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TEMPORARY LOW PROFILE BARRIER FOR ROADSIDE SAFETY : PHASE II

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EXECUTIVE SUMMARY

This final project report presents the design details and full-scale test results of the phase two low profile barrier. The phase one design was re-worked in order to permit horizontal and vertically curved layouts, and improve in-field ease of installation. The iterative design process was completed based on computer simulations of vehicle impact. The final product is a barrier system consisting of 12-foot segments with an 18-inch height. Segments are connected together with a unique system that allows both shear and moment-transfer while permitting flexibility in layout curvatures. No anchorage to the ground is required. Fifteen specimens were fabricated, installed as a system, and crash tested to the level 2 specifications in NCHRP Report-350. The tests were successful, and the barrier system was certified.

The restriction in the phase one design was the need to pass the connecting rod through a steel tube cast into the concrete from the inset steel angle bearing plate to the end of the segment. This arrangement allowed sufficient transfer of both shear and tensile forces from one barrier segment to the next, but also required that segments be carefully aligned and flush to adjacent segments to permit passage of the rod. Phase two was initiated to modify the phase one design such that the barrier is more easily adaptable to curved layouts.

As a solution, a design has been developed that allows for a curved layout and is able to tolerate minor misalignment between segments (another drawback of the phase one design). The high strength solid connection rod was shown in phase one crash tests to have adequate tensile strength to resist impact forces. This new design also uses the high strength threaded steel rod as the connector. Shear and tensile forces are now transferred between adjacent barriers using two separate connection mechanisms. The tensile force is transferred using a steel rod. In order to allow curved alignments, the volume of concrete from the triangular bearing plate through the end of the segment is removed. The rod will then pass from the bearing plate in one segment to bearing plate in an adjacent segment with no confining concrete or steel tube between bearing plates. This allows the placement of adjacent segments on a curvilinear layout. The current design allows a maximum angle between segments of 10 degrees, and will accommodate a convex or concave layout with a 65 foot radius of curvature.

Phase one used two recessed steel angles per segment, one at either end, connected by a cast-in steel rod to provide a load path for tensile forces throughout the installation. This required welding of four bearing plates per segment, one on either end of each steel angle. The modified design replaces this concept with a single steel channel that runs most of the length of the segment. This allows easier maneuvering of the rods that are installed in the field to connect adjacent segments, maintains a continuous load path for tensile forces, and reduces the bearing plate welds per segment from four to two. The figure shown below provides close up views of the connection system, and an installation of several segments for both the phase and phase two designs.

Shear transfer is vital to the resistance of the installation to lateral displacement upon impact. However, the lack of confinement of the connection rod removes the ability to transfer shear between segments, as the rod will simply rotate in response to relative transverse displacement between segments. A separate connection mechanism is therefore employed to provide shear force transfer. One end (the ‘male’ end) of each segment is tapered with an apex toward the center of the cross section. The apex has a cast-in coupler that allows the installation of a threaded bolt that protrudes horizontally from the apex. The opposite (‘female’) end of each section maintains a flat cross section, and contains a vertically aligned cast-in steel channel.

Adjacent segments are installed such that the steel channel receives the protruding bolt of the adjacent segment. The width of the channel is larger than the diameter of the bolt to allow placement of adjacent segments at an angle. This arrangement resists lateral separation between segments, but provides no tensile resistance. The vertical channel runs through the top of the segment to allow vertical removal of a single segment from an installation of multiple segments without the need to move any other segments. The final details of this design are provided in an appendix of the full-scale crash-test report that accompanies this report.

A concave or convex alignment can be easily achieved with this two-part tensile-shear connection system, and crash tests validate the redirection capability of the barrier, minimal lateral deflection upon impact, and the survivability of segments after impact.

a) Phase-one barrier design

b) Phase-two barrier design

Phase-one and phase-two barrier systems

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SUMMARY

A new low-profile portable concrete barrier for use in roadside work zone environments is presented. The primary innovative feature of this barrier is the ability to accommodate both horizontal and vertical roadway curvatures while still maintaining both a low profile and the ability to successfully redirect errant vehicles. Other desired features include its low profile, lack of required roadway-anchorage, and geometric flexibility. Nonlinear dynamic finite-element simulation is used for conceptual design refinement, and full-scale crash testing is used to validate the final design. The barrier installation is able to successfully redirect errant vehicles without causing rollover or snagging of the vehicle, and lateral deflection of the barrier was minimal during the most severe conditions of the NCHRP 350 level 2 tests.

The low profile traffic barrier presented in this report uses an entirely original segment-to-segment connection scheme in which shear forces and axial forces are carried by separate structural elements. Such a connection system provides reliable load transfer, uncomplicated field installation, and simple replacement of damaged segments. A unique method has been developed that permits the use of straight-line tensile bolts even in tightly curved alignments where the longitudinal axes of individual barrier segments may be rotated by as much as ten degrees from one segment to the next.

SECTION 1

INTRODUCTION

1.1 Motivation

Work zones represent a type of roadside environment in which special attention must be given to barrier height if adequate line of sight is to be provided to both the traveling public and work zone personnel. Longitudinal concrete barriers possessing a high profile (tall cross-section) provide excellent separation of roadway traffic from roadside work zone activities. Errant vehicles coming into contact with such barriers are safely redirected back onto the roadway, thus protecting both the driver and individuals present in the work zone. However, while high profile barriers provide excellent redirection and separation capabilities, they can also obscure a driver's field of view and lead to accidents.

Historically, the process used to design temporary longitudinal barrier systems focused primarily on issues such as redirection capability, minimization of vehicle intrusion into the area being protected, and portability. Barrier systems must be capable of redirecting a variety of different vehicle types in a smooth and stable manner without causing rollover. Simultaneously, they must limit vehicle intrusion into the work area to an acceptably small extent. High-profile barriers with substantial mass most easily achieve these design criteria. However, the temporary nature of most work zones also requires that barrier segments be lightweight and portable enough that they can be installed, repositioned, and removed with reasonably little effort. In order to simultaneously meet both the redirection and portability criteria, designers have most often turned to concrete barriers with high profiles but short segment lengths, thus producing relatively lightweight and portable segments.

Unfortunately, such design choices do not lead to optimal barriers. High profile barriers can obscure a driver's view of traffic. As a result, portable concrete barrier designs have emerged over the past decade that place additional emphasis on maintaining a *low profile*—thus avoiding the problems associated with limiting a driver's field of view—while still providing adequate protection and redirection performance. Low-profile barriers permit drivers to see traffic, encroaching vehicles, pedestrians, and construction traffic that might normally be obscured from view by tall barriers. Maintaining adequate line of sight through the use of low-profile barriers is particularly important in urban areas where vehicles pass numerous side streets and driveways at relatively low speed (e.g. less than 45 mph).

1.2 Low-Profile Barrier Systems

Ensuring vehicle stability during an impact is considerably more difficult with a low-profile system than in a high-profile system, especially for vehicles with high centers of gravity. A low barrier profile generally decreases vehicle stability during an impact, making it more difficult to redirect without causing rollover. Despite this fact, low-profile barriers *have* been developed that can redirect high-center-of-gravity vehicles without causing rollover or obscuring driver vision.

Guidry and Beason [1] developed a low-profile barrier having a height of 20 in. This low-profile barrier system successfully passed full-scale NCHRP Report 230 [2] crash testing with a profile considerably lower than that of the widely used New Jersey median barrier (which has a height of 32 in.). More recently, the FDOT sponsored UF research team (Consolazio, Gurley and Ellis) developed a barrier system with even lower profiles and reduced segment weights leading to increased barrier portability. This project is referred to as the phase one barrier design, and lead to the current phase two design being presented in this report. Consolazio et al. [3] developed the "linear alignment" portable barrier system (phase one system) consisting of concrete segments having a height of only 18 in., a length of 12 ft., and a weight of approximately 5000 lbs. each. This barrier successfully passed Level 2 NCHRP Report 350 [4] full-scale crash testing with minimal barrier deflections and no anchorage between the barrier and the roadway. However, the end geometry of the individual barrier segments in this system limited its applicability to linear (straight-line) installations with little or no horizontal or vertical roadway curvature. As a result, this report presents the design and evaluation of a new curvilinear barrier based on the phase one barrier [3], that maintains the successful system characteristics of this previous barrier system while increasing the applicability for curved alignments.

SECTION 2

PHASE TWO - CURVILINEAR BARRIER DESIGN

2.1 Introduction

To overcome the straight-line geometric limitations of the phase one barrier system, a new "curvilinear" low-profile barrier system has been developed. Individual segments in this new system have the same height and cross-sectional shape as those of the linear alignment phase one barrier [3]. However, significant modifications have been made both to the segment end-geometry and to the segment connector elements so that the new system can accommodate both horizontal and vertical curvature.

2.2 Benefits of Maintaining Flexural Continuity of the Barrier

The phase one barrier system consisted of concrete segments having planar end faces and the cross-sectional shape shown in Figure 1. To form a complete barrier system, bolts were used to connect adjacent segments together at each segment-to-segment interface. During an impact event, transverse loads act on the barrier segments producing both shear forces and moments at the joints. The compressive component of the moment is developed when the planar faces of the concrete segments contact each other (Figure 1d). Both the tensile component of the moment and the shear force between the segments are transmitted through the connector bolt.

Because each of the barrier segments individually has only a moderate weight (or mass) relative to that of an impacting pickup truck, successful redirection depends on mobilizing the inertial resistance not only of the segment being impacted, but also that of several adjacent segments. By maintaining flexural *continuity* through several segments in the system, the inertial resistance and stiffness of several mobilized segments acting as a single continuous system is developed and is sufficient to redirect vehicles. Evidence of the effectiveness of this approach was produced when the original straight-line barrier system was crash tested [3]. When impacted at 25 degrees by a 2000 kg pickup truck traveling at 45 mi/h, the system allowed only 6.5 in. of deflection with no barrier-to-roadway anchorage.

2.3 Accommodating Horizontal and Vertical Curvature

Preventing excessive lateral deflection into the work area by utilizing continuity was also a design goal for the new curvilinear phase-two barrier system. However, in order to accommodate the horizontal and vertical curvature requirements, the segment end-geometry had to be changed. Several options were explored including convexly curved end faces, matching-slope skewed end faces, and angled end faces. Ultimately, the solution chosen was to "facet" (represent with multiple planar surfaces) only one end of each barrier segment (Figure 2).

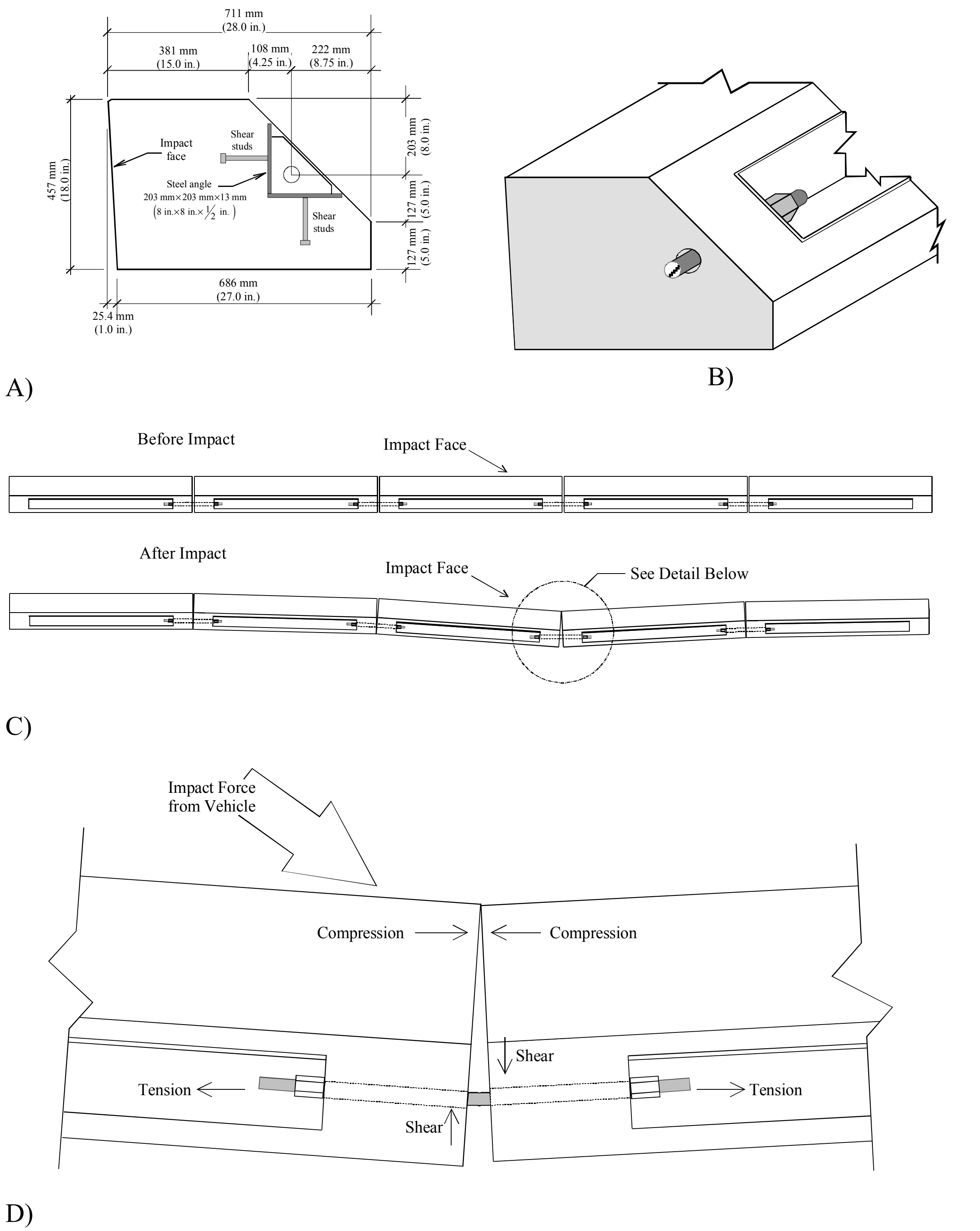


Figure 1. Straight-line barrier system A) Cross-sectional shape of barrier B) End view of barrier C) Plan view of multi-segment barrier D) Segment-to-segment forces transmitted during an impact event

The resulting end geometry allows for geometric roadway allowances, temporary slope changes in construction areas and a 65.0 ft. horizontal radius of curvature for both concave and convex alignments [5]. Concentrating all of the system curvature at one end of each segment permitted the use of a simple vertical channel on the opposite end (Figure 2d) as part of a shear force transfer mechanism. This end geometry also allowed for the creation of a void between the bearing plate for the tension bolt and the barrier end face, thereby allowing for curved alignments with a straight tension rod (Figure 2). The resulting pin and slot shear connection satisfies installation and removal requirements by permitting vertical removal and replacement of an individual segment within a continuous system of barrier segments.

Concentrating the curvature at one face brought several advantages but it also created new challenges not present in the phase one straight-line system. The new connection scheme has to carry both shear force and moment during impact. However, the connector element carrying the tensile component of the moment must span across the gap that is formed by "faceting" of the segment faces (Figure 2d). Both bolt and cable based connector solutions to this problem were considered but ultimately, all were abandoned due to excessive complexity or fabrication expense. Instead, the tension and shear elements were separated into two distinct parts and a new shear element was positioned at the apex of the faceted face. The need to transfer load even in curved alignment situations led to a connection scheme in which a pin and slot assembly transmit shear and compression forces while a separate bolt transmits tension forces (Figure 2).

A primary design challenge encountered in sizing the structural components of this new connection was to enforce continuity while also permitting a moderate increase in system flexibility in order to reduce vehicle roll angle during impact. Physical crash testing of the original straight-line barrier system using a 2000P test vehicle [3] produced a roll angle of 29.7 degrees, marginally larger than desirable. In the new curvilinear system, the investigators increased the lateral flexibility of the system—thereby reducing the vehicle roll angle—by modestly increasing the flexibility of the barrier-to-barrier connection system. Thus, a compromise between continuity and flexibility was made in which the curvilinear barrier was designed to mobilize multiple segments via continuity but still produce a moderate roll angle during vehicle impact.

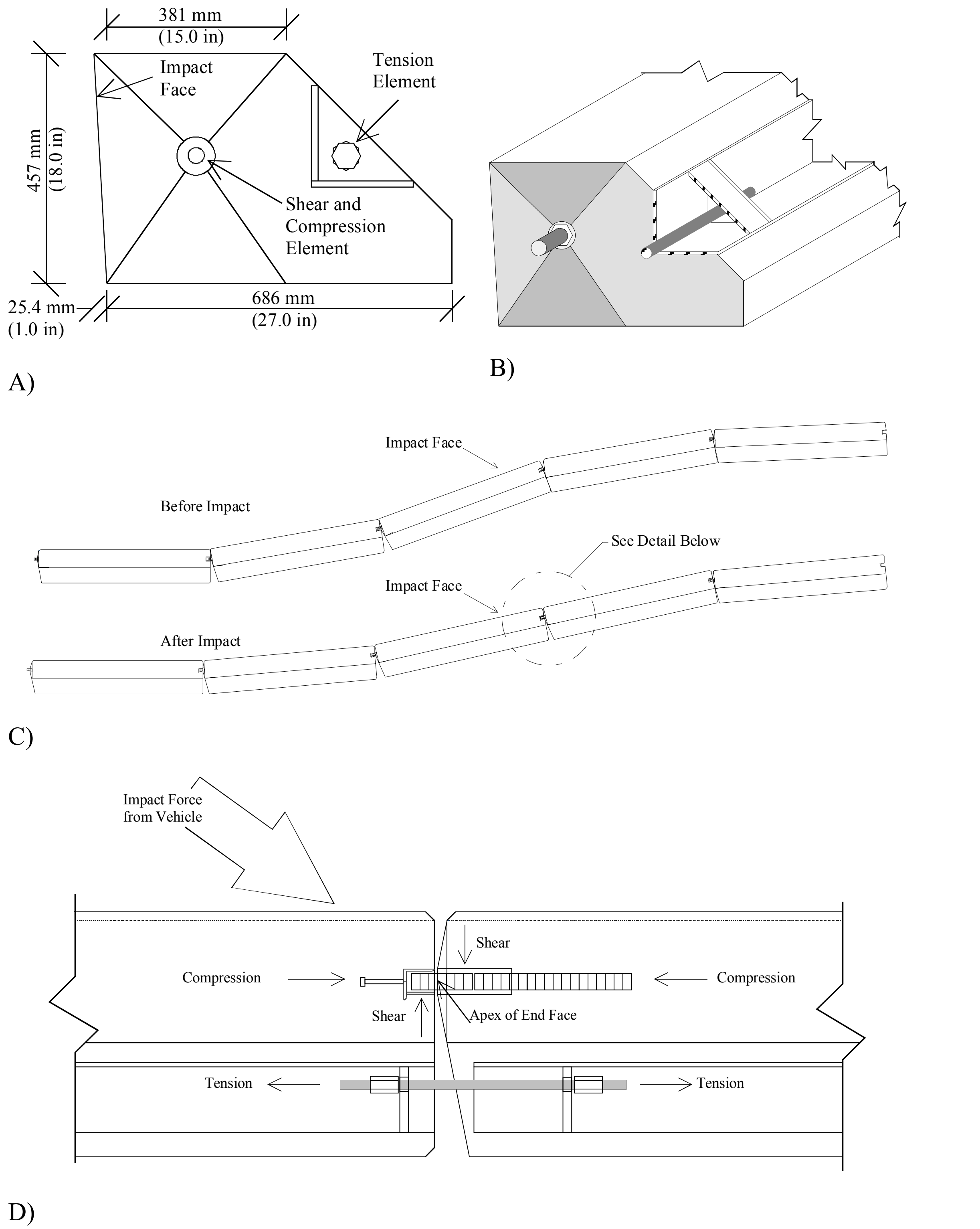


Figure 2. Curvilinear barrier system A) Cross-sectional shape of barrier B) End view of barrier C) Plan view of multi-segment barrier D) Segment-to-segment forces transmitted during an impact event

SECTION 3

CONCEPTUAL DEVELOPMENT AND MODELING OF BARRIER COMPONENTS

3.1 Introduction

Conceptual development of the new curvilinear barrier system was based primarily on results obtained from nonlinear dynamic finite-element simulations conducted using the LS-DYNA (version 950) finite-element code [6]. Before arriving at the final system configuration shown previously in Figure 2, a variety of different barrier design concepts (including varied section geometry and connection schemes) were evaluated numerically by simulating 2000 kg pickup truck impacts. NCHRP 350 [4] requires both 2000P and 820C vehicle impact tests to be run for longitudinal barriers, however, for low-profile barrier systems, the 2000P vehicle with its larger mass and higher center of gravity will control the design process in virtually all cases. For this reason, simulations were conducted only for the 2000P vehicle. The finite-element vehicle model used in this study was a modified version [3] of the NCAC reduced resolution C2500 pickup truck model (Version 8).

Key components of the barrier system were modeled first in coarse detail and then in increasingly fine detail as the final design concept took form. The key features modeled were the 2000P vehicle, the geometry of the concrete barrier segments, and the barrier-to-barrier connection system. Sub-elements of the connection system were also modeled and consisted of shear, compression, and tension transfer components. In addition to modeling the geometry and structural behavior of individual components, complete barrier systems consisting of multiple segments configured in both straight line and curved alignments were also modeled. By doing so the performance of the system was numerically estimated in both straight and curved alignments. However, NCHRP 350 level 2 certification only requires testing for straight alignments. A later section will discuss the full-scale testing, conducted only on straight alignments.

3.2 Shear Connection Modeling

Throughout the design process, the intent was to develop a physical shear connector that would transmit the full shear load with minimal deformation. However, discretely modeling such a connector for finite-element simulation requires a large number of solid elements and significant computational resources. Therefore, during the preliminary system development phase, idealized “constraints” were used to simulate the shear connectors and maintain lateral displacement compatibility between adjacent segments. Only relative displacements in the lateral direction (Figure 3a) were constrained since it was known in advance that the actual shear connection to be designed would not carry axial load; that is, it would permit relative motion between segments in the longitudinal direction.

Displacement constraints must be carefully constructed so that artificial stress concentrations are not created in the structural elements being connected. Simply constraining two nodes, one on each of the barrier segments being linked together, would imply that the entire shear transfer force occurs over the very small tributary area of concrete adjacent to the two constrained nodes. In reality, the physical shear pin has finite size and the shear force is distributed over a finite area. To approximately represent this condition in the models utilizing only nodal constraints, two collections of nodes—one on each side of the joint—were constrained (Figure 3a). In the LS-DYNA simulations, entities called “nodal rigid bodies” were used to distribute the shear force to collections of nodes on each face of the concrete barrier segments connected.

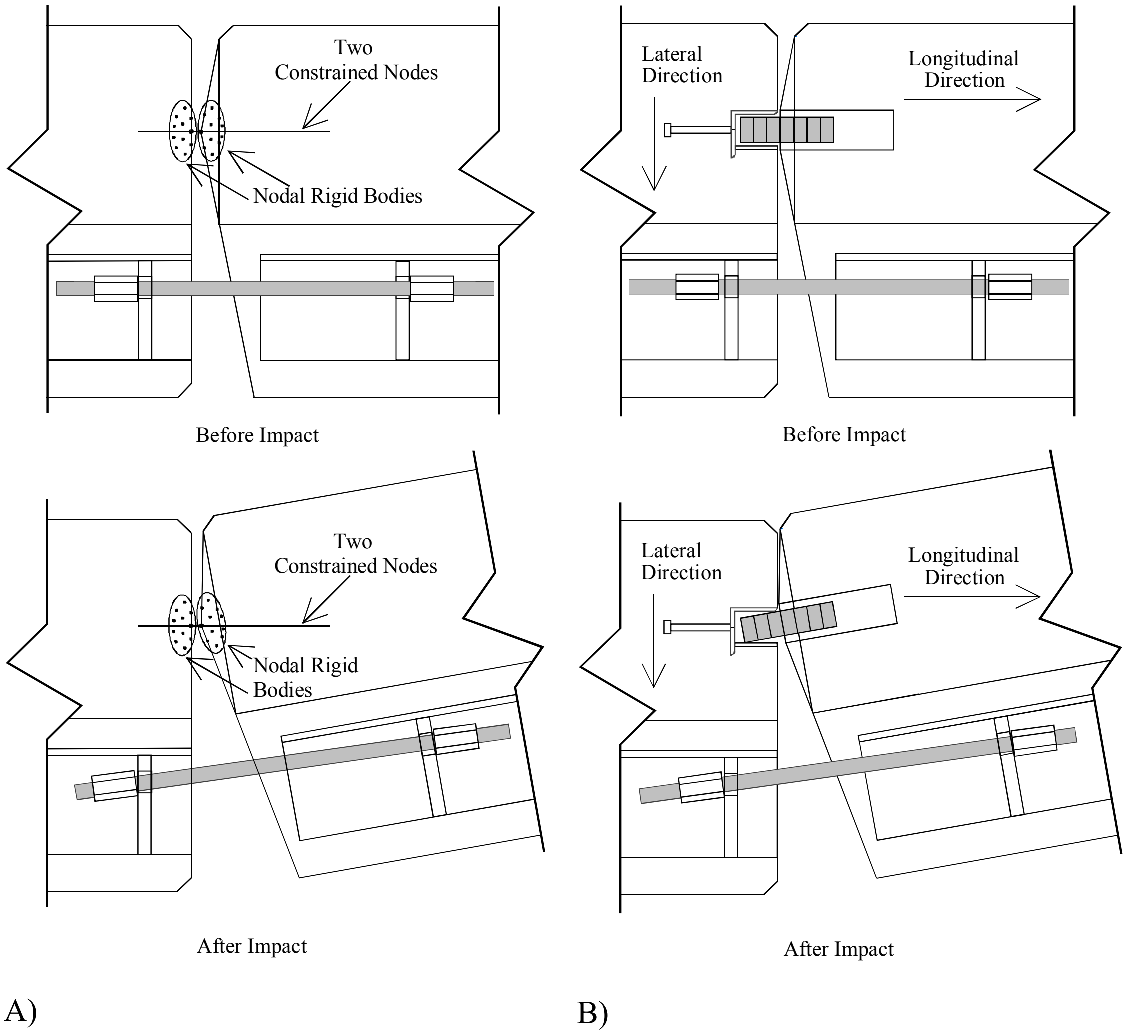


Figure 3. Modeling shear force transfer and lateral displacement compatibility A) Idealized constraint shear transfer B) Discrete model shear transfer

Once the overall behavior of the barrier system was deemed to be satisfactory at the coarse mesh scale (with the nodal shear constraints) the modeling of the shear connectors was enhanced so that stresses in the connector elements themselves could be determined. At this stage in the system development process, the actual physical geometry of the shear pin was modeled discretely using solid elements (Figure 3b). Each complete shear connection assembly was modeled as a combination of a 1.25 in. shear pin and a vertical channel with an interior width of 1.75 in. with appropriate contact definitions between the pin and slot parts. A pin and slot scheme was chosen because it allows individual segments to be removed vertically from the system without the need for longitudinally moving adjacent segments. In this manner, damaged segments can be lifted vertically out of the system and replaced with new segments with minimal effort.

3.3 Tension-Connection Modeling

Cable Connections

Accurately representing the behavior of the tension connector proved to be more challenging than modeling the shear connector. Initially, it was the intent of the investigators to carry the tensile component of the joint moments from one segment to another using semi-flexible high-strength cable elements (e.g. prestressing tendons). Given the mismatch in longitudinal alignment that occurs between barrier segments in curved alignment layouts, the use of semi-flexible cables held the promise of accommodating the longitudinal offset while still being capable of carrying the tensile loads.

However, two main problems persisted with this design concept that could not be satisfactorily resolved. First, a robust method for securing individual prestressing tendons at zero prestressing loads could not be determined. Typical anchorage methods for pre-stressing tendons work reliably only when the tendons carry prestress load. Second, simulation results indicated that several cables (between four and six) would be needed to carry the total tensile load acting at each joint. In order to transmit each and every cable load into the concrete segments, a complicated steel anchorage block with several anchorage points would be required. Such a system would have been unnecessarily complex, bulky, and expensive to fabricate.

Bolt Connections

For these reasons, all concepts involving the use of cable elements were abandoned and focus was shifted to designs utilizing bolts (threaded rods) at each joint to carry tensile loads. Initially, the goal was to select a diameter and material strength large enough so that the bolt would remain linearly elastic throughout impact loading. As such, each bolt was initially represented in the finite-element model as a discrete spring element with a linearly elastic force-displacement curve and a zero-stiffness compression curve (a detailed description of the compressive behavior is given later). A multitude of force-displacement curves were used to investigate the effectiveness of varying the connector length, location of end points, number of bolts, and the diameter and strength of the bolt.

The highest strength threaded rod material commonly available (150 ksi) was selected for the tension connector element. However, simulations indicated that the initially selected 1.25 in. diameter bolt would yield and become nonlinear during impact. Therefore larger diameter bolts were investigated. While such bolts have higher yield points, they are also structurally stiffer. As a result, each time a larger diameter bolt was modeled, the barrier system became considerably stiffer and the peak loads experienced by the bolt increased, thus indicating the need for an even larger bolt. Uncommonly large bolts that would have remained linear throughout the impact could have been utilized but such a bolt would have made the design expensive and impractical for construction. In addition, large diameter bolts would have also made the barrier system excessively stiff, potentially leading to an undesirable increase in vehicle roll angles.

In order to preserve moderate system flexibility while still providing sufficient tensile load capacity, the design procedure for the bolt was modified to permit both *yielding* and *plastic* *deformation*. The structural behavior of the bolt was represented using a discrete spring with a series of nonlinear load-deformation curves. These curves were developed using data from ASTM [7] stress-strain tests for high-strength steel bars (Figure 4). In order to obtain realistic results from nonlinear bolt models, two distinct phenomena needed to be represented in combination with the stress-strain requirements.

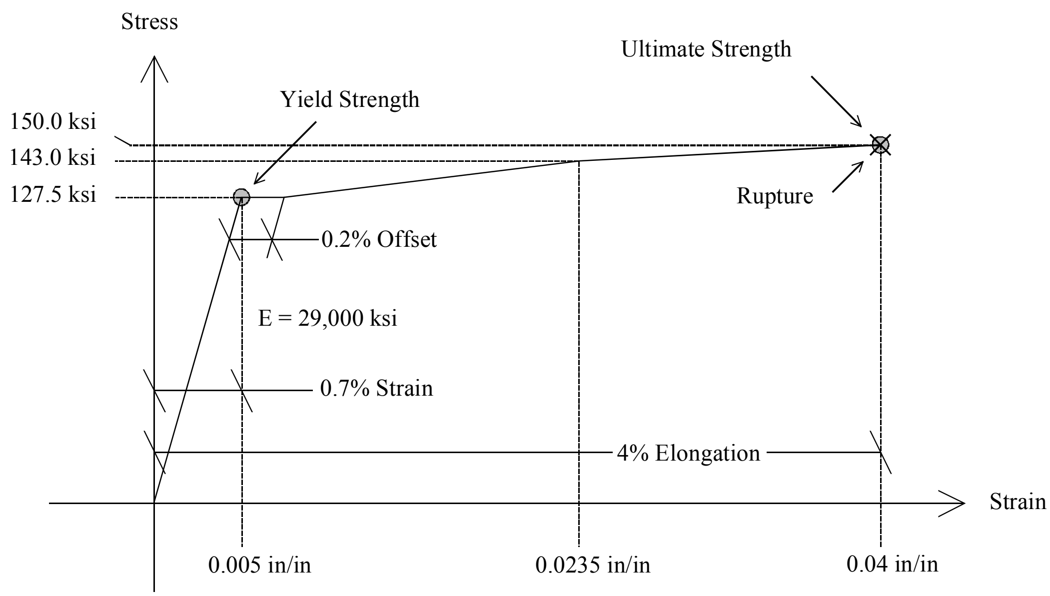


Figure 4. Material stress-strain curve for high strength tension connector

First, when bolts are loaded beyond their yield point, a permanent plastic change of length occurs and the bolt effectively hardens for subsequent cycles of loading. Second, due to the nature of the bolted connection used in this barrier system, the bolts can never carry compressive load (Figure 5). Closing the gap on the tension bolt side of the barrier will simply result in the bolts becoming slack against their respective bearing plates and no compressive resistance will be generated. Thus, the material model—the load vs. deformation curves—for the bolts needed to not only have zero stiffness when subjected to compression, but also needed to track the progressive hardening and permanent change of length that occurs during cycles of tensile loading and unloading. During a typical vehicle impact event, the bolts are subjected to several repeated cycles of tensile and unloading.

Thus, the investigators developed an accurate load-displacement curve in lieu of discretely modeling the tension bolt by accounting for elastic and plastic tensile behavior, zero compressive resistance, and gap formation due to plastic deformation and non-linear contact. As exhibited by Figure 5b, the tension element initially undergoes an elastic and plastic loading with strain hardening. The impact forces are then transferred to the adjacent segments by shear and flexural continuity and the tension element elastically unloads (Figure 5c). After unloading, the barrier end faces continue to close on the tension side, thereby creating distance between the connector nuts and the bearing plates. The total gap formation is now comprised of the permanent deformation of the bolt due to plastic deformation and the distance between the nut and bearing plate (Figure 5c). Both of the components producing this gap must be eliminated before the tension element elastically reloads (Figure 5d). Figure 5d also shows that strain hardening of the bolt has taken place and the effective yield load has increased. In Figure 5e, the barrier segments return to their initial positions with the tension element having undergone permanent deformation, a result of the inelastic deformations indicated in Figures 5b and 5d.

This load-deformation curve was intended to model the behavior of the entire connection assembly but it was based solely upon the performance of the high strength bolts spanning between sets of bearing plates. Therefore, in order for these curves to be accurate representations of the entire tension assembly, all elements of the connection other than the bolt must behave linearly with negligible deformations. In other words, the threaded rod must behave as the weakest link within the tension connection assembly and yield at a load level that is lower than any other element of the connection assembly.

In order to design a connection that could transfer the tensile bolt loads with negligible deformations, a discrete shell model of the entire tension bracket was developed and tested. This finite-element model was tested separately from the barrier system and consisted of the steel angle, a bearing plate, and a stiffening plate as shown in Figure 6. Several design iterations were performed in order to select the angle and plate thicknesses that would provide adequate strength and stiffness. Iterative design changes were made based on simulation results until a sufficiently strong bracket assembly was developed. The final bracket design was able to successfully carry tensile loads well in excess of the yield load of the bolt with negligible deformations. Therefore, the applicability of modeling the entire tension connection assembly with a simplified discrete spring element in the main impact models was verified.

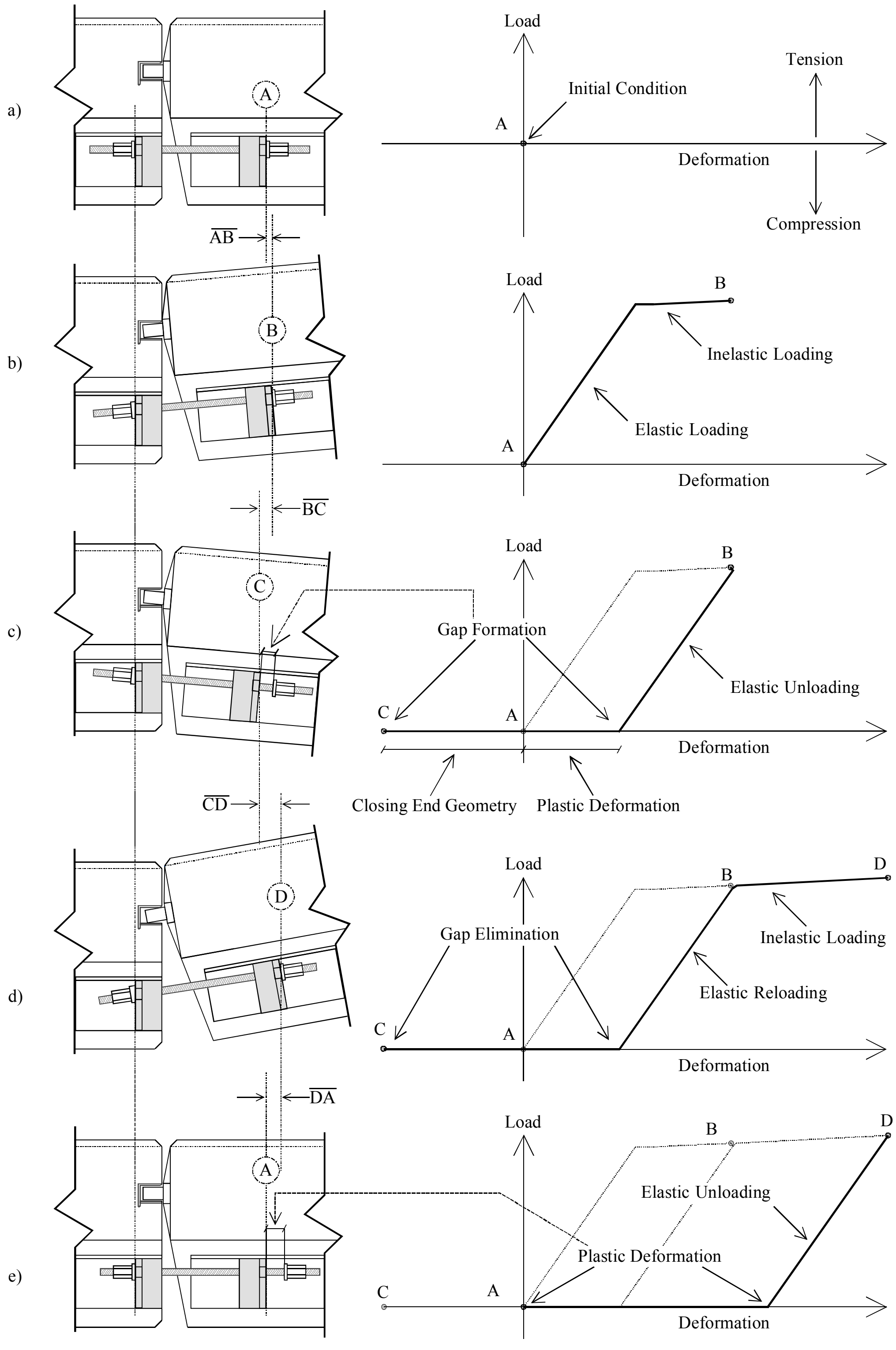


Figure 5. Modeling nonlinear tension element behavior

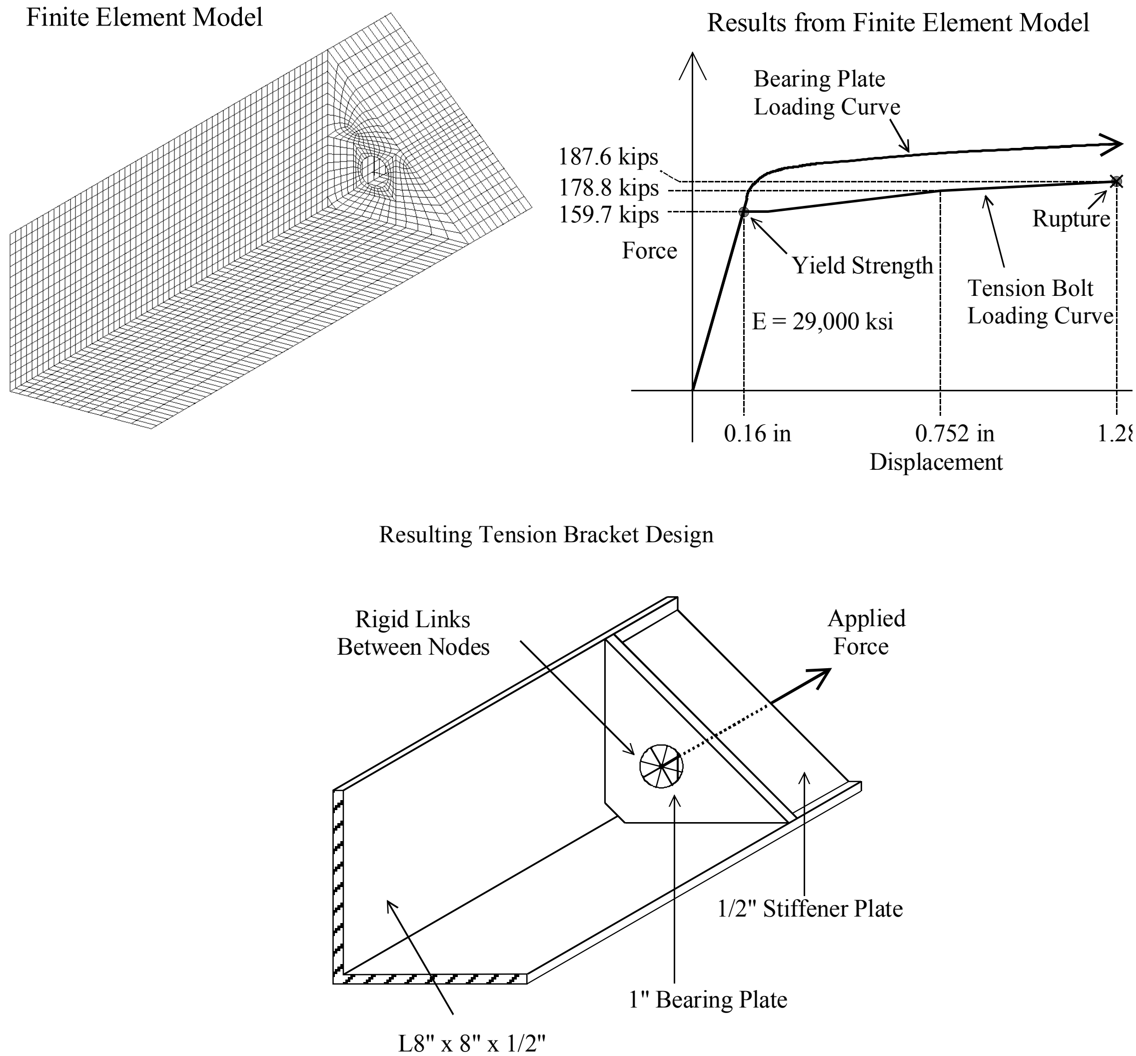


Figure 6. Modeling, response, and design of bracket model

SECTION 4

ESTIMATION OF SYSTEM PERFORMANCE USING SIMULATION

4.1 Introduction

A primary goal of this research was to develop a system that would successfully perform throughout a demanding range of field conditions. With this in mind, a parametric study of finite-element simulations was employed using the modeling concepts described previously. Frictional definitions, vehicle trajectories, and barrier alignments were varied in an attempt to envelope all likely impact scenarios. For each simulated condition, several overall system and barrier component behavior criteria were analyzed. The redirection capabilities of the system were assessed by examining vehicle roll angles, checking for the possibility of vehicle snagging, quantifying lateral barrier deflections, and qualitatively evaluating continuity of the barrier during impact. The effectiveness of the connection assemblies in transmitting critical design forces was determined by evaluating the behavior of shear, compression and tension elements.

4.2 Vehicle Modifications

Prior to developing a set of simulation parameters or even preliminary testing of the design concept, additional changes were made to the modified version [3] of the NCAC reduced resolution C2500 pickup truck model (version 8). Comparisons between simulation results and full-scale crash test results for the phase one barrier system [3] suggested enhancements should be made to modeling of the front tires and passenger side steering assembly. Alterations were made to this vehicle due to known inaccuracies in the tire material and steering stiffness, of which were independent of full-scale crash tests results. These changes included increasing the tire wall thickness from 0.12 in to 0.75 in. and changing the Young's modulus for the tire material from 357 ksi to 3570 ksi. This increased stiffness caused more realistic tire to barrier interaction. The front passenger side steering assembly was modified by introducing a 0.75 in steering-angle control rod made of steel (36 ksi) thereby adding stiffness similar to that present in actual vehicles.

Upon re-simulating the impact conditions for the phase one barrier system with the modified 2000P truck model, a greater level of agreement was observed between the simulation and full-scale crash tests. For example, previous simulations [3] of the straight line system predicted a roll angle of less than 10 degrees, however the actual roll angle from full-scale crash testing was 29.7 degrees. The model was predicting inaccurate behavior due to unrealistic tire material and steering rod stiffness. Using a 2000P vehicle model with the tire and steering modifications just described, impact simulation predicted a roll angle in excess of 20 degrees which is in much better agreement with the phase one barrier full scale crash tests.

4.3 Phase Two Barrier System Model

After the updated vehicle performed with an acceptable level of accuracy for predicting the impact behavior of the phase-one design, full multi-segment phase-two barrier system models were developed. The resulting finite-element models consisted of ten barrier segments connected by nine idealized constraint shear connections and nine tension connections. Barrier segments were modeled using fully integrated three dimensional solid brick elements with an elastic-plastic concrete material definition. Each barrier segment, consisting of approximately 650 brick elements (Figure 7), was placed along the right side of the roadway and aligned with the adjacent segment. Brick elements were primarily used for accurately depicting the mass of each barrier and the flow of force and stress into the connection elements. All elements were fully integrated with a density of 145 pcf, a Young's modulus of 4415 psi, and a yield stress of 5.1 ksi. The barriers were placed in either a straight alignment or one of two continuous 10-degree barrier-to-barrier curved alignment schemes (Figure 8). These severe concave and convex alignments were modeled in order to investigate the barrier's potential range of applicability for roadway curvatures.

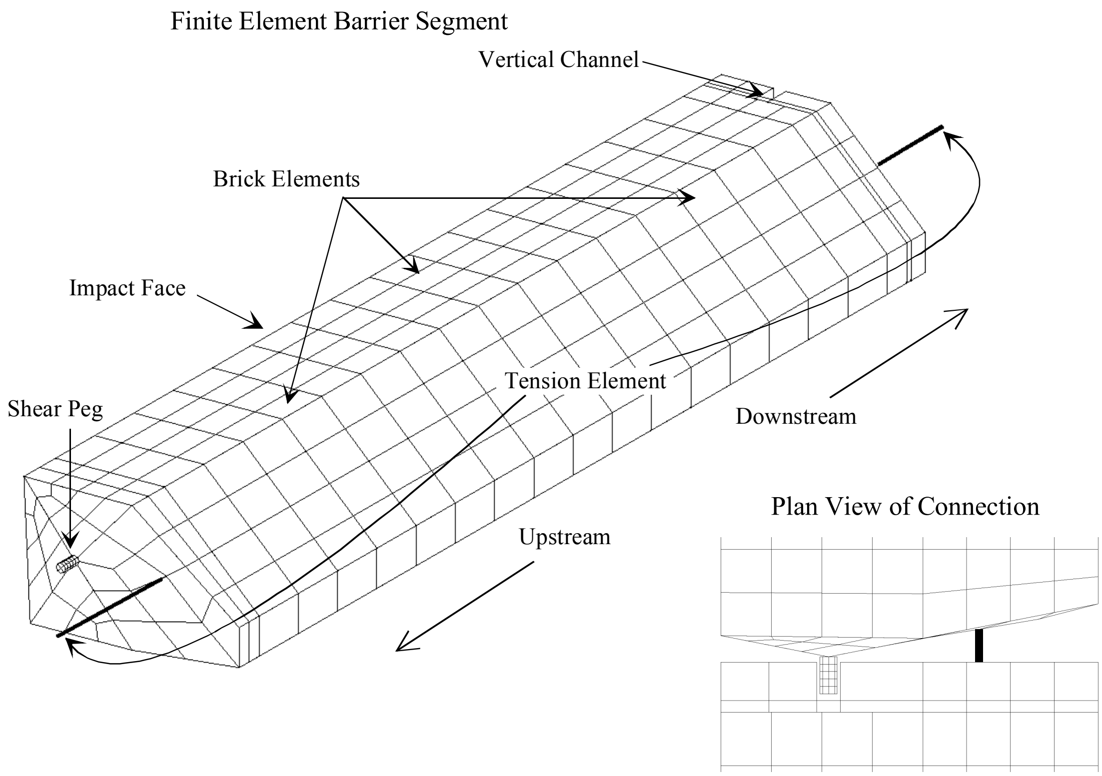


Figure 7. Finite model of a single barrier segment

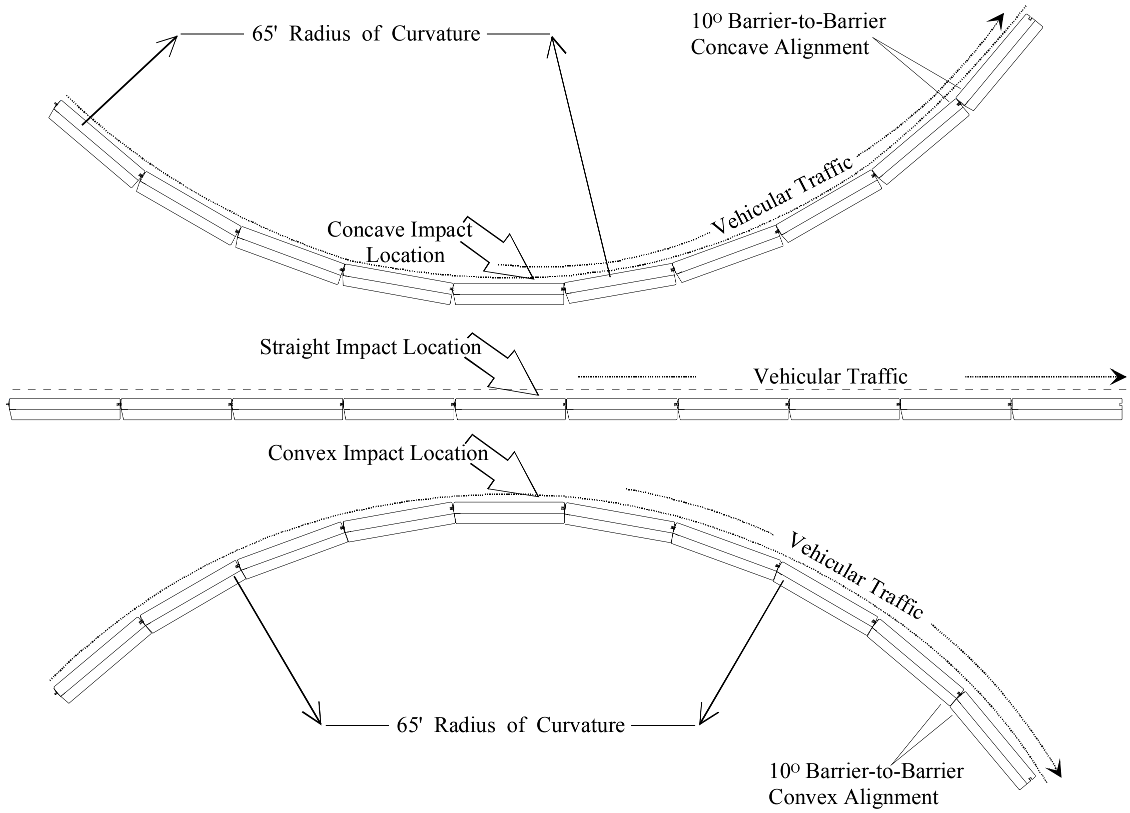


Figure 8. Plan view of barrier alignment

4.4 Preliminary Straight Alignment Impact Simulations

Three barrier alignment models were used in combination with a range of friction parameters to develop a comprehensive set of impact simulations. Results from this set of simulations were evaluated for development of a finalized design concept. Ranges of friction coefficients were used for the tire-to-barrier, tire-to-roadway, and barrier-to-roadway contact definitions. Frictional coefficients were chosen that exceeded probable values in both the lower and upper bound directions in order to simulate all probable vehicle and barrier system responses. With this in mind, simulations were performed with tire-to-barrier and tire-to-ground friction values from a lower bound of 0.10 to an upper bound of 0.60. In addition, the "realistic" friction curve developed by Consolazio et al. [3] was used to simulate expected actual field conditions. The vehicle was positioned so that the point of impact was approximately 0.8 m upstream from the impacted joint, according the NCHRP 350 requirements [4]. Anticipating the fact that many field installation sites will have poor quality surface conditions with minimal frictional shear transfer between the barriers and the roadway surface, the barrier-to-ground friction coefficients were varied from 0.25 to 0.40.

The resulting simulations were analyzed in order to identify cases that might cause system failure or unacceptable redirection performance. The two primary vehicle characteristics used for determining safe redirection were roll angle, measured at the center of gravity of the vehicle, and potential for snagging, quantified by the exit velocity of the vehicle after impact.

The highest roll angles were seen, as anticipated, in simulations with the lowest tire-to-barrier and tire-to-ground friction values and the highest barrier-to-ground friction values. In contrast, the possibility of snagging was greatest when all three friction parameters were at their upper bound values. Despite the additive effects arising in selected friction combinations, the worst-case roll angles were within acceptable limits and snagging was not observed.

A multitude of system responses for the barrier were examined, but for sake of brevity, lateral deflection and continuity will be used here as the two key criteria used to measure overall barrier performance. As would be expected, the largest dynamic and permanent lateral deflections of the barrier system occurred when the barrier-to-ground friction was at a minimum. Although barrier system "continuity" cannot be quantified with a single variable, visual inspection of the angle change and lateral displacement between adjacent barriers was sufficiently informative. The largest lateral deflections were acceptable, rollover did not occur, and at no time was continuity compromised in any of the simulations.

4.5 Preliminary Curved Alignment Impact Simulations

NCHRP 350 certification requires testing for straight alignments only. However, given that the phase two system was explicitly designed to allow concave and convex horizontal curvatures, and that the reliability of the computer simulations of impact performance were shown in phase one to be credible, the investigators conducted simulations to gain insight as to the viability of the barrier system when deployed in a curved alignment. The results presented here for curved alignments have not been confirmed through full-scale testing, but do provide some measurement of performance that the investigators feel is reliable.

Friction combinations causing the most severe vehicle and barrier responses during the straight alignment simulations were next simulated for horizontal concave and convex alignments. Due to the geometry of the barrier connection in the concave alignment, deflections of the barrier system during impact were minimal. Hence, the primary focus for evaluating system performance in this case was the vehicle roll angle.

More specifically, to investigate the possibility of rollover, several concave impacts were simulated with vehicle impact angles ranging from 25 degrees to 35 degrees (angle between the vehicle and the barrier segment being impacted). When the most extreme lower bound friction value for the tire-to-barrier and tire-to-ground contact was used, a large roll angle was observed, however more tolerable roll angles were observed when a more realistic friction curve was used. The potential for snagging was also investigated for both curved alignments and was found to be most severe for the convex alignment simulations having high friction values for the tire-to-barrier and tire-to-ground contacts. These simulations indicated more deceleration relative to other alignments but were not deemed severe enough for concern.

4.6 Simulation of NCHRP 350 Test Conditions Using the Refined Shear Model

Simulation results discussed thus far correspond to the phase two barrier system modeled using the idealized constraint-based shear connection technique described in Section 3.2. After selecting the material type and diameter of the shear pins based on simulation results obtained using the constraint based models, the investigators decided to also discretely model the pin and channel connection with a more refined resolution mesh (Figure 7). The effects of shear failure of the pin or disengagement of the pin from the channel upon overall system behavior were the primary reasons for developing this refined model.

Simulations for the phase two barrier system in a straight alignment using the discretely modeled shear connection were conducted for the entire range of tire-to-barrier, tire-to-roadway, and barrier-to-roadway friction values previously discussed. By re-simulating the lower, realistic, and upper bound friction cases, comparisons could be made between the responses obtained from the constrained shear model and the discrete shear model. Differences in vehicle behavior and barrier response were minimal between the two shear models. It was determined that discretely modeling the shear connection had minimal effect on system performance and due to the success of the idealized constraint model for the curved alignments, impacts were simulated with the more refined shear connection model for the straight alignment only.

The tension element affects the overall barrier system continuity differently for each alignment scheme due to the altered deformable length of connection bolt. The difference in element length alters the element deformation once yielding occurs, thereby moderately changing the distribution of tension forces. The force going through any tension element at any point in time during the impact event dictates the stiffness at that joint and therefore directly affects the distribution of loading to itself and adjacent segments. The loading curves for all three friction-model simulations (Figure 9) show extensive portions of time during which nonlinear material behavior is exhibited. Once the tension element yields, it is important that forces are redistributed through the remainder of the barrier system in order to prevent failure of the tension bolt. The results (Figure 9) indicated that the bolt at the impact joint is initially loaded to a nonlinear state in all three friction simulations and yet rupture failure does not occur, thereby indirectly indicating that force distribution away from the joint is occurring.

Properly defining the tension connection behavior was therefore important in depicting the barrier system stiffness and hence the overall system behavior. As can be seen in Figure 9, the tension element is initially loaded into the plastic region, attempts to undergo compression, and then reloads into the plastic region with strain hardening. Also displayed are zero-stiffness compressive states at several times throughout the span of the simulation indicating considerable lengths of time during which the element does not add stiffness to the system. In summary, the load-displacement curve specified accurately models the behavior of a high strength bolt by incorporating nonlinear material, zero compression stiffness and gap formation between the bearing plate and nut. Having verified the tension connection assembly with the bracket simulations (previously discussed), refinement of the tension connection modeling by incorporating a discrete finite-element model was deemed unnecessary. Using a load-displacement curve to model the actual connection behavior was sufficiently accurate.

Simulations including the refined shear connection barrier model and nonlinear load-deformation curve for the tension connection were extensively tested because they most accurately modeled the NCHRP test conditions. Although simulations covering a wide range of coefficients of friction were performed, only results obtained from simulations utilizing the lower bound, the upper bound, and realistic friction definition for the tire-to-barrier and tire-to-ground contacts are discussed herein. NCHRP 350 Level 2 crash test requirements for longitudinal barriers include full-scale crash tests at 45 mi/h for both a small car (820 kg, 1800 lbs., 20 degree impact angle) and a standard pickup truck (2000 kg, 4400 lbs., 25 degree impact angle). An 820 kg finite-element compact vehicle model was not used for the design of this barrier system because previous full-scale testing of the phase one barrier indicated that the 820C vehicle would not control the design of the barrier system [3]. Therefore, the 2000P vehicle—the standard pickup truck—was used to simulate full-scale crash test conditions.

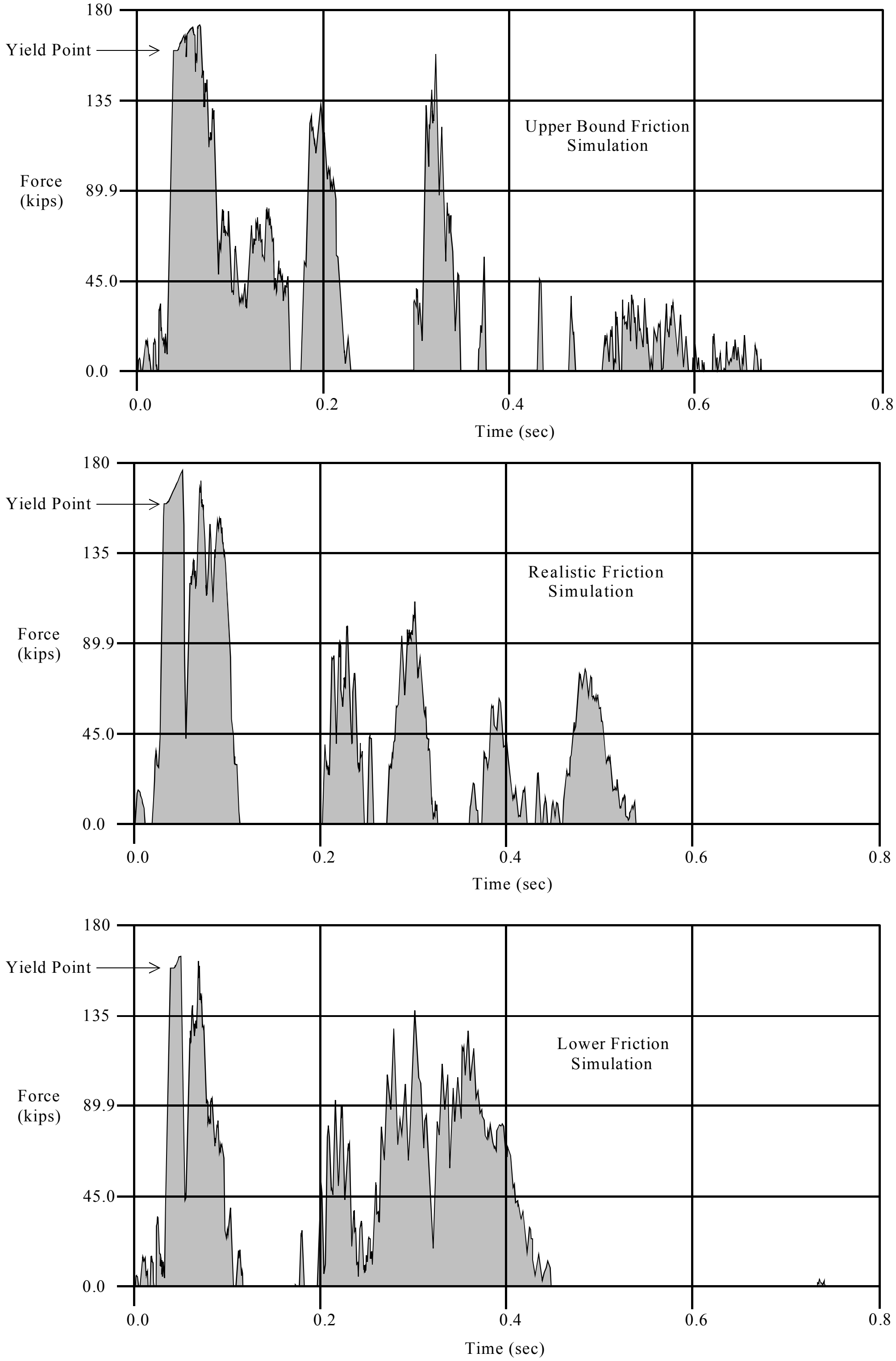


Figure 9. Loading Curves of the Tension Bolt During Simulation

The lower bound friction simulation used a constant coefficient of 0.1 for the tire-to-barrier and tire-to-ground contact definitions and was intended to investigate maximum roll angles. In contrast, the primary goal of the upper bound friction model was to test for the occurrence of vehicle snagging and/or connection failure, so the friction coefficients for these contact definitions were set at 0.6. The “realistic” friction curve used for these two contact definitions was the median of the upper and lower friction curves described by Consolazio et al. [3]. This curve is a function of the relative velocities between the contact surfaces and was intended to most closely approximate typical field conditions.

In all three NCHRP 350 impact simulation cases, the performance of the barrier system was deemed acceptable based on the analysis results obtained. In all cases examined, the 2000P vehicle was smoothly redirected without experiencing rollover or snagging. Vehicle roll angles predicted by simulation did not exceed 10 degrees in any case and lateral barrier deflections averaged approximately 24 in. in magnitude. As a result of the frictional models used, and based on the fact that construction tolerances were modeled between each pair of adjacent barrier segments (to represent non-ideal installation conditions), the lateral deflections produced by the simulations were considered to be worst case, conservative predictions. Even so, the deflections predicted were deemed to be within acceptable limits. In addition, as is discussed later in this report, physical crash testing confirmed that actual barrier deflections under normal installation conditions and typical frictional conditions were significantly less than the conservative estimates predicted by simulation. Finally, connection element forces predicted by impact simulation were also within the strength limits of the steel materials that had been selected during the design process.

SECTION 5

FULL SCALE CRASH TESTS: PERFORMANCE VALIDATION

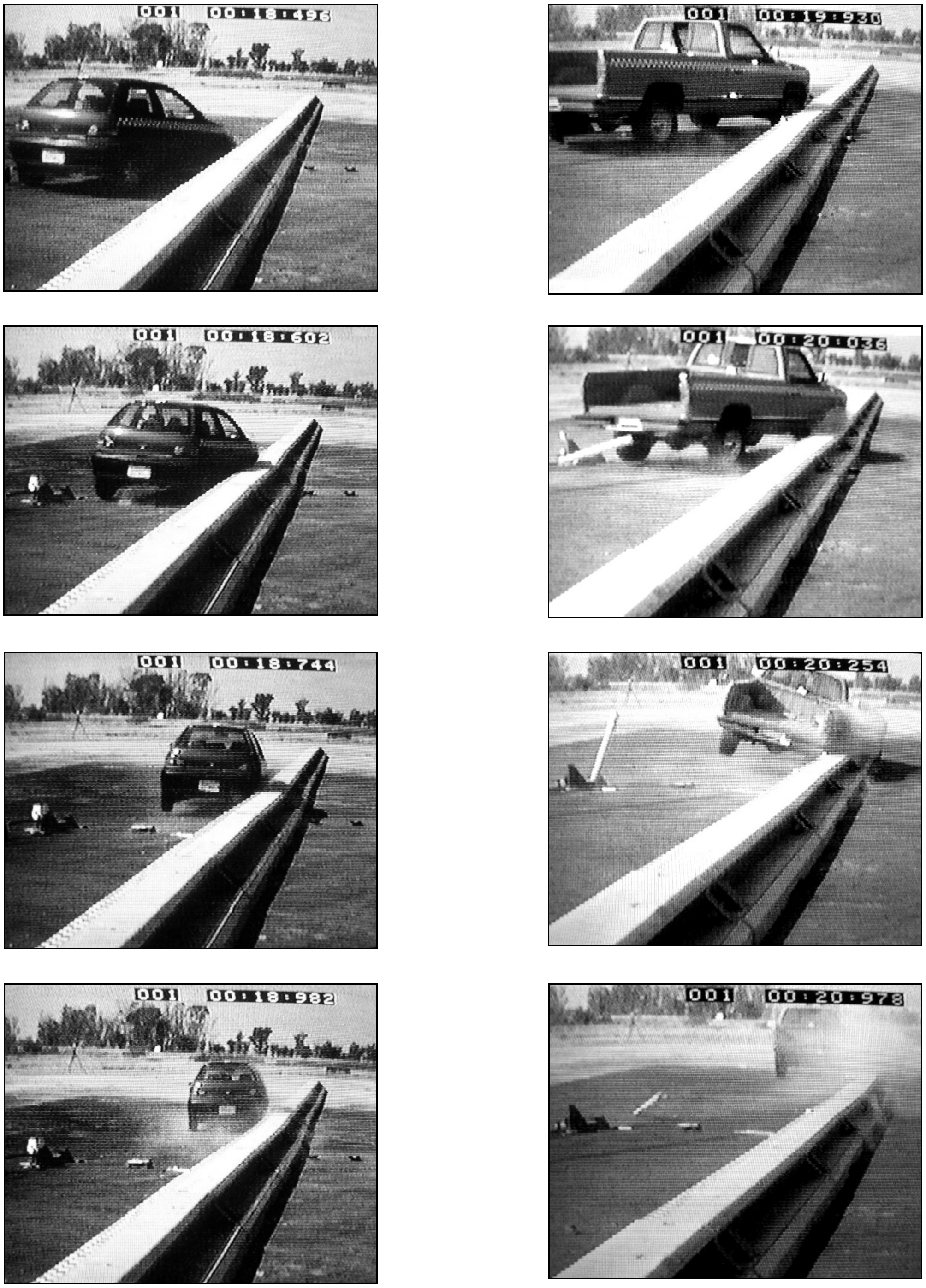
Although computer simulation has proven to be a useful design tool, it cannot replace the importance of full-scale crash testing of the barrier. The FDOT mandated NCHRP Report 350 level 2 performance for the barrier design. This requires a full-scale crash test of both a small car (820 kg., 1800 lbs.) and a standard pickup truck (2000 kg., 4400 lbs.). Specifications in Report 350 dictate acceptable performance in terms of structural adequacy, occupant risk, and post impact vehicle trajectory.

E-Tech Testing Services, Inc. of Rocklin, CA was contracted to test the phase two barrier system. The production of fifteen barrier segments was subcontracted to Kie- Con, a casting yard located in Antioch, CA near the E-Tech test facility. Quality control inspections were conducted during production by an E-Tech representative under a separate contract.

All fifteen barrier segments were installed in a straight line configuration at the test site used by E-Tech Testing. The test site is situated on a dusty, abandoned runway that has an aged asphalt concrete chip seal surface condition [8] thought to be a worst case scenario for in-field use of this barrier system. The barrier segments were not fastened to the road surface in any manner. A pulley system was used to tow the test vehicle up to the test speed and impact angle. The steering mechanism was disengaged just prior to impact, affecting a hands-off test condition. Impact was just upstream (0.8 meters) of a connection between segments, toward the middle of the 120 foot assembly. Six different high-speed cameras recorded the tests from different angles. Instrumentation in the vehicle provided a time history of vehicle accelerations to estimate the forces on occupants. Additional instrumentation was placed on the tension connection bolts between segments near impact to measure tensile forces during impact. Post-test data reduction determine if the barrier passed the structural adequacy, re-direction, and occupant safety criteria.

Both the 2000P and 820C tests were conducted within a few days of each other. The 2000P truck test was run first since it is a more severe impact condition than the small car impact and more likely to result in system failure (rolling, barrier override, poor vehicle redirection) given its larger diameter tires, higher center of gravity, and higher mass. The barrier passed the 2000P truck impact test with very minor damage (spalling) to the impacted barrier segments. However, as is standard procedure for such impact tests, the segments near the impact zone were removed and exchanged with undamaged segments previously used near the ends of the system in preparation for the 820C small car test. Subsequently, the 820C test was run and again, the barrier passed.

Both vehicles redirected safely into the roadway upon impact as shown in Figure 10. The dynamic barrier lateral deflections near the impact point were 9.1 in. and 3.2 in. for the truck and car, respectively [8]. E-Tech Testing has issued its final report [8] certifying that the barrier system passed the Level 2 test requirements. A copy of that report is included with this report. The reader is referred to the E-Tech report for further details of the test set up, data analysis, photos of pre- and post-impact conditions, and detailed drawings of the low profile concrete barrier.



a) Impact test involving an 1800 lb. (820 kg) compact car

b) Impact test involving a 4400 lb. (2000 kg) pickup truck

Figure 10. Validation of barrier performance using NCHRP 350 compliant full-scale crash testing

SECTION 6

CONCLUSION

By making extensive use of finite-element impact simulation, a new low-profile portable work zone barrier system has been successfully developed. Several cycles of design iteration were performed based purely on computational simulation thus substantially reducing both the time and costs associated with development of the system. This approach was validated from phase one, the straight-line barrier project, where full-scale crash tests proved the accuracy of finite-element simulations. Modifications to the 2000P reduced resolution pickup truck model were made to improve its accuracy for simulating low-profile barrier impacts. Appropriate consideration of frictional effects using upper and lower bound parameters was discussed and demonstrated.

The phase two barrier has a unique capability in that it can be laid out on both vertical and horizontal roadway curvatures—due to its innovative connection design—while also maintaining a low profile. The connection scheme presented herein appears to be the first of its kind and is designed to undergo nonlinear material behavior during impact. Although the nonlinearity results in larger lateral deflections than those of previous straight-line low-profile barriers, significant improvements in overall system performance are observed including reduced vehicle roll angle.

Full-scale crash testing confirms the excellent performance of the barrier. The phase two system has been certified to the standards of NCHRP 350 level 2.

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