# A FINITE ELEMENT MODEL OF THE MODIFIED ECCENTRIC LOADER BREAKAWAY CABLE TERMINAL (MELT)

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**Improving the performance of guardrail terminals and end treatments in impacts with passenger vehicles has been an active area of research over the past decade. One particular W-beam guardrail terminal that has been the focus of recent full-scale crash testing is the Modified Eccentric Loader Breakaway Cable Terminal (MELT). This paper describes the development of a nonlinear finite element model of a recent modification of the MELT which is being used to learn more about the performance of this type of guardrail terminal. A finite element model of the MELT was developed using the TrueGrid preprocessor and the LS-DYNA3D finite element software was used to perform the analysis. Results of the analysis are discussed and compared to data from a full-scale crash test involving a small passenger car.**

## INTRODUCTION

The breakaway cable terminal (BCT) was developed in the 1970's as an alternative to blunt guardrail ends and turned-down end treatments. The first full-scale crash tests of BCTs were performed as part of a National Cooperative Highway Research Program (NCHRP) project to investigate new and innovative W-beam terminal concepts.*(1)* The following decade resulted in a number of improvements in the impact performance, constructability and maintainability of the BCT design that made it a very popular system in the subsequent years. *(2) (3) (4) (5) (6) (7)* All of this early testing used the 2040-kg and 930-kg passenger cars recommended in the then-current crash testing specifications, NCHRP Report 230.*(8)(9)*

The relatively low cost of the BCT and the good crash test results reported in the NCHRP projects resulted in its wide-spread use in the United States. In the late 1970s more than 100,000 installations were in place and tens of thousands have been installed each year since.*(12)* In some

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states the BCT has been the primary W-beam guardrail terminal for more than 20 years. As the BCT became widely accepted, however, researchers began to observe performance problems in the field when BCT installations were struck by the new generation of smaller passenger vehicles.*(10) (11)* The eccentric loader BCT (ELT) and more recently the modified eccentric loader BCT (MELT) were developed to improve the performance of W-beam guardrail terminals in impacts with small cars.*(12) (13) (14) (15)*

Recently, tests have been performed on the MELT using the 2000-kg full-size pickup truck recommended in NCHRP Report 350.*(16)(17)* Stability and performance problems were observed in several of these tests motivating researchers to re-examine the performance characteristics of the MELT in light of the full matrix of test level three tests. While full-scale vehicle crash tests are the traditional method for such a re-examination, nonlinear finite element analysis can also be used to gain insight into the performance of the MELT. This paper describes the finite element model of the MELT and compares its performance to an existing test. If the model is useful in replicating full-scale test results, then finite element analysis could be another tool for evaluating possible design changes.

## FINITE ELEMENT MODEL

The "standard" MELT design is described in a 1991 Federal Highway Administration (FHWA) Memorandum and some of the testing is described in a 1991 FHWA research report.*(11) (14)* Specific dimensions and details for the MELT and its components used in this paper were taken from the 1995 revision of A Guide to Standardized Highway Barrier Hardware (Hardware Guide) for the W-beam guardrail terminal designated SEW05.*(18)*

Recently this design has been further modified during testing of the MELT according to the Report 350 test level three conditions. The MELT examined in the test and simulation described in this paper is somewhat different than the "standard" MELT described in the Hardware Guide. The differences include:

- Offset to the first post is 1500 mm rather than 1220 mm,
- First BCT post is weakened with a vertical slot.
- Shelf clip added at post six in addition to post two,
- Backup plates located at posts 4, 5, 7, 8, and 10,
- A 7620-mm circular flare is used instead of the "standard" parabolic flare, and
- Post seven and eight are CRT posts in addition to posts three through six.

The MELT, partially shown in Figure 1, is made up of the following parts (designators in parenthesis refer to drawings in the Hardware Guide):*(18)*

- A nose assembly including a buffered end section (RWE04a), two horizontal diaphragm plates (REE01) and a terminal connector (RWE02b),
- Two sections of 7620-mm radius circular flared W-beam guardrail sections (RWM14),
- Two breakaway BCT timber posts (PDF01), the first of which is modified with a vertical saw cut from just above the breakaway hole to just below the rail attachment bolt hole. The first two breakaway posts are mounted in steel foundation tubes (PTE05) with soil plates (PLS03),
- A strut-and-yoke assembly (PFP01) between posts one and two as well as three shelf clips (FPP02) mounted on posts two and six,
- Six breakaway CRT wood posts (PDE09) with blockouts (PDB01), embedded directly in the soil, and
- One cable anchor assembly including a post bearing plate (FPB01), cable (FCA01), and cable anchor bracket (FPA01) as well as an assortment of bolts and fasteners.

The first four meters of the system, shown in Figure 1, are the most critical in terms of predicting the behavior in an end-on impact. The buffered end section in combination with the terminal end connector and the two diaphragm plates form the nose of the MELT. Material properties for the terminal connector and buffer section were based on vendor compliance reports, AASHTO material specification M180-89 and a paper describing guardrail material properties by Wright and Ray.*(19)(20)* The piecewise linear isotropic plasticity material model (LS-DYNA3D material type 24) was used for the buffer section and terminal connector. Table 1 shows the material properties used for the buffered end section, the terminal connector and the guardrail in the simulation. The material properties used in the simulation represent typical properties rather than the minimum properties specified in AASHTO M-180 since the intent of the model is to replicate the actual behavior of the guardrail terminal. Typical properties were found by performing a series of tensile coupon tests of guardrail material and correlating the test results with the material properties used in a finite element simulation.*(19)(20)*

The W-beam guardrail was modeled as a 14-element high cross-section. The geometry was discretized such that the total depth, total width, moments of inertia, and radii of gyration were essentially the same as the actual W-beam guardrail as shown in Table 2. The cross-sectional properties of the discretized section (e.g., moments of inertia, area, radius of gyration) are all within 10 percent of the actual values for W-beam guardrail.

The first two posts in the modified MELT are 150x190-mm timber posts with a 64-mm diameter breakaway hole. The first post also contains a vertical saw cut to further weaken the post. Several assumptions were made in modeling the posts. First, the base of each post was assumed to be fixed 100 mm below the ground line. Assuming that the posts are fixed at the ground line would result in a post that is too stiff since the actual post can deflect a small amount (e.g., 20-30 mm) in the soil prior to fracturing. Accounting for the detailed deformations at the ground line would require that the soil, foundation tubes, and soil plates also be modeled. While these components could be modeled they would have increased the size and complexity of the model by an order of magnitude.

The method chosen to model the breakaway performance of the post necessitated the second assumption. Timber is a nonlinear orthotropic material with very complex material properties including a variety of possible failure modes. Nonlinear orthotropic material models are available in LS-DYNA3D but the material properties needed to characterize timber are not available, at least not without an extensive material testing program. Fortunately, there are many pendulum tests of both standard 190x150-mm posts and MELT breakaway posts available in the roadside hardware testing literature.*(21)* When timber posts are supported in rigid test brackets, or the MELT foundation tube, the post nearly always fails in bending.

The timber posts were modeled using solid elements and a combination of three material models. The portion of the post in the region of the hole was modeled with an elastic-plastic material model with failure (material type 13) using the 14-point integration element formulation option. The type 13 material model enabled the failure mode, in which the longitudinal fibers of the timber progressive fail in tension on the impact face of the post, to be modeled correctly. The failure criterion could be designated for tension only, thus eliminating any failure due to compression. The expensiveness of the 14-point integration formulation necessitated the separation of the materials in the post. The top portion of the post was modeled with an elastic material model (material type 1) to keep the simulation time to a minimum, and the portion extending below the groundline was modeled with a kinematic/isotropic elastic-plastic material model (material type 3). Table 3 gives the properties used for the material models of the post.

The values shown in Table 3 were obtained by comparing the acceleration history of a pendulum test of a wood BCT post and finite element simulations of the same scenario with a variety of LS-

DYNA3D material properties.*(22)* The simulated acceleration curve that was most similar to the pendulum test acceleration curve is shown in Figure 2. The event is about 20 msec long, and the initial peak acceleration is about seven g’s in both the simulation and test acceleration histories. The total energy dissipated by the fracturing post in the simulated event was 92 percent of the energy dissipated in the actual pendulum test. An analysis of the variance shows that the peak residual difference between the two curves is 0.25 g's (3.5 percent of the peak test acceleration) and the standard deviation of the residuals is 0.70 g’s (9.8 percent of the peak test acceleration). A t-statistic of 3.17 for the acceleration data lies just outside the 90-percent confidence t-statistic of 2.81. While the responses of the simulated and physical posts are a little different, the energy dissipated is nearly identical, the event duration is similar, and the initial peak loading is the same. The material properties shown in Table 3 result in a response that is very similar to the pendulum tests.

The next four posts in the MELT (posts three through eight) are CRT breakaway timber posts. These posts are not supported in foundation tubes like the BCT posts but are directly embedded in the soil. The same material properties used for the breakaway timber posts were also used for the CRT posts (see Table 3). The last two posts (posts nine and ten) are unmodified 190x150-mm timber guardrail posts with the properties shown in Table 3 except that there are no holes. In all cases the CRT and line posts were modeled with fixed boundary conditions 160-mm below the surface to account for the ability of the post to deflect at the ground line.

The cable anchor assembly is an important feature of the MELT design that provides anchorage in down-stream impacts. Without the cable anchor, the tensile forces in the guardrail during a down-stream impact would cause a large cantilever bending moment on the weakened first breakaway post that could cause it to fail. The cable anchor transfers this tensile load directly to the steel foundation tubes through a cable that is secured to the guardrail with the cable-anchor bracket. The cable fits through the breakaway hole in the post and attaches to a bearing plate on the front of the MELT post. During an end-on impact, the cable is released as soon as the first post breaks. The cable was modeled as a series of linear elastic truss elements. A modulus of elasticity of 90 GPa was used based on the published properties of 19-mm 6x19 strand internal-wire-rope-core (IWRC) cable at less than 20 percent of its loading.*(23)* LS-DYNA3D truss elements can transmit both tensile and compressive axial loads whereas real cables can only resist tensile loads. The cable was modeled as a series of 16 truss elements so that the cable would resist tensile forces properly while buckling if loaded in compression. A metal tube is also modeled in the hole of the first post to keep the cable from tearing through the post.

The cable anchor bracket in the MELT reinforces the circular section of the guardrail prior to the first breakaway post failing. This has the effect of increasing the buckling strength of the guardrail when hit end-on. The guardrail cable-anchor bracket also reinforces the guardrail locally inhibiting buckling near the second MELT post. The anchor details, while designed for downstream impact scenarios have important effects on the MELT performance in end-on impacts so they must be included in the model.

Shelf clips are located on the second and sixth posts in the modified MELT. This small L-shaped bracket keeps the rail from buckling downward in an end-on impact without restraining the lateral buckling of the guardrail. The shelf clip was modeled using shell elements with the material properties of A36 steel.

Lastly, a strut and yoke assembly is placed between the bases of the first two breakaway posts. This strut is designed to help distribute the axial guardrail loading between the first two posts. The strut is also made using A36 steel. The strut is primarily important in down-stream impacts that generate large rail tensile loads.

The method used for connecting the components is an important feature of the model. In the case of the MELT model, the method used to connect parts is particularly important because the overlapped portions of the guardrail and terminal nose (e.g., the splices) are stiffer than the rest of the guardrail because there are two thicknesses of material. Overlapping parts in the physical device are connected by bolts. The analogous method in the model was to use nodal constraints at the bolt locations. This method of connecting the parts results in deformations near the connections to appear quite realistic without resorting to the complexity and computational expense of actually modeling the geometry of all the bolts in the system.

The choice of contact surfaces is also an important modeling decision. One automatic contact surface with periodic surface redefinition (Type 15) was used in this analysis for all contact between the vehicle and the guardrail terminal. This type of contact automatically determines which elements are in contact and also periodically redefines the contact surface to account for the eroding elements on failing materials like the wood posts. The nodes-impacting-surface contact without segment orientation (Type 5a) was used for the contact between the anchor cable, anchor bracket, and the guardrail post and tube.

The vehicle model used in the small car simulation was a TrueGrid model of an NCHRP Report 350 820C vehicle.*(24)* The original model described by Cofie was extensively modified to provide a model with geometry and structure more similar to actual 820C vehicles used in full-scale testing.

## ANALYSIS RESULTS

Procedures for performing and evaluating full-scale crash tests are given in NCHRP Report 350.*(17)* Report 350 suggests a series of seven tests for gating terminals like the MELT. Report 350 also has three test levels for terminals where test level three is presumed to be appropriate for most terminals that will be used on the National Highway System. One of the most important terminals tests involves an 820-kg passenger car striking the nose of the terminal at 100 km/hr and 0 degrees (Test 3-30). The crash test literature was searched for a small-car test of the wood-post-in-foundation-tube MELT that corresponded to NCHRP Report 350 Test 3-30 conditions. Test 405541-2 was performed at Texas Transportation Institute (TTI) in 1996 as a part of the investigation of the performance of the MELT in the Report 350 test level three tests.*(25)* The results of the finite element analysis and a comparison to a full-scale test are shown below.

Figure 3 through Figure 5 show plots of the finite element simulation of the small car collision (Test 3-30). Figure 3 is a comparison of the overhead sequentials from the simulation and the actual test. The vehicle contacts the nose at time 0.00 and quickly collapses the nose section until the vehicle bumper contacts the first breakaway timber post at about 27 msec. Vehicle damage begins to accumulate in the process of breaking the first post. After the first post fractures, the W-beam guardrail begins to buckle just behind the point where the terminal connector bolts to the W-beam guardrail. The vehicle continues intruding into the MELT, rolling the collapsed nose and crumpled W-beam rail in front of the vehicle. The vehicle continues forward until it strikes the second breakaway post at about 100 msec as shown in Figure 3. The second post breaks away and a second large buckle appears between posts two and three. The vehicle continues, yawing in a clock-wise direction, until the front left corner of the vehicle strikes and breaks the first CRT post (post three) at about 205 msec. Upon breaking the first CRT post (post three), the vehicle is directed just behind the line of remaining unbroken CRT posts. As a result, the vehicle does not directly impact any of the remaining posts, but rather pushes the guardrail into the posts. After the second CRT post has broken, a third buckle forms just downstream of the splice in the guardrail located at the first CRT post. The formation of this buckle coupled with the breaking of the third CRT post causes the vehicle to reverse its direction of yaw and begins to yaw counter-clockwise. The vehicle continues until the fourth CRT post has broken, at which time the simulation was terminated.

A comparison of the left (e.g., simulation) and right (e.g., test) sides of Figure 3 shows that the simulation reasonably captures the basic sequence of events. The gating action of the terminal is apparent in the simulation and both the guardrail and vehicle responses are similar. There are, however, some notable differences. The vehicle in the test rotates (yaw and roll) more than the finite element simulation. The friction between the ground and the vehicle will significantly affect the rotations. Ground friction was modeled in the simulation using a simple friction coefficient that could be refined to obtained more realistic rotations. Although the buckles occur in the correct places at the correct times, the buckles are "sharper" in the test than in the simulation. This is probably a mesh density effect since coarser meshes will tend to have a stiffer response than finer meshes. Overall, however, the finite element simulation seems to reasonably replicate the response of the actual full-scale test.

Figure 4 shows a top view of the collapse of the nose of the MELT from the finite element simulation (the vehicle is not shown for clarity). The buffer section collapses during the first 20 msec of the event. The vehicle becomes fully engaged with the first breakaway post between 20 and 30 msec. At this point the terminal connector begins to rotate, introducing a moment into the guardrail beam and forming a buckle where the terminal connector is bolted to the rail. The portion of the W-beam guardrail overlapped into the buffer section and connected to the post remains very stiff throughout the event as it should since there are two layers of material at that point. At about 30 msec the post breaks and the anchor cable begins to go slack. The vehicle rides over the broken post stub and continues buckling the W-beam rail until the second breakaway post is reached. The behavior shown in Figure 4 is consistent with the behavior observed in actual full-scale crash tests of the MELT.

Figure 5 shows deformation plots of the event near the first breakaway post (the vehicle is again not shown for clarity). The buffer plate is fully collapsed against the post at 20 msec. The first fracture in the post appears at 25 msec and expands over the next 10 msec until the post is completely fractured at 35 msec. The vehicle then pushes the broken post and collapsed nose elements in front of it as it continues on to the second breakaway post. The cable goes slack when the post breaks and the bearing plate falls once the post has broken away.

Table 4 shows a variety of statistics indicating the computational performance of the simulation. The amount of computer resources require to perform a 500-msec long analysis are quite large even for this relatively coarse model. Impacts with terminals will typically require such long run times since, as illustrated by this simulation and test, there is still vehicle-to-barrier contact nearly 500 msec after impact.

As shown by the Figure 3 through 5, the basic phenomena that typically occur in small car full-scale crash tests of the MELT were also observed in the finite element analysis:

- The crushing of the nose,
- The fracture of the posts
- The formation of three buckles in the guardrail,
- The pitching and yawing of the vehicle and,
- The basic gating mechanism of the barrier

## COMPARISONS TO CRASH TESTS

While the finite element simulation was qualitatively similar to full-scale tests, the simulation also must be compared quantitatively to physical full-scale tests. Figure 6 shows a comparison of the acceleration and velocity histories in the impact direction at the vehicle center of gravity for both the physical test and the finite element simulation.

The finite element analysis is stiffer than the physical test (the acceleration peaks are higher and narrower than the physical peaks), especially in the early parts of the impact. For example, in both the simulation and the physical test, the first 20 msec of the event is dominated by the crushing of the nose of the MELT. In the physical test this is apparent in three or four 10 to 15 g acceleration peaks spaced over the 20-msec interval. The simulation, however, is characterized by a couple of relatively large, narrow 30 g peaks in the same interval. The reason for this may be that the diaphragm plates (the horizontal plates inside the nose) are attached continuously to the vertical elements of the buffer section in the simulation, but in the physical device the plates are attached by six bolts. The connection between the diaphragm plates and the buffer section is more flexible in the physical device than in the modeled device resulting in a possibly stiffer response.

Important events during the collision are indicated on Figure 6. The major events (e.g., posts breaking and buckles forming) occur at approximately the same time in both the physical test and the simulation, but the magnitude of the acceleration is usually a little larger in the simulation. While they are far from identical, the two curves do display similar dominant characteristics.

Some of the more important evaluation factors given in NCHRP Report 350, are the occupant risk criteria. The occupant impact velocity in the simulation was 7.96 m/sec, which compares closely to the value indicated by the full-scale crash test of 8.51 m/sec.

A statistical analysis of the variations between the two curves was also performed to determine how well the two curves correspond to each other.*(26)* The average difference between the matched accelerometer readings of the two curves was 0.19 g's, about 0.6 percent of the 32-g peak test acceleration. The standard deviation was 7.3 g's or 23 percent of the peak test acceleration. The t-statistic for this data was 0.51, which is much less than the critical 90-percent confidence t-statistic of 2.81. The t-statistic indicates that the two curves describe statistically indistinguishable events. These results suggest that the MELT model reasonably replicates the results of the full-scale test.

## CONCLUSIONS

The finite element analysis of the MELT under Test 3-30 conditions demonstrates that the finite element model replicates the basic phenomological behavior of the MELT in an end-on impact with a small car. One of the primary reasons for performing this work was to develop a model of the MELT that could be used to investigate the performance of the MELT when struck by a 2000P pickup. The performance of the MELT in Test 3-31 (2000P at 100 km/hr and 0 degrees) is already known to be unsatisfactory based on recent full-scale crash tests. The finite element model will be a useful tool for exploring the affects of design changes on the performance of the MELT prior to performing crash tests. Once the model has demonstrated that it can reasonably reproduce full-scale crash test results, it can be used to evaluate new design alternatives prior to testing to gain insight into the expected performance improvements.

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**Table 1**. GUARDRAIL MATERIAL PROPERTIES USED IN THE ANALYSIS.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Typical Mechanical Properties: | | | | | | | | |
| Yield Stress | | | | | | | 415 | MPa |
| Ultimate Stress | | | | | | | 538 | MPa |
| Elongation | | | | | | | 25.5 | % |
| AASHTO Specification | | | | | | | M-180 | *(19)* |
| Source: | | | | | | | | *(20)* |
| LS-DYNA3D Properties: | | | | | | | | |
| Material Type | | | | | | | 24 | |
| Element Type | | | | | | | BT | shell |
| Mod. of Elasticity | | | | | | | 200 | GPa |
| Yield Stress | | | | | | | 415 | MPa |
| Effective Plastic Strain at Failure | | | | | | | 0.66 | |
| Poisson's Ration | | | | | | | 0.33 | |
| Integration Points | | | | | | | 8 | |
| Hardening Type | | | | | | | Kinematic/Isotropic | |
| Density | | | | | | | 7860 | kg/m$^3$ |
| Effective Plastic Strain Increments | 0.0 | 0.02 | 0.08 | 0.16 | 0.33 | 0.50 | 0.66 | |
| Effective Stress Increments | 415 | 415 | 548 | 585 | 591 | 595 | 600 | |

**Table 2**. DISCRETIZED AND ACTUAL SECTION PROPERTIES OF W-BEAM GUARDRAIL.

| | | Actual Shape | Discretized Shape | Percent Difference |
|---|---|---|---|---|
| Depth | (mm) | 81 | 81 | 0 |
| Width | (mm) | 214 | 214 | 0 |
| Area | (mm$^2$) | 1290 | 1200 | -7 |
| $I_{weak}$ | ($10^6$ mm$^4$) | 1.00 | 1.03 | +3 |
| $r_{weak}$ | (mm) | 27.9 | 29.3 | +5 |

**Table 3**. WOOD POST MATERIAL PROPERTIES USED IN THE ANALYSIS.

| | | |
|---|---|---|
| LS-DYNA3D Properties: | | |
| Element Type | BT | solid |
| Density | 610 | kg/m$^3$ |
| Poisson's Ration | 0.30 | |
| Upper portion: | | |
| Material Type | 1 | |
| Mod. of Elasticity | 11 | GPa |
| Region of the hole: | | |
| Material Type | 13 | |
| Shear Modulus | 4231 | MPa |
| Bulk Modulus | 9167 | MPa |
| Yield Stress | 27 | MPa |
| Failure pressure | -120 | MPa |
| Below groundline: | | |
| Material Type | 3 | |
| Mod. of Elasticity | 200 | GPa |
| Yield Stress | 40 | MPa |

**Table 4** FINITE ELEMENT ANALYSIS COMPUTATIONAL CHARACTERISTICS FOR A SIMULATION OF MELT TEST 3-30.

| | |
|---|---|
| No. of Elements *(Vehicle and Barrier)* | |
| Shell | 7,034 |
| Solids | 11,838 |
| Beams | 126 |
| Performance | |
| Hardware | HP J210 |
| Simulated time | 500 msec |
| CPU cycles | 640,093 cycles |
| CPU time | 227.4 CPU hrs |
| Speed | |
| Simulation | 2.2 msec/CPU hr |
| Machine | 0.78 cycles/CPU sec |