vertical tear developed from the bottom tip of the induced vertical tear and continued (approximately straight downward) through the entire w-beam cross section resulting in a complete transection of the w-beam at the impact location. Based on an analysis of the overhead high-speed video data, the deflection of the rail was 533 mm (21 inches) at 90 ms after initial impact, which was just prior to penetration of the w-beam section. At 118 ms after initial impact, the w-beam was completely transected. The overall damage and the post damage due to impact are shown in Figure 16. Other than at the damage location, there were no other tears evident in the w-beam.

The right portion of Figure 17 shows time sequence snapshots of Test 03-5 obtained from the high speed camera positioned overhead. The performance of the analogous 3-cable test (not shown), Test 01-3, was very similar with the pendulum penetrating the barrier section due to a full cross-section tear at the impact location. Post damage and relative movement of the w-beam sections at the splice was similar. Again, the post-rail connection at the splice remained intact while the post-rail bolt pulled through the rail at the non-splice location.

For the 0.5-inches (13 mm) vertical tear damage in Test 08-2, the barrier was able to contain the pendulum mass with a maximum deflection of 711 mm (28 inches). A vertical tear developed from the bottom tip of the induced vertical tear, at 13 mm from the w-beam edge, and continued (roughly straight downward) through approximately half of the w-beam cross section. The overall damage and close-up views of the tear propagation are shown in Figure 18.

4.4 Recommendation

Pendulum testing of a strong-post w-beam barrier with a vertical (transverse) tear resulted in complete rail rupture. This was due both to the loss in an available cross section to carry the tensile load as well as the introduction of a stress concentrator. Although the vertical tear in the pendulum test was relatively severe (roughly one-fourth of the w-beam cross section), the research team believes that any vertical tear represents a stress concentrator sufficient to cause further tearing should the barrier be subjected to a secondary impact. A second pendulum test was conducted for a small vertical tear of 13 mm (0.5 inches) in length. A pendulum impact at 20 mph caused this small tear to grow ominously to a length of 4 inches The research team concluded that no vertical tear is safe. To be cautious, the research team has classified vertical rail tears of any length as a damage mode that should be repaired with high priority (Exhibit 1.0).

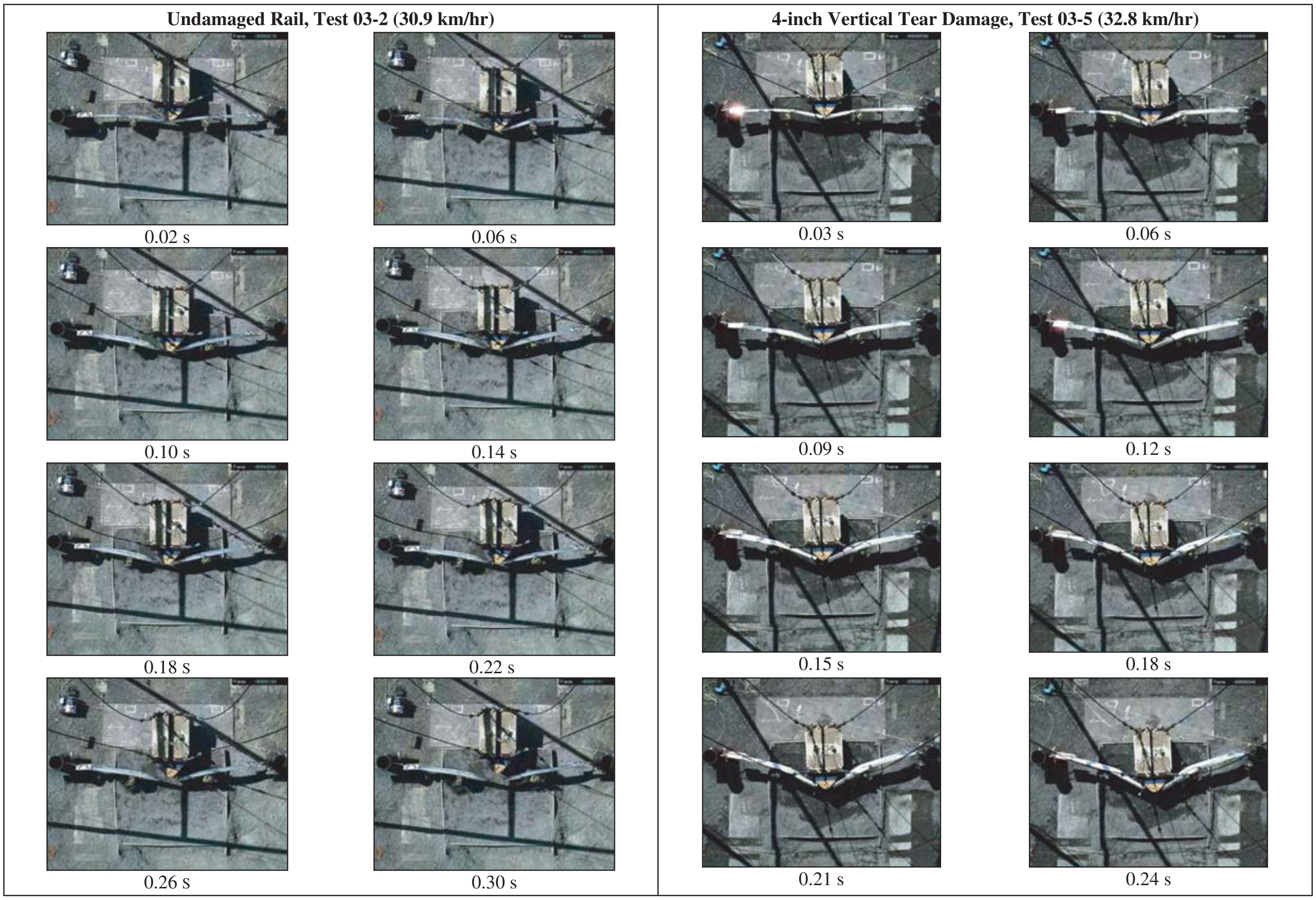


Figure 17. Sequential overhead photographs for undamaged section (left) and 4-inch vertical tear damage (right).

Figure 18. Test 08-2: overall damage (left) and detail views of the additional tearing caused by the pendulum impact (center), and post damage at splice location (right).

Exhibit 1.0. Recommendations for vertical tear damage repair.

Damage Mode	Repair Threshold	Relative Priority
Horizontal tears	Horizontal (longitudinal) tears greater than 12 in. long or greater than 0.5 in. wide should be repaired with a medium priority. Note: for horizontal tears less than 12 in. in length or less than 0.5 in. in height, use the non-manufactured holes guidelines.	Medium

CHAPTER 5

Evaluation of Horizontal Tear Damage

The objective of this evaluation was to determine the effect of a horizontal tear on barrier crash performance (Figure 19). The approach was to subject a barrier test section with an artificially introduced horizontal tear to a pendulum test. The performance of the barrier section with the flaw was compared to the performance of a similar barrier section with no flaw. The pendulum test setup is described in an earlier chapter on the research approach.

5.1 Method of Introducing the Damage

A horizontal tear was simulated by cutting a longitudinal notch in the center of the upper protrusion of the w-beam using a reciprocating saw. Each end of the notch was cut into a "V" shape to provide a stress concentrator similar to those observed in the field in a crash-induced horizontal tear. The location of the tear corresponded to the pendulum mass impact location, as this was believed to have the largest risk for rail rupture. The horizontal tear was a total of 306 mm (12 inches) long. The middle 204 mm (8 inches) of the tear was 13 mm wide (0.5 inches) with a 51 mm (2 inches) "V" shaped taper on either end.

5.2 Results

The horizontal tear damaged barrier in Test 07-3 contained the pendulum mass impacting at 29.3 km/hr (18.2 mph), which was calculated using the data from the high speed video footage. The maximum dynamic deflection of the test section was 579 mm (22.8 inches) at 130 ms after the initial impact, computed from the pendulum acceleration data. The maximum static crush at the center of the w-beam was 406 mm (16.0 inches). The damage at the impact location and individual post damages are shown in Figure 20. Both post-rail connections remained intact and there was 16 mm (0.63 inches) of relative movement between the two w-beams at the splice location. Figure 21 shows time sequential snapshots of Test 07-3 obtained from the high speed camera positioned overhead.

In Test 02-1, the horizontal tear damaged barrier (overhead sequence not shown) was unable to contain the pendulum mass impacting at 31.2 km/hr (19.4 mph), which was calculated using the data from the high speed overhead video. The deflection of the rail was 699 mm (27.5 inches) at 128 ms after the initial impact, which was just prior to penetration of the w-beam section. The barrier section failed at the splice due to

Field Example

Pendulum Test Setup

Figure 19. Horizontal tear evaluated in pendulum tests.

Figure 20. Test 07-3: detailed view of impact location (left), post damage at splice (center), and non-splice location (right).

the splice bolts pulling through holes in the rail with none of the individual splice bolts fracturing. At both the splice and non-splice location, the post bolt pulled through the rail element. The splice failure and post damage is shown in Figure 22.

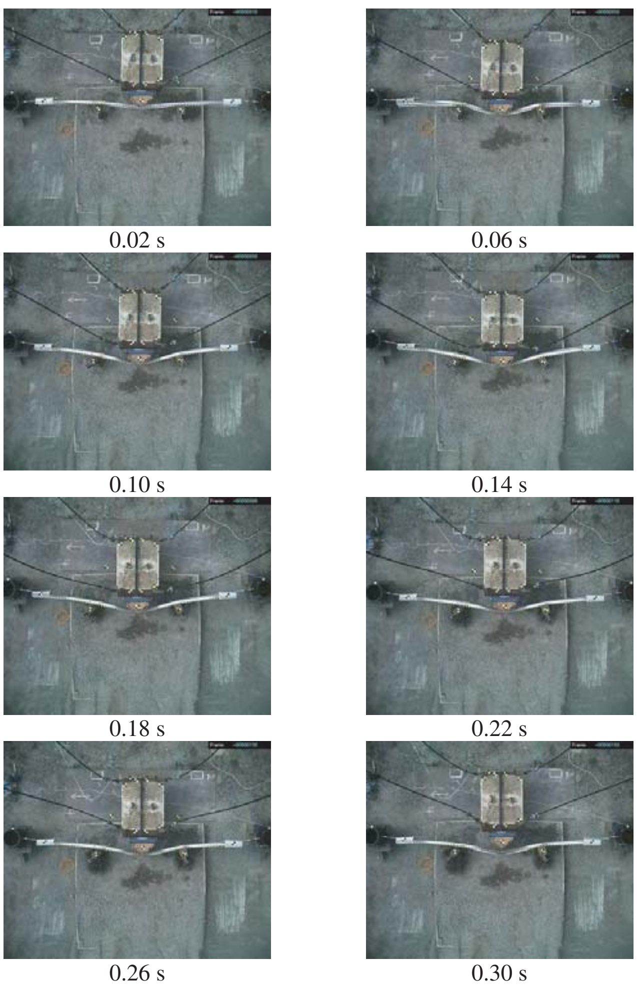


Figure 21. Sequential overhead photographs for 29.3 km/hr pendulum impact of barrier with horizontal tear damage (Test 07-3).

5.3 Recommendation

Pendulum tests show that horizontal tears less than 306 mm (12 inches) in length and 13 mm (0.5 inches) in width do not significantly alter the performance of the barrier. In the 29.3 km/hr (18.2 mph) test, the damaged barrier was able to contain the impacting pendulum mass. In the higher speed 31.2 km/hr (19.4 mph) test, a splice failure was observed, although there was no evidence of rail rupture near the location of the horizontal tear.

A pendulum test (18.2 mph impact speed) of a strong-post w-beam barrier section with a 12-inch horizontal (longitudinal) tear (0.5 inches wide) resulted in successful containment of the pendulum mass. For this test, the horizontal tear was located at the impact location in the upper fold of the w-beam in order to represent a practical worst case. The performance of this damaged barrier section was virtually identical to that of the undamaged strong-post barrier section tested at the 17.5 mph impact speed. In a slightly higher speed 31.2 km/hr (19.4 mph) test, a splice failure was observed, although there was no evidence of rail rupture near the location of the horizontal tear.

As a result, the research team has recommended that the repair threshold for horizontal tears be those exceeding a length of 12 inches and a width of 0.5 inches. The rationale for the width specification is that horizontal tears with sufficient width reduce the tensile capacity of the rail through a reduction in available cross-section area in the area of the tear. The research team's recommendation is that larger horizontal tears should be repaired with a medium priority (Exhibit 2.0).

Figure 22. Test 02-1: detailed view of splice failure (left), post damage at splice (center), and non-splice location (right).

Exhibit 2.0. Recommendations for horizontal tear damage repair.

Damage Mode	Repair Threshold	Relative Priority
Horizontal tears	Horizontal (longitudinal) tears greater than 12 in. long or greater than 0.5 in. wide should be repaired with a medium priority. <u>Note</u>: for horizontal tears less than 12 in. in length or less than 0.5 in. in height, use the non-manufactured holes guidelines.	Medium

CHAPTER 6

Evaluation of Splice Damage

The objective of this evaluation was to determine the effect of splice damage on barrier crash performance by pendulum testing (Figure 23). The performance of the barrier section with splice damage was compared to the performance of a similar barrier section with no flaw. The pendulum test setup is described in an earlier chapter on the research approach.

Splice damage was simulated by removing a rectangular block of material directly in line with a single splice bolt and having width equal to the diameter of the splice bolt. The intent was to simulate complete loss of bearing capacity for a single bolt (of 8 bolts total) in the splice connection.

6.1 Results

In Test 07-4, the splice damaged barrier contained the pendulum mass impacting at 29.3 km/hr (18.2 mph), which was calculated using the overhead high-speed video footage. The maximum dynamic deflection of the test section was 574 mm (22.6 inches) at 130 ms after the initial impact. Both post-rail connections remained intact and no serious splice separation was observed in the splice damage created prior to the impact. There was approximately 13 mm (0.5 inches) of relative movement between the two w-beams at the splice location. A detailed view of the splice damage and the individual post damage is shown in Figure 24. Figure 25 shows time sequence snapshots of the test obtained from the overhead camera.

6.2 Recommendation

A pendulum test of a strong-post w-beam barrier with splice damage resulted in successful containment of the pendulum mass. The splice damage consisted of extending the hole for a single splice bolt to the end of the rail (e.g., no bearing capacity for that particular bolt). Under a pendulum impact at 29.3 km/hr (18.2 mph), this barrier was able to contain the impacting pendulum mass with performance indistinguishable from the undamaged barrier section. It is known however from full-scale crash testing as well as the splice failures observed in the pendulum tests that the splice is a weak point in the guardrail system. Balancing these two observations, the research team recommends a repair threshold of 2 or more splice bolts with any guardrail material missing around the bolts with high priority. In the case of damage to a single splice bolt, the research team assigned the repair a medium priority (rather than a low priority) based on the fact that the splice is the weak point in the rail element (Exhibit 3.0).

Figure 23. Splice damage evaluated in pendulum tests.

Figure 24. Test 07-4: Detail view of splice bolt damage after test (left) and post damage at splice (center) and non-splice location (right).

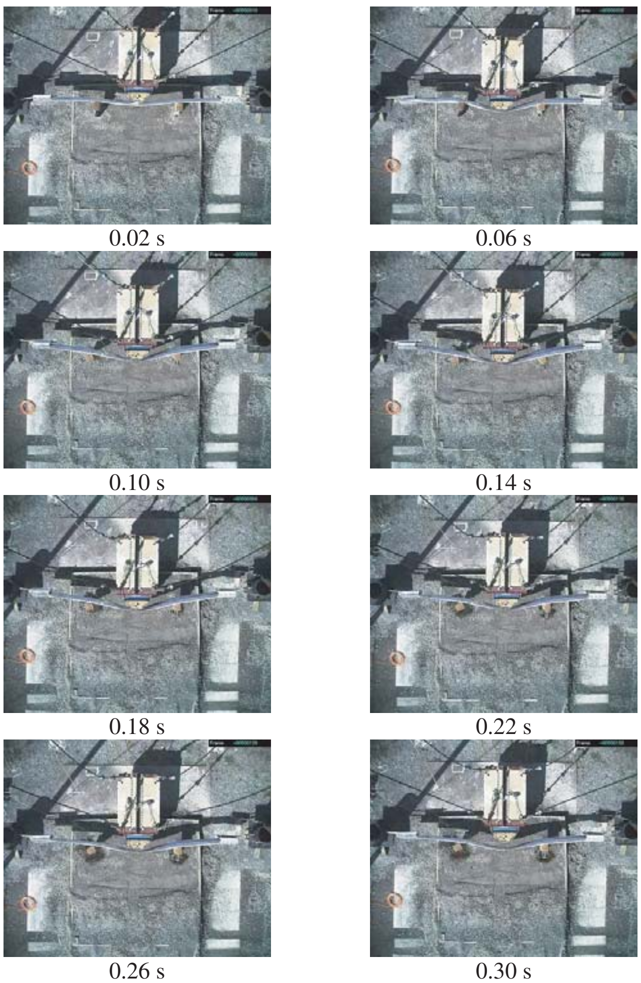


Figure 25. Sequential overhead photographs for splice damage, Test 07-4 (29.3 km/hr).

Exhibit 3.0. Recommendations for splice damage repair.

Damage Mode	Repair Threshold	Relative Priority
Damage at a rail splice	More than 1 splice bolt: • Missing, • Damaged, • Visibly missing any underlying rail, and • Torn through rail.	High
	1 splice bolt: • Missing, • Damaged, • Visibly missing any underlying rail, and • Torn through rail.	Medium

CHAPTER 7

Evaluation of Twisted Blockout Damage

The objective of this evaluation was to determine the effect of twisted blockouts on barrier crash performance by pendulum testing (Figure 26). The performance of the barrier section with twisted blockouts was compared to the performance of a similar barrier section without this flaw. The pendulum test setup is described in an earlier chapter on the research approach. In this case, the routed wooden blockout at the splice was installed rotated about the post-rail bolt. The blockout was rotated approximately 45 degrees with respect to the vertical in all tests.

7.1 Results

In Test 03-8, the twisted blockout damaged barrier contained the pendulum mass impacting at 31.2 km/hr (19.4 mph). The impact velocity was calculated using the data from the pendulum-mounted accelerometers. Based on the analysis of the high-speed overhead video, the maximum dynamic deflection was 691 mm (27.2 inches) at 131 ms after the initial impact. The maximum static crush at the center of the w-beam was 356 mm (14 inches). The overall damage and the post damage due to impact are shown in Figure 27. Figure 28 shows time sequential snapshots of Test 03-8 obtained from the overhead high speed camera.

The posts experienced similar damage to that in previous tests that contained the pendulum. The post at the splice location experienced more torsion than the non-splice post and had some minor cracking at the flange. The post at the splice remained connected to the rail while the post-rail bolt at the non-splice location pulled out of the slot in the rail. There were no failures in the anchor cables in this test, and there was no separation of the cable from the swage portion of the anchor cable assembly. Splice separation was similar to previous tests with approximately 19 mm (0.75 inches) of relative motion between the w-beam sections. No tears developed in the guardrail and no bolts failed. The analogous 3-cable test (not shown), Test 02-2, also contained the pendulum mass with very similar impact performance.

7.2 Recommendation

The performance of the barrier section with this damage was indistinguishable from that of the undamaged barrier section

Field Example

Pendulum Test Setup

Figure 26. Twisted blockout evaluated in pendulum tests.

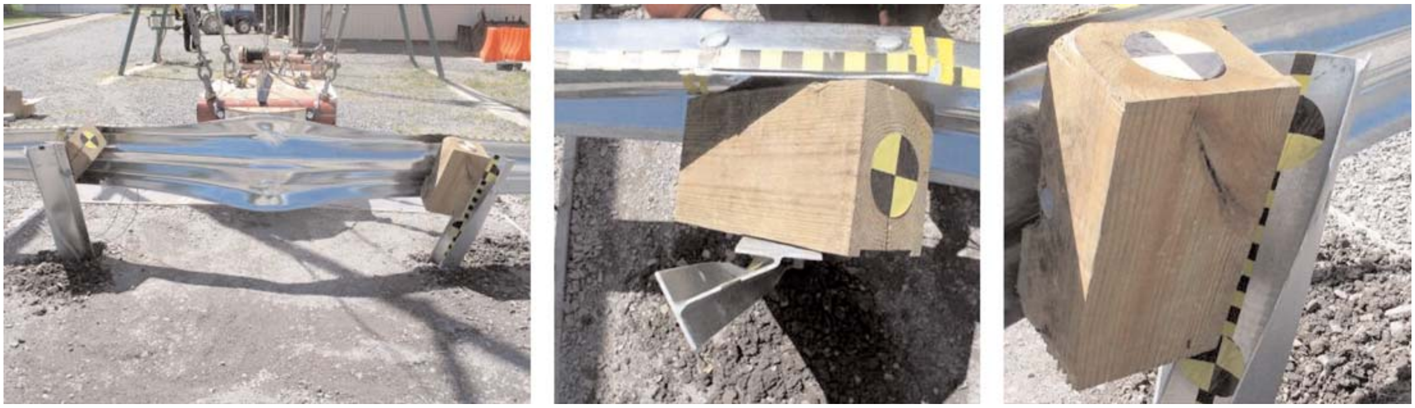


Figure 27. Test 03-8: Overall damage (left) and post damage at splice (center) and non-splice location (right).

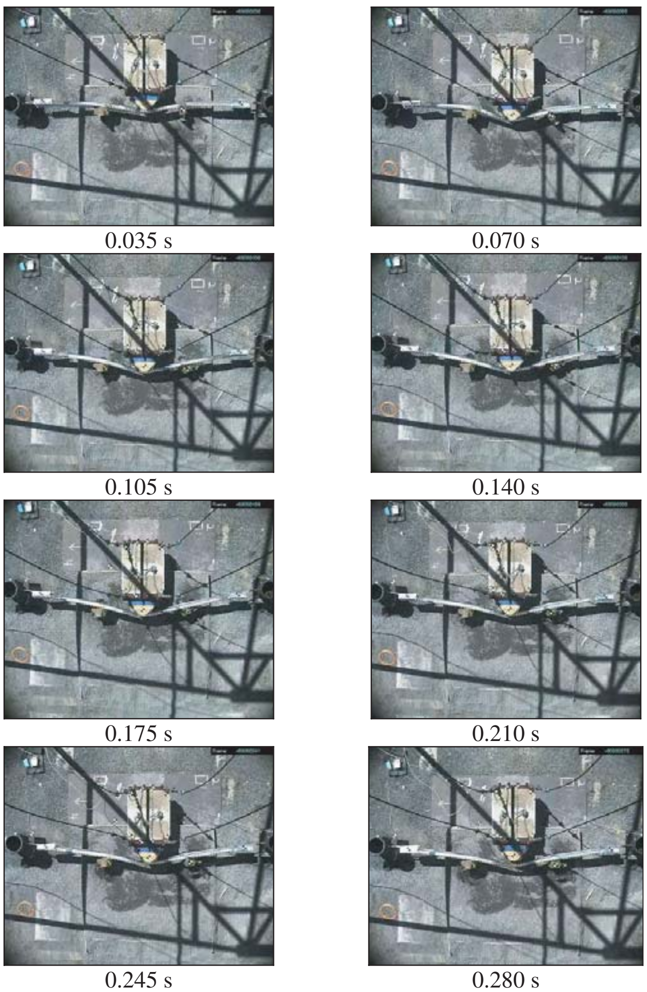


Figure 28. Sequential overhead photographs for barrier with a twisted blockout, Test 03-8 (31.2 km/hr).

in two higher speed tests conducted. This suggests that this damage mode has little effect on the structural adequacy of the barrier. A pendulum test of a strong-post w-beam barrier section with a twisted blockout (~45 degrees relative to the vertical position) at the splice location successfully contained the pendulum mass.

The performance of this damaged barrier section was virtually identical to that of the undamaged strong-post barrier section tested. As a result, the research team has recommended a repair threshold of one or more twisted blockouts. To be conservative, the twist threshold level for a misaligned blockout was set at 6 inches or more difference between the top and bottom edge of the blockout. This linear distance corresponds to an angle of approximately 25 degrees relative to the vertical position, half the angle of the twisted blockout in the pendulum test.

The priority assigned was low due to the indiscernible performance difference from the undamaged condition (Exhibit 4.0). The research team notes that the repair of twisted blockouts is relatively inexpensive, and there is little reason to delay this repair.

Exhibit 4.0. Recommendation for twisted blockout damage repair.

Damage Mode	Repair Threshold	Relative Priority
Twisted blockouts	Any misaligned, top edge of block 6 in. or more from bottom edge <u>Note</u>: Repairs of twisted blockouts are relatively quick and inexpensive.	Low

CHAPTER 8

Evaluation of Missing Blockout Damage

The objective of this evaluation was to determine the effect of a missing blockout on barrier crash performance through pendulum testing (Figure 29). The performance of the barrier section with a missing blockout was compared to the performance of a similar barrier section with a blockout in place. The pendulum test setup is described in an earlier chapter on the research approach.

For this damage mode, the blockout at the splice location was not installed. The post-rail bolt remained connected to simulate a wooden blockout that had split completely and was no longer present. Two pendulum tests were conducted—one at 19.0 mph and one at 18.2 mph. In both tests, there was approximately 178 mm (7 inches) of separation between the near flange of the post and the back of the w-beam rail. The splice location was thought to be the critical case as the splice is the weakest link in the rail element.

8.1 Results

For the missing blockout damage, a high-speed test and low-speed test were performed. In the high-speed test (Test 03-7), the barrier was unable to contain the pendulum mass impacting at 30.6 km/hr (19.0 mph). Impact velocity was calculated based on the high-speed video footage. The barrier section failed at the splice due to the splice bolts pulling through holes in the rail with none of the individual splice bolts fracturing. This failure was similar to that observed in Test 02-1 with the horizontal tear damaged section. Based on an analysis of the overhead high-speed video data, the deflection of the rail was approximately 678 mm (26.7 inches) at 106 ms after the initial impact, which was just prior to penetration of the w-beam. At 116 ms, the splice was completely separated.

The deformation of the posts was less than in the undamaged section test, as there was almost no torsion experienced by the post at the splice location. There was no visible cracking of either post. As with most previous tests, the post-rail bolt pulled through the w-beam rail at the non-splice location. The post-rail bolt at the non-splice location experienced large bending deformation while the bolt at the splice location fractured in the threaded region. Figure 30 shows the post damage and the splice failure. No tear developed and none of the splice bolts failed, but rather the bolt holes deformed enough to allow the two sections to separate. Figure 31 shows time sequential snapshots of the Test 03-7 obtained from the overhead high speed camera.

In the lower speed test (overhead sequence not shown), the barrier was able to contain the pendulum mass impacting at 29.3 km/hr (18.2 mph) (Figure 32). Impact velocity was calculated based on the high-speed video footage. The deflection of the rail was approximately 467 mm (26.7 inches) at 121 ms after the initial impact.

In Test 01-4, the barrier had a different impact performance. The barrier section contained the pendulum mass impacting at 30.9 km/hr (19.2 mph). Based on an analysis of the overhead high speed video data, the maximum dynamic deflection of the rail was 719 mm (28.3 inches) at 146 ms after the initial impact. The asymmetry caused by the missing blockout resulted in a significant twisting of the pendulum (approximately 6 degrees) in the horizontal plane. The vertical tear that developed at the splice location was 229 mm (9 inches) in length (approximately two-thirds of the total w-beam cross section) and along the line of the splice bolts. A close-up of the tear is shown in the center image in Figure 33.

8.2 Recommendation

A pendulum test conducted at 20 mph of a strong-post w-beam barrier section with a missing blockout at the splice location resulted in successful containment of the pendulum mass (Test 01-4). There was strong evidence, however, that this damage mode could result in tearing of the w-beam. During the test, the absence of the blockout allowed the rail to be

Field Example

Pendulum Test Setup

Figure 29. Missing blockout damage evaluated in pendulum tests.

driven into the steel post resulting in a 9-inch tear in the rail. It is possible that there may have been less of a propensity for tearing for wood posts. Another pendulum test was conducted at an impact speed of 17.5 mph to better represent the kinetic energy loading to a single section of barrier during a full-scale *NCHRP Report 350* test. In this test, the barrier successfully contained the pendulum mass with no evidence of w-beam tearing. To be cautious, the research team has proposed a threshold of one or more missing blockouts. This damage has been assigned a medium priority based on the potential for rail tearing that has been observed in the pendulum test.

With regards to potential vehicle instability resulting from impact, the research team's rationale was that collisions into barriers with a missing blockout would fall between a missing post case and the undamaged case. Finite element simulations of a 2000P pickup truck collision with the post missing the blockout were conducted to verify this. The results of finite element simulations of collisions into an undamaged barrier and into a barrier with a missing post are described later in this report. In the missing blockout simulations, the vehicle response was very similar to the missing post simulations in the early phase of the collision. Early in the collision, the vehicle interacts with a rail with no blockout or post support. However, once the vehicle has deflected the rail the width of a blockout, the vehicle begins to interact with the post. The simulation from this point on greatly resembles an ordinary collision into an undamaged rail section. The missing blockout case does however result in elevated vehicle instability, but not to the extent of the missing post case. The research team has set the repair priority of a missing post accordingly as "medium" which falls between the undamaged case and the high-priority repair of a missing post damage mode. Note that this repair priority is also consistent with the rail-post separation case which allows small amounts of separation (less than 3 inches), but rates higher rail-post separation as a medium-priority repair (Exhibit 5.0).

Figure 30. Test 03-7: splice failure (left) and post damage at splice (center) and non-splice location (right).

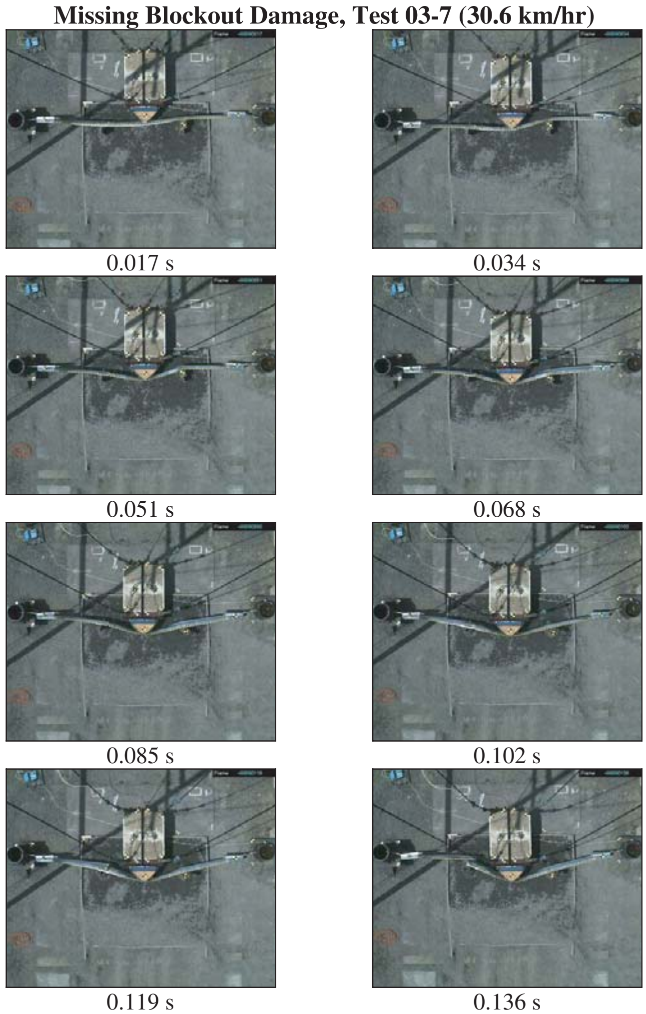


Figure 31. Sequential overhead photographs for missing blockout damage.

Figure 32. Test 07-5: overall damage (left), detail view of damage at splice (center), and post damage at non-splice location (right).

Figure 33. Test 01-4: overall damage (left), rail tear at splice (center), and post damage at splice location (right).

Exhibit 5.0. Recommendation for missing blockout damage repair.

Damage Mode	Repair Threshold	Relative Priority
Missing Blockout	Any blockouts that have the following issues: • Missing, • Cracked across the grain, • Cracked from top or bottom of blockout through post-bolt hole, and • Rotted.	Medium

CHAPTER 9

Evaluation of Hole in Rail

The objective of this evaluation was to determine the effect of a hole in a rail on barrier crash performance through pendulum testing (Figure 34). The performance of the barrier section with an artificially introduced hole was compared to the performance of a similar barrier section with no flaw. The pendulum test setup is described in an earlier chapter on the research approach.

Test 07-2 investigated the performance of a two-post section of strong-post w-beam barrier with a 1.25-inch hole. For this test, a hole in the rail was simulated by drilling through the rail. The location of the hole corresponded to the pendulum mass impact location and was on the upper fold of the w-beam.

9.1 Results

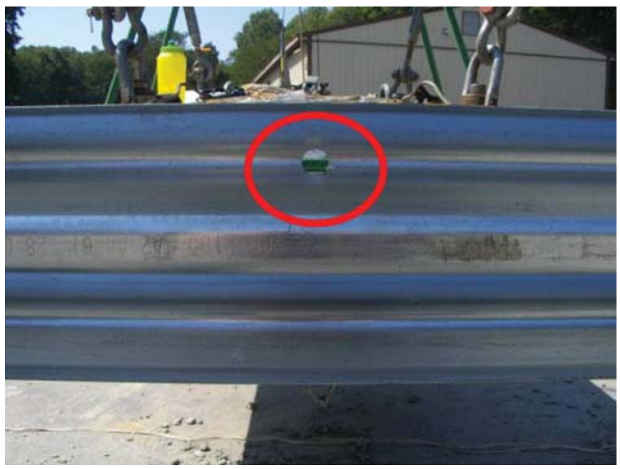
The barrier with a hole in the rail successfully contained the pendulum mass impacting at 18.2 mph. Based on an analysis of the overhead high-speed video data, the maximum dynamic deflection of the rail was 22 inches and occurred 120 ms after trigger. Based on an analysis of the overhead high speed video data, the maximum static deflection was 15.4 inches The rail was intact at the position of the hole (Figure 35). Figure 36 shows time sequential snapshots of the test obtained from the high speed camera positioned overhead.

9.2 Recommendation

A pendulum test (18.2 mph impact speed) of a strong-post w-beam barrier with a 1.25-inch diameter hole resulted in successful containment of the pendulum mass. To represent worst case conditions, the hole was aligned with the impact location and in the upper fold of the w-beam section. Based on the results of the test, the performance of the hole-damaged rail section was virtually identical to that of the undamaged strong post barrier section tested at the 17.5 mph impact speed. As a result, the research team has recommended that the repair be initiated if the hole exceeds 1 inch in height. Note that the limit on size of a non-manufactured hole has been specified in the vertical, rather than the horizontal, direction because the vertical direction is perpendicular to predominant (tension) loads, and is thus more likely to cause failures. A medium priority was assigned to smaller holes in the rail because of the possibility that holes may serve as the initiation point for horizontal tearing on impact. The only exception would be if this hole was located near the splice as described below.

Multiple holes in a rail section or holes with a diameter exceeding a height of 1 inch could lead to rail tearing as seen in the vertical tear pendulum tests. To avoid the possibility of catastrophic rail failure, these modes were assigned a high priority for repair. A special case was a hole of any size which intersects either the top or bottom edge of the rail. Because a hole which disrupts either the upper or lower surface of a rail has the characteristics of a vertical tear, this damage mode has the potential for the same catastrophic failure of the rail that was observed in the pendulum tests of vertical tears. This damage mode was given a high priority for repair (Exhibit 6.0).

Field Example



Pendulum Test Setup

Figure 34. Hole damage evaluated in pendulum tests.

Figure 35. Damage near a hole in Test 07-2.

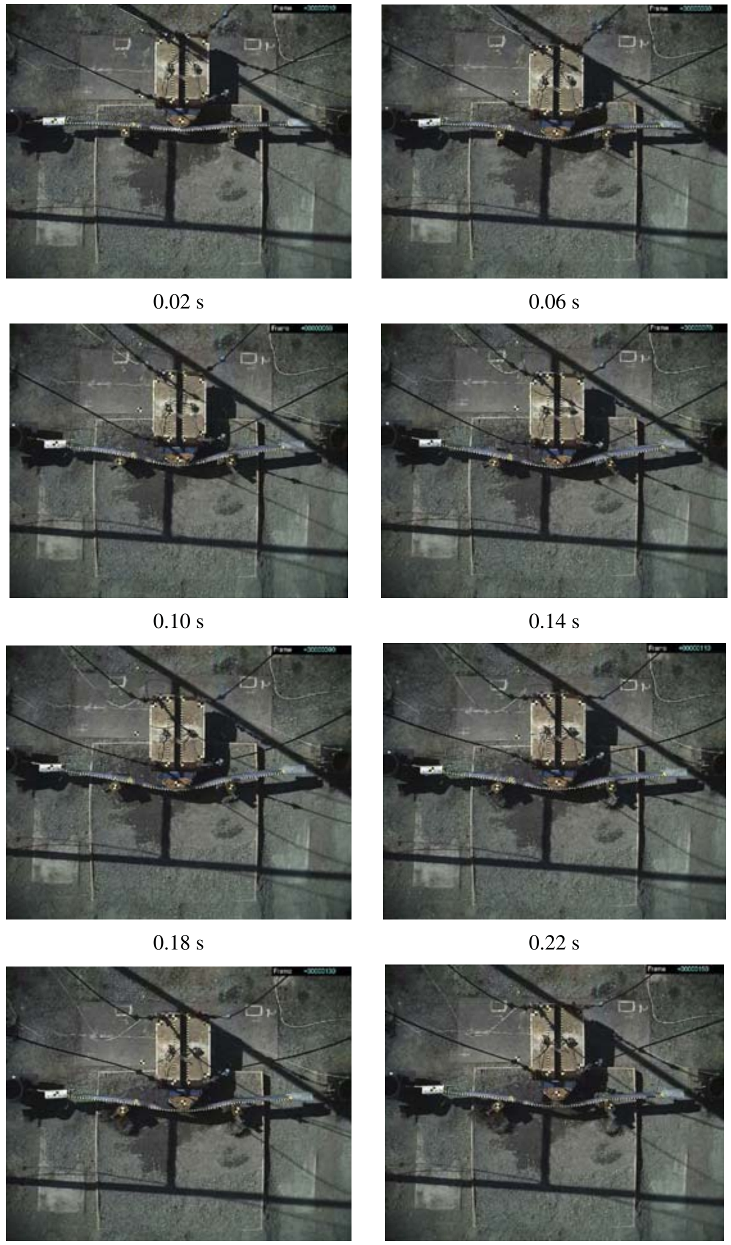


Figure 36. Sequential photographs for 1.25-inch hole damage (Test 07-2): overhead view.

Exhibit 6.0. Recommendations for hole in rail damage.

Damage Mode	Repair Threshold	Relative Priority
Non-Manufactured holes (such as crash-induced holes, lug-nut damage, or holes rusted-through the rail)	• More than 2 holes less than 1 in. in height in a 12.5-in. length of rail. • Any holes greater than 1in. in height. • Any hole which intersects either the top or bottom edge of the rail.	High
	1 or 2 holes less than 1 in. in height in a 12.5-in length of rail.	Medium

CHAPTER 10

Evaluation of Crash-Induced Rail and Post Deflection

Rail and post deflection is one of the most prevalent types of damage in guardrail, most often caused by a lower severity crash. An example of this damage mode is shown in Figure 37. Impacts where the vehicle speed is lower may result in localized minor damage. Depending on the impact angle, the damage may be incurred only to the rail element, with minimal or no damage to the supporting posts and soil. Impacts with a higher speed but shallower angle can also result in more distributed rail and post deflection.

The amount of deflection that can be sustained by a guardrail before its safety is compromised is a major concern. Maintenance crews and highway agencies are often forced to balance the expense of continual repairs against the potential liability if the damaged guardrail is struck again. The survey of U.S. states and Canadian provinces presented earlier in this report revealed that very few agencies have quantitative criteria underlying the decision of when to replace a deflected guardrail. Among those agencies that have quantitative guidelines, the threshold deflection was most commonly set at 6 inches (152 mm) of deflection. This is also the recommended limit for minor damage specified by the Federal Highway Administration (FHWA, 2008). Individual agencies had limits as low as 3 inches (76 mm) or as high as 12 inches (305 mm). This study is intended to test the performance of guardrail with rail and post deflection to support a unified deflection limit based on quantitative data.

10.1 Objective

The objective of this chapter is to present the results of an evaluation of crash induced guardrail rail and post deflection. The evaluation was conducted using a combination of full-scale crash tests and simulations.

10.2 Evaluation Through Crash Tests

In August 2009, a test series was conducted by the MGA Research Corporation to evaluate the performance of damaged strong-post w-beam guardrails. This test was comprised of two parts: (1) an initial, low-speed impact to create a realistic representation of minor rail deflection and (2) a subsequent full-scale impact into the damaged section of guardrail. The goal of this test was to observe the effect of the guardrail damage on the vehicle performance and to test the outcome as well as to provide additional data for the validation of the finite element models.

The strong-post w-beam guardrail installed for the purpose of this two-part crash test was 162 feet (49.5 meters) in total length from end-to-end. All posts were steel strong posts and the w-beam rails were spaced out from the posts via the use of routed wood blockouts. Tensioned end terminals were installed at both ends of the guardrails. The guardrail was oriented such that the vehicles would approach at a 25-degree angle of impact with the initial point of impact located 1.94 feet (591 mm) before post 11. This impact point was computed using the critical impact point procedures described in *NCHRP Report 350.* No modifications were made to the guardrail in between the first and second impacts. Further details on the guardrail design can be found in the crash test reports (Fleck and Winkelbauer, 2008a, 2008b).

10.2.1 Low-Speed Impact Test

In the first impact, the impacting vehicle, a 1997 Chevrolet C2500 pickup weighing 4,632 lb (2101 kg), struck the guardrail at a speed of 30 mph (48.3 km/hr) at 26.0 degrees. This impact resulted in damage to 36 feet (11 meters) of barrier length of the total 162-foot (49.4 meters) length. The maximum permanent post and rail deflection was approximately 14.5 inches (368 mm). The barrier successfully contained the vehicle. The vehicle came to rest alongside the barrier due to the low initial speed of the vehicle. Figure 38 shows an overhead time series of the impact.

10.2.2 High-Speed Impact Test

The day following the first, low-severity impact, a high-speed test was run. In this test, another 1997 Chevrolet C2500 pickup

Figure 37. Guardrail with rail and post deflection.

truck impacted the guardrail at the same initial impact point and area damaged by the previous vehicle. The impact conditions were 62.1 mph (99.9 km/hr) at 25.5 degrees (*NCHRP Report 350* Test 3-11 conditions). Due to the damage that had already incurred to the guardrail, the vehicle failed to redirect and overrode the guardrail. The vehicle returned to the ground on the opposite side of the guardrail and continued to travel at 43.2 mph (69.5 km/hr) and at an angle of 18.7 degrees from the guardrail. Post 13 failed to separate from the guardrail despite the significant amount of post and rail deflection during the test. A series of photographs showing the vehicle as it vaulted over the guardrail is shown in Figure 39. As shown in these photographs, the pickup truck vaulted over the barrier and came to rest upright behind the test installation.

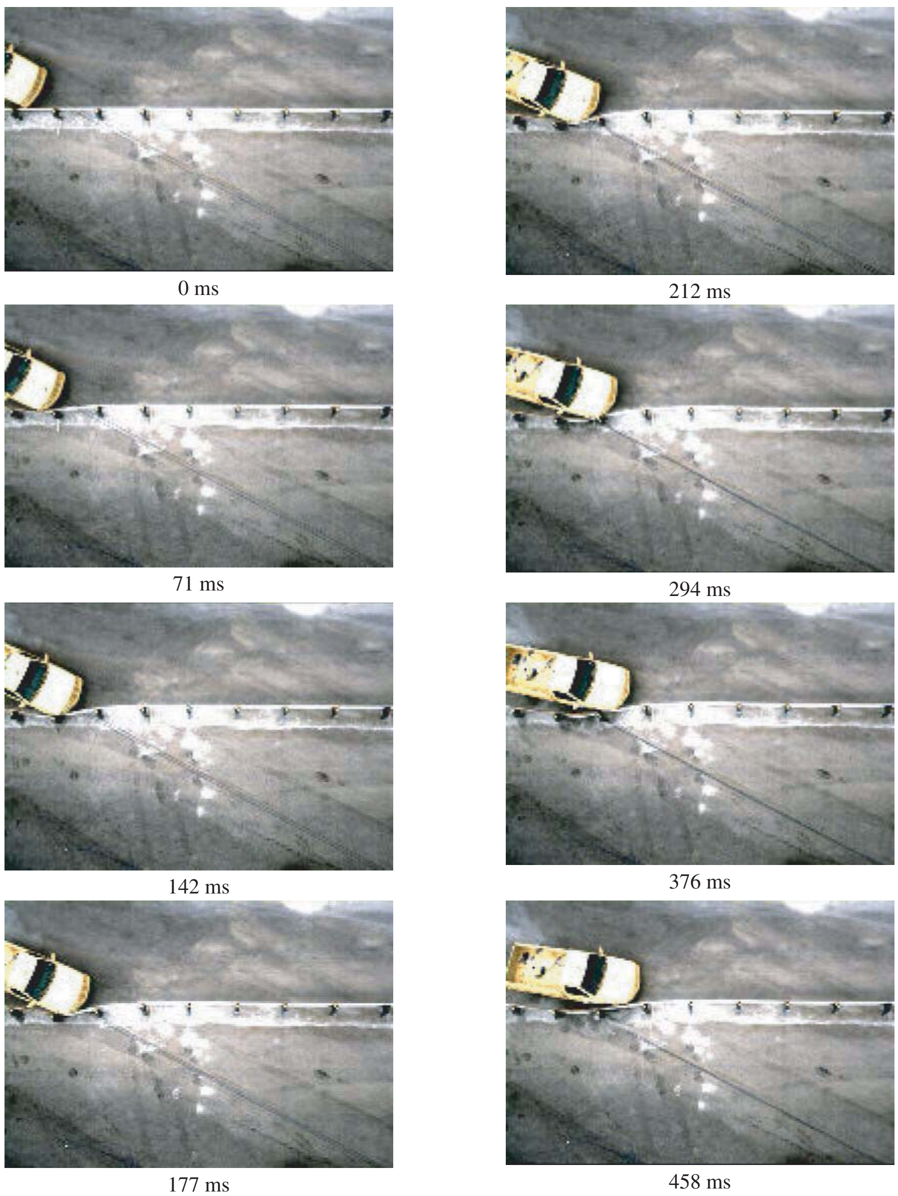


Figure 38. Time series for low-speed impact.

Figure 39. Time series for second, high-speed impact into damaged guardrails.

10.2.3 Results of the MGA Tests

With the exception of the vehicle roll, pitch, and yaw for the initial low-speed test, all of the *NCHRP Report 350* criteria were computed. These values are shown in Table 16. The results for Test TTI 405421-1, a crash test of undamaged strong-post w-beam guardrail with a Chevrolet C2500 pickup truck, are provided for comparison purposes.

For the low-speed crash test, all values were below what would be expected from a standard crash test. This was expected as the initial speed of the vehicle was much lower than for a TL-3 crash test. For the high-speed crash test, all of the accelerations and OIV scores were lower than observed in the test of undamaged guardrail. This was because the vehicle overrode the guardrail rather than being redirected, resulting in less crash energy being dissipated. This was reflected in the higher exit speed.

The guardrail deflection was far larger for the full-scale MGA test than for the typical TL-3 crash test into an undamaged guardrail. This difference was attributed to the difference in

Table 16. *NCHRP Report 350* criteria for MGA test.

	TTI Test 405421-1	MGA C08C3-027.1	MGA C08C3-027.2
Impact Conditions			
Speed (mph)	63.1	30.0	62.1
Angle (deg)	25.5	26.0	25.5
Exit Conditions			
Speed (mph)	34.2	12.9	43.2
Angle (deg)	16.0	11.4	18.7
Occupant Kinematics			
Longitudinal OIV (m/s)	7.1	3.8	6.1
Lateral OIV (m/s)	4.4	3.3	3.7
Longitudinal Ridedown (G)	-7.9	-3.3	-6.1
Lateral Ridedown (G)	8.4	-1.9	-5.6
Vehicle Kinematics			
50 ms X Acceleration (G)	-5.3	-2.9	-5.5
50 ms Y Acceleration (G)	4.3	-2.6	-3.1
50 ms Z Acceleration (G)	-4.8	1.8	-4.1
Guardrail Deflections			
Dynamic deflection (ft)	3.3	1.4	7.2
Static Deflection (ft)	2.3	1.2	3.3
Vehicle Rotation			
Maximum Roll (deg)	-10	Not reported	29.7
Maximum Pitch (deg)	-4	Not reported	12.1
Maximum Yaw (deg)	42	Not reported	-10.2

outcome, i.e., redirection vs. vaulting, as well as the increased deflection of the supporting posts.

10.2.4 Conclusions of the Crash Tests

The outcome of the crash tests demonstrated that there are limits to the amount of damage that can be sustained by guardrails while still maintaining its functional capacity. The test series showed that a guardrail with 14.5 inches (368.3 mm) of rail and post deflection in a guardrail represents an unacceptable condition that warrants high-priority repair. The performance of guardrail with lower amounts of deflection was evaluated with finite element models, as described in the following sections, to determine the limit of deflection that can be allowed.

10.3 Evaluation Through Finite Element Modeling

The crash tests show that 14 inches of lateral post and rail deflection is a damage level which requires repair. The level of damage below 14 inches of post/rail deflection which may be acceptable was investigated by finite element simulation. A series of simulations was conducted to determine how much deflection could be permitted in a strong-post w-beam guardrail without compromising the safety of the system. All simulations were conducted with the LS-DYNA software as described earlier in this report. Simulations with combined rail and post deflection were conducted for 3, 6, 9, and 11 inches of deflection. A small number of simulations with rail deflection only were also conducted for 3 and 6 inches of deflection. Higher extents of rail only deflection were not considered since it was unlikely that the posts would be unaffected as well.

Rail and post deflection is typically produced by a low-severity impact. Therefore, the best way to reproduce this damage would be to simulate such an impact. Low-speed impacts in the range of 30–60 kph (18.6–37.3 mph) with an impact angle of 25 degrees were used to cause 3, 6, 9, and 11 inches of deflection in the rails, often with concurrent post deflection as well. In some models, artificial constraints were introduced to prevent post motion so that the effects of the rail deflection could be studied in isolation. An example of a completed full-scale model with 6 inches of rail and post deflection is shown in Figure 40.

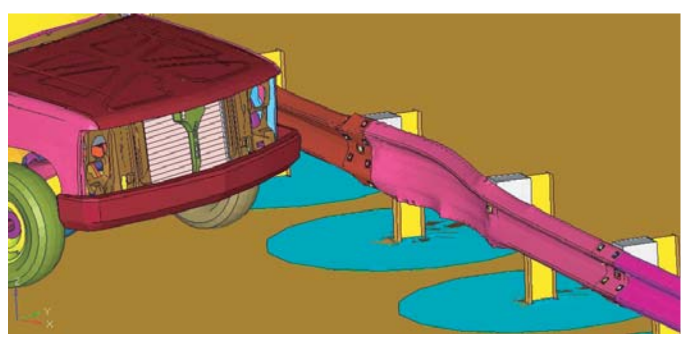


Figure 40. Simulated guardrail with rail and post deflection.

10.3.1 Validation of the Finite Element Model

The model was validated using the MGA test series in which two Chevrolet 2500 pickup trucks impacted a guardrail (MGA, 2008a; 2008b). By using multiple crash tests, the acceptability of using the finite element approach to model a wide range of crash conditions could be assured.

The MGA crash tests were conducted to evaluate the performance of a guardrail with rail and post deflection. In the first test, a 30 mph (47 kph) impact was used to create 14.5 inches (368 mm) of deflection. The second test was performed according to *NCHRP Report 350* standards with the impact occurring at the same point as the previous test. Because of the damage incurred by the first impact, the second test resulted in a failure due to the vehicle vaulting over the guardrail. These MGA crash tests were invaluable as a source of validation data for the finite element models.

A series of photos from the second crash test and associated simulation is shown in Figure 41. For this test, there was visually good agreement between the real crash test and the finite element model. The models were also compared by the *NCHRP Report 350* criteria, as shown in Table 17.

The first MGA impact, a low-speed collision intended to cause a minor amount of deflection, was successfully reproduced. A simulation speed of 32 mph (52 km/hr) was required to reproduce the 14.5 inches (368 mm) of deflection observed in the 30 mph (48.3 km/hr) crash test. For the second MGA crash test, initial attempts at reproducing the results were unsuccessful. After an investigation, a critical factor in the outcome of the crash test was found to be the failure of a single post, located roughly 12.8 feet (3.9 meters) downstream of the impact point, to separate from the rail during both the first and second impacts. The addition of a constraint on the same post in the finite element model resulted in a drastic change in the predicted outcome of the impact, changing a successful crash into a failure with the vehicle vaulting over the guardrail. Occupant impact velocities and ridedown accelerations were below the *NCHRP Report 350* limits in all the crash tests and simulations.

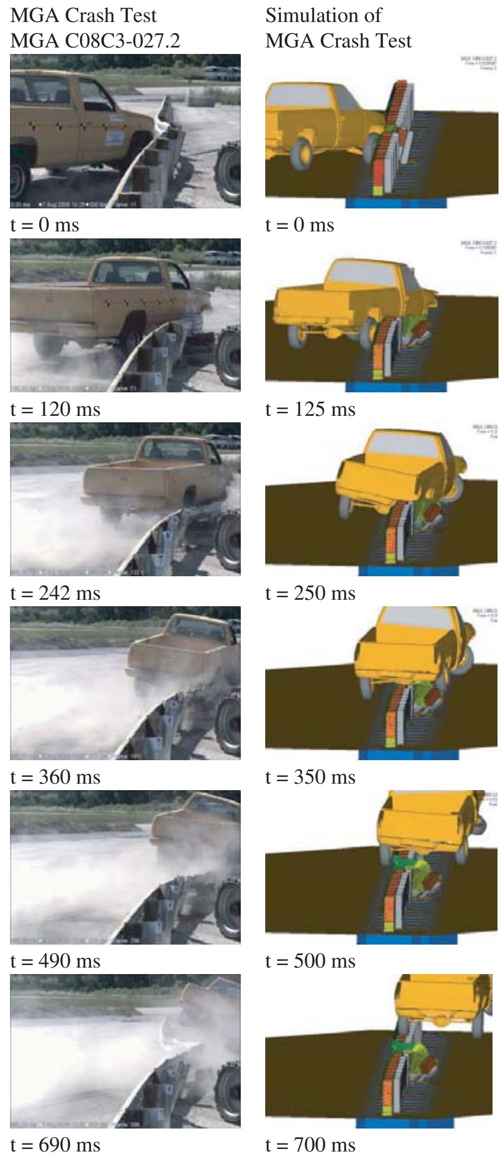


Figure 41. Comparison of finite element simulations against second MGA crash test.

10.3.2 Results of Finite Element Simulations

The MGA tests demonstrated that the separation of posts from the rails can radically change the crash performance of strong-post w-beam guardrail. Finite element modeling may not be able to accurately predict which behavior will occur in a real crash when relevant factors such as soil strength or bolt position are not known. The approach was to bracket the crash performance by conducting two series of simulations. In the first series, the rails and posts were allowed to separate. In the second series, a single post was prevented from separating. The post to which this constraint was applied was 12.5 feet (3.8 meters) downstream, which maximized the effect on vehicle performance.

In the first set of simulations, a guardrail with combined rail and post deflection of 3, 6, 9, and 11 inches (76, 152, 229, and 279 mm) was tested. The *NCHRP Report 350* test values recorded for each simulation are shown in Table 18. Despite the huge difference in performance between the MGA test simulation of 14.5 inches of deflection and the undamaged simulation, there was very little variation in performance between the simulations of lesser damage. Even the simulation with 11 inches of deflection yielded virtually the same crash results and test values as the undamaged simulation.

Table 17. Validation of finite element simulations against second MGA crash test.

	MGA Crash Test C08C3-027.2	MGA Crash Test Simulation
Impact Conditions		
Speed (kph)	99.9	100.0
Angle (deg)	26.4	26.4
Exit Conditions		
Speed (kph)	69.5	57.0
Angle (deg)	18.7	5.7
Occupant		
Impact Velocity X (m/s)	6.1	9.3
Impact Velocity Y (m/s)	3.7	5.4
Ridedown X (G)	-6.1	-10.4
Ridedown Y (G)	-5.6	-5.4
50 ms Average X (G)	-5.5	-10.0
50 ms Average Y (G)	-3.1	-6.3
50 ms Average Z (G)	-4.1	-6.5
Guardrail Deflections		
Dynamic (m)	2.2	1.00
Static (m)	1.0	0.80
Vehicle Rotations		
Max Roll (deg)	30	7.1
Max Pitch (deg)	12	11.5
Max Yaw (deg)	-10.2	-21.3

In the second set of simulations, the models were set up in an identical manner, except that a constraint was added to a post located 12.5 feet (3.8 meters) downstream of the impact point to prevent the post and rail from separating. The *NCHRP Report 350* test values recorded for each simulation are shown in Table 19. Figure 42 shows the orientation of the vehicles in each of these crash test simulations at 700 ms after impact. The vehicle began to move upward and roll with increasing amounts of prior deflection damage. The vehicle eventually rolled onto its side when the deflection damage reached 11 inches (279 mm). However, even at 6 inches (152 mm) of deflection, the roll was very high and reached over 35 degrees before the vehicle began to recover.

Figure 43 shows the local vehicle velocity at the center of gravity as a function of time for both the normal and fixed post simulations. There was almost no difference in the velocity between the undamaged simulation and the unmodified rail and post deflection simulations. All of the exit speeds were in the range of 31–35 mph (50–56 km/hr). The velocities for the simulations with a fixed post were a little more varied. The vehicle in the 11-inch simulation retained the most speed due to rolling on its side, which limited the amount of interaction with the guardrail. The 3-inch simulation vehicle showed the lowest amount of roll and lost more speed because of more opportunities to interact with the posts.

The maximum deflection of the guardrail increased as the extent of rail and post deflection increased for both sets of simulations as shown in Figure 44. The increases were much larger for the simulations without separation due to the deflecting posts pulling the rails out. However, for both sets, each additional 3 inches (75 mm) in pre-existing deflection yielded only 0.8–1.6 inches (20–40 mm) of extra dynamic deflection. The limited effect of the pre-existing deflection was attributed to the narrow range over which the damage was incurred on the rail.

Table 18. Simulation results for rail and post deflection with no rail and post separation constraints.

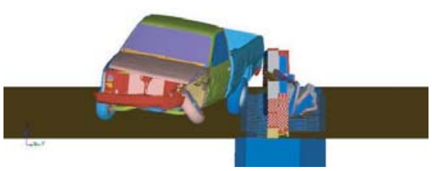
	Undamaged Model	3 in. Rail and Post Deflection	6 in. Rail and Post Deflection	9 in. Rail and Post Deflection	11 in. Rail and Post Deflection
Impact Conditions					
Speed (kph)	100	100	100	100	100
Angle (deg)	25	25	25	25	25
Exit Conditions					
Speed (kph)	53	53	52	56	50
Angle (deg)	14.5	13.2	13.8	15.6	15.0
Occupant					
Impact Velocity X (m/s)	7.5	8.0	8.0	8.6	8.3
Impact Velocity Y (m/s)	5.5	5.6	5.5	5.5	5.9
Ridedown X (G)	-11.8	-12.0	-12.2	-10.7	-12.8
Ridedown Y (G)	-12.3	-13.0	-10.1	-12.0	-10.4
50 ms Average X (G)	-6.7	-6.7	-6.8	-7.9	-7.1
50 ms Average Y (G)	-6.8	-6.7	-6.5	-6.5	-6.8
50 ms Average Z (G)	-3.8	-3.9	-3.0	-4.2	-4.6
Guardrail Deflection					
Max Dynamic (m)	0.69	0.72	0.74	0.76	0.78
Static Deflection (m)	0.55	0.62	0.55	0.60	0.64
Pre-existing deflection (m)	0.00	0.07	0.15	0.22	0.28
Vehicle Rotation					
Max Roll (deg)	-14.4	-12.9	-13	-16.6	-13.2
Max Pitch (deg)	-9.9	-10	-6.6	-5.6	10
Max Yaw (deg)	40.3	40	40	41	40.5

Table 19. Simulation results for rail and post deflection with one rail and post separation constraint.

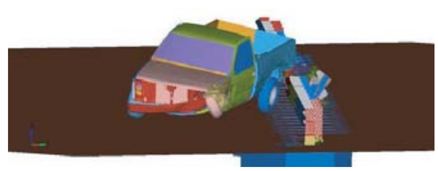
	Undamaged Model	3 in. Rail and Post Deflection	6 in. Rail and Post Deflection	9 in. Rail and Post Deflection	11 in. Rail and Post Deflection
Impact Conditions					
Speed (kph)	100	100	100	100	100
Angle (deg)	25	25	25	25	25
Exit Conditions					
Speed (kph)	53	46	55	55	64
Angle (deg)	14.5	19.1	12.3	15.6	3.4
Occupant					
Impact Velocity X (m/s)	7.5	8.4	7.9	8.1	7.9
Impact Velocity Y (m/s)	5.5	5.5	5.1	5.2	5.4
Ridedown X (G)	-11.8	-11.7	-13.2	-14.5	-8.8
Ridedown Y (G)	-12.3	-10.4	-11.9	-11.7	-8.7
50 ms Average X (G)	-6.7	-8.8	-8.2	-8.3	-7.0
50 ms Average Y (G)	-6.8	-6.5	-6.2	-6.2	-6.0
50 ms Average Z (G)	-3.8	-3.9	-3.7	4.6	5.2
Guardrail Deflection					
Max Dynamic (m)	0.69	0.82	0.86	0.86	0.90
Static Deflection (m)	0.55	0.64	0.66	0.67	0.77
Pre-existing deflection (m)	0.00	0.07	0.15	0.22	0.28
Vehicle Rotation					
Max Roll (deg)	-14.4	32.1	35.5	39.7	Roll
Max Pitch (deg)	-9.9	-14.6	-19.8	22.7	28.2
Max Yaw (deg)	40.3	46.2	35.8	39.0	23.3

Rail Deflection Only Simulations. To determine the relative contributions of the rails versus those of the posts, two simulations were conducted in which rail deflection was introduced between two adjacent posts. No post deflection was permitted in the first impact. The posts were free to move however in the second impacts of these simulations. These rail deflection only simulations were limited to 3 and 6 inches (76 and 152 mm) of deflection since larger rail deflections generally do not occur without also deflecting the posts.

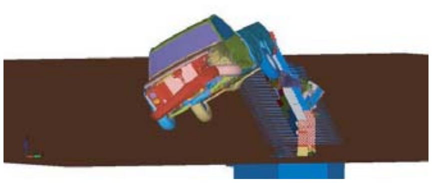
The *NCHRP Report 350* test criteria were almost entirely unchanged from the values recorded for the undamaged simulation. Between the undamaged and 6 inch rail only deflection simulation, the roll and pitch decreased by less than 4 degrees and the maximum dynamic deflection increased by less than 3 percent. The longitudinal occupant impact velocity showed the greatest increase, rising to 27 ft/s (8.2 m/s) from 24.6 ft/s (7.5 m/s), but was still within the recommended limit. The lack of change in crash test outcome for



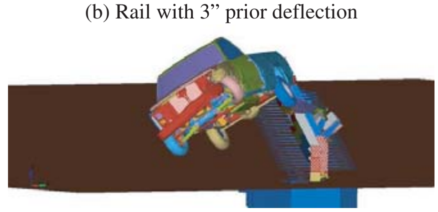
(a) Undamaged rail



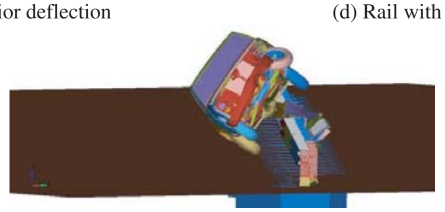
(b) Rail with 3” prior deflection



(c) Rail with 6” prior deflection



(d) Rail with 9” prior deflection



(e) Rail with 11” prior deflection

Figure 42. Damaged guardrail simulations after impact (t = 700 ms).

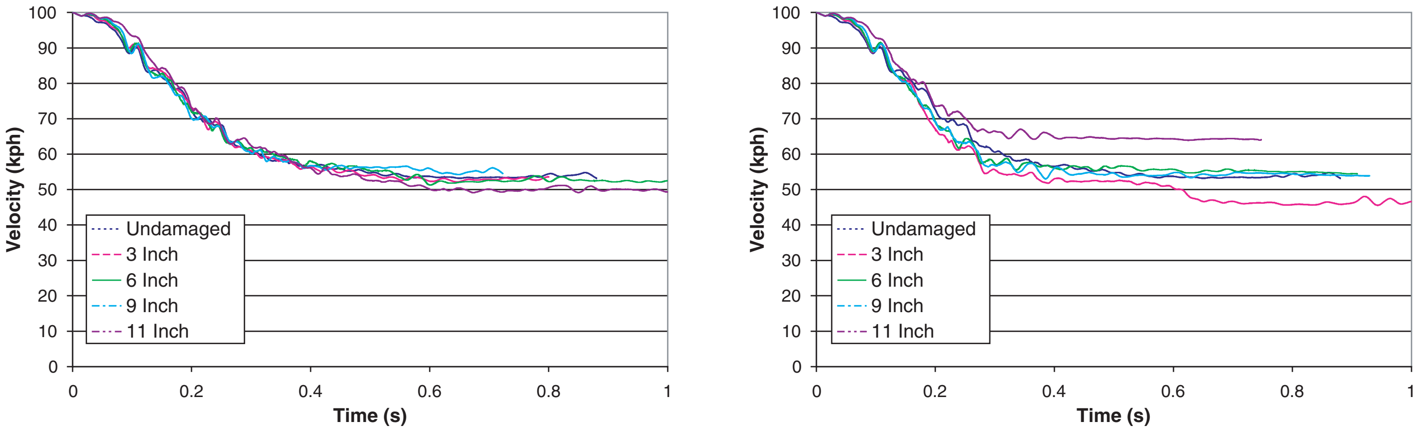


Figure 43. Vehicle velocities for rail and post deflection simulations (left) and the same simulations with one post prevented from separating (right).

rail deflection only supports the earlier theory that the contributions of the posts may be more important in predicting the outcome of a crash.

10.4 Discussion

10.4.1 Importance of Rail and Post Separation

A critical contribution to the vaulting of the vehicle in the MGA crash test was believed to be the failure of some of the posts to detach from the guardrail. In the second MGA crash test, a post failed to separate from the rail during impact. In a preliminary simulation of this crash, the post did separate from the rail, and the vehicle was successfully redirected. When a constraint was added to prevent the rail from separating from the post, the vehicle vaulted over the guardrail. The deflection of this post during impact was believed to have pulled the rail downward which permitted the vehicle to vault over the guardrail.

10.4.2 Simulations of Rail and Post Deflection

In the simulations of the 3, 6, 9, and 11 inches (76, 152, 229, and 279 mm) of rail and post deflection with no separation constraints, minor rail and post deflection had very little effect on the simulation results. The OIV, ridedown, and 50 ms average accelerations were satisfactory and the increases in maximum deflection were less than the increase in prior deflection. When the simulations were altered to prevent a post from separating from the rail, different outcomes were observed. The vehicle roll increased with increasing preexisting deflection. The vehicle overturned during impact with a guardrail having 11 inches (279 mm) of pre-existing rail deflection. Even for as little as 6 inches of rail deflection, substantial rolling was observed.

When the rail and posts fail to separate, two different hazardous conditions can be created. If the post remains mostly upright the vehicle may be at greater risk of snagging. Another possible outcome was reflected in the results of the MGA crash test. If an unseparated post was deflected backwards and

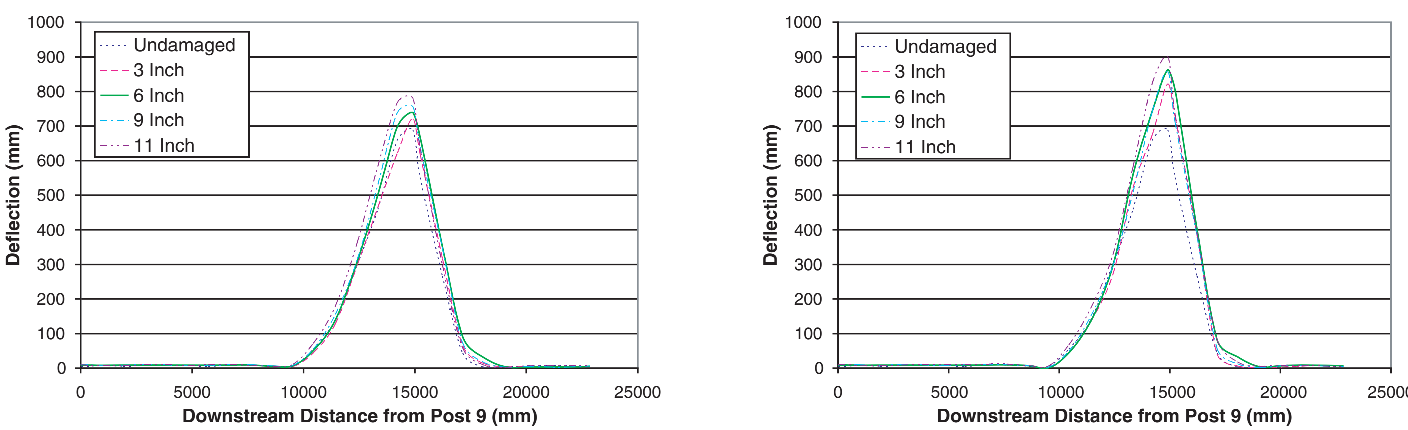


Figure 44. Maximum dynamic deflection for rail and post simulations (left) and the same simulations with one post prevented from separating (right).

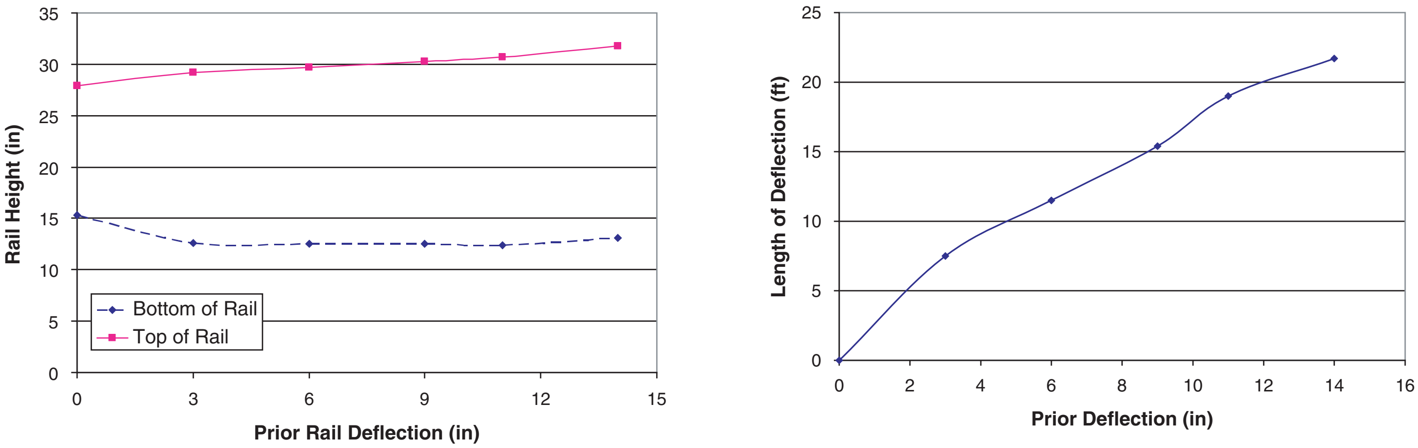


Figure 45. The height of the rails (left) and the length of damage (right) vs. the extent of prior deflection.

downwards, as in the simulations with greater than 6 inches (152 mm) of deflection, the rail is pulled downward as well and the risk of vaulting is increased.

The vehicle behavior for both 3 and 6 inches (76 and 152 mm) of prior rail deflection without post deflection was no different from that of the undamaged rail simulation. The static and dynamic guardrail deflections were also unchanged. These results provide further support for the theory that the behavior of the posts in strong-post guardrail systems can strongly influence the outcome of a crash test.

10.4.3 Effects of Prior Damage on Rail Height

Existing literature has suggested that rail height can be a major contributor to vaulting (Marzougui et al., 2007). The rails in the finite element simulations were examined to determine whether the minor rail deflection incurred in the first impact resulted in changes in the rail height that could be correlated to the outcome of the simulated second impact. The hypothesis was that the pre-existing damage would lower the rail height and lead to the vehicle vaulting.

Figure 45 and Table 20 present the minimum height of the rail bottom, maximum height of the rail top, and the length of pre-existing deflection after the first impact but before the second impact. All of the measurements were made from the simulations with a separation constraint added. This situation represented the worst case scenario for vaulting because the deflection of the post would pull the rail downward as it deflected.

Figure 45 shows that one consequence of an impact is that the rail flattens. The bottom of the rail moved downward from 15.3 inches (388.6 mm) to 12.6 inches (320 mm) above the ground surface. The top of the rail moved upward from 27.9 inches (709 mm) to 31.8 inches (808 mm). The maximum height of the guardrail increased with increasing deflection, indicating that the guardrail was becoming increasingly flattened. The length of deflection also increased with increasing magnitude of deflection. These results indicate that, in addition to rail height, the flattening of the rail and the damage length may also exert a significant influence on the crash outcome in these simulations. However, further testing will be needed to draw any conclusions about the relative importance of each of these factors on vaulting or rollover risk.

10.4.4 Evaluation of Rail Rupture Potential

Ray et al. conducted a study on rail rupture in crash tests which showed that rails can carry up to 92.2 kip (410 kN)

Table 20. The height of guardrails and length of damage in simulations with pre-existing damage.

	Minimum Height of Rail Bottom (mm)	Maximum Height of Rail Top (mm)	Difference in Max and Min (mm)	Length of Damage (m)
Undamaged	388	709	321	NA
3 in.	320	742	422	2.3
6 in.	317	755	438	3.5
9 in.	317	769	452	4.7
11 in.	314	781	467	5.8
14.5 in.	334	807	473	6.6

Table 21. Maximum rail tensions in rail and post deflection simulations.

	Maximum Rail Tension (kN)		% Increase Over Undamaged	
	Separation allowed	No separation allowed	Separation allowed	No separation allowed
Undamaged	237.4		0.0%	
3 in. Rail and Post	247.1	258.1	4.1%	8.7%
6 in. Rail and Post	282.9	229.2	19.2%	-3.5%
9 in. Rail and Post	292.6	237.6	23.3%	0.1%
11 in. Rail and Post	261.1	235.5	10.0%	-0.8%

under quasistatic loading. However, rupture may also occur at lower rail tensions. Localized tearing is possible in impacts of this type, but the research team's model was not configured to accurately compute element tearing resulting from localized stress concentrations and did not include failure criteria for the steel components. The model was meshed using large element sizes 0.4–0.6 in (10–40 mm), which were appropriate for determining vehicle dynamics but were too coarse to realistically model the initiation and propagation of tears. As an alternative, the tension carried by the rails was used to determine the relative risk of rail rupture.

The tensions for the rail and post simulations are tabulated in Table 21 under the column for separation allowed simulations. The tension for the rail deflection only did not vary significantly from the undamaged simulation. However, all of the post and rail deflection simulations showed an increase in rail tension compared to the undamaged simulation, with the tension steadily increasing to a maximum of 292.6 kN at 9 inches of deflection. Although this tension was below the 410 kN limit of w-beam rail, rupture can occur at a lower tension (Ray et al., 2001). The higher tension carried by the damaged rails implied that there was a modest increase in the chance that a rail rupture would occur.

The tension was also tabulated for the simulations in which post separation was not permitted. These tensions are listed under the "No separation allowed" column. The recorded maximum tensions were not much different than that of the undamaged simulation. Because the connection between the post and rail was maintained, more of the crash energy was transmitted to the posts.

10.5 Conclusions

This study has examined the crash performance of strong-post w-beam guardrail with rail and post deflection from a previous impact. The MGA crash tests and finite element simulations of second impacts into damaged guardrails have shown that the combination of rail and post deflection can negatively affect the crash performance. The research team's conclusions are the following:

- Crash tests demonstrated that 14.5 inches (368 mm) of post and rail deflection with a damage length of 36 feet (11 meters) was a damage level requiring high-priority repair. Two full-scale crash tests were conducted to evaluate the limits of acceptable rail and post deflection in crash-damaged strong-post w-beam guardrail. The damaged barrier failed to contain a Chevrolet 2500 pickup truck that impacted the damaged section at 62 mph (100 km/hr) and 26.4 degrees. The vehicle vaulted over the guardrail and came to rest upright behind the barrier. A critical factor in the outcome of the test was the failure of a post near the area of impact to separate from the rails during impact.
- Finite element simulations were employed to investigate the acceptability of damage levels below 14.5 inches (368 mm) of rail and post deflection. Simulations were conducted for post and rail deflection varying from 3 to 11 inches (76 to 279 mm). A series of simulations were run in which a single post was prevented from separating from the rail. In this simulation series, the vehicle experienced a significant roll beginning at 6 inches (152 mm) of deflection and eventually rolled over when the deflection reached 11 inches (279 mm). The crash performance of rail with 3 inches of deflection was not markedly different than undamaged rail.
- Finite element simulations were conducted of impacts into guardrail with rail deflection between two adjacent posts. No post deflection was permitted in the first impact. The posts were free to move however in the second impacts of these simulations. Rail deflection of 3 and 6 inches between the posts was investigated. The vehicle and guardrail performance in these simulations were almost unchanged from the undamaged simulation. These results support the conclusion that the contributions of the post during an impact were important.
- Rail tension was examined in all simulations as an indicator of rail rupture potential. The tension carried by the

guardrail changed very little for any simulation where a post was prevented from separating. However, when the posts could freely separate from the posts, rail tension increased with increasing pre-existing rail deflection. For 9 inches (229 mm) of pre-existing deflection, peak rail tension was 23 percent higher than the rail tension in the undamaged rail simulation. Peak rail tension in the simulation of 6 inches (152 mm) of deflection was 19 percent higher than in the undamaged rail simulation. These results indicated that the risk of rupture increased modestly as the magnitude of prior rail/post deflection increased.

- The maximum rail height and length of deflection both increased with increasing amounts of pre-existing deflection. The minimum rail height was roughly constant for any amount of prior deflection. Rail height, length of damage, and flattening extent were all factors which appeared to contribute to crash income, but the relative influence of each could not be isolated. Further study will be needed to better understand these factors.

10.6 Recommendation

This guideline was based upon two quantitative metrics: (1) lateral post and rail deflection and (2) post height.

10.6.1 Lateral Post and Rail Deflection

Two full scale crash tests were conducted to evaluate this guideline. In the first test, a 2000P vehicle (Chevrolet C-2500 pickup truck) impacted a strong-post guardrail system at 30 mph (48.3 km/hr) and 26 degrees to induce damage to the barrier. The barrier successfully contained the vehicle in this lower speed test. The vehicle came to rest alongside the barrier. The impact resulted in damage to 36 feet (11 meters) of barrier length and a maximum post and rail deflection of approximately 14.5 inches (368 mm). In the second test, another Chevrolet C-2500 pickup truck collided with the area damaged by the first test at a speed of 62 mph (100 km/hr) and 25 degrees. The damaged barrier failed to contain the impacting 2000P vehicle. The 2000P vehicle vaulted over the barrier and came to rest upright behind the test installation.

These tests show that 14.5 inches of lateral post and rail deflection is a damage level damage mode which requires repair. The levels of damage below 14.5 inches of post and rail deflection which may be acceptable were investigated by finite element simulation. Simulations were conducted for post and rail deflection varying from 3 to 11 inches (76 to 279 mm). The crash performance of rail with 3 inches of deflection was not markedly different than an impact into undamaged rail. However, the vehicle experienced significant roll beginning at 6 inches (152 mm) of deflection and eventually rolled over when the deflection reached 11 inches (279 mm).

For strong soils, the crash performance of barriers with post deflection up to 9 inches was satisfactory, whereas higher amounts of deflection were not. Impacts into rail with 11 inches of prior deflection resulted in a rollover in the simulation. The crash test into a rail with 14.5 inches of deflection resulted in the vehicle vaulting over the rail. Adjusting for an extra margin of safety, e.g., to account for softer soils or overlapping damage modes, the limit of acceptable post and rail deflection was set to 9 inches. Impacts into rail with 6–9 inches of prior deflection were satisfactory in the simulations, but were associated with significant amounts of vehicle instability. The presence of any amount of deflection in the guardrail was found to increase the amount of maximum dynamic deflection, so repairs to guardrail with hazardous objects directly behind the guardrail should also be repaired as quickly as practical.

Based on these initial simulations, a damage threshold of 6 inches of post and rail deflection has been set as the threshold for strong-post w-beam barrier repair. Deflection from 6–9 inches was associated with significant amounts of vehicle instability, and should be repaired with medium priority. Barriers with rail and post deflection above 9 inches should be repaired with a high priority as vehicle stability and rollover appears to be a significant threat with barrier damage of this magnitude. The guideline further requires that this damage be fairly localized and form a pocket in the rail in order to require repair. The deflection must occur over a 25-foot or shorter length of rail. The rationale is that 6 inches of deflection spread over 300 feet of rail would have an insignificant effect on performance whereas the pocket formed by 6 inches of deflection measured over 25 feet of rail would be a potential safety concern.

10.6.2 Post Height

Depending on the extent of post and rail deflection, the height of the w-beam in the damaged section may be lower than the original height of the strong-post w-beam. Several crash studies conducted in New York (Zweden and Bryden, 1977; Carlson et al., 1977; Bryden, 1984) have shown lower rail heights to be associated with more vehicle penetrations. Concern over the effects of lower rail height have led to the recent development of new barrier systems such as the Midwest Guardrail System (Faller et al., 2007), the Gregory Mini-Spacer (Baxter, 2006), and the Trinity T-31 Barrier (Baxter, 2005). In these new systems, the top of the rail is 31 inches from the ground line compared to 27 inches for the modified G4(1S) strong post barrier system. More recently, full-scale crash testing at FOIL has shown that a strong-post w-beam rail height that is 2 inches lower than the standard installation height resulted in the 2000P test vehicle vaulting over the barrier (Marzougui et al., 2007). Based on this information, the research team recommends barrier repair for any crash damaged strong-post barrier where the top of the w-beam rail is 2 or more inches below the original top of the rail height (Exhibit 7.0).

Exhibit 7.0. Recommendations for crash-induced rail and post deflection.

Damage Mode	Repair Threshold	Relative Priority
Post and Rail Deflection	One or more of the following thresholds: • More than 9 inches of lateral deflection anywhere over a 25-ft length of rail. • Top of rail height 2 or more inches lower than original top of rail height.	High
	• 6-9 inches of lateral deflection anywhere over a 25-ft length of rail.	Medium
Rail Deflection Only	6-9 inches of lateral deflection between any two adjacent posts. Note: For deflection over 9 inches, use post and rail deflection guidelines.	Medium

CHAPTER 11

Evaluation of Missing or Broken Posts

This section aims to quantitatively assess the effects of missing posts in an otherwise undamaged section of strong-post w-beam guardrail. The ultimate goal was to develop recommendations to be used by maintenance personnel for the repair priority of missing posts. Posts can be missing from a guardrail for a variety of reasons. The posts in steel guardrail may be missing, severely twisted, or completely flattened from a prior crash. The posts from a wooden post guardrail might be missing due to rot, insect damage, or shattering due to a crash. Note that for this study, the research team also categorizes posts as missing if they are present but so weakened due to damage or deterioration that they present little to no effective support of the rail.

11.1 Approach

A series of finite element simulations were run to determine the number of posts which could be removed from the strong-post w-beam guardrail while still maintaining acceptable crash performance. Simulations were conducted using the LS-DYNA software (LSTC, 2003) for strong-post w-beam guardrail with 1, 2, and 3 missing posts. For each missing post simulation, two different impact points were used to examine the effect that the impact point had on the crash performance. These impact points were (1) at the post beginning at the unsupported span and (2) the mid-point of the unsupported span.

The missing post damage mode was a straightforward damage condition to simulate. To reproduce the damage, the entire post, along with all the supporting elements, was deleted from the model. The supporting elements consisted of the soil, post bolt, post nut, and blockout. No compensatory options such as nesting were added to the model to improve the strength of the resulting section of unsupported rail. An example of a completed full-scale model with a missing post is shown in Figure 46.

11.2 Validation of Finite Element Model

Ideally, the validation of strong-post w-beam systems with missing posts could be determined from crash tests, but there were no crash tests to the research team's knowledge with missing posts in unmodified strong-post w-beam guardrail. As an alternative, the finite element model was validated against a crash test of a specialized variation of guardrail called a long-span system (Polivka et al., 1999a; Polivka et al., 1999b).

Long-span systems have posts that are missing by design. They are used wherever posts cannot be driven into the ground, most commonly due to the presence of medium to large culverts under the roadway. Long-span systems are typically modified in order to compensate for the loss of one or more posts. Typically, the rails are nested (doubled up) over the unsupported portion of the guardrail and the adjacent sections of the rail that would be involved in the impact. Other long-span systems may also incorporate changes to the post spacing, the number of blockouts, or the substitution of wooden posts near the unsupported area to reduce the chance of snagging.

The crash test selected for validation was the crash test of a long-span guardrail system missing three posts, performed by the University of Nebraska-Lincoln (UNL) as part of a study of long-span systems (Polivka et al., 1999a). In this report, this test will be referred to as OLS2. This guardrail system included a 25-foot (7.62 meters) unsupported span with nested guardrail used as compensation for the reduced strength in the unsupported region. A TL 3-11 impact of a Chevrolet C-2500 pickup truck into the long-span section test resulted in the pickup truck overturning as it exited the guardrail.

This crash test differed from the missing/broken model in several respects: (1) OLS2 used wood rather than steel posts, (2) OLS2 used nested guardrail rather than the standard single guardrail simulated in this study, and (3) the test used a 25-foot

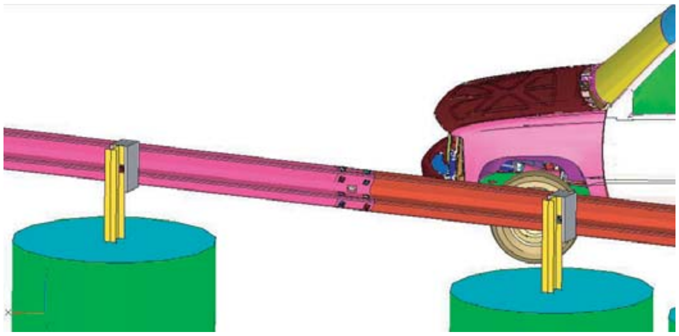


Figure 46. Simulated guardrail missing on post.

guardrail section rather than a 12.5-foot guardrail section simulated in the research team's model. For this crash test, the finite element model was carefully adapted to match the exact length of nested rail and the substitution of weakened wooden controlled releasing terminal (CRT) posts near the unsupported span.

Visually, good agreement was observed between the finite element model predictions and the reported outcome of the OLS2 crash test up to 760 ms. After 760 ms, the vehicle in the OLS2 crash test rolled whereas the simulated vehicle did not. A comparison between each crash test and simulation is shown in Figure 47. The results required by the *NCHRP Report 350* test criteria for both the original crash test and the simulations reproducing the results are shown in Table 22. The post-impact exit speed of 55 km/hr (34.1 mph) was lower in the simulation than in the exit speed in the crash test of 66 km/hr (41.1 mph). The vehicle in the simulation did not overturn. These differences were attributed to the difficulty of modeling wooden posts. The maximum observed dynamic guardrail deflection was 0.3 meters (1 foot) lower in the simulation than in the crash test. The lower deflection of the simulation was related to the higher stiffness of the soil in the finite element model relative to the crash test.

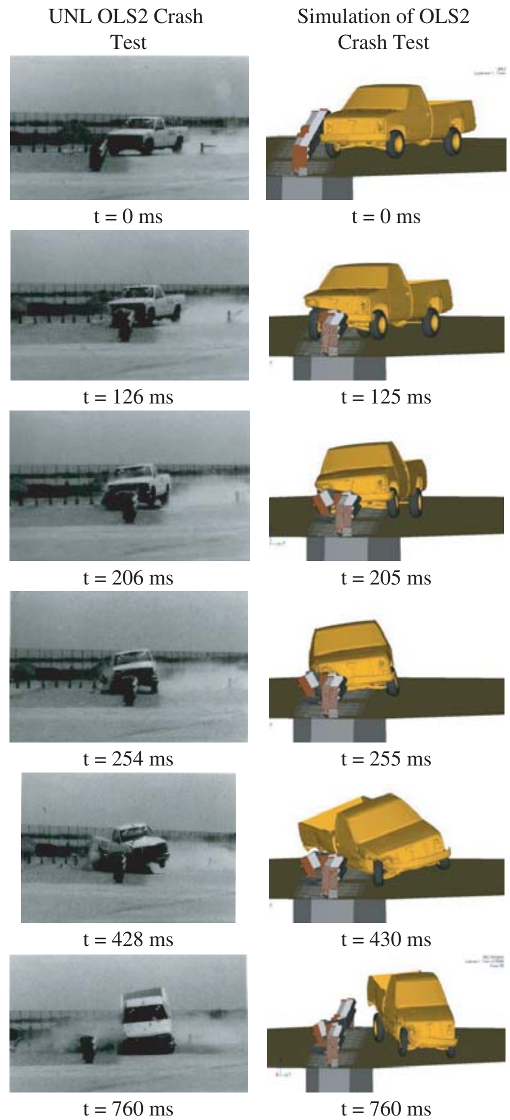


Figure 47. Comparison of missing post finite element model against OLS crash test.

11.3 Results

A series of finite element simulations was conducted to determine the effect of missing posts on the guardrail crash performance. In this model, unlike the long-span validation simulation, all of the posts around the impact area in these models were steel posts and none of the guardrails were nested. Table 23 presents the results of simulations missing 1, 2, and 3 posts when the impact point was at the beginning of the span. Table 24 presents the results of simulations missing 1, 2, and 3 posts when the impact point was at the midpoint of the unsupported span. Figure 48 presents a graphical comparison of the simulations missing 1, 2, and 3 posts under both impact points.

The initial point of impact had a strong effect on the simulation results. Simulations in which the vehicle struck the guardrail at the beginning of the unsupported span predicted less severe roll and pitch (all less than 10 degrees). Mid-span simulations, on the other hand, showed a much higher roll and much higher pitch values. Most severe was the system missing one post and impacted at the mid-span in which the vehicle pitched 45 degrees but maintained stability.

The results for missing post simulations in which the impact point was mid-span are summarized in Table 23. For the vehicle, the exit speed decreased sharply for each additional missing post. The guardrail dynamic deflection also increased as more posts were removed as the lateral strength provided by the posts was eliminated. When three posts were missing, the

Table 22. Comparison of missing post model results with UNL long-span crash test OLS2.

	OLS Crash Test	OLS2 Simulation
Impact Conditions		
Speed (kph)	102.7	102.7
Angle (deg)	24.5	24.5
Exit Conditions		
Speed (kph)	66.2	55.0
Angle (deg)	16.7	16.3
Occupant		
Impact Velocity X (m/s)	6.7	8.6
Impact Velocity Y (m/s)	5.0	-6.3
Ridedown X (G)	6.4	-14.0
Ridedown Y (G)	8.3	14.6
50 ms Average X (G)	NR	-9.1
50 ms Average Y (G)	NR	8.6
50 ms Average Z (G)	NR	-4.9
Guardrail Deflections		
Dynamic (m)	1.3	1.0
Static (m)	1.0	0.7
Vehicle Rotations		
Max Roll (deg)	Rolled	14.3
Max Pitch (deg)	NR	-15.5
Max Yaw (deg)	NR	-43.5

dynamic deflection increased by a little over 50 percent. All occupant injury metrics, i.e., occupant ridedown acceleration and occupant impact velocities, were well below the *NCHRP Report 350* limits.

In Table 24, the results for the missing post simulations for which the point of impact was the beginning of the unsupported span are presented. Maximum rail deflection, maximum rail tension, and vehicle exit speed increased as the number of missing posts increased. All occupant injury metrics, i.e., occupant ridedown acceleration and occupant impact velocities, were well below the *NCHRP Report 350* limits.

11.4 Discussion

For all simulations, there was a large increase in dynamic deflection for each post that was removed from the system. The maximum dynamic deflection contours are shown in Figure 49. For most of the simulations, the maximum deflection typically occurs around 0.2 seconds after impact. At this time, the vehicle was just beginning to redirect due to contact with the rails. As would be expected, the dynamic deflection increased as more posts were removed from the system. For the simulation with three missing posts, the guardrail deflection exceeded that of the OLS validation simulation, which was also missing three posts. However, the OLS test made use of nested guardrail to reduce the deflection, so this was not unexpected. The static deflection varied greatly between simulations. This was partly due to twisting in the rails, but also because of the manner in which the vehicle exited the guardrail. For the simulations with one and two posts missing, the snagging of the vehicle tires on the posts caused the vehicle to slide away from the rails. In the simulations with undamaged and 3 posts missing, the vehicle remained in contact with the rails longer which caused the damage contour to smooth out more.

Table 23. Results for missing post simulations with mid-span impacts.

	Undamaged	1 Post Missing	2 Posts Missing	3 Posts Missing
Impact Conditions				
Speed (kph)	100	100	100	100
Angle (deg)	25	25	25	25
Exit Conditions				
Speed (kph)	53	60	47	32
Angle (deg)	14.5	20.9	29.4	13.3
Occupant				
Impact Velocity X (m/s)	7.51	7.55	6.81	7.63
Impact Velocity Y (m/s)	5.54	5.56	3.65	3.56
Ridedown X (G)	-11.77	-9.50	-13.98	-12.88
Ridedown Y (G)	-12.27	-9.02	-9.87	-9.71
50 ms Average X (G)	-6.68	-6.67	-8.11	-8.52
50 ms Average Y (G)	-6.82	-6.10	-7.00	-6.44
50 ms Average Z (G)	-3.85	4.29	-3.18	-6.73
Guardrail Deflections				
Dynamic (m)	0.69	0.86	0.97	1.05
Static (m)	0.55	0.71	0.78	0.60
Vehicle Rotations				
Max Roll (deg)	-14.4	-15.4	-13.2	-19.4
Max Pitch (deg)	-9.9	-44.6	-17.8	-23.4
Max Yaw (deg)	40.3	44	78.8	40
Max Rail Tension				
	237.4	267.5	299.8	352.8

Table 24. Results for missing post simulations with beginning of span impacts.

	Undamaged	1 Post Missing	2 Posts Missing	3 Posts Missing
Impact Conditions				
Speed (kph)	100	100	100	100
Angle (deg)	25	25	25	25
Exit Conditions				
Speed (kph)	53	39	57	63
Angle (deg)	14.5	-11.5	11.4	15.3
Occupant				
Impact Velocity X (m/s)	7.51	8.88	7.53	6.51
Impact Velocity Y (m/s)	5.54	5.81	5.75	5.48
Ridedown X (G)	-11.77	-9.10	-12.13	-10.22
Ridedown Y (G)	-12.27	-10.08	-8.89	-10.30
50 ms Average X (G)	-6.68	-7.93	-6.37	-6.32
50 ms Average Y (G)	-6.82	-6.76	-6.75	-7.27
50 ms Average Z (G)	-3.85	-4.82	3.21	1.71
Guardrail Deflections				
Dynamic (m)	0.69	0.78	0.89	1.00
Static (m)	0.55	0.51	0.68	0.70
Vehicle Rotations				
Max Roll (deg)	-14.4	-7.6	-7.8	-6.5
Max Pitch (deg)	-9.9	-7.6	-6.9	2
Max Yaw (deg)	40.3	23.8	37	40
Max Rail Tension (kN)				
	237.4	268.4	286.2	336.7

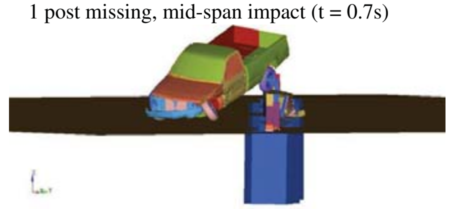
Because of the coarse sampling, the damage contours shown in Figure 49 do not always show the same maximums that were recorded in Tables 23 and 24. However, the contours are useful for observing the shape of the guardrail during the time of maximum deflection. The contours shown all begin at that same point, starting at post 9. The deflection was sampled roughly every 953 mm (3.1 feet) until post 21 was reached. The total length sampled was just under 23 meters (75.5 feet) which covers the full area of contact. In all of the curves, the peak was formed around the corner of the vehicle, with relatively smooth leading and trailing edges created by the vehicle's front and side, respectively. The difference in the locations of the peak deflections was due to changes in the impact point relative to the reference post.

Figure 50 shows the vehicle velocity for each simulation. All velocities were reported in the vehicle local coordinate system.

1 post missing, beginning of span impact (t = 0.7s)

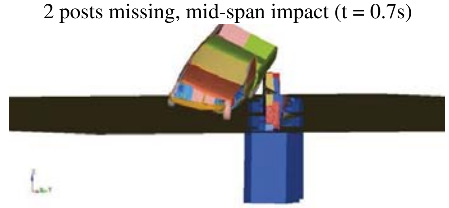
1 post missing, mid-span impact (t = 0.7s)

2 posts missing, beginning of span impact (t = 0.7s)



2 posts missing, mid-span impact (t = 0.7s)

3 posts missing, beginning of span impact (t = 0.7s)



3 posts missing, mid-span impact (t = 0.7s)

Figure 48. Post-impact behavior of the vehicle for missing post simulations.

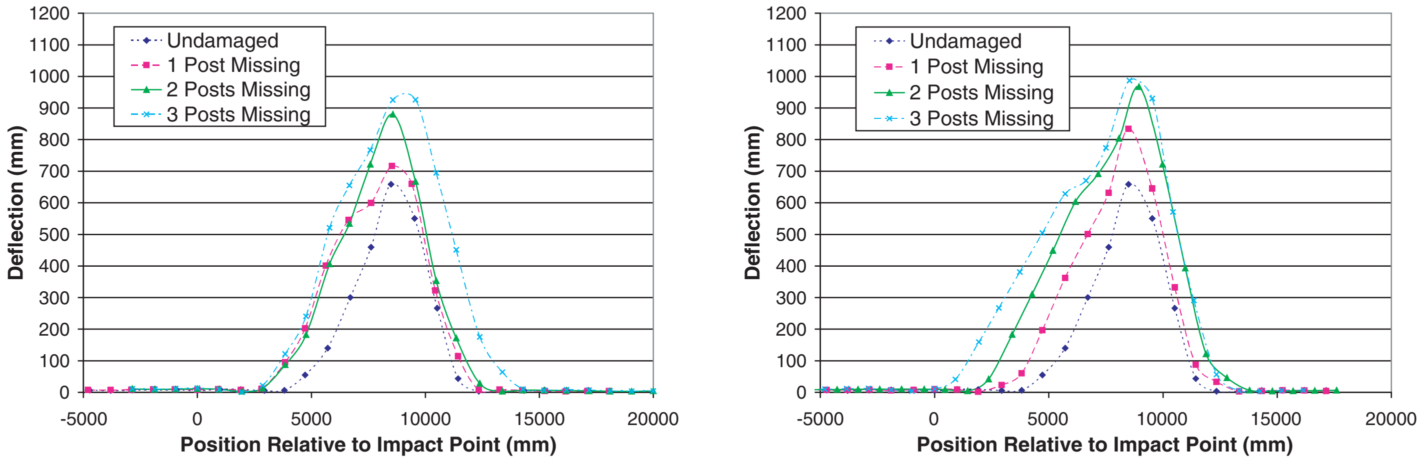


Figure 49. Maximum dynamic deflection contours; impacts at the beginning of the unsupported span (left) and the middle of the unsupported span (right).

Many of the vehicles showed decreases in velocity due to friction after exiting the guardrail. All exit velocities were recorded at 700 ms as a common reference velocity. Although this did not eliminate any loss in speed due to friction, this approach ensured that the measurements were consistent across all the simulations. The magnitude of the Y and Z velocity components tended to be the highest for the simulations where there was a short distance between the point of impact and the first downstream post. This was attributed to the front left tire snagging on the downstream posts.

For simulations where the impact point was at the beginning of the unsupported span, the exit speed of the vehicle increased as the number of posts removed from the system was increased. The most likely explanation for this was that the increased distance to the next post in the guardrail prevented severe wheel snagging from occurring. By contrast, for the three simulations were the impact point was at the middle of the unsupported span the exit speed decreased as more posts were removed.

To explore the possible causes of this difference, the distance between the vehicle's point of impact and the first downstream post was examined. For mid-span impacts, the distances to the next post were 1.9, 2.86, and 3.8 meters (6.2, 9.4, and 12.5 feet) for 1, 2, and 3 posts missing, respectively. For the beginning of span impacts, the same distances were 3.8, 5.7, and 7.6 meters (12.5, 18.7, and 24.9 feet). The two simulations where the vehicle was 3.8 meters (6.2 feet) from the next post resulted in the two lowest exit velocities, whereas the exit speed for the vehicle increased as the distance either increased or decreased. This behavior was attributed to the existence of a critical impact point for which the chance of the vehicle snagging on the posts was maximized.

11.4.1 Evaluation of Rail Rupture Potential

Rail rupture is a great concern for guardrails with long stretches of unsupported rail. Ruptures are occasionally ob-

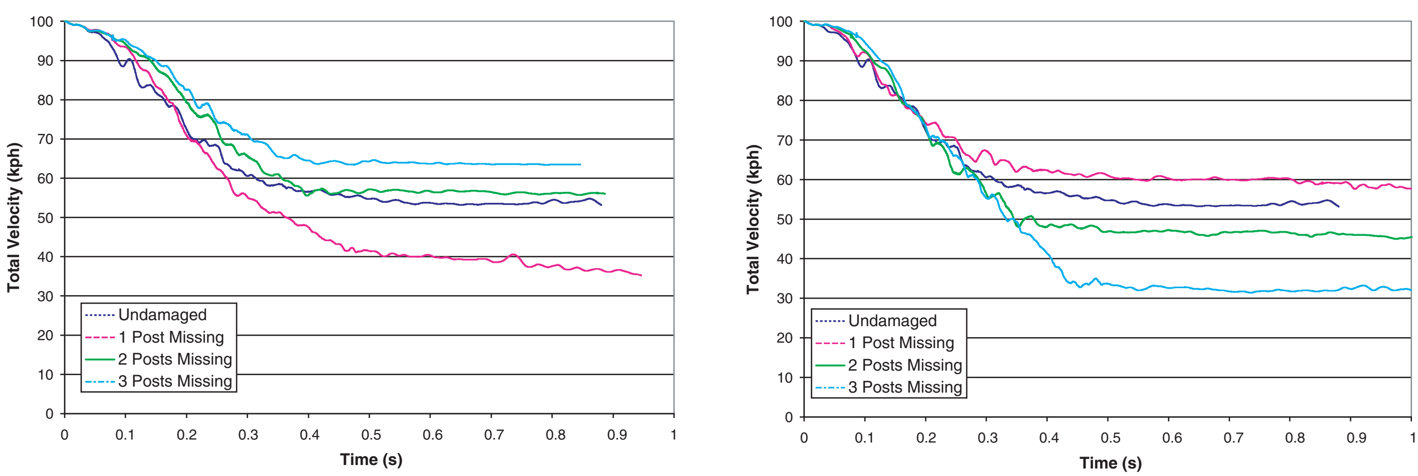


Figure 50. Vehicle velocity at center of gravity. Velocity for impacts at the beginning of the unsupported span (left) and the middle (right).

served even in crash tests of standard, unmodified guardrails (Ray et al., 2001). These failures also occur at lower tensions than the reported quasistatic tensile strength of 410 kN (92.2 kip). By removing posts from the guardrail, the forces of impact are concentrated on fewer posts. This increased the likelihood of a rail rupture.

To assess the possibility of rail rupture, measurements of rail tension in the simulations were made between different pairs of adjacent posts to identify the section carrying the largest load. Tensions were tabulated for all rail sections located between post 9 and post 21, which included the entire area of contact between the rail and vehicle. There were clearly observed increases in the rail tension as the number of posts removed from the system increased. The rail tensions for all simulations peaked at roughly 200 ms, although the tensions remained high during the full duration of vehicle redirection, which occurred between 0 and 400 ms.

In Figure 51, the maximum observed tensions from the undamaged simulation are tabulated for each of the missing post simulations. For each additional post removed from the guardrail system, the maximum tension in the rail increased by 20–50 kN (4.5–11.2 kip). The maximum tension observed was 352.8 kN (79.3 kip) for the guardrail missing three posts with a mid-span impact. This was almost a 50% increase in rail tension compared to the undamaged simulation, where the maximum tension recorded was 237.4 kN (53.4 kip).

While the increase in rail tension as posts were removed was large, the maximum tension observed in the simulations was still below the quasi-static tension limit of 410 kN. However, this did not necessarily mean that rail rupture could not occur, as Ray et al. (2001) have shown that rail rupture typically occurs at much lower rail tensions that can be reached in quasi-static testing. This has been attributed to the development of high localized stresses around the splices in full-scale crash tests. Localized tearing is possible in impacts where posts are missing, but the finite element model was not configured to look for element tearing resulting from localized stress concentrations because the model did not include any failure criteria for the steel components. However, based on the results of the rail tension analysis, the likelihood of the rails rupturing during impact increased as more posts were removed.

11.5 Recommendation

This study has examined the crash performance of strong-post w-beam guardrail with missing posts. The finite element simulations conducted clearly showed that the removal of posts from a guardrail had a strong adverse effect on the crash performance of both the vehicle and guardrail, as summarized below:

- Vehicle collisions with guardrail systems missing posts have an increased risk of vehicle instability. While none of the vehicles in the simulations overturned, several vehicles were unstable after impact which could have led to rollover under some field conditions. Some of the vehicles exhibited significant skidding upon exiting the system, and these vehicles would be easily tripped by irregularities in the ground.
- The removal of even one post can be expected to increase the system deflection by as much as 25 percent. Further increases in deflection and stress were expected as more and more posts were removed from the system. The most severe condition simulated (three posts missing) resulted in a 50 percent increase in the maximum deflection of the

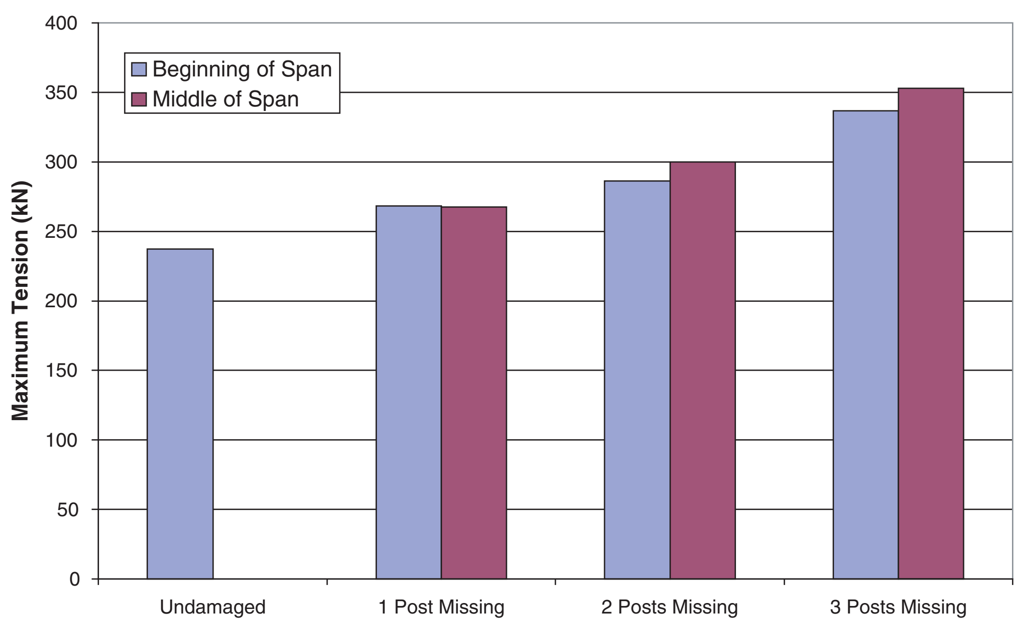


Figure 51. Maximum rail tension as a function of number of missing posts.

guardrail. Therefore, it would be especially important to repair missing posts whenever there is a substantial crash risk immediately behind the barrier.

- Rail tension, a possible predictor of rail rupture, increased as posts were removed from the system regardless of where the impact point was located. With three posts missing from the system, the tension was increased by nearly 50 percent but was still below the quasi-static failure limit of 410 kN. However, rail ruptures have been observed in crash tests at much lower tensions than can be reached at quasi-static loading due to localized stresses around the splices. Thus, the increased rail tension, combined with the higher stresses, indicates an increased risk of the rail rupturing during impact.

The research team's recommendation is that maintenance crews should repair any strong-post w-beam systems that are missing any number of posts (Exhibit 8.0). Even a single missing post in a strong-post w-beam guardrail can seriously degrade the performance. Impacts into guardrail systems with missing posts were found to have a higher risk of vehicle instability, greater maximum guardrail deflection, and an increased risk of rail rupture.

Exhibit 8.0. Recommendations for repair of missing or broken posts.

Damage Mode	Repair Threshold	Relative Priority
Missing/Broken Posts	1 or more posts missing Cracked across the grain Broken Rotted With metal tears	High

CHAPTER 12

Evaluation of Post Separation from Rail

This chapter evaluates the effect of post and rail separation in strong-post w-beam guardrail systems. This type of damage commonly occurs in combination with minor rail deflection, but in this study it was considered in isolation. Figure 52 shows an example of post and rail separation in the field and a finite element model of this damage mode.

12.1 Approach

Finite element simulations were completed in which a 2000P vehicle impacted a barrier (at TL-3 conditions) with detached posts. Based on the field inspections of damaged barriers, the research team found that detached posts typically occur in tandem with some amount of post deflection away from the rail. For this study two simulations were conducted—the first for a single detached post and the second for two adjacent detached posts. To create a model of a rail with detached posts, the connection to the rail was severed and both posts were pushed out of line 3 inches with respect to their original position perpendicular to the barrier face. The procedure by which the post and rail separation was induced in the finite element model is described in the appendices. The resulting model is shown in Figure 52 for 3 inches of deflection of two adjacent posts. The vehicle was given the initial conditions specified by the *NCHRP Report 350* test criteria. The impact velocity was 100 kph at an impact angle of 25 degrees.

12.2 Results

The results of the rail and post separation simulations are summarized in Table 25. Many of the *NCHRP Report 350* required criteria did not vary between the different simulations. The occupant impact velocity, occupant ridedown acceleration, and vehicle 50 ms moving average acceleration did not change between the undamaged and post-and-rail-separated simulations. The vehicle exit speed and angle were also unchanged.

The greatest changes between each of the simulations were observed in the vehicle rotation, particularly the roll and pitch. Both roll and pitch decreased as more posts were detached from the guardrail indicating better vehicle stability. There was also a small increase in the maximum amount of dynamic and static deflection in the guardrail system. However, the increases associated with the rail and post separation damage mode were the smallest of all of the examined damage modes.

In Table 26, the vehicle rotations (roll, pitch, and yaw) are shown. All of the simulations showed the same trends. As mentioned earlier though, the simulation of two posts separated by 3 inches showed that the minor damage to the guardrail improved the vehicle stability by lowering both the roll and pitch. As a consequence, the vehicle also returned to the neutral position at roughly 600 ms, which was faster than for the other two simulations which reached the neutral position at roughly 750 ms. The yaw did not vary between the three simulations.

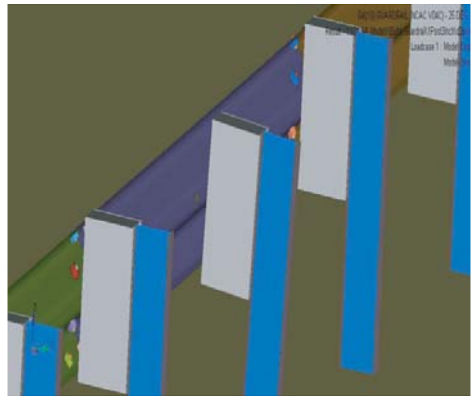
The vehicle velocities, shown in Figure 53, were also very similar between all three simulations. There was a noticeable amount of lateral skidding during the impact (in the range of 50–400 ms) that diminished as the vehicle began to exit the guardrail. The exit speed for the vehicle was completely unaffected by the minor damage and ranged between 53 and 54 kph.

The guardrail deflection did not vary much between the simulations of post and rail separation and the undamaged simulation. As shown in Figure 54, all of the simulations resulted in a maximum dynamic deflection of roughly 2.3 feet (0.7 meters) and maximum static deflections around 1.8 feet (0.55 meters).

12.3 Discussion

Two simulations were run to evaluate the effect of post and rail separation. The first simulation modeled the effect of one post separated by 3 inches and the second simulation modeled two posts separated by 3 inches. Intuitively, it was expected that the introduction of damage into the guardrail would worsen the overall performance. However, this damage mode was

Field Example



FE Model

Figure 52. Post separation from guardrail.

found to have little effect on the safety of the vehicle and its occupant.

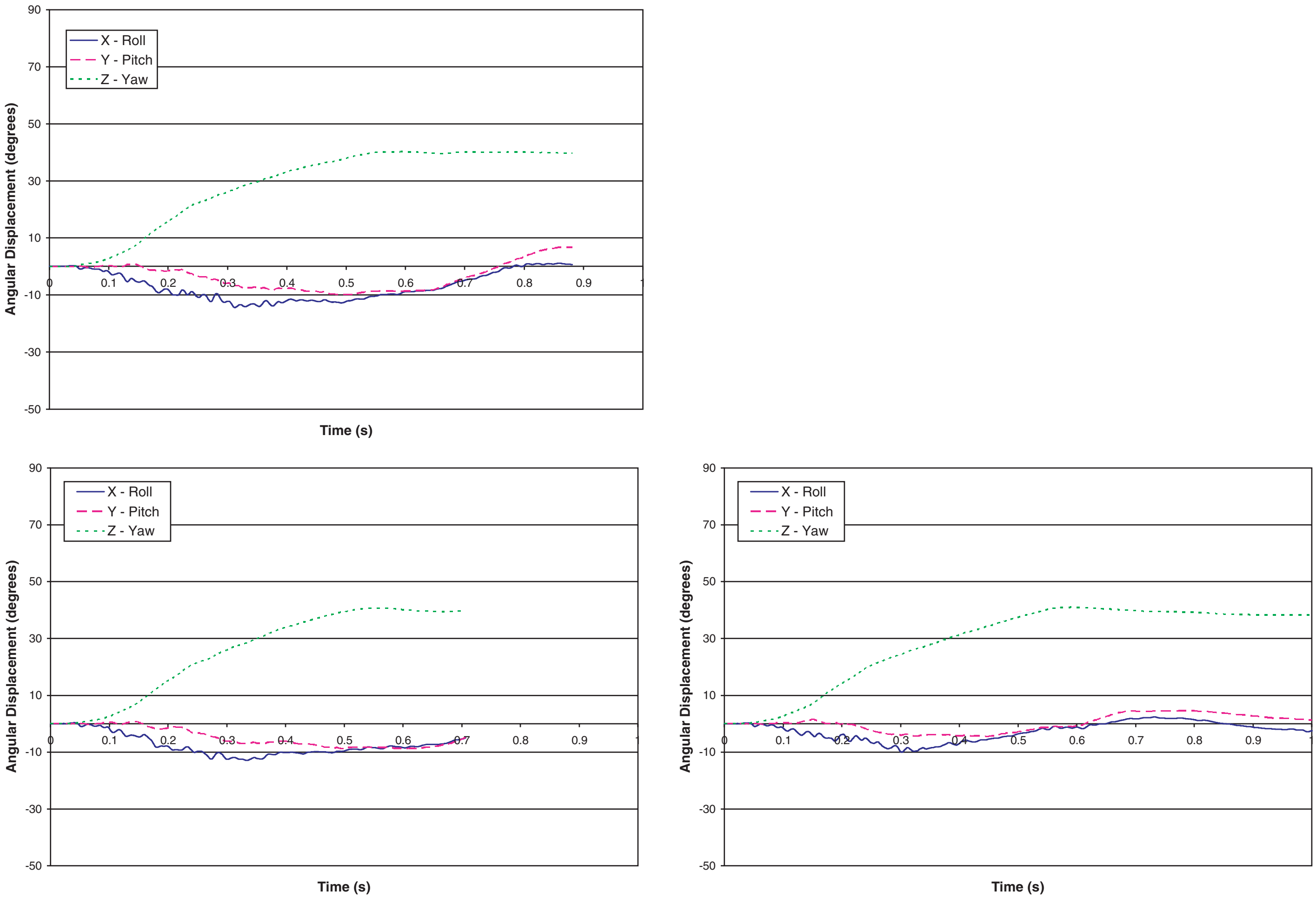
The maximum deflection of the guardrail itself did not change greatly as more posts were separated from the rail. The most severe damage condition modeled, which was two posts separated by 3 inches, resulted in a 5.6 percent increase in maximum dynamic deflection. The increases associated with rail and post separation were smaller than those of the missing post, rail and post deflection, and rail flattening damage conditions. It was interesting that the increase in maximum dynamic deflection for the simulation of one separated post increased by 0.1 meters (3.9 inches), which was roughly equal to the 3 inches which the damaged post was deflected.

The minimal effect of rail and post separation on the crash simulation results appeared reasonable. By design, the posts and rails in strong-post systems are supposed to separate during impact. By allowing separation, the posts and rails can deform by large amounts without the rails being pulled down toward the ground. Because the posts were not connected to the rails, the posts could deform more freely and reduce the risk of the vehicle snagging on the posts. The posts were still able to provide a significant amount of lateral resistance to deflection even though they were not attached to the rail. Because of these factors, the ability of the guardrail to redirect the vehicle and absorb crash energy was not significantly reduced.

Table 25. Results for rail and post separation simulations.

	Undamaged	1 Post 3 in.	2 Posts 3 in.
Impact Conditions			
Speed (kph)	100	100	100
Angle (deg)	25	25	25
Exit Conditions			
Speed (kph)	53	53	54
Angle (deg)	14.5	14.8	14.8
Occupant			
Impact Velocity X (m/s)	7.5	7.7	7.7
Impact Velocity Y (m/s)	5.5	5.8	5.7
Ridedown X (G)	-11.8	-13.1	-11.3
Ridedown Y (G)	-12.3	-14.0	-12.0
50 ms Average X (G)	-6.7	-7.3	-6.6
50 ms Average Y (G)	-6.8	-7.2	-6.6
50 ms Average Z (G)	-3.8	-2.6	-4.1
Guardrail Deflections			
Dynamic (m)	0.69	0.70	0.73
Static (m)	0.55	0.59	0.58
Vehicle Rotations			
Max Roll (deg)	-14.4	-12.9	-10.0
Max Pitch (deg)	-9.9	-8.8	4.6
Max Yaw (deg)	40.3	40.8	41.0

Table 26. Roll, pitch, and yaw for post and rail separation simulations.



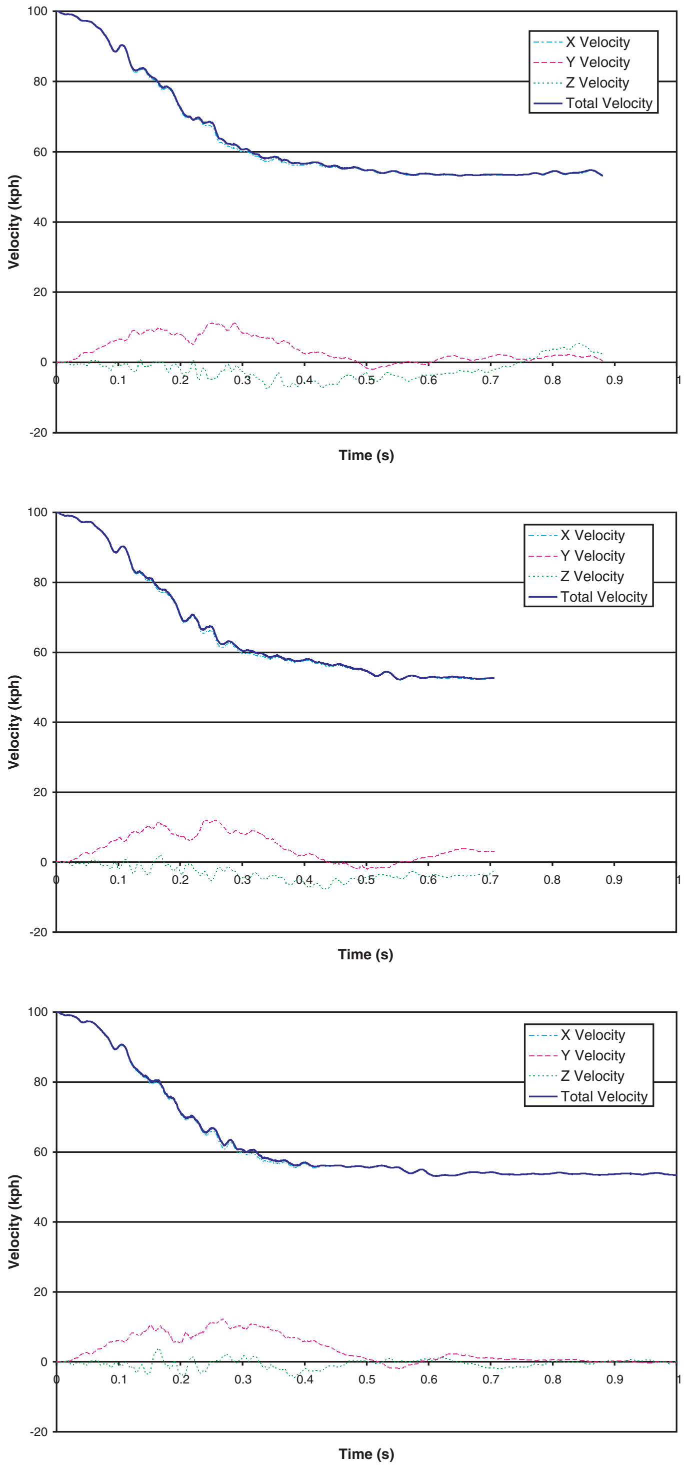


Figure 53. Vehicle velocities for post and rail separation simulations.

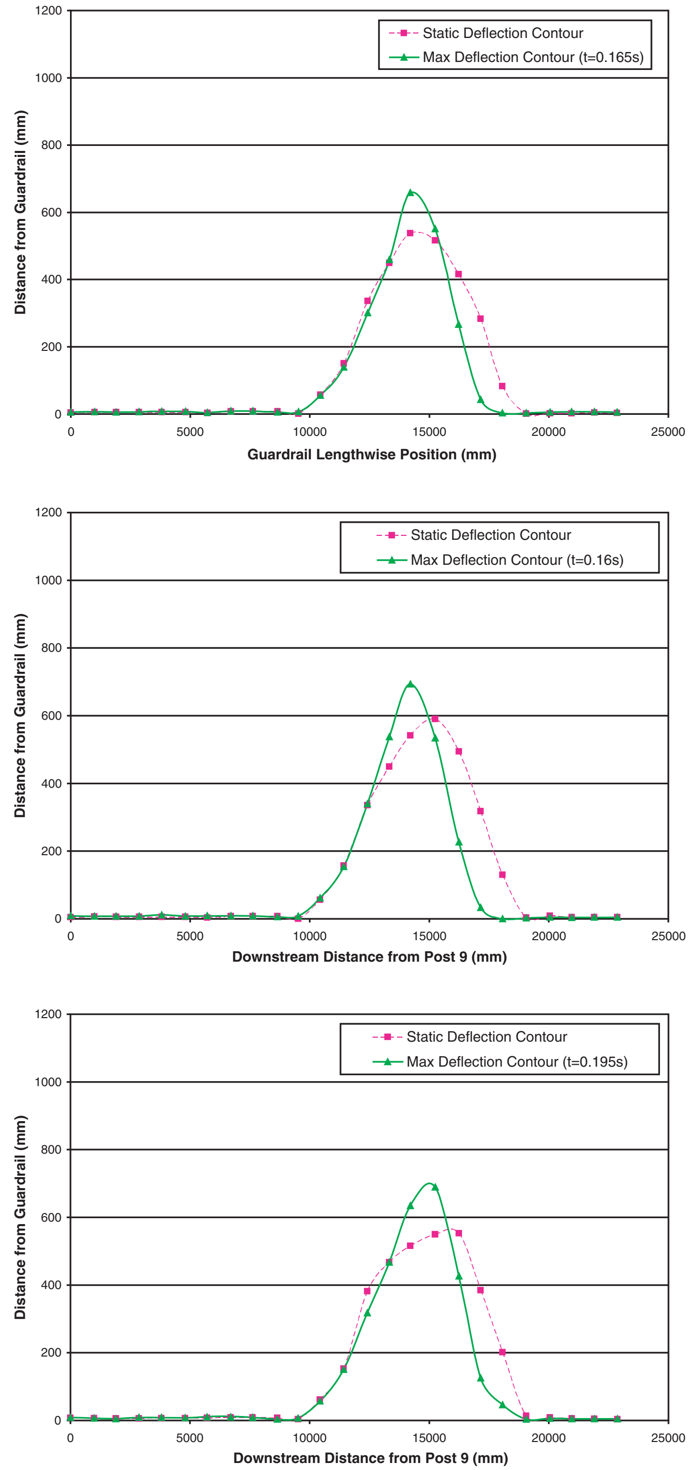


Figure 54. Guardrail damage contours for post and rail separation simulations.

Exhibit 9.0. Recommendations for posts separated from rail repair.

Damage Mode	Repair Threshold	Relative Priority
Posts Separated from Rail	• 2 or more posts with blockout attached with post-rail separation less than 3 in. • Post-rail separation which exceeds 3 in. Note: If the blockout is not firmly attached to the post, use the missing blockout guidelines. Note: Damage should also be evaluated against post/rail deflection guidelines.	Medium
	• 1 post with blockout attached with post-rail separation less than 3 in.. Note: If the blockout is not firmly attached to the post, use the missing blockout guidelines. Note: Damage should also be evaluated against post/rail deflection guidelines.	Low

12.4 Recommendation

The simulations conducted for this study indicate that the separation of up to two adjacent posts from the rails of the guardrail did not pose a risk to the vehicle or occupant. Indeed, it was found that the crash performance from this damage mode was almost indiscernible from that of the undamaged barrier performance. The recommended repair threshold is 2 or more adjacent posts that are detached from the rail; each deflected no more than 3 inches away from the rail. The priority assigned to this damage was medium for consistency with the post and rail deflection guidelines. Post and rail separation which exceeds 3 inches begins to take on the characteristics of the missing blockout damage mode. Repair for any single post with post and rail separation over 3 inches is recommended. The priority assigned to this damage was medium to be consistent with the missing blockout guideline.

Post and rail separation rarely occurs without post and rail deflection or damage to other components. In the recommendation in Exhibit 9.0, the research team recommends that the damage should also be evaluated using the deflected post and rail guidelines. Similarly, if the blockout is damaged or missing, maintenance personnel should use the damaged blockout repair guidelines.

CHAPTER 13

Evaluation of Rail Flattening

Rail flattening in strong-post w-beam guardrail was a damage mode of concern to many state agencies, ranking just below rail and post deflection. In the field, rail deflection is often associated with collisions at shallow angles or caused by a snowplow rubbing against the rail. Rail flattening was characterized by loss of depth in the w-beam rail element, which was often accompanied by rail deflection and post deflection. Concurrent with the loss of depth was an increase in the height of the guardrail, i.e., the upper edge of the guardrail extended higher while the lower edge moved closer to the ground. Figure 55 shows an example of rail flattening caused by a snowplow, and a finite element model of this damage mode.

Rail flattening was of concern for two reasons. First, the loss of depth in the rail reduced the spacing between the striking vehicle and the posts. Thus, rail flattening may increase the risk of vehicle snagging on the posts. Second, the flattening of the rail increases the maximum height and lowers the minimum height of the guardrail, changing the way in which the vehicle interacts with the guardrail system.

13.1 Approach

A series of simulations of impacts into flattened strong-post w-beam guardrail were run and compared to the performance of the undamaged guardrail simulation. The flattening in these simulations varied from 25 to 100 percent. This type of damage commonly occurs in combination with minor rail deflection, but in this study it was considered in isolation. The detailed procedure for inducing rail flattening in the finite element model is described in the appendices. The complete set of finite element models covered all degrees of flattening between 25 and 100 percent, in increments of 25 percent. These simulations are shown in Figure 56.

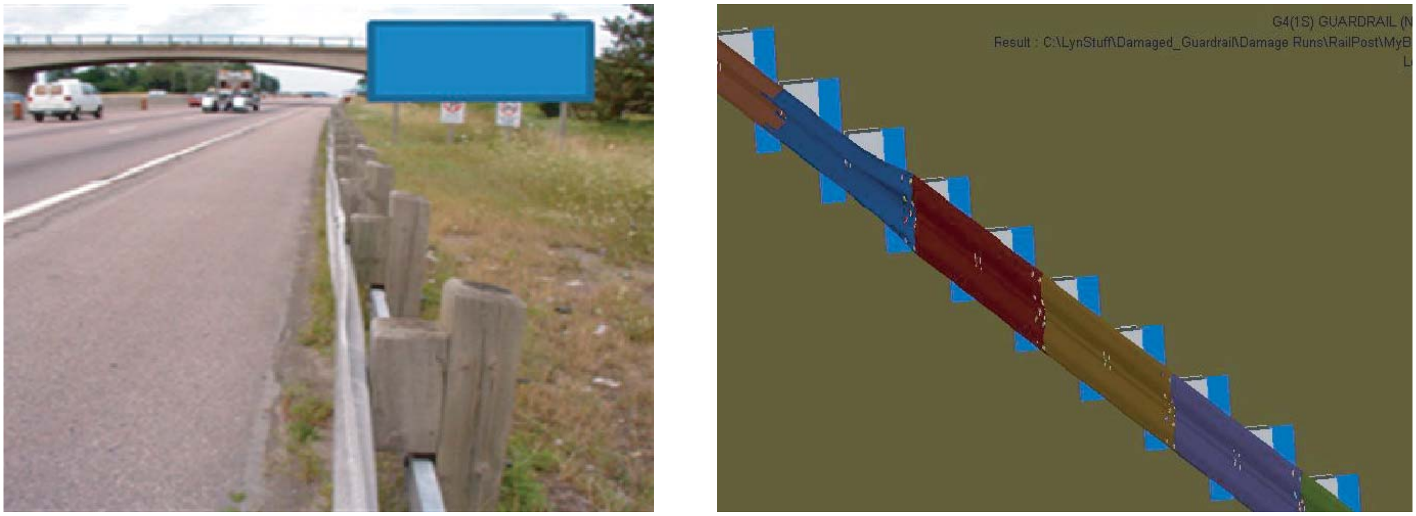
13.2 Results

Each of the flattening simulations was run on the Inferno2 computer system using four processors. Each run required roughly 26 hours per simulation to complete. The results of the simulations at 700 ms are shown in Figure 57. The vehicle exit behavior became increasingly unstable as the rail was flattened by greater amounts. Both roll and pitch increased with the amount of flattening. However, the yaw and exit angle decreased with increasing flatness. At 100% flattening, the vehicle was unable to remain upright and rolled to the right after exiting the guardrail.

In Table 27, the *NCHRP Report 350* test criteria are shown for both the undamaged simulation and all of the flattening simulations. As observed in Figure 57, the roll and pitch were higher and the yaw was lower for all of the flattening simulations. The degree of flattening in the guardrail had a strong effect on the exit speed and angle of the vehicle. The increase in exit speed was particularly pronounced at the highest levels of flatness, with a 13 kph (8.1 mph) increase in exit speed between 75 and 100 percent flattening. Exit angle showed the opposite behavior, i.e., it decreased with increasing flatness, from 14.5 degrees for the undamaged simulation to only 10 degrees for the 100 percent flattened simulation. The deflection of the guardrail, particularly the maximum dynamic deflection, increased along with flattening. The maximum deflection increased by 15.5 percent for a completely flattened rail. All occupant injury metrics, i.e., occupant ridedown acceleration and occupant impact velocities, were well below the *NCHRP Report 350* limits.

Figure 58 shows the roll, pitch, and yaw vs. time curves for the undamaged simulation and all of the flattening simulations. As expected, the roll for the 100 percent flattening simulation was the largest. The yaw for all of the flattening simulations peaked in the range of 400–500 ms, after which it started to decline. As the yaw was directly related to the heading of the vehicle, this implied that the vehicle was turning back toward the guardrail after exiting. The opposite sign on the pitch for the 100 percent flattening simulation implied a possibility of vaulting.

Figure 59 shows the local vehicle CG velocities for the undamaged and all flattening simulations. All of the simu-



Field Example (courtesy of Ontario Ministry of Transportation) FE Model

Figure 55. Rail flattening—field example vs. finite element model.

lations showed stable exit velocities. The 50 percent and 75 percent simulations also showed a relatively large amount of lateral skidding and upward motion as the vehicle was exiting the guardrail. This skidding motion was caused by the edge of the vehicle bed catching on a fold in the guardrail near a post, which also contributed to the decrease in yaw.

Figure 60 presents approximate damage contours for the guardrail. All of the damage contours were measured starting at post 9 (position = 0) up to post 21 (position = 22860 mm). For all simulations, except the 100 percent flattening simulation, the maximum dynamic deflection occurred at 165 ms. At this time, the vehicle was still moving into the guardrail and was just starting to be redirected. The static deflection contours for 25–75 percent flattening were very uneven. This was due to vibrations induced in the rail when the pickup truck bed slapped the guardrail.

13.3 Discussion

A full series of simulations, with flattening ranging from 25–100 percent, were run to determine whether rail flattening posed a risk to vehicle and occupant safety. It was found that the vehicle became unstable above 75 percent flattening.

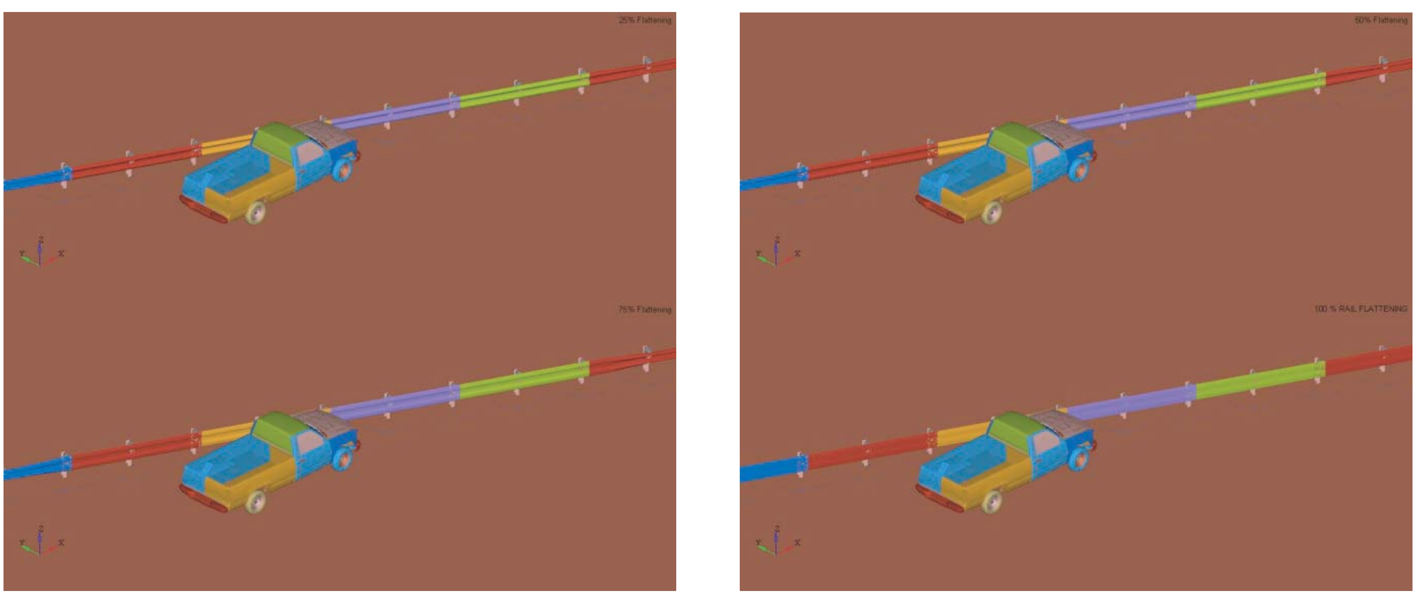


Figure 56. Rail flattening simulations before impact: 25% flattening (top left), 50% flattening (top right), 75% flattening (bottom left), and 100% flattening (bottom right).

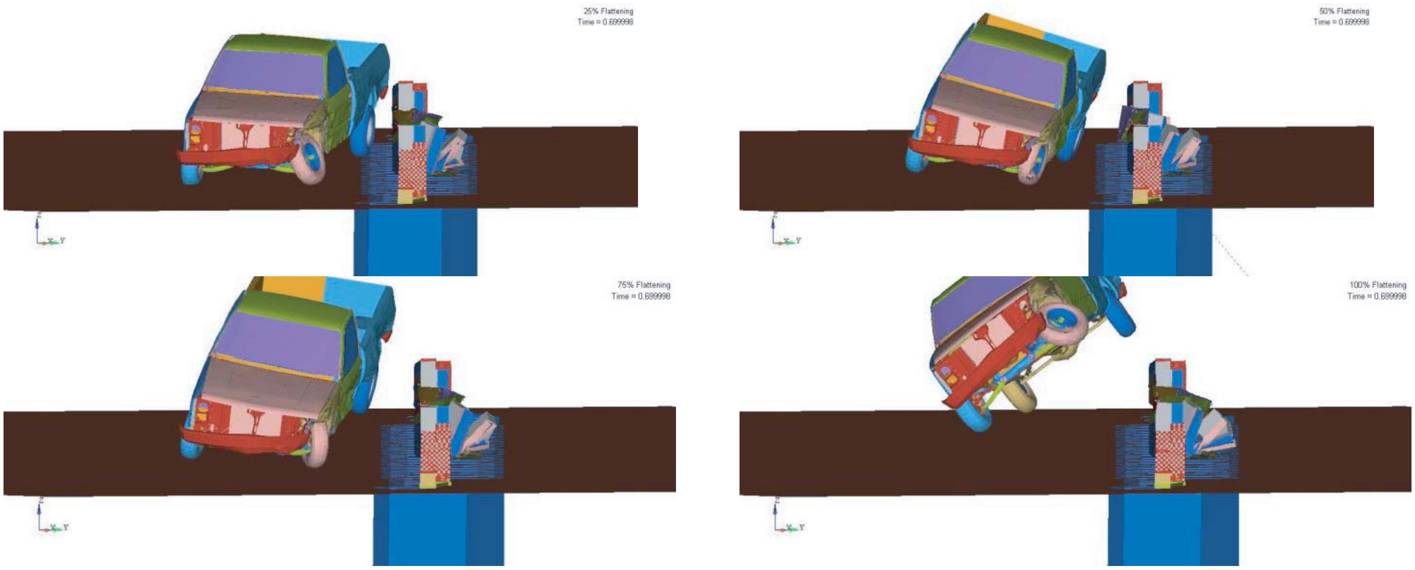


Figure 57. Flattening simulation results at t = 0.7s. 25% flattening (top left), 50% flattening (top right), 75% flattening (bottom left), and 100% flattening (bottom right).

At 100 percent flattening, the vehicle rolled over as it exited the guardrail.

A key factor in the exit behavior of the vehicle was the motion of the front left tire. Figure 61 shows the vertical displacement of the center of the front left and rear left tires over time, relative to each tire's original position at the start of the simulation. The simulation of 100% flattening showed the greatest displacement of the tire, reaching over 1600 mm (63 inches) by the end of the simulation. Such a large change in the vertical position of the vehicle can be an indicator of vaulting. However, in this case the vehicle was redirected before this could occur. The undamaged simulation showed the lowest amount of vertical tire motion, which was an indicator of vehicle stability. In the plot of the front left tire displacement for the undamaged simulation, the time at which the wheel struck and rolled over a post can be easily discerned by the peaks in the displacement.

Table 27. Results for rail flattening simulations.

	Un-damaged	25% Flattening	50% Flattening	75% Flattening	100% Flattening
Impact Conditions					
Speed (kph)	100	100	100	100	100
Angle (deg)	25	25	25	25	25
Exit Conditions					
Speed (kph)	53	56	59	60	73
Angle (deg)	14.5	12.1	9.1	10.7	10.0
Occupant					
Impact Velocity X (m/s)	7.51	7.3	7.5	6.8	5.9
Impact Velocity Y (m/s)	5.54	5.5	5.7	5.7	5.7
Ridedown X (G)	-11.77	-14.7	-10.9	-14.1	-7.4
Ridedown Y (G)	-12.27	11.4	-11.6	-12.3	-11.4
50 ms Average X (G)	-6.68	-5.6	-6.0	-6.1	-5.4
50 ms Average Y (G)	-6.82	-6.6	-7.1	-6.9	-7.2
50 ms Average Z (G)	-3.85	3.3	-3.7	-4.1	2.6
Guardrail Deflections					
Dynamic (m)	0.69	0.74	0.75	0.75	0.80
Static (m)	0.55	0.57	0.44	0.43	0.62
Vehicle Rotations					
Max Roll (deg)	-14.4	-15.8	-16.7	15.2	Roll
Max Pitch (deg)	-9.9	-12.3	20.2	-20.7	> 18
Max Yaw (deg)	40.3	38.3	38.0	38.0	33.5

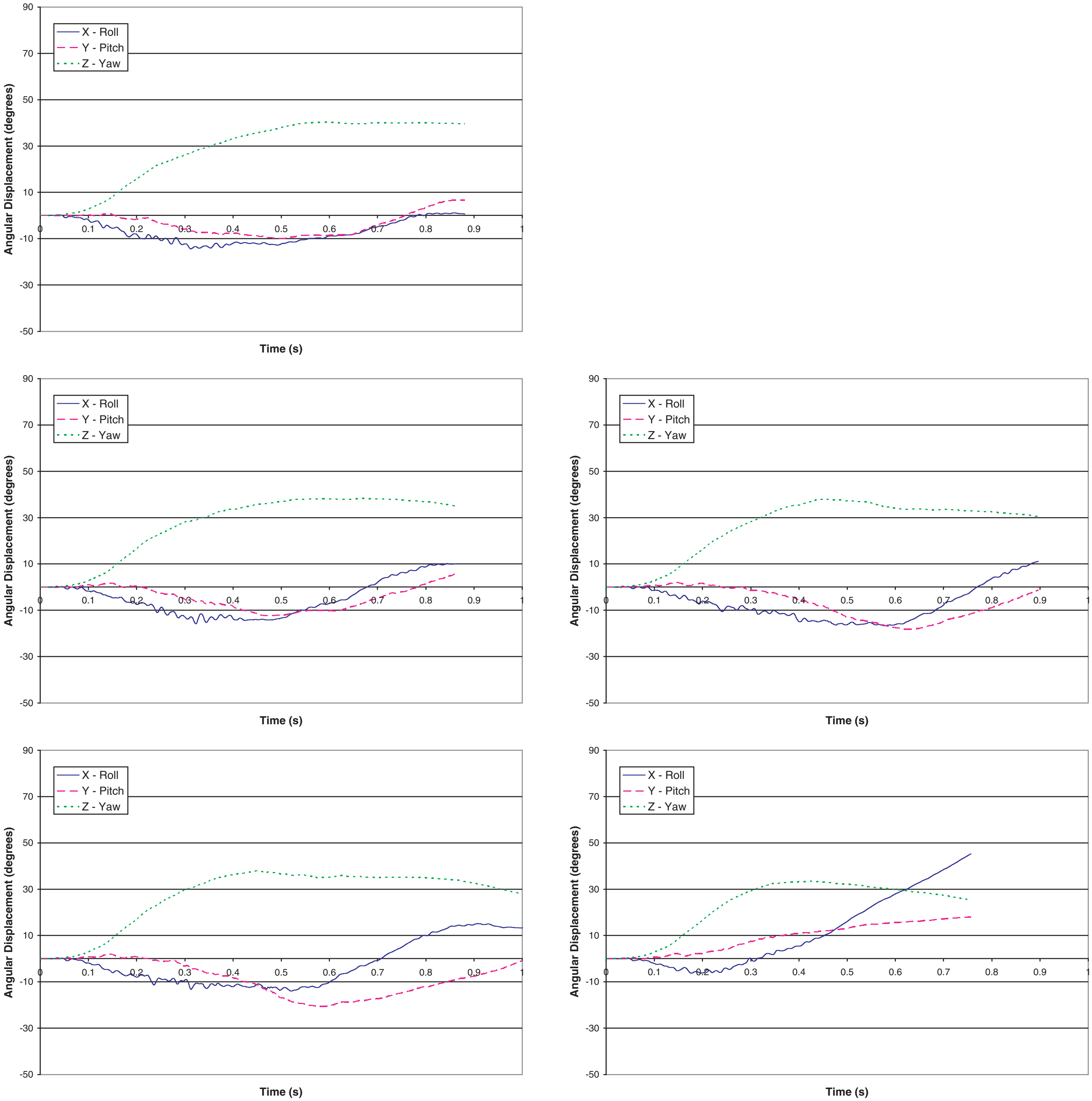


Figure 58. Roll, pitch, and yaw curves for flattening simulations: undamaged (top), 25% flattening (middle left), 50% flattening (middle right), 75% flattening (lower left), and 100% flattening simulations (lower right).

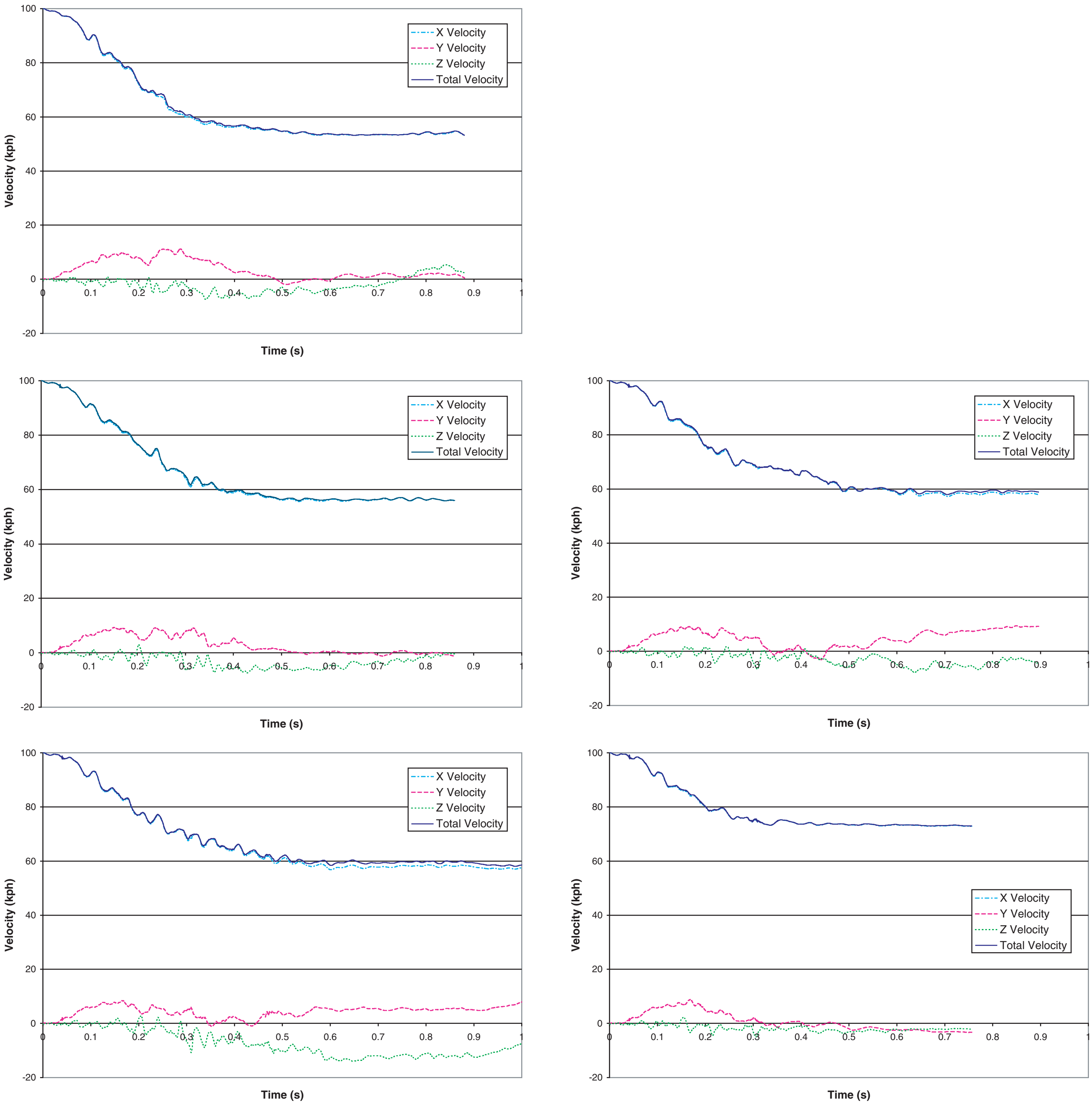


Figure 59. Velocity curves for flattening simulations: undamaged (top), 25% flattening (middle left), 50% flattening (middle right), 75% flattening (lower left), and 100% flattening simulations (lower right).

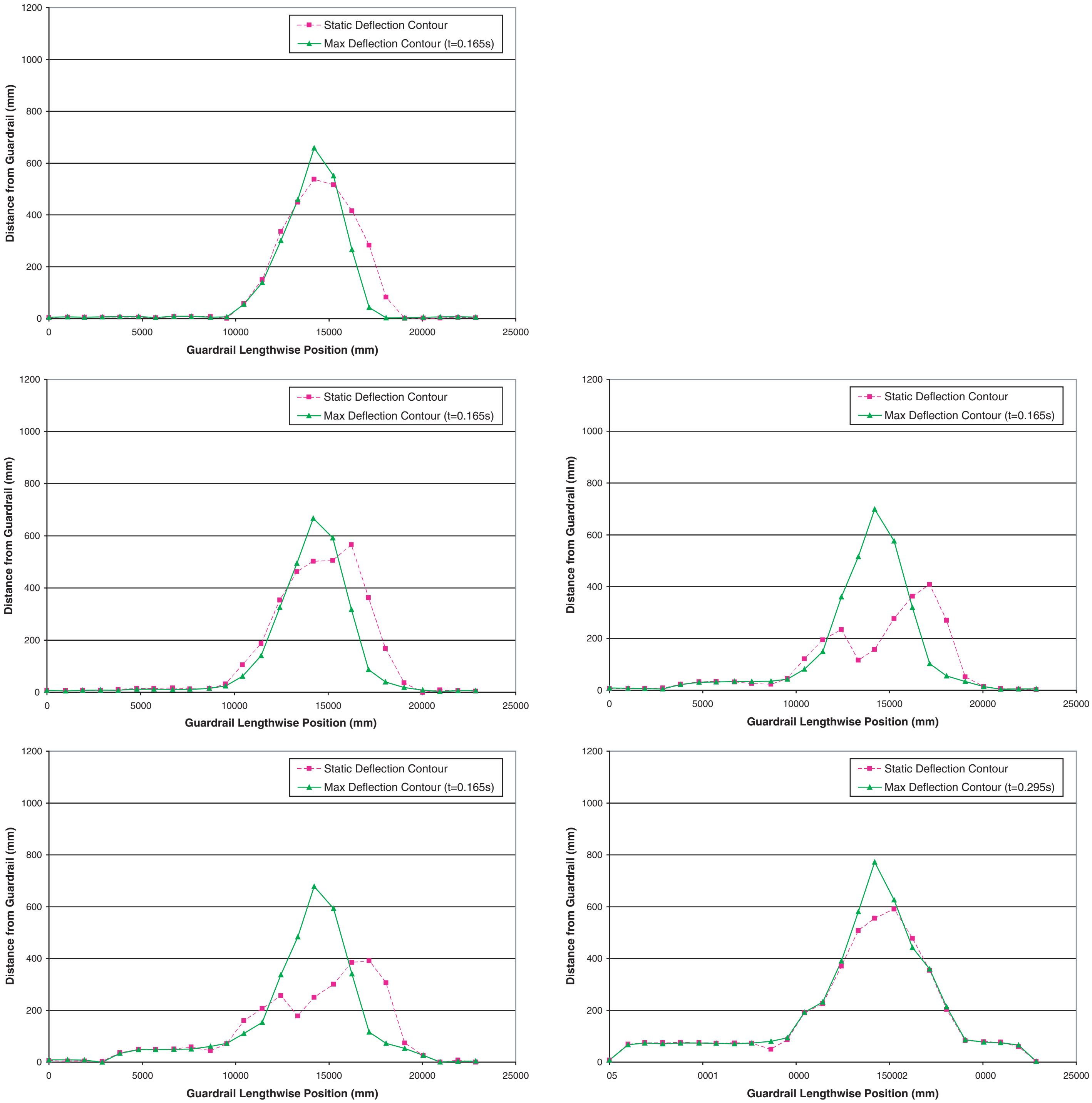


Figure 60. Guardrail damage contours for flattening simulations: undamaged (top), 25% flattening (middle left), 50% flattening (middle right), 75% flattening (lower left), and 100% flattening simulations (lower right).

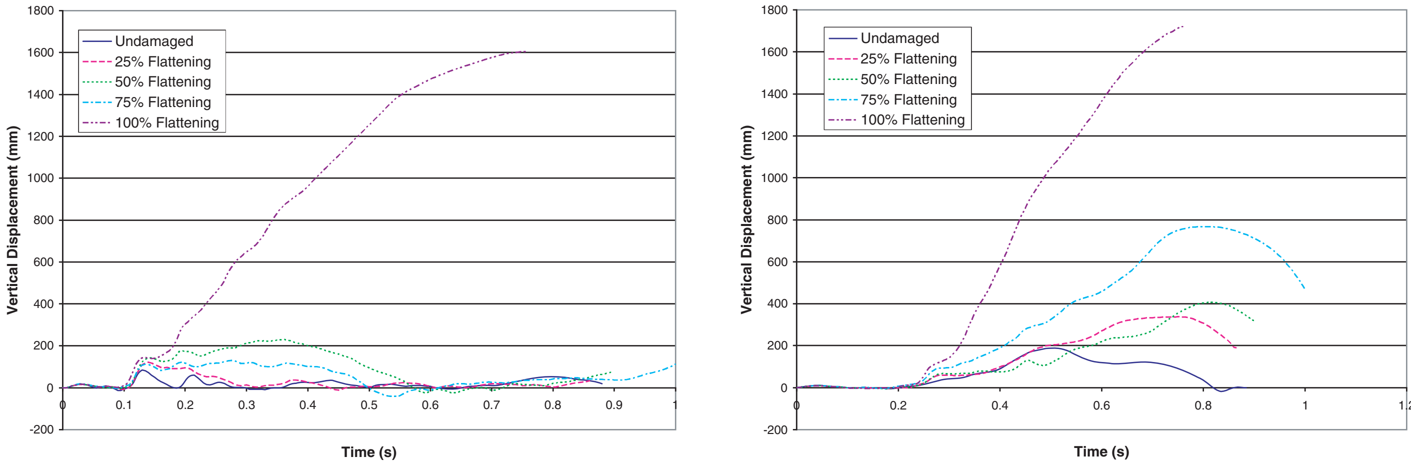


Figure 61. Displacement of vehicle tires for the flattening simulations: front left tire (left) and rear left tire (right).

The vehicle instability at greater than 75 percent flattening was caused by the vehicle riding up the flattened rail. Both the flatness of the rail and the lower bottom height of the rail were contributors to the rollover. As shown in Figure 62, a maximally flattened rail extends both higher and lower than an undeformed rail would and also presented a much smoother surface.

In the undamaged simulation, because of the height of the rails, the collision force was concentrated on the front of the fender, leading to extensive crush on the front left corner of the vehicle. This deformation allowed the top half of the rail to penetrate the space above the front left tire. The presence of the rail above the tire provided a downward force that prevented the tire from moving upward. The upward motion caused by the left tires hitting the post bases was counteracted by the downward force exerted by the rail.

When the rail was 100% flattened, a different behavior was observed. Because of the higher top height of the rail and the flatness of the surface, the force of the collision was distributed over a larger portion of the fender. These factors prevented the rail from penetrating the space above the tire. The lower bottom height of the rails also presented a problem. As the tire was forced upward by contact with the posts, the elevation of the tire increased so that the majority of the tire was on or above the rails. This, combined with a slight outward slope in the rail caused by the crash damage, provided a ramp for the tire to ride up. The increase in rail height, which was concentrated on the left side of the vehicle, imparted a rolling motion that the vehicle was unable to recover from.

The vehicle exit speed also varied by the degree of flattening. For the undamaged simulation the exit speed was 53 kph, whereas for the 100 percent flattening simulation the exit

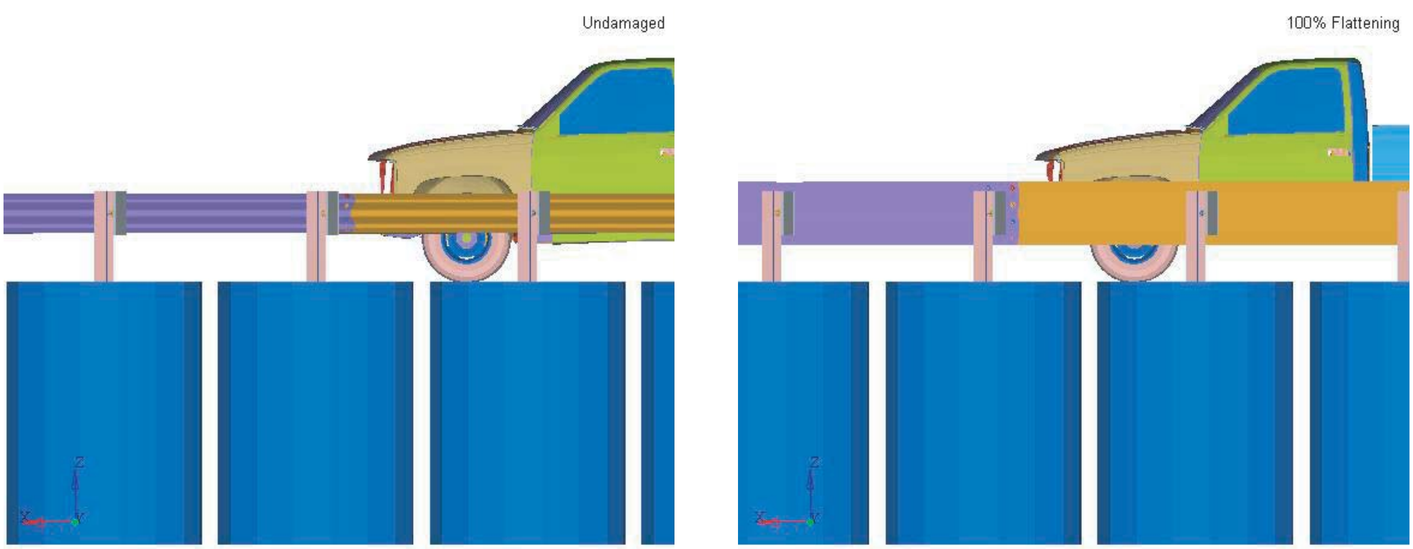


Figure 62. Height of the rails relative to the vehicle: undamaged (left) and 100% flattening (right).

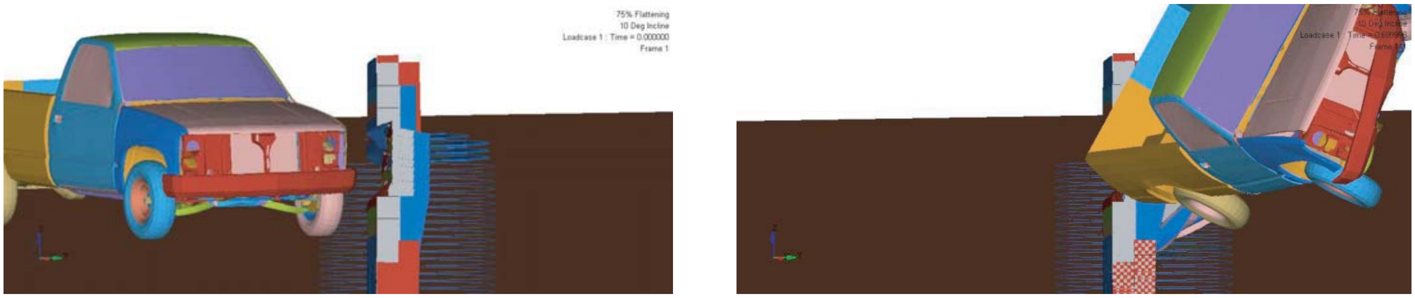


Figure 63. Simulation of 75% flattened guardrail leaning back by 10 degrees. Vehicle before impact on the left, and after the impact (t = 0.7s) on the right.

speed was 73 kph. It was believed that by flattening the rails before impact, the ability of the guardrail to absorb kinetic energy was being reduced. To check if this was the case, the energy absorbed by the vehicle and guardrail was broken down by component.

In the 100 percent flattening simulation, the guardrail absorbed roughly 40 kJ less than, or 83 percent of, the energy that was absorbed by the undamaged simulation. When broken down even further, it was found that the rails actually absorbed about 45 kJ less energy, but the other components of the guardrail absorbed 5 kJ more energy, resulting in the net drop in energy absorption of 40 kJ. The components of the guardrail that absorbed more energy were the posts and blockouts, as the flattening of the guardrail allowed the vehicle to engage these components more easily.

Since it was believed that the flattened rails created a ramp-like surface, a supplementary simulation was performed to examine how the angle of the guardrail would affect the performance. The finite element model of 75 percent flattened rail was modified by bending the posts and rails in the area of contact backwards. This resulted in an 80-degree angle between the post and ground line rather than the standard 90 degrees, as shown in Figure 63. The slight incline in the rails was sufficient to cause the vehicle to both vault and roll. From these results, it was evident that the angle of the guardrail, whether caused by damage or pre-existing because the ground was sloped, could drastically alter the outcome of a crash. However, the same incline in an otherwise undamaged guardrail had little effect on the outcome of the simulation. In the future, the full effect of combined incline and flattening should be examined in more detail.

13.4 Recommendation

A series of finite element simulations of impacts into flattened strong-post w-beam guardrail were run and compared to the performance of the undamaged guardrail simulation. The flattening in these simulations varied from 25 percent to 100 percent. The following observations were noted:

- Vehicle roll and pitch increased with increasing degrees of flatness. The vehicle became unstable once the flattening reached 75 percent. At 100 percent flattening, the vehicle rolled as it exited from the guardrail. Note that these simulations were conducted for perfectly upright posts. Based on field inspections of damaged barriers, the research team has observed that rail flattening almost always occurs in tandem with some degree off post and rail deflection. Any incline in the post would exacerbate the tendency for vehicle rollover or instability. Therefore it is recommended that all guardrails for which there is 50 percent or greater flattening be repaired as soon as possible due to a greatly increased risk of vaulting and rollover.
- In any situations where there is a hazardous object directly behind the guardrail, the damage should be repaired immediately because even a small amount of rail flattening increased the maximum deflection of the guardrail by roughly 10 percent.

One observation from the field inspections of damaged barriers was that it was difficult to quantify the amount of rail flattening by direct measurement of the w-beam cross section. As an alternative method of determining the amount of rail flattening, the research team is proposing a method where the maintenance personnel can measure the maximum section width of the flattened w-beam cross section, a much easier measurement to obtain. Based on finite element simulations of flattened w-beam barriers, the research team has correlated the maximum deformed cross section height to the approximate portion of rail flattening. Fifty percent flattening corresponds to a growth in section width from 12 inches for undamaged rail to 18 inches. In the guidelines, the 50 percent flattening limit is prescribed as a section width of 18 inches or greater. See Exhibit 10.0 for recommendations for rail fattening repair.

Exhibit 10.0. Recommendation for rail flattening repair.

Damage Mode	Repair Threshold	Priority for damage above the threshold
Rail Flattening	Rail cross-section height more than 17 in. (such as may occur if rail is flattened)	Medium
	Rail cross-section height less than 9 in. (such as a dent to top edge)	

CHAPTER 14

Generic End Terminal Guidance

This chapter specifies the rationale for repair criteria for generic end terminals. The intent was to specify guidance which was applicable to all end terminal types (except as noted). Manufacturers of proprietary end terminal systems may recommend additional repair thresholds specific to an individual terminal. Note that this guidance was based solely on engineering judgment; no finite element simulations or pendulum tests evaluating these end terminal damage modes were conducted. The guidelines which follow were based on an Ohio Department of Transportation Energy Absorbing End Terminal Maintenance Checklist (Focke, 2007).

14.1 Generic End Terminal Damage Modes

Damaged end post. The first post of a w-beam end terminal provides crucial anchorage of the w-beam section to the ground, typically through the use of a swaged anchor cable. If the first post is broken or missing, the redirective capabilities of the barrier downstream of the end terminal are likely compromised, depending on the proximity of the second impact to the damaged terminal. To be conservative, the research team recommends the replacement of any terminal end post which is sufficiently damaged that it cannot fulfill its functions. Posts in this category include broken, severely cracked, missing, or rotted terminal end posts. An example is shown in Figure 64. The relative priority assigned to this damage type is high due to the likelihood of a loss of redirective capability of the barrier.

Missing/slack anchor cable. Similar to the terminal end post, the anchor cable allows the w-beam section to develop adequate tension to redirect the vehicle. As with a broken end post, a missing anchor cable will impair the capability of the barrier to redirect an impacting vehicle. Based on this rationale, a missing anchor cable was assigned a high-priority repair. A loose anchor cable or cable bracket was assigned a medium priority as the w-beam may still be able to develop a large portion of tension through the anchor cable. Examples

Figure 64. Wood post with cross-grain cracking (photo: courtesy of South Dakota DOT).

of missing or incorrectly aligned cable bracket bearing plates are shown in Figure 65. A slack anchor cable has been defined as a cable that can be pushed down by hand by more than 1 inch based on the Ohio DOT end terminal checklist.

Improper Stub Height. In some guardrail end terminal installations, the steel tubes or hinged posts may be too high for proper activation of the breakaway mechanism of the end terminal (Figure 66). Stub heights above the ground level should not exceed 4 inches. Stub heights have been observed to exceed this limit due both to incorrect installation and, in some areas, due to frost heave. A medium-priority repair has been assigned to this damage mode because an incorrect stub height will not cause the end terminal to fail but nevertheless may lead to small vehicle snagging or less than optimal operation of the end terminal.

Missing/Failed Lag Bolts on Impact head. Energy absorbing terminals such as the ET-2000 and SKT-350 use an im-

Figure 65. Misaligned or missing bearing plates (photo: courtesy of South Dakota DOT).

pact head to deform the w-beam rail during a head-on impact with the end terminal. The deformation of the w-beam absorbs the kinetic energy of the impacting vehicle to bring it to a safe and controlled stop. As such, the alignment of the impact head is crucial to the functioning of this terminal in a head-on configuration. This can result from missing or failed lag screws at the end post or a w-beam that is not properly seated in or is outside of the impact head. An example is shown in Figure 67.

Figure 66. Incorrect stub height (photo: courtesy of South Dakota DOT).

Figure 68 shows a failed attachment between lag screws and the end post. A high-priority repair has been assigned to this damage due to the potential for vehicle spearing, especially in the case where the end of the rail is outside the impact head.

14.2 Recommendation

The criteria for repair of generic end terminals are summarized in Table 28. These guidelines have been based on an Ohio Department of Transportation Energy Absorbing End Terminal Maintenance Checklist (Focke, 2007).

Figure 67. Misaligned impact head because of missing lag bolts (photo: courtesy of Ohio DOT).

Figure 68. Failed attachment of lag bolts to end post.

Table 28. Summary of generic end terminal repair guidance.

Damage	Repair Threshold	Relative Priority
Damaged end post	Not functional (sheared, rotted, severely cracked)	High
Anchor cable	Missing	High
	Loose—more than 1 inch of movement when pushed down by hand	Medium
Cable Anchor Bracket	Loose or not firmly seated in rail	Medium
Stub height of steel tube or hinged post	Height which exceeds 4 inches	Medium
Lag bolts on impact head (Energy Absorbing Terminals Only)	Missing or failed lag bolts	High
Bearing Plate	Loose or Misaligned	Medium
	Missing	High

CHAPTER 15

Conclusions

Damage to a longitudinal roadside barrier is not always characterized by the large rail deformations and sheared posts characteristic of a high severity crash. Much more common is minor damage such as a shallow dent which is a result of a low-speed collision or sideswipe. Unfortunately, the effect of this minor damage on the performance of the barrier in subsequent impacts is not well understood, and there is little barrier repair guidance available for highway personnel tasked with maintaining these systems.

The goal of this research project was to develop guidelines to assist highway personnel in identifying levels of minor barrier damage and deterioration that require repairs to restore operational performance. The focus of the project was on the length of need of w-beam barriers. This chapter presents the conclusions of the project including (1) current practices for repairing damage to longitudinal barriers, (2) the approach to develop objective criteria for measuring damage to longitudinal barriers, (3) the approach for quantitatively evaluating these guidelines, and (4) the recommended guidelines with threshold values for which barrier repair is recommended.

15.1 Summary of Current Practices

Current practices and research needs were determined based upon the results of a literature review and a survey of State and Canadian Provincial transportation agencies. A literature review on the repair and maintenance of longitudinal barriers revealed the following:

- There appears to be no scientific basis for the existing national guardrail repair guidelines. Current guidelines appear to be based exclusively on engineering judgment.
- With the exception of a select few state agencies, a majority of state agencies with published barrier maintenance guidelines or rating schemes lack quantitative descriptions and examples of deficient barriers.
- Five tort cases and one documented crash found in the literature show that impacts with previously damaged barriers do occur in the field.

A survey was distributed to the State and Canadian Provincial Transportation agencies to ascertain current practices with respect to the repair and maintenance of longitudinal barriers. Based on the responses of 39 agencies, the research team has the following conclusions:

- Two-thirds of responding agencies indicated more quantitative guidelines for the repair of guardrails would be beneficial.
- Approximately 60 percent of responding agencies reported specific guidelines for when to repair damaged guardrail. Less than one-third of these agencies indicated tangible and numeric criteria to identify when barrier repair is necessary.
- Half of the top 10 damaged barrier modes deal exclusively with the w-beam rail element.
- Post and rail deflection in excess of 6 inches is found to be the most prevalent type of guardrail damage; however, this damage is generally classified as moderate damage. Of the minor damage modes, rail deflection only, post and rail deflection (< 6 inches), and rail flattening are most common.
- Repair priority is found to be high for post and rail damage greater than 6 inches, rail tears, cable damage, w-beam splice damage, and loss of tension in the cable barrier.

15.2 Method of Evaluation of Guidelines

A set of target damage modes was selected for evaluation based upon the results of the survey of U.S. and Canadian transportation agencies, and inspection of a catalog of minor barrier damage categories. Target damage modes were selected based on their frequency of occurrence and perceived threat to

Table 29. Methods of evaluating each damage mode.

Damage Mode	Pendulum Tests	Full-Scale Crash Tests	Finite Element Modeling
Rail / Post Deflection	x	x	x
Vertical Tear	x		
Horizontal Tear	x		
Twisted Blockout	x		
Missing Blockout	x		
Splice Damage	x		
Hole in Rail	x		
Missing Posts			x
Post-Rail Separation			x
Rail Flattening			x
Generic End Terminal Damage			

the motorist. The objective was to evaluate the crash performance of barriers with each of these minor damage modes, and to develop quantitative criteria for when repair of this minor barrier damage is warranted. To develop a strong technical foundation for the guidelines, the research team's approach was to evaluate the more common damage types with a combination of controlled experiments and computational modeling and adjust the preliminary proposed guidelines as necessary. The generic end terminal repair guidelines were based upon a procedure developed by the Ohio Department of Transportation. Table 29 presents the target damage modes and the method(s) used to evaluate each of these damage modes.

The results of each damaged barrier impact experiment or simulation were evaluated using criteria based heavily on *NCHRP Report 350*. Pendulum tests were evaluated based on the ability of the barrier to contain the pendulum, i.e., no pendulum penetration, underride, or override. For the full-scale crash tests and computational simulations of full scale crash tests, the criteria shown in Table 30 were used to evaluate crash performance. The full scale crash tests and simulations were also assessed for vehicle instability resulting from impact including roll, pitch and yaw, wheel snagging, and the presence/absence of vaulting. The results of each evaluation were used to set the threshold for repair.

15.3 Recommended Criteria for Restoration of Longitudinal Barriers

This section presents guidelines for repairs to damaged longitudinal barriers in order to restore them to operational performance. Included are guidelines for repair of minor damage to w-beam, generic end-terminals, and guidance for repair of more severe barrier damage.

The following guidelines are based on the assumption that a damaged barrier will be subjected to a second collision with impact conditions similar to *NCHRP Report 350* test level 3 (TL-3) conditions. The crash performance of barriers with different types of damage was assessed under the same impact conditions. Depending on individual conditions at a specific site, however, the probability of a second impact to a previously damaged longitudinal barrier will vary considerably. The determination of the risk of a second collision is beyond the scope of this document but should be another factor that

Table 30. Barrier crash performance requirements.

Criterion	Required Performance
Structural Adequacy	1. Barrier contains and redirects the vehicle
	2. No vehicle penetration, underride, or override
Occupant Risk	3. Vehicle should remain upright during and after the collision; moderate pitch and roll are acceptable
	4. Lateral and longitudinal occupant impact velocity < 12 m/s (as computed by the flail space model)
	5. Lateral and longitudinal occupant ridedown acceleration < 20 G (as computed by the flail space model)
Vehicle Trajectory	6. Vehicle intrusion into adjacent traffic lanes is limited or does not occur
	7. Vehicle exit angle should preferably be less than 60 percent of the impact angle

is considered when determining the repair priority of a damaged barrier section.

15.3.1 W-Beam Repair Guidelines

The w-beam barrier repair guidelines are summarized in Table 31. These guidelines are intended to mark the level of barrier damage that begins to significantly affect the crash performance of the barrier and are intended to be the base thresholds to which barrier repair is recommended. The rationale for each of the guidelines has been presented throughout the report.

Barriers with damage less than the threshold values shown in Table 31 have a crash performance that is indistinguishable from new barriers. For damage extent above the threshold, Table 31 provides a relative repair priority for each damage mode using a three category scale: high, medium, and low. While the priority assignments are not intended to dictate an exact time frame in which to repair a damaged barrier, they do provide maintenance personnel with general guidance on how differing damage modes are expected to affect the crash performance of the barrier relative to one another. A brief description of each priority level is provided below:

- **High Priority:** Indicates damage where the crash performance of the barrier has been compromised to such a degree that a second impact to the damaged barrier would result in unacceptable vehicle and/or barrier performance. This would include vehicle penetration of the barrier (via rail rupture, vehicle override, or vehicle underride) and vehicle rollover.
- **Medium Priority:** Indicates damage where the crash performance of the barrier has likely been compromised to some degree but the damage is less likely to result in unacceptable vehicle and/or barrier performance than high-priority damage.
- **Low Priority:** Indicates damage where the crash performance of the barrier is indistinguishable from the undamaged condition.

15.3.2 Generic End Terminal Guidance

The criteria for repair of generic end terminals are summarized in Table 32. These guidelines have been based on an Ohio Department of Transportation Energy Absorbing End Terminal Maintenance Checklist (Focke, 2007).

15.3.3 Guidance for Substantial Barrier Damage

National guidance regarding the repair of w-beam barriers is provided by the Federal Highway Administration (FHWA) in a 2008 report entitled "W-Beam Guardrail Repair" (FHWA, 2008). Based on this document, a damaged barrier is classified into one of three categories: (1) Non-Functional, (2) Damaged but should function adequately under the majority of impacts, and (3) Damaged, but should not impair the guardrail's ability to perform.

The intent of this section is to provide improved guidance for classification of barriers into categories 1 or 2 based on the simulation and testing conducted under NCHRP Project 22-23. Table 33 summarizes the details of categories 1 and 2 from the original w-beam guardrail repair guide.

Table 34 summarizes the proposed changes to the criteria for categories 1 and 2 based on the findings of the research team to date.

The full-scale crash test conducted at MGA Research consisted of a TL-3 impact of a 2000P test vehicle into a strong-post w-beam barrier with approximately 14 inches of rail deflection. The vehicle impacted the barrier, climbed the deflected posts, and subsequently vaulted the barrier. Marzougui et al. (2007) showed that if rail height declines by 2 inches, vehicles can rollover or vault over the rail. A 2-inch decrease in rail height corresponds to a 10.5 inch deflection. Based on the results of the full-scale test and the findings of the Marzougui study, the research team recommends reducing the category 1 deflection from 18 inches to 10 inches.

Finite element simulations have shown that a 2000P pickup truck striking a section missing even a single post will become unstable. Hence the guidelines have been revised to recommend the repair of a rail with any missing posts.

15.3.4 Barrier Locations with More than One Damage Mode

Note that the thresholds and corresponding repair priorities above have been based on the presence of a single damage mode. Often, longitudinal barrier damage consists of more than one damage mode. For instance, rail flattening almost always occurs in tandem with post and rail deflection. A majority of the current analysis has focused on individual damage modes in an effort to more fully understand the effect of a single damage mode on the crash performance of the barrier. The research team, however, does recognize the need for guidance regarding barriers with multiple damage modes. Until a more thorough analysis of barrier damage combinations can be conducted, the research team proposes that barrier repair be based on the highest priority level of the combined damage modes. For instance, if a barrier has both a twisted blockout along with rail flattening, the repair priority would be "medium" based on the rail flattening.

15.3.5 Limitations

This study had several limitations. The approach was to evaluate longitudinal barriers with damage under the worst practical conditions. However, there are a number of other conditions, not examined in this study, to which these barriers may be subjected to potentially adverse consequences. The

Table 31. Summary of W-Beam barrier repair threshold guidelines.

Damage Mode	Repair Threshold	Priority for Damage above the Threshold
Post and Rail Deflection	One or more of the following thresholds: • More than 9 in. of lateral deflection anywhere over a 25-ft length of rail • Top of rail height 2 or more in. lower than original top of rail height	High
	6-9 in. lateral deflection anywhere over a 25-ft length of rail	Medium
	Less than 6 in. of lateral deflection over a 25-ft length of rail	Low
Rail Deflection Only	6-9 in. of lateral deflection between any two adjacent posts Note: For deflection over 9 in., use post/rail deflection guidelines.	Medium
	Less than 6 in. of lateral deflection between any two adjacent posts	Low
Rail Flattening	One or more of the following thresholds: • Rail cross-section height more than 17 in. (such as may occur if rail is flattened) • Rail cross-section height less than 9 in. (such as a dent to top edge)	Medium
	Rail cross-section height between 9 and 17 in.	Low
Posts Separated from Rail	• 2 or more posts with blockout attached with post-rail separation less than 3 in. • 1 or more posts with post-rail separation which exceeds 3 in. Note: If the blockout is not firmly attached to the post, use the missing blockout guidelines. Note: If separation over 3 in., use deflected post/rail guidelines.	Medium
	• 1 post, with blockout attached, with post-rail separation less than 3 in.	Low
Missing/Broken Posts	1 or more posts • Missing • Cracked across the grain • Broken • Rotted • With metal tears	High
Missing Blockout	Any blockouts • Missing • Cracked across the grain • Cracked from top or bottom of blockout through post bolt hole • Rotted	Medium
Twisted Blockouts	Any misaligned blockouts, top edge of block 6 in. or more from bottom edge Note: Repairs of twisted blockout are relatively quick and inexpensive.	Low
Damage at a rail splice	More than 1 splice bolt: • Missing • Damaged • Visibly missing any underlying rail • Torn through rail	High
	1 splice bolt: • Missing • Damaged • Visibly missing any underlying rail • Torn through rail	Medium

(continued on next page)

Table 31. (Continued).

Damage Mode	Repair Threshold	Priority for Damage above the Threshold
Non-Manufactured holes (such as crash-induced holes, lug-nut damage, or holes rusted-through the rail)	• More than 2 holes less than 1 in. in height in a 12.5' length of rail • Any holes greater than 1 in. in height • Any hole which intersects either the top or bottom edge of the rail	High
	1-2 holes less than 1 in. in height in a 12.5-ft. length of rail	Medium
Vertical Tear	Any length vertical (transverse) tear	High
Horizontal Tear	Horizontal (longitudinal) greater than 12 in. long and greater than 0.5 in. wide Note: for horizontal tears less than 12 in. in length or less than 0.5 in. in height, use the non-manufactured holes guidelines.	Medium

Table 32. Summary of proposed generic end terminal repair guidance.

Damage	Repair Threshold	Relative Priority
Damaged end post	Not functional (sheared, rotted, cracked across the grain)	High
Anchor cable	Missing	High
	Loose—more than 1 in. of movement when pushed down by hand	Medium
Cable Anchor Bracket	Loose or not firmly seated in rail	Medium
Stub height of steel tube or hinged post	Height which exceeds 4 in.	Medium
Lag bolts on impact head (Energy Absorbing Terminals Only)	Missing or failed lag bolts	High
Bearing Plate	Loose or Misaligned	Medium
	Missing	High

Table 33. FHWA W-beam damage classification details (FHWA, 2008).

Damage Category	Damage Attributes
(1) Non-Functional	A. Rail element is no longer continuous. B. 3 or more posts are broken off or no longer attached to the rail. C. Deflection of rail element is more than 18 in. D. Rail element is torn. E. Top of rail is less than 24 in.
(2) Damaged but should function adequately under majority of impacts	A. Rail element is continuous (can be bent or crushed significantly). B. 2 or fewer posts are broken or separated from the rail element. C. Deflection of the rail element is less than 12 in.

Table 34. Proposed revisions to original FHWA W-beam damage classification.

Damage Category	Damage Attributes
(1) Non-Functional	A. Rail element is no longer continuous. B. 1 or more posts are broken off or severely bent. C. Deflection of rail element is more than 10 in. D. Top of rail is less than 26 in. E. Rail element is torn.
(2) Damaged but may still work	A. Rail element is continuous (can be bent or crushed significantly). B. Deflection of the rail element is less than 10 in.

research team recommends that the items below be considered in future evaluations of repair guidelines:

- Conduct deeper sensitivity analyses for other impact conditions. Examples would be alternate impact speeds, impact angles, and impact points. The finite element modeling was applied to only some of the damage types, and if extended to other damage modes could yield further insight into the crash performance of damaged barriers.
- Conduct additional full-scale crash tests of damaged longitudinal barriers both as a means to evaluate the crash performance of these systems, and to provide an additional source of finite element model validation data.
- Assess the implications of "damage" under MASH criteria. The MASH criteria use a larger pickup truck than the standard 2000P vehicle used in *NCHRP Report 350.*
- The approach in this project to focus on worst case scenarios led to the decision to evaluate impacts with larger vehicles. However, there can also be significant issues associated with impacts with smaller vehicles. A follow-up project should assess the risk of smaller vehicle impacts with damaged longitudinal barriers.
- Rail tensions in the finite element simulations were examined to determine the risk of rupture occurring in the guardrail system as a whole. While localized tearing is possible in vehicle-guardrail impacts, this guardrail model did not include failure criteria for the steel components and was not configured to look for element tearing due to localized stress concentrations.

15.3.6 Recommendations for Additional Damaged Barrier Repair Guidelines

This project has evaluated the crash performance of a number of the most commonly encountered damage modes incurred by longitudinal barriers. The research team's evaluation has not however been exhaustive. There is a continuing need for development of repair guidelines for a number of additional damage modes beyond those which could be evaluated under this contract. The research team recommends that these additional damage modes be given first priority for evaluation in a future follow-up phase to NCHRP Project 22-23. Additional damage modes for which repair guidelines should be developed in a follow-up phase to the current project include the following:

- **Wood post systems:** This project has evaluated steel post systems—the most common variety of strong-post w-beam barrier systems. Wood post systems are heavily used in many installations however, and because these systems fail in a very different manner than steel post systems, there is a need to determine repair criteria which are unique to wood posts.
- **Overlapping damage modes:** Longitudinal barrier damage often consists of overlapping damage modes, e.g., rail deflection with flattening. There is a need to better understand the interaction between overlapping damage types.
- **Generic end treatments:** The current guidelines are based on engineering judgment and would benefit from quantitative assessment. It would also be useful to extend the guidelines for generic end treatments to proprietary end treatments.
- **Damage to barriers near end terminals:** A previously deflected rail element within the first 50 feet of rail in an energy absorbing terminal may not properly activate the end terminal in a head-on crash. If these rails are not straight, the rail may lose column strength and be unable to resist buckling when impacted end-on.
- **Transitions:** It would be useful to broaden the guidance to full systems by addressing damage to transitions.

15.4 Guideline Format for Maintenance Personnel

The end customer for these repair guidelines are highway maintenance personnel. In addition to being based upon a strong analytical foundation, the guidelines must be easily understood and implemented. Chapter 16 presents the repair threshold guidelines in a graphical format that clarifies how damage to w-beam barriers should be measured and repair priority assessed.

CHAPTER 16

A Field Guide for the Restoration of Longitudinal Barriers

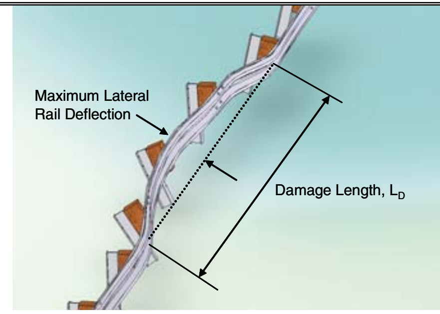
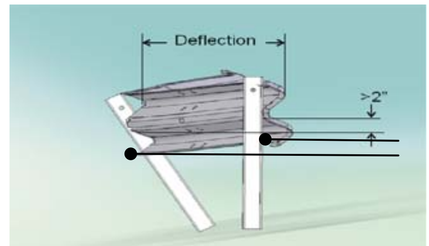
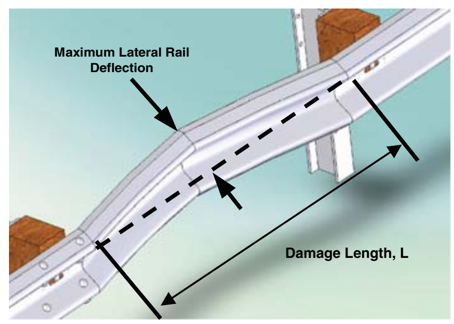
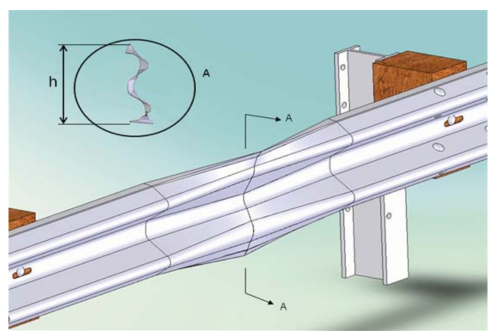
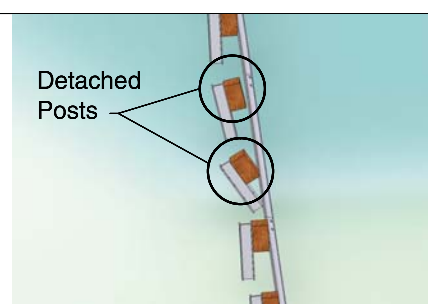
This document presents guidelines for the level of damage to longitudinal barriers that requires repair in order to restore a barrier to operational performance. The guidelines are presented in a format designed for use in the field by highway maintenance personnel. Included are guidelines for repair of w-beam, generic end-terminals, and guidance for repair of more severe barrier damage. The relative priority for repair is presented for each damage mode as described in Table 35.

The following guidelines in Tables 36 and 37 are based on the performance of a damaged barrier if a second collision should occur. The second collision is assumed to occur at typical highway speeds of 100 km/hr (62.1 miles/hour) at an angle of 25 degrees. The guidelines are based upon the outcome of a second impact—should it occur. The guidelines are not based upon the probability of a second impact to a previously damaged barrier. The probability of a second impact will depend on many factors, e.g., traffic volume, and is beyond the scope of this document. The probability of a second impact should be another factor that is considered when determining the repair priority of a damaged barrier section.

Table 35. Repair priority scheme.

Priority Level	Description
High	A second impact results in unacceptable safety performance including barrier penetration and/or vehicle rollover.
Medium	A second impact results in degraded but not unacceptable safety performance.
Low	A second impact results in no discernible difference in performance from an undamaged barrier.

Table 36. Summary of W-beam barrier repair thresholds.

Damage Mode	Repair Threshold	Relative Priority	Measurement
Post and Rail Deflection	One or more of the following thresholds: • More than 9 in. of lateral deflection anywhere over a 25-ft length of rail • Top of rail height 2 or more inches lower than original top of rail height	High	
	6-9 in. lateral deflection anywhere over a 25-ft length of rail	Medium	
	Less than 6 in. of lateral deflection over a 25-ft length of rail	Low	(Weak Post W-Beam Shown Only for Clarity. Each measurement taken at the rail's middle fold)
Rail Deflection Only	6-9 in. of lateral deflection between any two adjacent posts Note: For deflection over 9 in., use post/rail deflection guidelines.	Medium	
	Less than 6 in. of lateral deflection between any two adjacent posts	Low	
Rail Flattening	One or more of the following thresholds: • Rail cross-section height is more than 17 in. (such as may occur if the rail is flattened) • Rail cross-section height is less than 9 in. (such as a dent to the top edge)	Medium	
	Rail cross-section height is between 9 and 17 in.	Low	
Posts Separated from Rail	• 2 or more posts with blockout attached with a post/rail separation less than 3 in. • 1 or more posts with a post/rail separation which exceeds 3 in.	Medium	
	• 1 post with blockout attached with post/rail separation less than 3 in.	Low	Note: 1. If the blockout is not firmly attached to the post, use the missing blockout guidelines. 2. Damage should also be evaluated against post/rail deflection guidelines.

(continued on next page)

Table 36. (Continued).

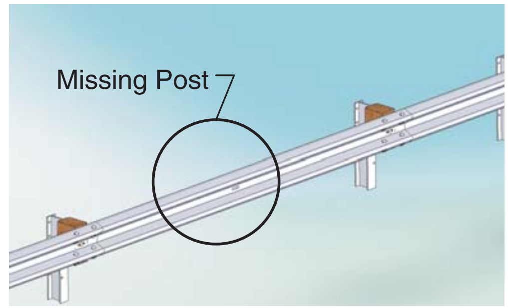
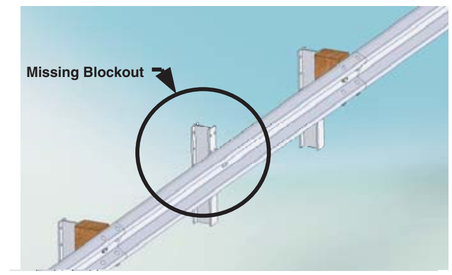
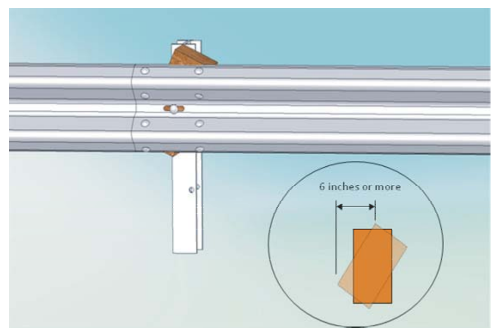
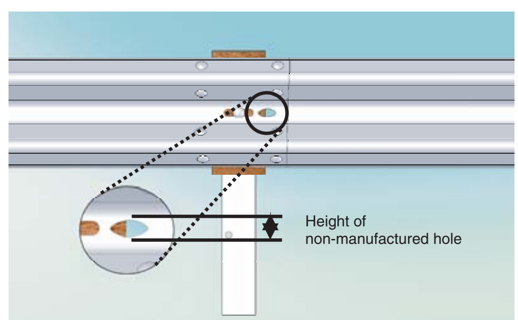
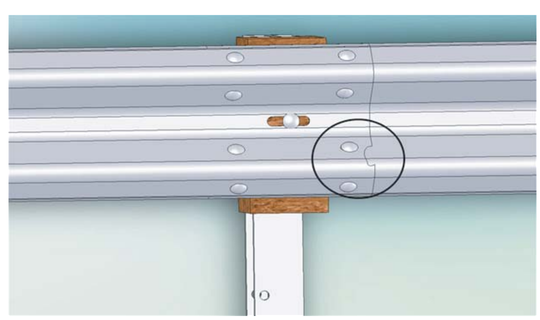
Damage Mode	Repair Threshold	Relative Priority	Measurement
Missing/Broken Posts	1 or more posts • Missing • Cracked across the grain • Broken • Rotted • With metal tears	High	
Missing Blockout	Any blockouts • Missing • Cracked across the grain • Cracked from top or bottom of blockout through post bolt hole • Rotted	Medium	
Twisted Blockouts	Any misaligned blockouts and the top edge of the block is 6 in. or more from the bottom edge <u>Note</u>: Repairs of twisted blockout are relatively quick and inexpensive.	Low	
Non-Manufactured holes (such as crash-induced holes , lug-nut damage, or holes rusted-through the rail)	• More than 2 holes with a height less than 1 in. on a 12.5-ft length of rail • Any holes with a height greater than 1 in. • Any hole which intersects either the top or bottom edge of the rail	High	
	1-2 holes with a height less than 1in. on a 12.5-ft. length of rail	Medium	
Damage at a rail splice	More than 1 splice bolt • Missing • Damaged • Visibly missing any underlying rail • Torn through rail	High	
	1 splice bolt • Missing • Damaged • Visibly missing any underlying rail • Torn through rail	Medium	

Table 36. (Continued).

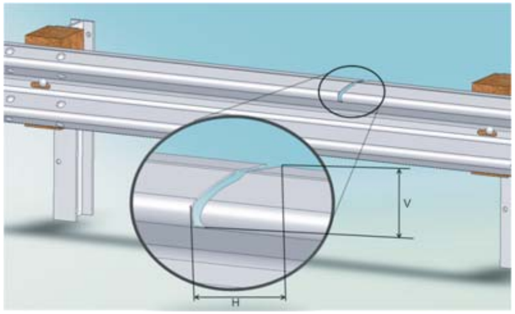
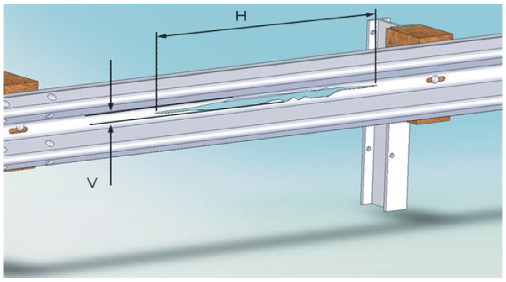
Damage Mode	Repair Threshold	Relative Priority	Measurement
Vertical Tear	Any length vertical (transverse) tear	High	
Horizontal Tear	Horizontal (longitudinal) tears greater than 12 in. long or greater than 0.5 in. wide Note: for horizontal tears less than 12 in. in length or less than 0.5 in. in height, use the non-manufactured holes guidelines.	Medium	

Table 37. Summary of generic end terminal repair thresholds.

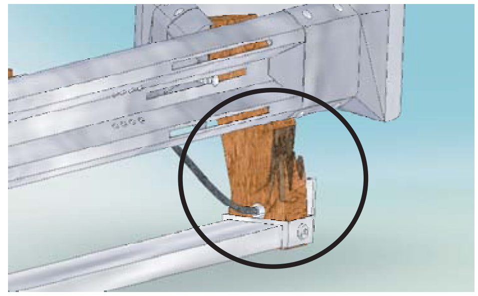
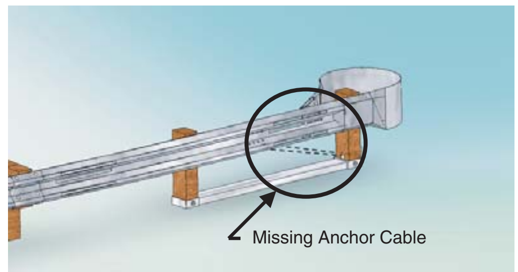
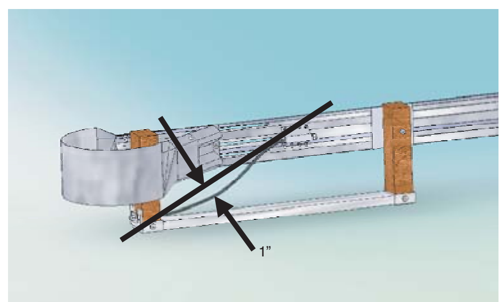
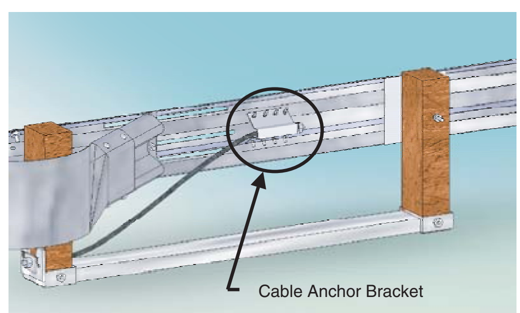
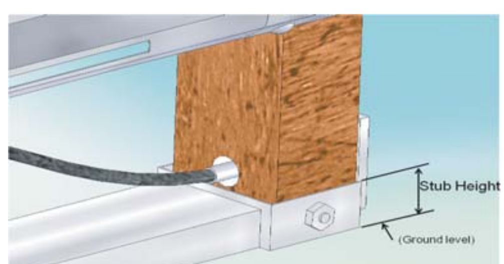
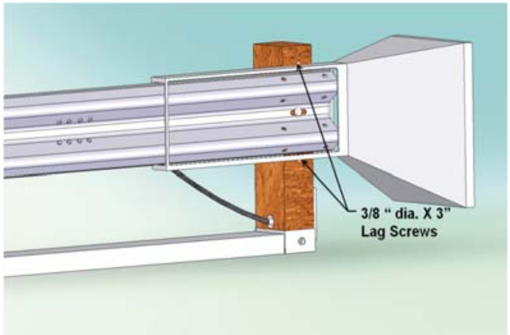
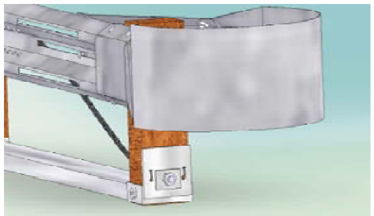
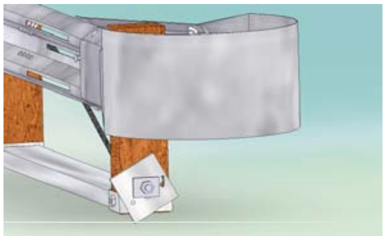
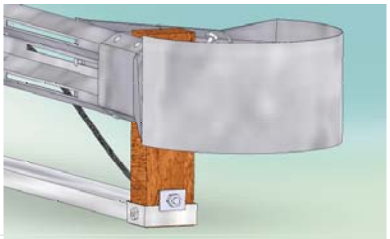
Damage Mode	Repair Threshold	Relative Priority	Measurement
Damaged End Post	Not functional (sheared, rotted, cracked across the grain)	High	
Anchor Cable	Missing	High	
Anchor Cable	More than 1 in. of movement when pushed down by hand	Medium	
Cable Anchor Bracket	Loose or not firmly seated in rail	Medium	
Stub Height	Height which exceeds 4 in.	Medium	

Table 37. (Continued).

Damage Mode	Repair Threshold	Relative Priority	Measurement
Lag Screws (Energy Absorbing Terminals Only)	Missing or failed lag screws	High	
Bearing Plate	Loose or misaligned	Medium	 (Correct Bearing Plate)  (Misaligned Bearing Plate)
	Missing bearing plate	High	 (Missing Bearing Plate)

Note: Any damage extent below the threshold is assumed to be low priority.

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Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation