Development and Validation of a Finite Element Model of an Energy-absorbing Guardrail End Terminal

Yunzhu Meng[1], Costin Untaroiu[1]
[1] *Department of Biomedical Engineering and Virginia Tech, Blacksburg, VA, USA*

Abstract

Guardrail end terminals are installed along roads to minimize the severity of vehicle crashes by avoiding their contact with fixed objects along the road. Energy-absorbing guardrail end terminals are designed to help preventing the rail from spearing through the car in an end-on collision as well as to dissipate significant amounts of the striking vehicle energy after the collision while keeping the rate of deceleration tolerable for the occupants. The main objective of this study was to develop and validate a Finite Element (FE) model for a common guardrail end terminal (ET-Plus). Although several standard impact tests have been performed on ET-Plus, few efforts were dedicated to develop a high-fidelity FE model that can facilitate investigation of its performance under various conditions. In this study, a computational efficient FE model of ET-Plus end terminal was developed in LS-DYNA®. The dimensions were collected from published design drawings and the dimensions of a mounted end terminal were recorded and used as supplementary in this model. Material types were identified based on a previously published patent and material parameters were estimated from literature. FE simulations of Car-to-ET-Plus collisions were performed in LS-DYNA based on the NCHRP-350 test conditions to validate the end-terminal model. The end terminal model developed in this study predicted the full energy absorbing mechanism during the collision using simple impactor. In addition, the ET-Plus model showed numerical stability during small car impact simulations. Compared with a car impact test data (1/4 offset, 27 in guardrail height, test 27-30), the simulated yaw angles showed a good agreement with the average error less than 3°. In a second offset test (1/4 offset, 31 in guardrail height, test 31-30), the car model showed higher values of yawn angle than the tested car. Overall, a computationally efficient FE model of ET-Plus end-terminal was developed in this research. This model can be used by safety researchers to improve the design of new vehicles front ends and new guardrail end terminals for better protection of vehicle occupants.

Introduction

Traffic barriers are common fixed objects involved in vehicle collisions. In 2015, 909 fatal and 28,000 injurious collisions with guardrails were recorded in the United States[1]. End terminals were firstly developed to reduce the risk of injury or death while a vehicle drives off road, but it became a hazardous part by increasing the possibility of barrier penetrating the vehicle[2, 3]. 20-24% of fatalities in guardrail collisions involved end terminals from 2009 to 2013 in U.S based on Fatality Analysis Reporting System (FARS) database[3].

ET-Plus end terminal is a common guardrail end terminal used along U.S. roads. This is a typical energy absorbing guardrail end terminal which dissipates energy during collision, reduces the vehicle travelling distance after impact, and reduces the possibility of penetration during head-on impacts. ET-Plus was designed pursuant to NCHRP 350 test criteria, which is a recommended test procedure for all US highway safety hardware. However, these test conditions are significantly simplified compared to the actual traffic situation. Among all the eight tests performed on ET-Plus, only car type, impact angles, impact offset and the installed height are slightly varied. Numerical modeling became an alternative of testing to understand the crash details. Although Finite Element (FE) models were commonly in crashworthiness area, few guardrail end terminal models were developed [4].

In this paper, the development and validation of the ET-Plus FE model is presented. The geometry was collected from published data or measured on mounted end-terminals. The end-terminal model was impacted under simple condition to investigate its working mechanism, and then it was validated under NCHRP-350 test conditions.

Methods

Development of a Finite Element Model of ET-Plus Guardrail End Terminal

Geometry

The ET-Plus includes the impact head, block-outs, posts, ground strut, and anchor cable (Figure 1). The geometry of each component (except the anchor cable) were developed in Rhino (Robert McNeel & Associates, Seattle, WA, USA). The energy absorbing guardrail end terminals normally have a large square impact plate, its size representing the most distinguish feature to identify the end terminal type. Most of ET-Plus impact head dimensions were collected from published design drawings[5, 6]. Meanwhile, one representative ET-Plus mounted in Blacksburg (Virginia) was also measured to verify the data (Table 1). In addition, the models of five guardrail barriers, nine wood block-outs, 11 wood posts and 11 soil bases were developed and implemented into the whole guardrail system. The model of guardrail barrier was developed based on a standard highway W-beam guardrail, designated AASHTO M180 Type 2 (12-gauge). The dimensions of block-outs and posts are based on literature data, and corresponds to 152 × 203 × 356 mm and 152 × 203 × 1829 mm cuboids, respectively. A soil base model was developed as a set of cylinders with a 1600 mm diameter and a 2018 mm height. The distance between two consecutive posts mounted into soil bases was 1.9 m. After the posts were mounted, ET-Plus and block-out models were constrained to the posts. The barrier model was constrained to the adjacent barrier and wood posts/blocks. A surface-to-surface contact was setup between ET-Plus and guardrail to simulate the absorbing energy process.

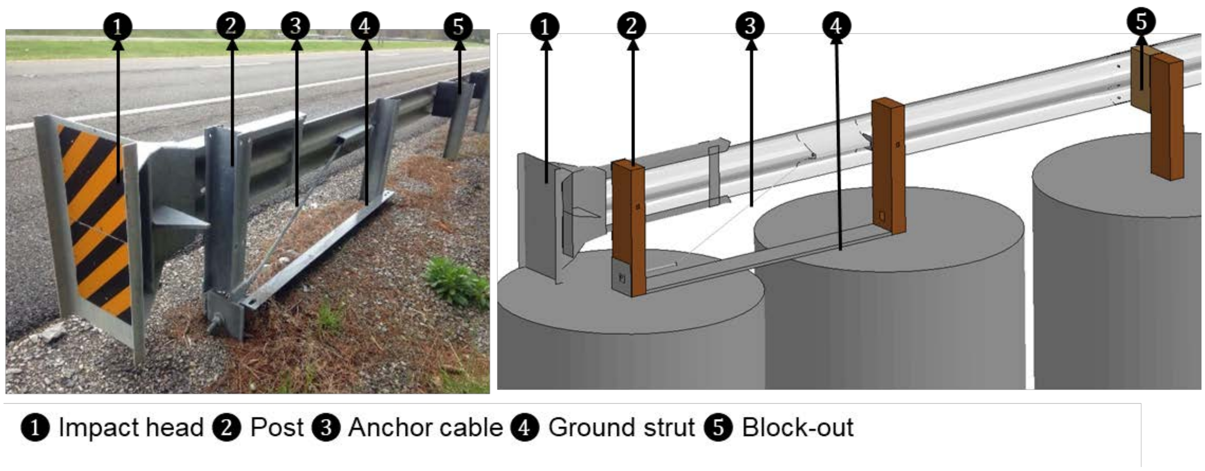

Figure 1. ET-Plus components: a) product; b) FE model

Table 1. ET-Plus dimensions

	Mass (kg)	Length (m)	Impact head size (mm×mm)
ET-Plus	79	1.44	711 ×381
FE model	78	1.43	711 ×381

Mesh generation

The mesh of this model was generated in Hypermesh (Altair HyperWorks, Troy, MI). ET-Plus and barriers models were modelled using shell elements, while other parts were modeled using the solid elements. The thickness of shell elements corresponding to the impact head plates were assigned different values based on the product drawings. Rigid constraint (CONSTRAINED_NODE_SET) was used between the plate edge and its adjacent plate to simulate the weld. Solid elements were used for block-outs, posts and ground strut models. Although either metal or wood posts could be used with ET-Plus, only wood posts were simulated to coincide with test condition.

The impact head mesh consists of quad elements with relatively fine element size to describe all the geometry features and to provide good contact load distribution throughout the impact event. While most of the initial shell elements obtained by auto meshing passed the criteria, the elements below quality thresholds were edited manually. Other components were modeled separately using solid map method. Firstly, a surface was chosen from each component and meshed with quad shell elements. Then, the shell elements were extended along vector through the solid volume and hex solid elements were generated. The soil part was meshed using large size solid elements to save computational time, but finer meshes were used in other solid parts.

Material properties

All the material models of the end-terminal system were selected from the existing LS-DYNA material library. An elastic-plastic model corresponding to steel was assigned to ET-Plus and guardrail barrier models (Table 2). MAT_WOOD (Type 143) was specifically designed to predict the roadside safety wood components performance under an impact by car[7]. The material properties used in the block-outs and posts model are based on the recorded static and dynamic wood bending test data. The bending tests were performed both parallel and perpendicular, anisotropic behavior was observed during testing. The anchor cables were modeled using beam element with elastic properties (Table 2). Furthermore, a "MAT_DRUCKER_PRAGER" (Type 193) material model was assigned to the soil model based on literature data.

Table 2. Material properties of each component

Component	Density (kg/m^3)	Elastic modulus (MPa)	Yield stress (MPa)	Poisson's ratio
ET-Plus and barrier	7.89×10^3	2×10^5	307	0.29
Wood post	6.731×10^2	Parallel: 1.135×10^4 Perpendicular: 247	Parallel: 40 (tension) 13 (compression) Perpendicular: 0.96 (tension) 2.57 (compression)	0.16
Anchor cable	7.89×10^3	2×10^5	NA	0.3

Simple Frontal Impact simulation with a cylinder impactor

A frontal collision was initially setup between a cylindrical impactor and the end-terminal model to better understand the energy absorbing mechanism. The impactor has a diameter as 800 mm and a 2 ton mass corresponding to a medium size sedan (~2 ton). The frontal impact between the rigid impactor at 100 km/h initial velocity and the impact head was only simulated to check qualitatively the energy absorbing mechanism.

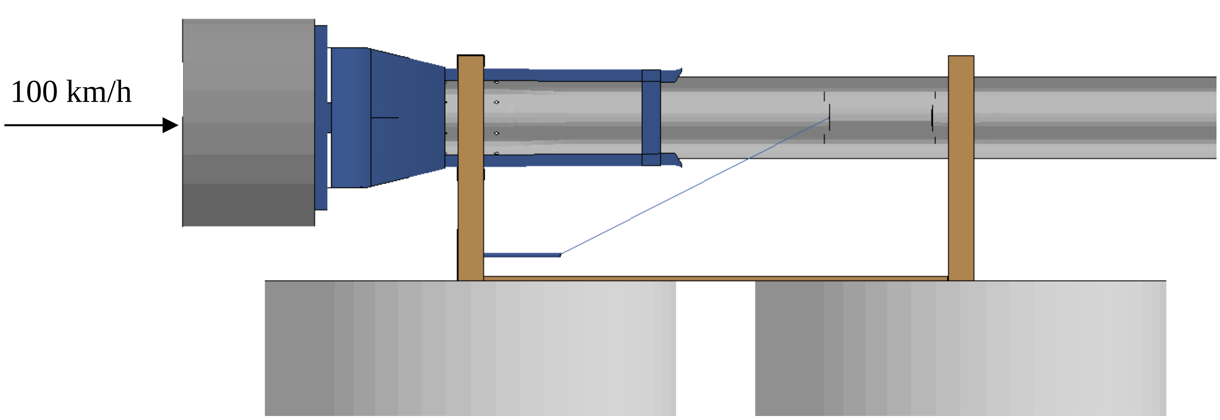

Figure 2. ET-Plus - cylinder impactor collision setup

National Cooperative Highway Research Program (NCHRP) recommended test procedures (NCHRP-350) for all the highway safety products, includes guardrail end terminals[5, 6]. A total of eight tests were performed on ET-Plus and two of them (test 27-30 and 31-30) were used to validate the FE model. In both tests, a head-on collision was performed with a 100 km/h initial velocity. The offset between the car and guardrail was assigned as ¼ of the car width. The only difference between the two tests were the installed height. The top edge of the guardrail barrier was installed at 27 ¾ inches and 31 inches in test 27-30 and 31-30, respectively (Figure 3).

A publically available FE model of 1997 Geo-Metro (GM) was used in the impact simulation. It was observed that this model is 79 kg lighter than the car used in test. Impact velocities and angles were adjusted slightly to coincide the test data (Table 3). It should be mentioned that the vehicle FE model is simplified and do not include interior parts, so the mass (75 kg) corresponding to the dummy used in testing was added on vehicle floor directly using "ELEMENT_MASS_NODE_SET".

Table 3. Simulation setup parameters

	Guardrail height (in)	Impact velocity (km/hr)	Impact angle (degree)	Impact offset	Dummy Position
Test 27-30	27	102.5	0.1	1/4	Driver
Test 31-30	31	102.8	0.2	1/4	Driver

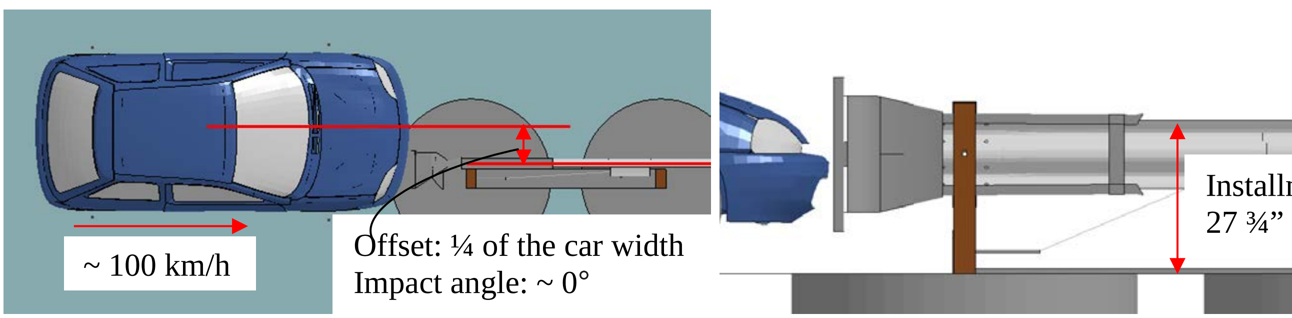

Figure 3. Car – ET-Plus simulation setup

Results

Model Development

The final ET-Plus model has 16,369 nodes and 15,705 shell elements. The model for the whole system consists of approximately 217,800 nodes and 187,100 elements. The mesh has a high quality with over 99.99% of the elements pass the criteria (Table 4).

Table 4. Element quality

Element type	Mesh quality criterion	Min (m) / Max (M)	Allowable limit	Element under allowable limit (%)
Shell (49677)	Jacobian	0.434 (m)	0.3	0 (0%)
	Warpage	25 (M)	10	4 (0.00805%)
	Aspect Ratio	9.26 (M)	10	0 (0%)
Solid (137422)	Jacobian	0.53 (m)	0.3	0 (0%)
	Warpage	0.35 (M)	10	4 (0.00805%)
	Aspect Ratio	2.59 (M)	10	0 (0%)

During the head-on impact, the ET-Plus end-terminal head moved backward along the guardrail barrier. Meanwhile, the impact head flatted and then curled the guardrail barrier to absorb the vehicle energy (Figure 4a). The cross sectional view showed a detail explanation about the energy absorbing mechanism (Figure 4b).

a) b)

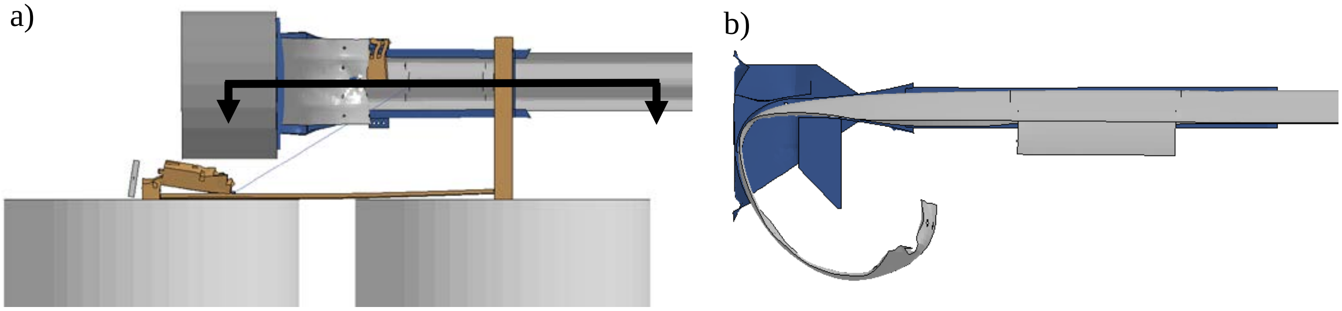

Figure 4. Post-impact ET-Plus: a) side view; b) cross sectional view

Car – ET-Plus Collision Validation Based on Test 31-30

In the simulation of car-to-end-terminal impact, the ET-Plus model showed numerical stability under the test conditions published in NCHRP 350 test 31-30[6]. At the beginning of the crash (0-0.05s), a deformation of the car front zone with a slight rotation of the whole car (yaw angle <5º) were observed. The first wood post failed at around 0.05s. Then, the barrier was firstly flatted and then extruded out of the impact head to the side far away from the traffic. The vehicle velocity decreased with time, and the front bumper separated from the ET-Plus between 0.25 and 0.3s (Figure 5).

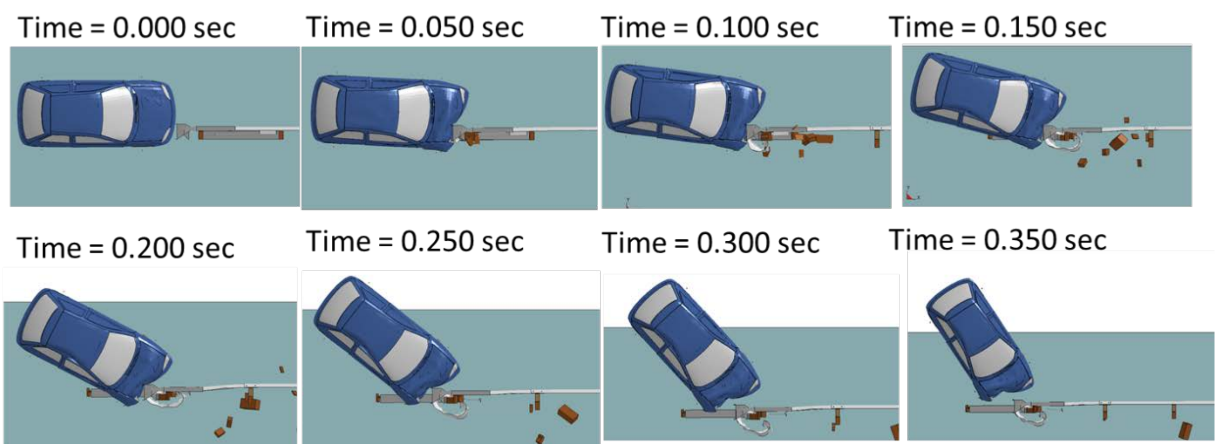

Figure 5. Car- ET-Plus collisions under NCHRP 31-30 test condition

Top view figures were taken every 0.05 sec during tests, the yaw angles were measured from each figure and used to validate the model (Figure 6). Since the yaw angles were not recorded continuously during test, a line connecting each point was used as the approximate test data (dash line in Figure 6). Although the simulated yaw angles were larger than test data between 0.05s and 0.35s, the simulation results showed good agreement with the test data. The average error was 2.6° and the largest difference was recorded as 12.74°.

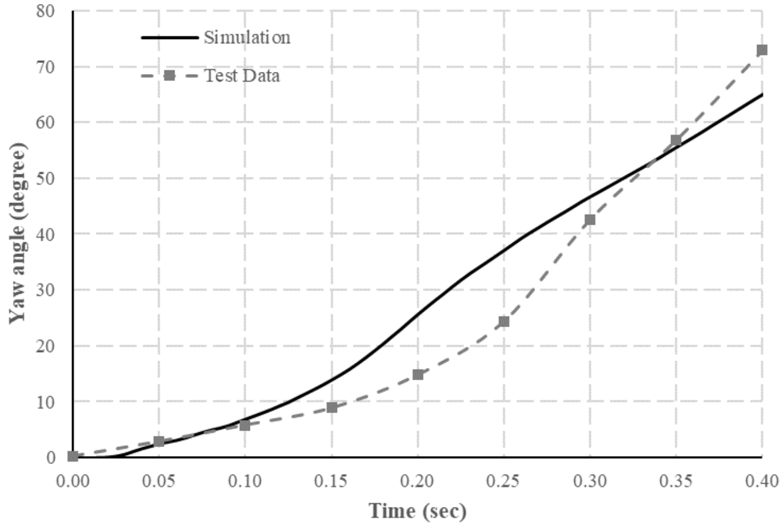

Figure 6. Yaw angle vs. time during car- ET-Plus simulation under NCHRP 31-30 test condition

Car – ET-Plus Collision Validation Based on Test 27-30

The ET-Plus model showed numerical stability under the NCHRP 350 test conditions (27-30)[5]. Similar to the first validation, the crash began at the first time car front bumper impacted the ET-Plus impact head (time = 0s). The large deformation and the broken of the first wood post occurred at around 0.05s. After 0.05s, the whole car started rotating around the impact head. The simulation was terminated at the time the vehicle moved away from the guardrail (around 0.35s). The vehicle model went backward and separated from the impact head between 0.3 and 0.35s, which was later than the time in the first validation simulation.

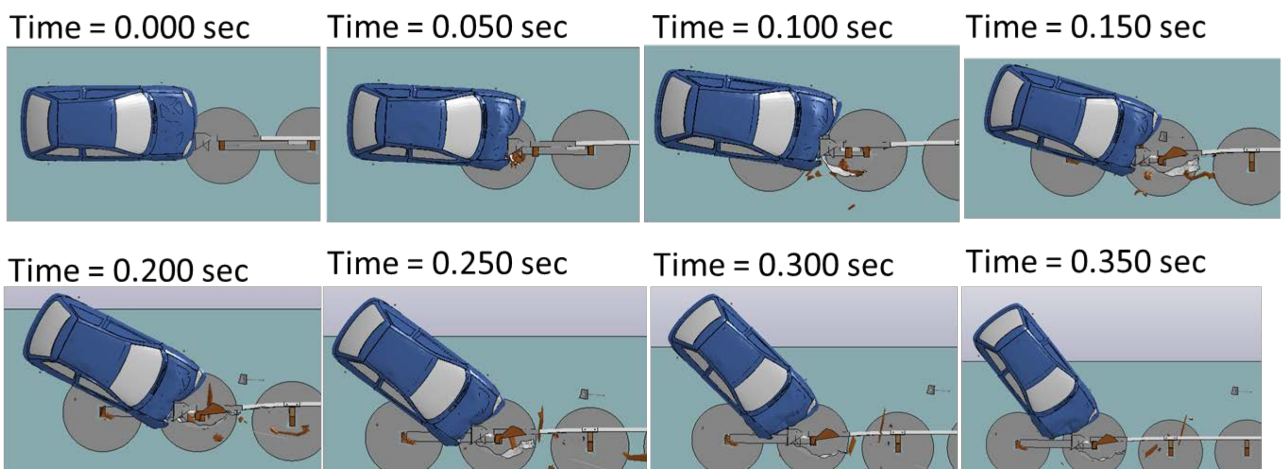

Figure 7. Car- ET-Plus collisions under NCHRP 27-30 test condition

The yaw angle in the simulation was recorded and compared with the similar data measured from the top views photos recorded in testing (0.05s time interval). While the vehicle model showed a similar increasing trend of the yaw angle as the test vehicle, a faster rotation of the vehicle model than the test vehicle is observed (Fig. 8).

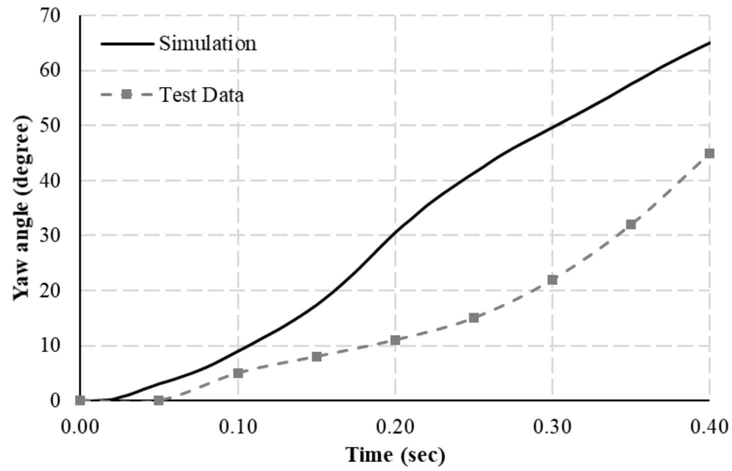

Figure 8. Yaw angle vs. time during car- ET-Plus simulation under NCHRP 27-30 test condition

Discussion and Conclusions

A computationally efficient FE model was developed based on the ET-Plus which is a representative energy-absorbing guardrail end terminal used along U.S. roads. The final FE model has good mesh quality and the dimensions similar to the physical end-terminal. In the FE simulation of cylindrical impactor- ET-Plus impact, the end-terminal model worked properly showing an accurate energy absorbing mechanism. The barrier was flattened and extruded out of the ET-Plus impact head during crash. The ET-Plus FE model was preliminary validated under two NCHRP test conditions. A good agreement with the average error less than 3° was observed in the 27-30 impact test data. However, higher rotation of the car model was observed in the simulation of a second offset test (test 31-30). Although the current ET-Plus model could be used in simulation of car impacts, further model validation is recommended using the available test data from other six different tests. Overall, a computationally efficient FE model of ET-Plus end-terminal was developed in this research. This model can be used by safety researchers to improve the design of new vehicles front ends and new guardrail end terminals for better protection of vehicle occupants.

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