DESIGN AND ANALYSIS OF APPROACH TERMINAL SECTIONS USING SIMULATION

By John D. Reid,¹ Dean L. Sicking,² Member, ASCE, and Gene W. Paulsen³

(Reviewed by the Highway Division)

ABSTRACT: Turned-down guardrail terminal sections were analyzed using LS-DYNA3D, a dynamic, nonlinear, large deformation finite-element modeling package with capabilities for simulating vehicular impacts into roadside hazards. A baseline simulation was conducted on the existing turned-down approach terminal section, as well as on various retrofit options. Simulation findings were used to identify potential design changes and to select the two most promising options. Modified designs were subjected to six low-speed and one high-speed full-scale crash tests with a minisize automobile. The crash testing verified that one of the retrofit designs would allow the W-beam rail to drop down without causing vehicle rollover when impacted end on by a minisize automobile. However, the revised design did not meet recommended safety standards when one of the weakened posts failed to break away as designed. It is believed that by revising the post installation procedures, the modified turned-down terminal section would perform satisfactorily.

INTRODUCTION

W-beam guardrails have been widely used to protect the motoring public from serious roadside hazards for many years. Early W-beam systems utilized stand-up terminals that incorporated no mechanism for mitigating the severity of head-on end impacts. When these terminals were impacted on the end, the W-beam often speared through the impacting vehicle, leading to serious injuries or fatalities. The first efforts to eliminate this "spearing problem" involved twisting the W-beam and sloping the end down to the ground. These turned-down terminals gained wide popularity and apparently provided an effective W-beam guardrail end treatment for a number of years. However, as the U.S. vehicle fleet began to downsize, in response to the 1973 oil shortage, these terminals were found to cause rollover when impacted by small automobiles.

The first attempt to resolve this problem involved weakening the attachment between the W-beam and the first few guardrail posts (Hirsch et al. 1977). This system incorporated steel clips that wrapped around the front of the W-beam rail and held it against a W-shaped backup plate. The steel clips were designed to release the rail and allow it to drop during end-on impacts, thereby reducing the propensity for causing small-vehicle rollover. Although initially incorporated by a number of states, these systems were found to have both operational and safety problems that prevented widespread application. The steel clips were found to be too strong for minisize automobiles, and hence the new designs continued to cause rollovers for some impact conditions. Further, the clip angles were found to release due to thermal and/or vibratory stresses; therefore, the weakened or "floppy end" turned-down terminal proved to require excessive maintenance.

Several researchers attempted to resolve the safety and maintenance problems associated with the "floppy end" turned-down terminal (Hinch et al. 1984; Pfeifer et al. 1989).

These efforts primarily focused on reducing the bending strength of the guardrail in the turned-down section. The controlled release terminal (CRT) (Hinch et al. 1984), the most widely publicized of these systems, incorporated a flat steel plate as well as weakened wood posts near the guardrail terminal. These systems never gained widespread acceptance due to a failure to meet NCHRP Report 230 (Michie 1981) test standards.

Even though the turned-down guardrail terminal was never able to meet NCHRP Report 230 standards, it continued to be widely used for many years. It is estimated that almost 500,000 turned-down terminals were installed along U.S. highways prior to 1989 when their use began to be restricted to low speed or low-volume highways. In light of this large installed base of turned-down guardrail terminals and the need to upgrade these systems during any major reconstruction projects, the Nebraska Department of Roads funded a research project to explore the feasibility of developing a retrofit for turned-down terminals that would be capable of meeting nationally recognized safety standards (Michie 1981). The scope of this project involved identifying retrofit mechanisms that could be used to improve the impact performance of the turned-down terminal sufficiently to meet recommended safety standards.

The underlying physics of the problem were determined using nonlinear, large deformation finite-element analysis (FEA). This knowledge was then used to formulate and test various retrofit design concepts. Research, for the most part, using nonlinear, large deformation FEA for crashworthiness has focused on the vehicle (Khalil and King 1989; Reid and Yang 1993). A paper by Wekezer et al. (1993) did show the feasibility of using the technique for roadside safety. However, that paper did not present any actual design using the FEA method.

CONCEPT ANALYSIS AND DESIGN

Development of retrofit turned-down designs involved several steps. The first step was to simulate full-scale crash testing of the original design in order to identify reasons for its poor impact performance and to develop confidence in the analysis technique. Upon completion of this effort, retrofit options were identified that could improve impact performance without creating excessive maintenance problems. The potential safety performance of these options was then explored using the same simulation techniques utilized with the baseline design. Finally, the static strength of the final design details was evaluated.
Baseline Simulation

A critical step in the analysis is to develop a baseline model of the existing system to be modified. The baseline test to be simulated was reported by Faller et al. (1992). Fig. 1 shows the model of a small vehicle impacting a turned-down guardrail head on at 26.8 mm/ms, or 96.5 k/h (60 mi/hr). The Nebraska turned-down guardrail terminal is composed of a steel W-beam attached to 13 wooden posts. Fig. 2 depicts the terminal section of the guardrail (from the terminal anchor to post 1). This section is referred to as the turned-down approach terminal section and is 7.62 m long. Complete details of the guardrail system can be found in Pfeifer et al. (1989). Partial details will be described in the testing sections of the present paper.

The initial minize vehicle model was obtained from Anthony Lee at Lawrence Livermore National Laboratories (LLNL). The front end structure of the vehicle was primarily modeled with shell elements. The rear end of the structure was modeled with beam elements because that portion of the vehicle exhibits very little deformation during a frontal collision and thus, detailed modeling is not required. The suspension system was modeled using beam elements. Total mass of the vehicle model was approximately 840 kg (1,850 lbs). Gravity was applied to the model.

Because a vehicle exhibits little damage when riding up a guardrail, the majority of the vehicle was merged into a single rigid body. The exceptions were a few parts underneath the carriage (low radiator tie-bar, oil pan, cradle, rear midrail and rear channel), the suspension system, and the tires. These parts were deformable throughout the crash event.

The guardrail was modeled using shell elements from the upstream end of the turned-down section up until post 6. This was done because after post 6 the W-beam rail is rigidly attached to the posts and is not part of the release mechanism. Thus, the remainder of the guardrail has little or no influence on the baseline simulation. Standard W-beam backup plates were attached to each post. The W-beam rail was then attached to the backup plates with No. 10 bolts at posts 1, 3, 5, and 6. The turned-down guardrail is designed to drop when these bolts shear. The bolts were modeled as small welds with a shear strength comparable to the bolts incorporated into the physical system. The W-beam is simply held up by the backup plates at posts 2 and 4 with no hard connections. Mesh of the W-beam rail is refined at the posts due to the contact interface with the backup plates.

Because of its advanced sliding interfaces and shell element formulation algorithms, the dynamic, nonlinear, large deformation finite-element analysis code LS-DYNA3D (Hallquist et al. 1993) was used to perform the simulation. Fig. 3 shows the completed simulation at 350 ms. The vehicle has now hit post 1 and is beginning to roll over. The timing and trajectory of the simulation was in close correlation with the physical test done previously (Faller et al. 1992). The model could now be used for redesign.

This simulation required 10 h on a Cray C90 supercomputer. Initial model development was performed on a Sun Sparc 10 Model 51. Complete simulation of the vehicle-rail impact takes approximately one week on the Sparc 10.

Modeling Difficulties: Contacts

Modeling the contact region between the vehicle and the turned-down section proved to be the most difficult part. Fig. 4 shows the geometry of the rear midrail and channel of the vehicle just prior to hitting the rail. The weight and speed of the vehicle and the sharpness of the geometry proved too difficult to accurately simulate the impact. Nodes on the rail would shoot off into space after a few milliseconds of contact (see Fig. 5). When shooting nodes occur, it is often referred to as “blowing up.” This phenomenon is not physically possible and thus, modeling changes are required.

Reduced models of the vehicle and rail (one similar to just the components shown in Fig. 4) could be successfully simulated. However, when the entire vehicle was added, the severity of the impact became too great.

Solving this problem required the creation of a contact plate attached underneath the vehicle in the vicinity of the rear midrail and channel (see Fig. 6). By defining the contact between this plate and the guardrail, simulation became feasible. How-
ever, the choice of contact type used proved to be another challenge. As a first attempt, for simplicity, automatic single surface contact was employed. This choice of contact had various effects depending upon slight variations in the model. Usually, the simulation resulted in shooting nodes, similar to those shown in Fig. 5, which were not acceptable.

The contact penalty factor was changed to try to prevent the vehicle from penetrating the rail a little more forcibly—which was caused by the weight and speed of the vehicle. This proved to be incorrect. The higher the contact penalty the sooner the rail blew up (Fig. 5). After analysis, this made sense. This higher the restoring force the more likely nodes would fly.

Next, orientation of the W-shaped beam was thought to be the reason for LS-DYNA3D having difficulties with automatic contact. Thus, the contact for nodes impacting surfaces was attempted, first with the rail segments being defined as the master segments, then second with the rail node being defined as the slave nodes. Neither of these options worked any better; again the simulation resulted in shooting nodes.

Next, the node-to-surface constraint method was attempted, with the thought that the penalty method was causing the problems. Results showed that this method was also inappropriate due to shooting nodes.

Finally, single surface contact was tried. At first, the results were no better than previous attempts. Ultimately, it was determined that the problem rested in local vibrations of the connecting nodes. This was fixed by engaging viscous damping within the single surface contact. Fig. 7 shows the front rail before and after being impacted by the underbody of the vehicle structure. Contact between the lower radiator tie-bar, oil pan, and cradle with the rail also improved with this choice of sliding interface.

Retrofit Design I

Until recently, the only means of redesigning most highway safety hardware was through physical testing, which has been found to be too costly to correct the small vehicle head-on impact problem. The FEA simulation of the accident scenario now allows multiple design concepts to be tested at a fraction of the cost. Additionally, a detailed analysis is possible through the immense amount of data available from FEA. Many parameters were studied, including the connection methods between the W-beam and the posts, the anchor post design that holds the end of the turned-down portion of the W-beam at ground level, and the beam shape over the turned-down section.

One particular area of detailed scrutiny was the rail connection at post 1. Fig. 8 shows the baseline model simulation of the rail just before the vehicle reaches post 1. In this figure, it can be seen that the rail is still strongly being held up by the backup plate with little deformation. It is known that larger vehicles would, by this time in the accident, have forced the rail to drop to the ground.

By examining cross sections in the rail before and after post 1 it is possible to determine the forces and moments that are holding the rail up (Reid and Sheh 1993). The cross section analysis showed that during impact, the rail is forced both downward and toward the post (Fig. 9). The force toward the post is casued by the twisted guardrail geometry and the angle of the rail as it approaches post 1. Due to the backup plate being the same shape as the rail, the force toward the post resists the downward force, thus preventing the release of the rail. For larger vehicles, the downward force is large enough to overcome the inward force.

History of the backup plate shows that its importance was mainly for rail systems with steel posts, to prevent cutting of the rail. These backup plates were adapted to wooden posts on turned-down terminals as a mechanism for holding the rail up during redirectional impacts. After several concepts, the backup plate was reduced to a steel angle bracket. This bracket is strong enough to hold the dead weight of the rail, yet will bend down when large forces are exerted downward, allowing the rail to drop as desired.
Connection of the rail to the new brackets was changed to include shear-away bolts at posts 1, 3, and 6. There are no direct rail connections at posts 2, 4, 5, and 7–9, while standard hard connections are applied at posts 10 and 11. Effectively, the release mechanism is extended from post 5 back to post 10. This allows a longer moment arm to be applied to the dropping of the rail during the accident. Figs. 10 and 11 indicate the possibility of success with this new design concept. The new steel angle bracket backup plate can be seen attached to the post in Fig. 11.

Retrofit Design II

Unfortunately, the new backup plate concept does not change the direction of the rail-to-post forces. With the new design the direction of the twist in the rail still produces a major inward force in the rail toward the post, which may require very high impact forces to overcome, causing the rail to drop. This means that slower speed tests may not drop the rail.

To redirect the forces away from the posts an additional modification was made to retrofit design I. This concept involves twisting the turned-down section clockwise (CW) instead of the standard counterclockwise (CCW) direction, as shown in Fig. 12. The reverse twist provides a redirection of the rail forces away from the post, allowing it to drop even in low-speed impacts. Additionally, using the modified backup plates reduces the downward forces needed to drop the rail. Combining these concepts constitutes the proposed design II.

Simulation results of retrofit design II were similar to design I. The rail behavior was as desired. Notable exceptions include the positive aspect of achieving redirection of the rail forces away from the post. These forces are actually achieved through the reverse moment acting on the rail due to the reverse twist. Additionally, however, it should be noted that the reverse twisted rail indicates that the vehicle has an increased tendency to pitch forward. This behavior is caused by gouging into the upward-facing sides of the W-beam.

New Backup Plate Design

The configuration of the system in the finite-element model needed to be design detailed so that it would accurately represent the model. The components would also be designed so that they would support the weight of the guardrail. It was proposed that the backup plate be constructed of 2.657 mm (12-gauge) A36 steel. In the present Nebraska turned-down guardrail, there are 2.54 cm between the top of the rail and the top of the wood blockout. It was proposed that the backup plate be fastened to the blockout in this 2.54 cm gap with an 0.635 cm diameter lag screw. This steel angle bracket used as a backup plate will be called the “bracket backup plate.” The new rail-to-post connection is shown in Fig. 13.

Analysis was performed on these components to ensure that the A36 steel plate, with a yield strength of 250 MPa, could support the weight of the guardrail. Design calculations were also performed to confirm that there was sufficient strength in the connection between the lag screw and the timber blockout.

TEST CONDITIONS

The performance criteria used to evaluate the crash test were taken from NCHRP Report No. 230 (Michie 1981). The safety performance of the Nebraska turned-down approach terminal section was evaluated according to three major factors: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. These three evaluation criteria are defined
and explained in NCHRP 230. Additionally, the turned-down approach terminal section with attached W-beam should readily activate in a predictable manner by dropping toward the ground during a head-on impact. Achieving this last performance criterion was the major objective of the study.

NCHRP 230 test designation No. 45 was chosen for testing of the modified turned-down guardrail system. Test 45 has been shown to be the most demanding test for end impacts (Faller et al. 1992). Vehicle positioning for test 45 is shown in Fig. 14 and is described later in the present paper.

The initial installation of the Nebraska turned-down guardrail was constructed so that it physically represented the finite-element model previously described. The installation consisted of four major structural components: (1) turned-down approach terminal section; (2) timber posts; (3) W-beam guardrail; and (4) backup plates. Fig. 15 shows a detailed plan and elevation view of the system, with an explanation of the post numbering system. Again, Fig. 13 shows the post, blockout, and backup plate configuration. Complete design details can be found in Paulsen et al. (1995).

TESTING

Low Speed Tests: NETD-LS (1–6)

Low-speed, full-scale crash tests were performed with a 1979 Honda Civic to evaluate design modifications in a controlled atmosphere. Low-speed testing enabled several tests to be run in a short amount of time and reduced the risk of the turned-down section rolling the car over. In the low-speed tests, the effect of different design concepts could be evaluated without destroying the test vehicle. The Test matrix and corresponding results are shown in Table 1.

The six low speed tests represented various iterations on retrofit designs I and II. The beam twist (CW or CCW), vehicle offset (0 or 36 cm), and beam anchorage (above or below grade) were varied in these tests.

Results showed that retrofit design II performed best on the low-speed tests, and therefore, was used for the high-speed test. In all tests of this system, the W-beam rail dropped to the ground as the impacting vehicle’s bumper traversed the midpoint of the turned-down section.

High Speed Test: NETD-3

Test NETD-3 was conducted with a 1979 Honda Civic under the impact conditions of 96 kph and 0° (head-on) with respect to the tangent section of guardrail. The vehicle was offset 36 cm toward the roadway (Fig. 14). The system was set up so that it had the same configuration as test NETD-LS6. The turned-down section for this test was rotated in such a manner so that it contained a 90° CW twist. The end of the beam was anchored below grade. A No. 8 shear bolt fastened the W-beam rail to the bracket backup plate at posts 1 and 6.

The test vehicle impacted the rail 1.5 m downstream from the anchor. The shear bolt at post 1 failed approximately 0.088 s after the initial impact with the turned-down approach terminal section. At this point the vehicle was not quite halfway to post 1. The rail only partially dropped at this point since the shear bolt at post 6 was still intact. The vehicle continued traveling forward and impacted post 1 approximately 0.208 s after impact. At approximately the same time, the shear bolt at post 6 failed, causing the rail to completely drop to the ground. The vehicle fractured post 2 approximately 0.382 s after impact.

When the test vehicle impacted post 3, the post was pulled out of the ground instead of fracturing. After post 3 pulled out of the ground, it slid along the surface of the ground. This additional drag on the underside of the car caused the test vehicle to begin to pitch forward. The vehicle continued to pitch over its front end as it sheared off posts 4, 5, and 6. The car rotated 180° about its front axle and came to rest on its roof downstream of post 7 (Fig. 16).

High-Speed Test Evaluation

Although the modified Nebraska turned-down approach terminal section did not meet NCHRP Report 230 standards for impact performance, the turned-down section did drop as designed and did not contribute to the vehicle rollover. The rollover was attributed to the failure of post 3 to fracture as intended. The process of pulling post 3 out of the ground and dragging it along under the vehicle initiated a pitch motion that eventually caused the vehicle to pitch over 180° as it came to rest. The unacceptable rotation of post 3 can be eliminated by incorporating a ground line cable similar to that used in the original versions of the ET-2000 guardrail terminal (Sicking et al. 1988). Therefore, the modified Nebraska turned-down approach terminal section is believed to have the potential for satisfying nationally recognized impact performance criteria with additional modifications.
TABLE 1. Test Matrix

<table>
<thead>
<tr>
<th>Test number</th>
<th>Impact Conditions</th>
<th>Twist direction</th>
<th>Anchorage</th>
<th>Test results</th>
</tr>
</thead>
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<td>Speed (kph)</td>
<td>Vehicle offset (cm)</td>
<td>(4)</td>
<td>(5)</td>
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<td>NETD-LS1</td>
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<td>36</td>
<td>counterclockwise</td>
<td>below grade</td>
</tr>
<tr>
<td>NETD-LS2</td>
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<td>36</td>
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</tr>
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<td>0</td>
<td>clockwise</td>
<td>below grade</td>
</tr>
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<td>counterclockwise</td>
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<td>36</td>
<td>clockwise</td>
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</table>

FIG. 16. NETD-3 Post Test

ANALYSIS

After tests NETD-LS1 and NETD-LS2 were conducted with bracket backup plates on posts 1–9, it appeared that retrofit design I was inadequate at low speeds. When the guardrail was twisted 90° in a CW direction (reverse twist) as in retrofit design II, the performance of the system was greatly improved.

When the W-beam was twisted in a CCW manner, it contained a residual stress that produced a torque that directed the W-beam toward the posts. This force prevented the rail from falling down when impacted by an automobile. Reversing the twist in the turned-down section changed the direction of this torque so the W-beam tended to pull away from the posts. The degree by which this reverse twist improved the turned-down system was extensive, as seen in tests NETD-LS3, NETD-LS6, and NETD-3. This design change was probably more important than the changes made by substituting the bracket backup plate for the standard W-beam backup plate.

The final design, with bracket backup plates, reverse twist, and anchor below grade, is based on the premise that once the rail falls down, the energy of the moving vehicle is to be absorbed by shearing the posts. To allow the posts to shear more easily, an 8.89 cm diameter hole was bored in the posts parallel to the direction of traffic, 71.12 cm below the top of the post. In crash test NETD-3, posts 1 and 2 sheared off nicely, and the test vehicle continued in a forward path with no signs of rollover. However, post 3 failed to shear; instead, it was pulled completely out of the ground.

Some time after post 3 was pulled from the ground, the vehicle began to pitch forward. The forces involved with pulling post 3 out of the ground were, most likely, the primary contributors to the pitching motion. Gouges on post 3 indicate that it may have snagged on the bumper or the underside of the test vehicle. Once the car began to pitch forward, the vehicle impact with the remaining posts magnified the pitching motion until the vehicle’s rear end became airborne.

To fix the post shear-off problem, and potentially complete a successful design, a mechanism can be added to assist in the fracturing of the posts. A mechanism was developed by the Texas Transportation Institute in 1988 by Sickling et al. (1988) that allowed the posts to fracture more readily. This mechanism would consist of clamping a 1.1 cm diameter cable to the terminal post anchor of the terminal and running the cable through the holes in each of the posts. A 10 cm x 10 cm x 1.3 cm steel bearing plate was clamped to the downstream side of the first nine posts. This mechanism should eliminate any problems resulting from inadequately tamped soil, snagging of posts on vehicles, and overly stiff posts.

SUMMARY AND CONCLUSIONS

The safety of the turned-down guardrail has been a focus of many researchers for a long time. Analysis and testing of the design concepts developed in this present research indicate that a retrofit for improving the safety performance of the turned-down guardrail is obtainable. By using nonlinear FEA, the underlying physics of the problem were determined. This knowledge was then used to formulate and test various retrofit design concepts.

Additionally, this research has shown some of the difficulties in modeling complex contact situations. The mass, speed, and geometry of an impact influences the type of contact algorithm to be used and the parameters associated with each type. Currently, there are no "rules" for solving difficult contact problems. However, the present paper has outlined one specific trial-and-error exercise that proved to be successful for this project. Knowledge gained from this process should prove to be valuable for the next difficult contact situation that arises.

DISCLAIMER STATEMENT

The contents of the present report reflect the views of the writers who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska Department of Roads nor the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENTS

The writers wish to acknowledge several sources that made the present project possible: (1) the Midwest States Regional Pooled Fund Program funded by the Iowa Department of Transportation, Kansas Department of Transportation, Missouri Highway and Transportation Department, Nebraska Department of Roads, and Minnesota Department of Transportation for sponsoring the project; (2) Maher Tadros—director of the Center for Infrastructure Research Center and Samy Elias—associate dean for
engineering research centers of the University of Nebraska-Lincoln for matching support; (3) Tsung-Liang Lin and Khahn Bui from Livermore Software Technology Corporation who helped a great deal with the contact problems; (4) Dennis Lam of Cray Research for aid with the Cray C90 supercomputer; (5) The University of Nebraska-Lincoln Research Council for sponsoring a trip to Cray Research; and (6) Tony Lee from Lawrence Livermore National Laboratories for supplying the initial small vehicle model.

APPENDIX. REFERENCES


