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Continued Development of a Non-Proprietary, High-Tension, Cable End Terminal System

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CONTINUED DEVELOPMENT OF A NON-PROPRIETARY, HIGH-TENSION, CABLE END TERMINAL SYSTEM

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16. Abstract

   A non-proprietary, cable guardrail system is currently under development for the Midwest States Pooled Fund Program. A cable guardrail end terminal was necessary to accompany the cable guardrail system. The objective of this research project was to develop design recommendations for the cable end terminal. Bogie testing that was previously completed on a design concept indicated delayed cable release, which was an undesired performance that led to vehicle instabilities. Several design changes were recommended for better end terminal performance and to reflect the changes made to the cable median barrier.

   An LS-DYNA model of the modified cable end terminal was developed. Simulations of 0- and 15-degree impacts on the end of the cable anchor bracket with a bogie model indicated that the cables would release easily and not induce vehicle instabilities. This behavior still needs to be verified through bogie and full-scale crash testing. Simulations of a 25-degree reverse impact between post nos. 2 and 3 with small car models indicated that cables did not release easily and may interlock around the car resulting in excessive vehicle decelerations or instabilities.

   Simulations of various line post designs found that the MWP and weakened MWP have lower forces and energies during impact than the S3x5.7 posts used in previous three-cable end terminals. This finding would suggest improved performance with respect to vehicle override and instability. However, vehicle simulations with multiple line posts impacted were inconclusive. Further design modifications, evaluation, and testing are recommended.

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1 INTRODUCTION

1.1 Background

A three-cable, low-tension, end terminal system, shown in Figure 1a, was previously developed and successfully tested at the Midwest Roadside Safety Facility [1] according to the safety performance criteria specified in the National Cooperative Highway Research Program (NCHRP) Report No. 350 [2]. The low-tension, end terminal system was modified to add a fourth cable, as shown in Figure 1b, during the development of a four-cable, high-tension cable median barrier [3-14]. However, the high-tension end terminal was never subjected to full-scale crash testing according to the safety performance criteria specified in NCHRP Report No. 350 or the current *Manual for Assessing Safety Hardware* (MASH) [15].
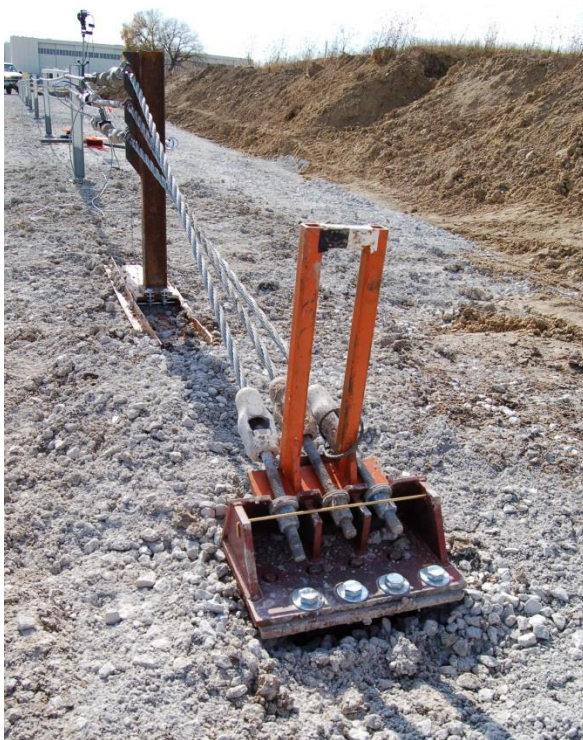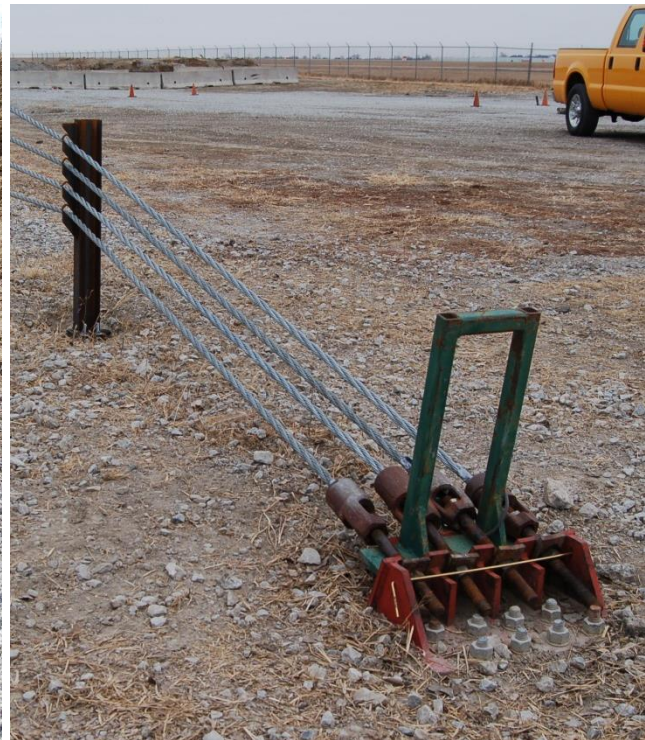
<table>
<tr><td>(a) 3-cable, low-tension</td><td>(b) 4-cable, high-tension</td></tr>
</table>

Figure 1. Cable End Terminal Systems

As part of previous research into a four-cable, high-tension, end terminal, a dynamic bogie test, test no. HTCT-1, was conducted on the high-tension end terminal system at a velocity of 44.9 mph (72.3 km/h) and at an angle of 0 degrees, which is end-on to the system [16]. Several things were noted from this testing:

(1) All four cables released by 18 ms after impact;

(2) The notched cable plate, which held the cables in place, sustained permanent deformation;

(3) The cables wrapped around the cable release lever and pulled it downstream; and

(4) When the cables were tensioned, the clearance between the cable anchorage fittings was limited.

Prior testing with the low-tension end terminal showed the cables released approximately 8 ms after impact [1]. While the 18 ms release times seen in test no. HTCT-1 did not produce an undesirable behavior, a quicker release time, similar to the 8 ms seen in the low-tension cable end terminal tests, was desired.

Prior testing also demonstrated that the cable release lever could potentially become a tripping hazard for the vehicle when it is pulled downstream by the cables and may cause vehicle instabilities [1]. Therefore, it was important that the cables did not wrap around the release lever and that the lever was retained on the cable anchor bracket in an end-on or angled impact on the upstream end terminal.

According to AASHTO's *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals,* substantial remains of breakaway supports shall not project more than 4 in. (102 mm) above groundline, so that a car can easily traverse above any remaining stub [17]. MASH does not have any requirements for the stub height of fixed supports. While the cable anchor bracket assembly is not technically a breakaway support, the

fixed anchor portion of the assembly could potentially cause vehicle instabilities due to undercarriage snag or wheel override if the anchor stub is too high. Therefore, the height of the bracket was reduced to 4 in. (102 mm) to conform to the AASHTO specification.

Eliminating permanent deformations in the anchor bracket and release lever and adding more clearance around the cable anchorage fittings were also desired. So, the cable end terminal was redesigned in a prior project, and finite element analysis demonstrated that the new end terminal design met the desired goals [16]. This cable anchor bracket concept is shown in Figure 2.
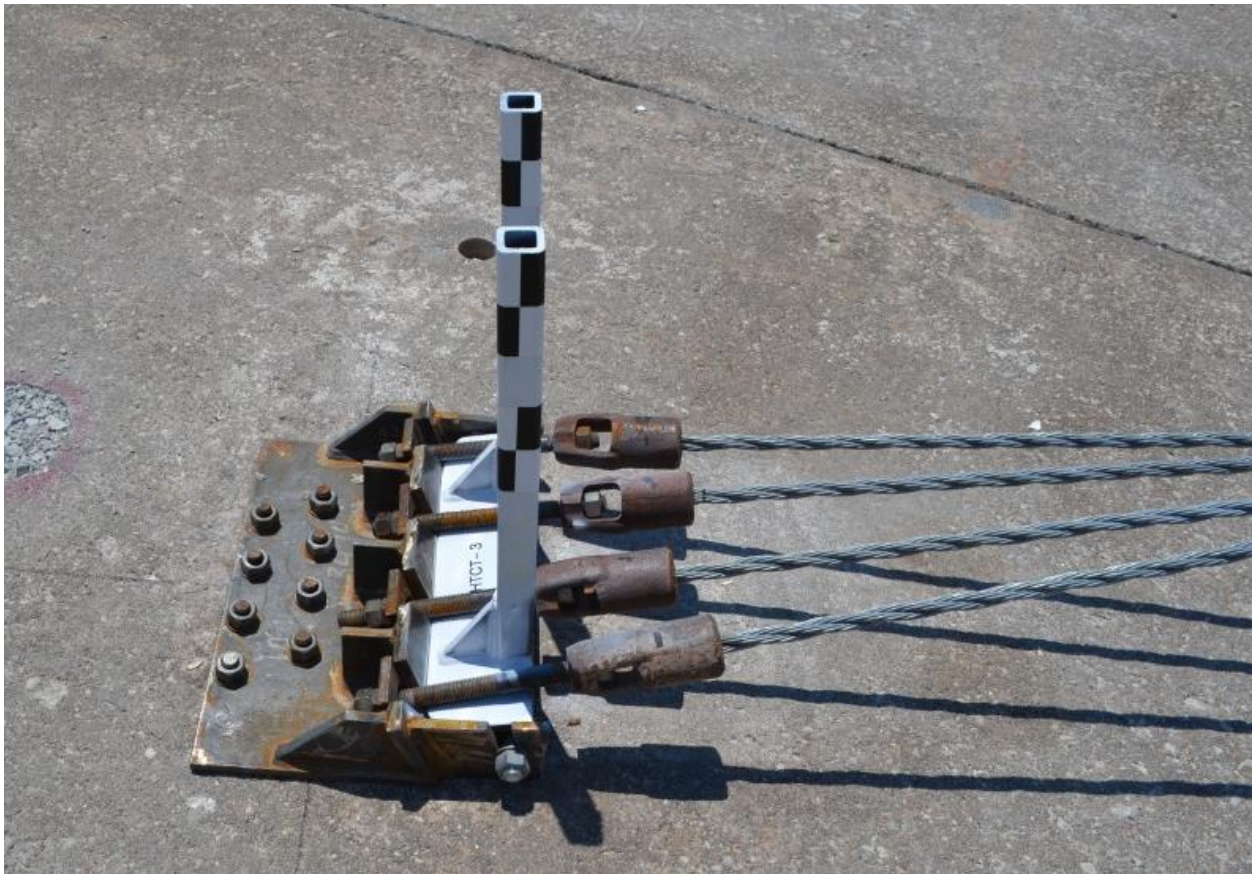
Figure 2. Re-Designed Cable Anchor Bracket

Two bogie tests were conducted on the redesigned cable end terminal [18]. In test no. HTCT-2, a 1,961-lb (890-kg) bogie vehicle impacted a 58-ft 2¼-in. (17.7-m) long end terminal

system at a speed of 52.8 mph (85.0 km/h) and at an angle of 0 degrees, which is end-on to the terminal, at the centerline of the anchor bracket. The cable release lever was retained with the rotational joint, and three of the four cables released by 18 ms. However, the second cable did not release from the cable anchor bracket as desired. Minor permanent deformation was found in the cable release lever.

In test no. HTCT-3, an 1,853-lb (841-kg) bogie vehicle impacted a 58-ft 2¼-in. (17.7-m) long end terminal system at a speed of 51.1 mph (82.2 km/h) and at an angle of 25 degrees at the centerline of the anchor bracket [18]. All cables released from the cable anchor bracket and the cable release lever was retained. However, the cable release times were later than desired and likely contributed to the bogie vehicle becoming airborne and subsequently rolling. Significant permanent deformation was found in the cable release lever.

1.2 Objectives

The objective of this research was to provide further recommendations to enhance the cable release and performance of the non-proprietary, high-tension, cable end terminal when impacted on the end and in 25-degree reverse direction impacts.

1.3 Scope

Modifications were recommended to the previous cable end terminal design based on results of test nos. HTCT-2 and HTCT-3. The proposed design was evaluated using LS-DYNA non-linear, finite element analysis software. A summary, recommendations, and conclusions were provided.

2 DESIGN MODIFICATIONS

After reviewing the cable end terminal evaluated in test nos. HTCT-2 and HTCT-3, several components were identified for potential modifications, including:

1) Reducing cable anchor plate thickness from ⅝ in. (15.9 mm) to ½ in. (12.7 mm) to eliminate excessive material;

2) Combine base plate and rear plate on cable anchor bracket to form one piece and simplify fabrication;

3) Change weld thickness/strength as needed;

4) Eliminate the two bolts that form the rotation point for the cable release lever and create a single rotation bar welded to the bottom of the kicker plate to prevent the kick plate from permanently deforming;

5) Redesign post no. 2 cable hanger bracket redesign to accommodate height ranges for various barrier placements including slopes;

6) Relocate anchor bracket gusset and slot locations for symmetry, to present interference with cable release lever during cable installation and release, and to prevent anchor rod interference with anchor bolts;

7) Reduce height of cable anchor bracket by ½ in. (12.7 mm) to be under 4-in. (102-mm) total height, and redesign slot and washer sizes as needed to enhance cable release;

8) Redesign the release lever kick plate, including orientation, rotation height, length, location relative to cable slots, supporting shelves, and coped corners, to enhance cable release;

9) Change anchor rod locations to be symmetric and fit with the current concrete foundation; and

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10) Minimize number of parts and welding.

The four-cable high tension (from test no. HTCT-1), and the redesigned four-cable high tension (from test nos. HTCT-2 and HTCT-3) systems were compared to the three-cable, low-tension cable end terminal. The angle of the kick plate rotation point was important to releasing the cables. An elevation view of the cable anchor brackets and release levers from the three-cable low tension, four-cable high tension, and the redesigned four-cable high tension systems are shown in Figure 3. The rotation path of the cable release lever is shown in Figure 4 with the center of the initial rotation point and the circular path that the front of the kick plate may follow. The direction of force applied by the cable release lever to the cables is marked with an in arrow in Figure 4.

In the three-cable, low-tension cable end terminal, the back of the kick plate and rotation point is higher than the front of the kick plate that is in contact with the cable ends, and the direction of the force applied to the cable ends facilitates cable release. In the four-cable high tension cable end terminal, the rotation point was at the same height as the front of the kick plate, which did not optimize the direction of the force to release the cable ends. When a fixed rotation bar was added to the bottom of the back of the kick plate in the redesigned four-cable, high tension cable end terminal, the rotation point was lower than the front of the kick plate that was in contact with the cable ends, and the direction of the force applied to the cable ends impeded cable release. With the rotation bar on the bottom of the kick plate and the 4-in. (102-mm) height limitation, it was not possible to achieve the same kick plate angle and optimized cable release that was in the three-cable, low-tension cable end terminal. Both of the four-cable cable end terminals exhibited problems releasing the cables rapidly upon impact, whereas the three cable end terminal did not. The rotation point location in relation to the kick plate was believed to inhibit the cable release in both the four-cable end terminals. Therefore, the cable anchor bracket

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was to be modified to be similar to the three-cable, low-tension cable anchor bracket and cable release lever rotation.
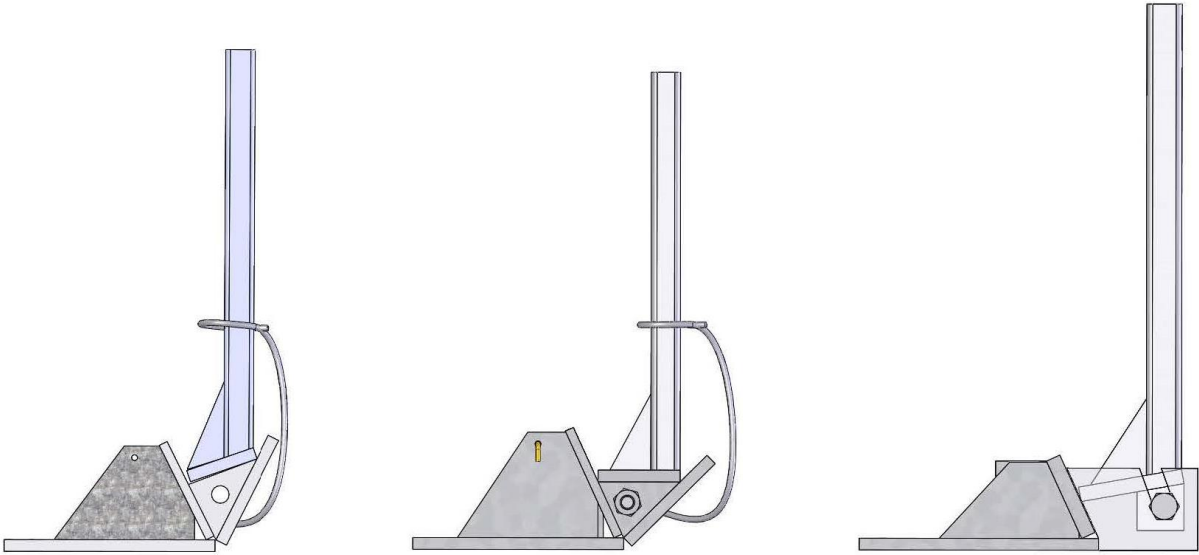
  3-Cable Low Tension   4-Cable High Tension   Redesigned 4-Cable High Tension
Figure 3. Comparison of Cable Anchor Brackets Elevation View
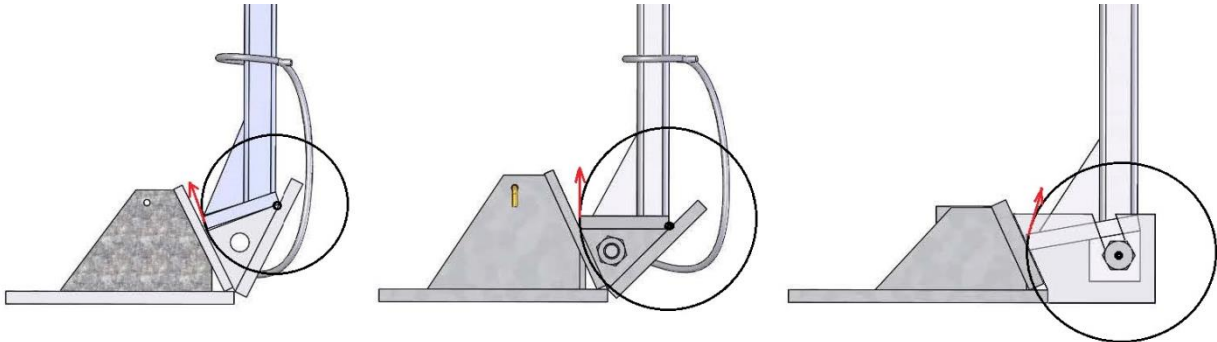
  3-Cable Low Tension   4-Cable High Tension   Redesigned 4-Cable High Tension

Figure 4. Rotation Point for Cable Anchor Bracket Kick Plates

Several of the potential design modifications were implemented as well as changing the cable release lever function. The new concept for the cable anchor bracket is shown in Figure 5. The overall height of the cable anchor bracket was reduced. The cable release lever and cable anchor bracket were modified to provide similar rotation and rapid cable release as the 3-cable,

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low-tension bracket. The base plate was bent to eliminate welds. The number of anchor bolts were reduced from eight to seven and spaced symmetrically along the plate. Changing the anchor bolt arrangement helped prevent interference between the cable ends and the threaded portion of the anchor bolt that is above ground. The angle of the slotted cable anchor plate was increased to be more perpendicular to the cable termination angle. The depth of the cable anchor slots was decreased and the plate washers were reduced in size to promote quick cable release. Plate thicknesses and weld sizes were adjusted as needed to meet strength requirements. Full details of the modified cable anchor bracket are shown in Figures 6 through 20.

During the development of the 4-cable, high-tension cable median barrier system, several modifications have been made that affect the end terminal system. The design cable tension was decreased from 4,213 lb (18.7 kN) to 2,500 lb (11.1 kN) per cable at 100 degrees Fahrenheit [10]. The cable heights have also been changed, and the current design has cable heights at 15½ in. (394 mm), 23 in. (584 mm), 30½ in. (775 mm), and 38 in. (965 mm) above the groundline. The median system previously had S3x5.7 line posts and now has Midwest Weak Posts (MWPs) [9-10]. It was desired that the end terminal posts 3 through the end of the end terminal system maintain the posts, connections, and other hardware consistent with the length-of-need system to minimize the number of unique parts required.
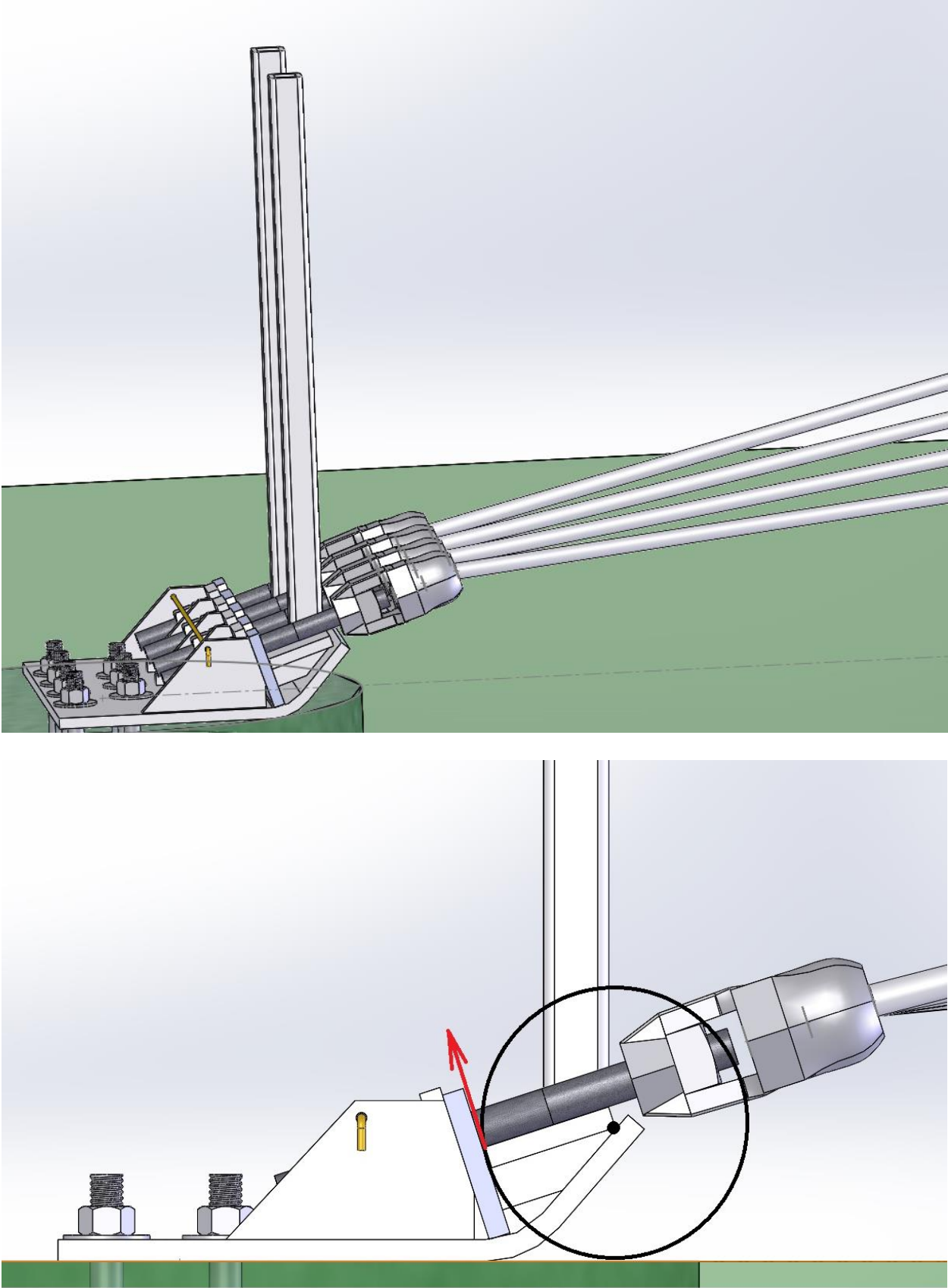
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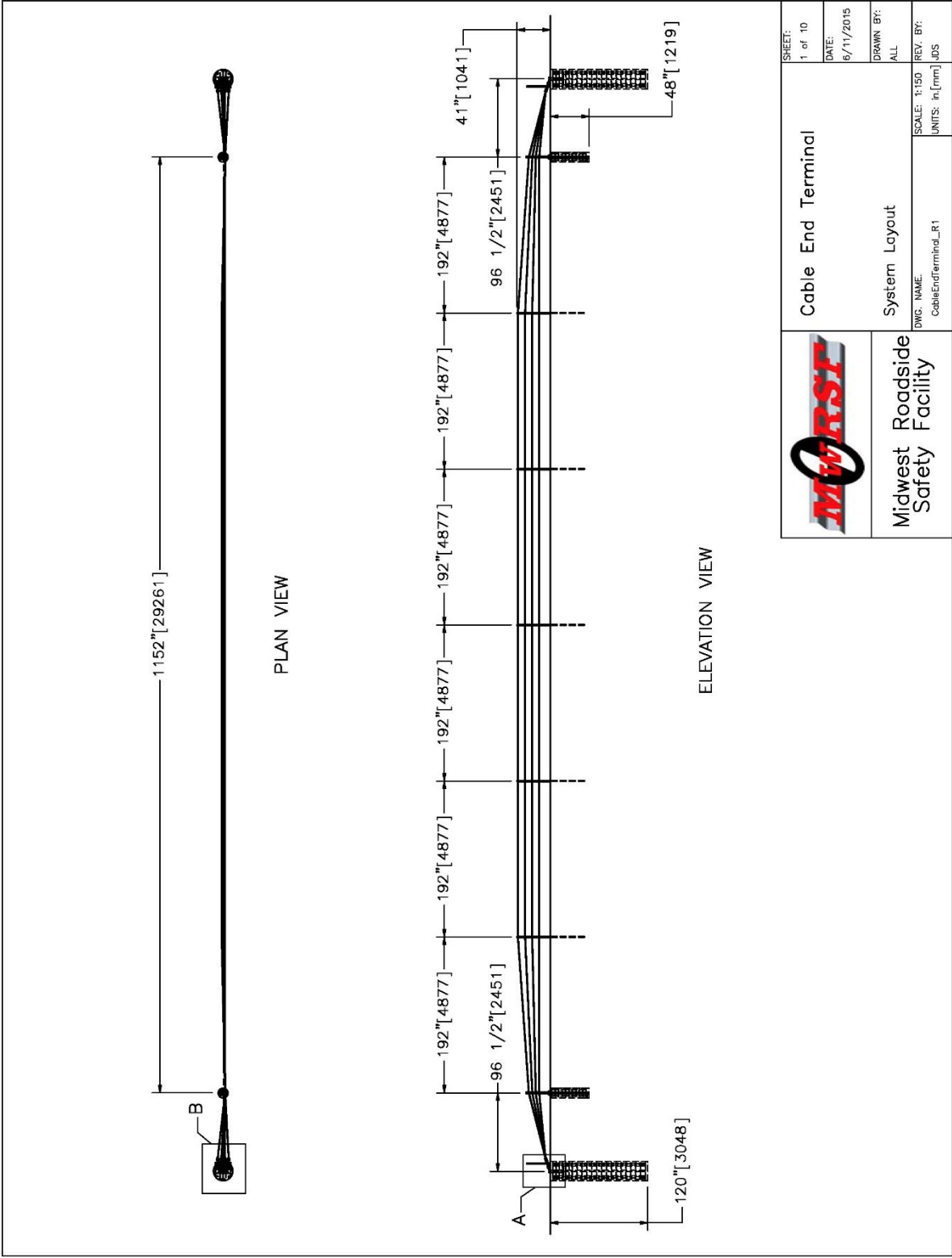
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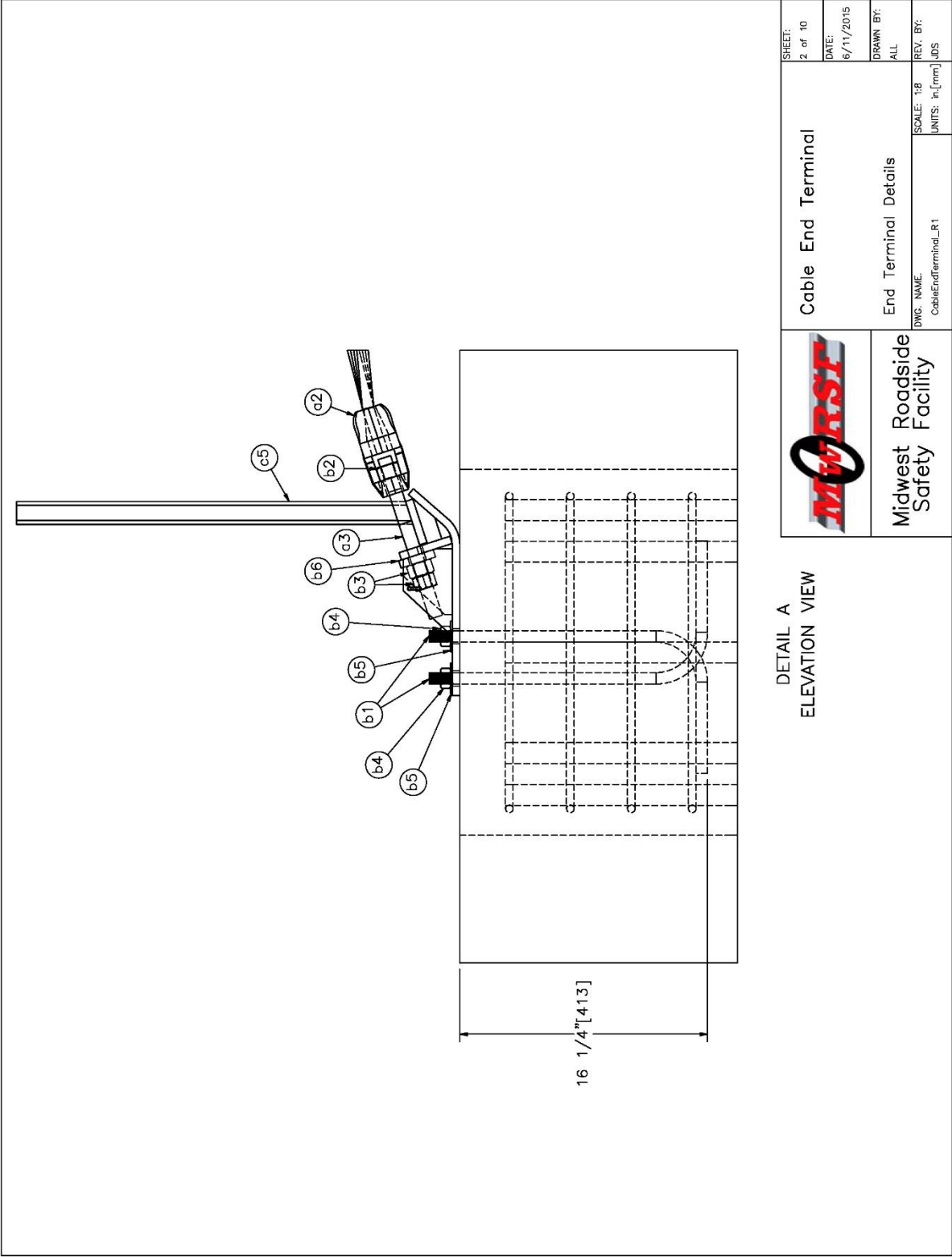
Figure 7. Cable Anchor Bracket

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Figure 8. Cable Anchor Bracket
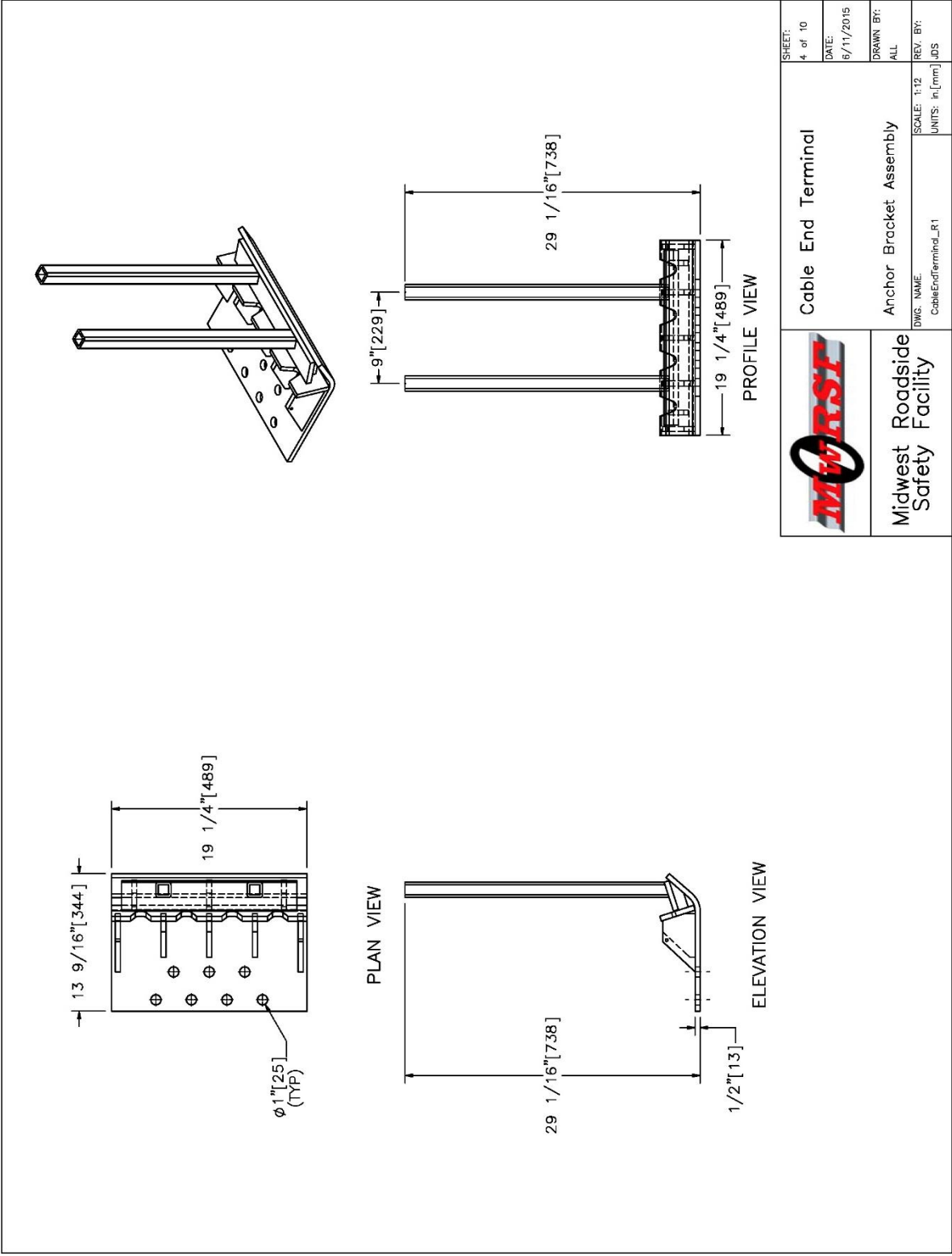
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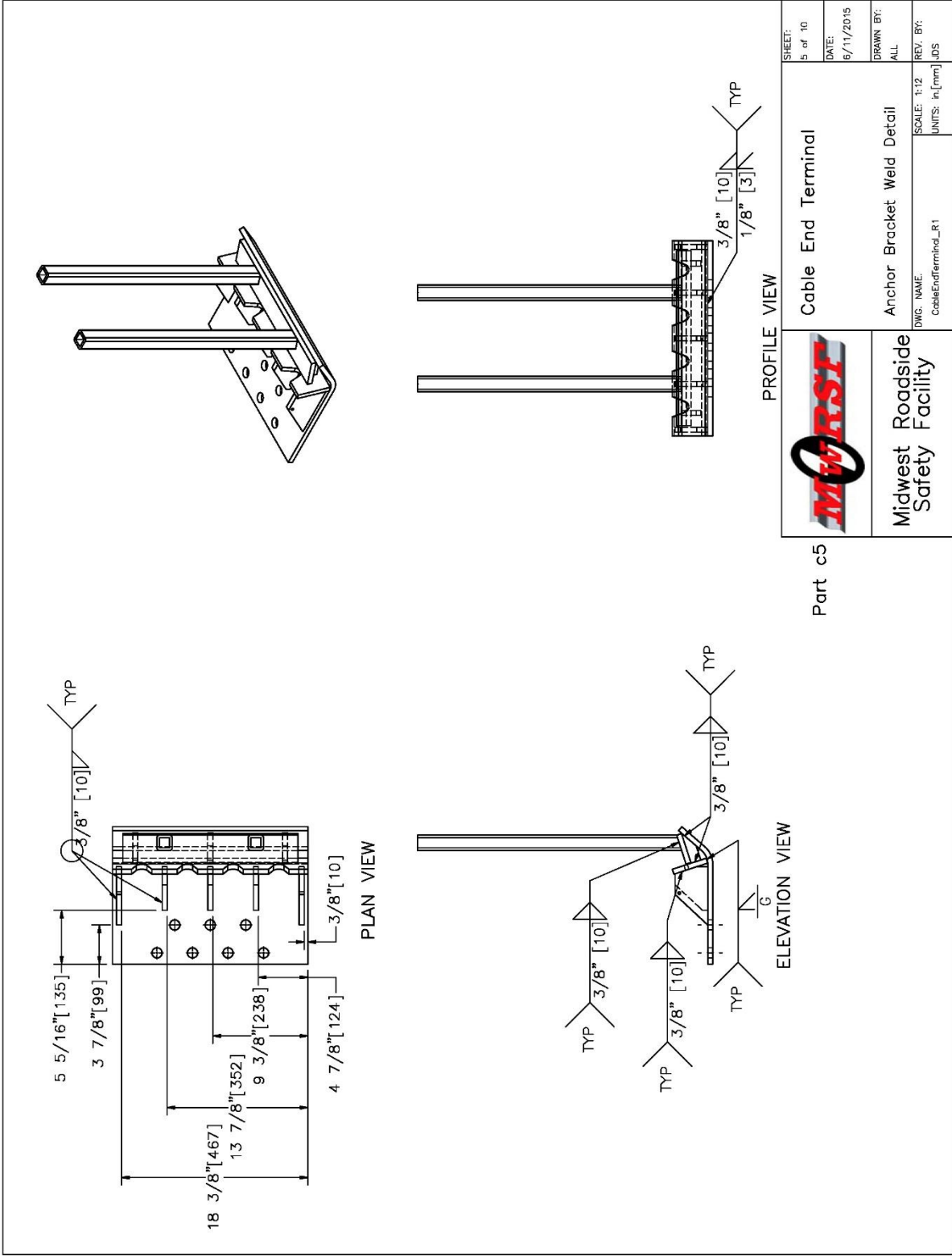
Figure 10. Cable Anchor Bracket Weld Details

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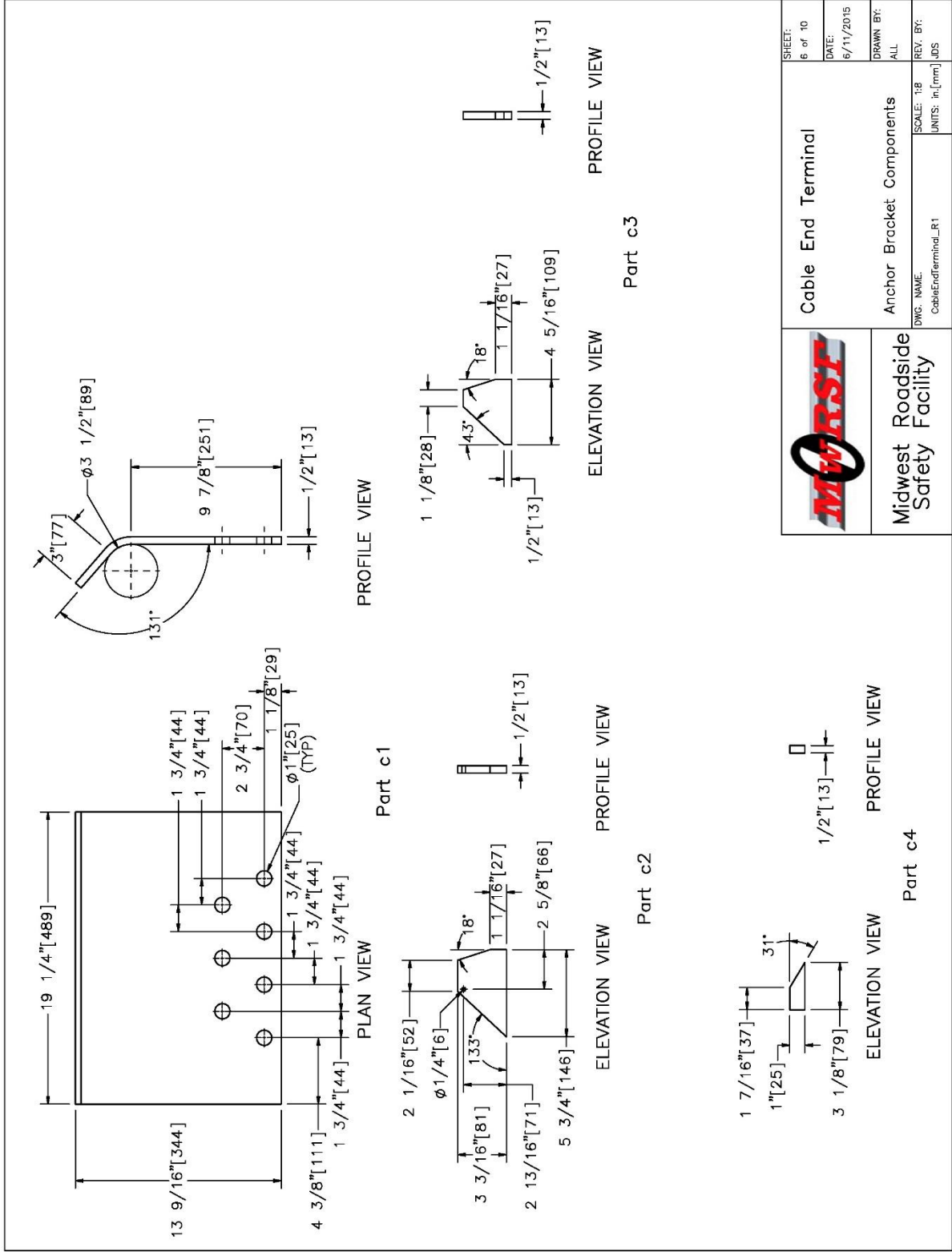
Figure 11. Cable Anchor Bracket Components

Figure 12. Cable Anchor Bracket Components

Figure 13. Cable End Details

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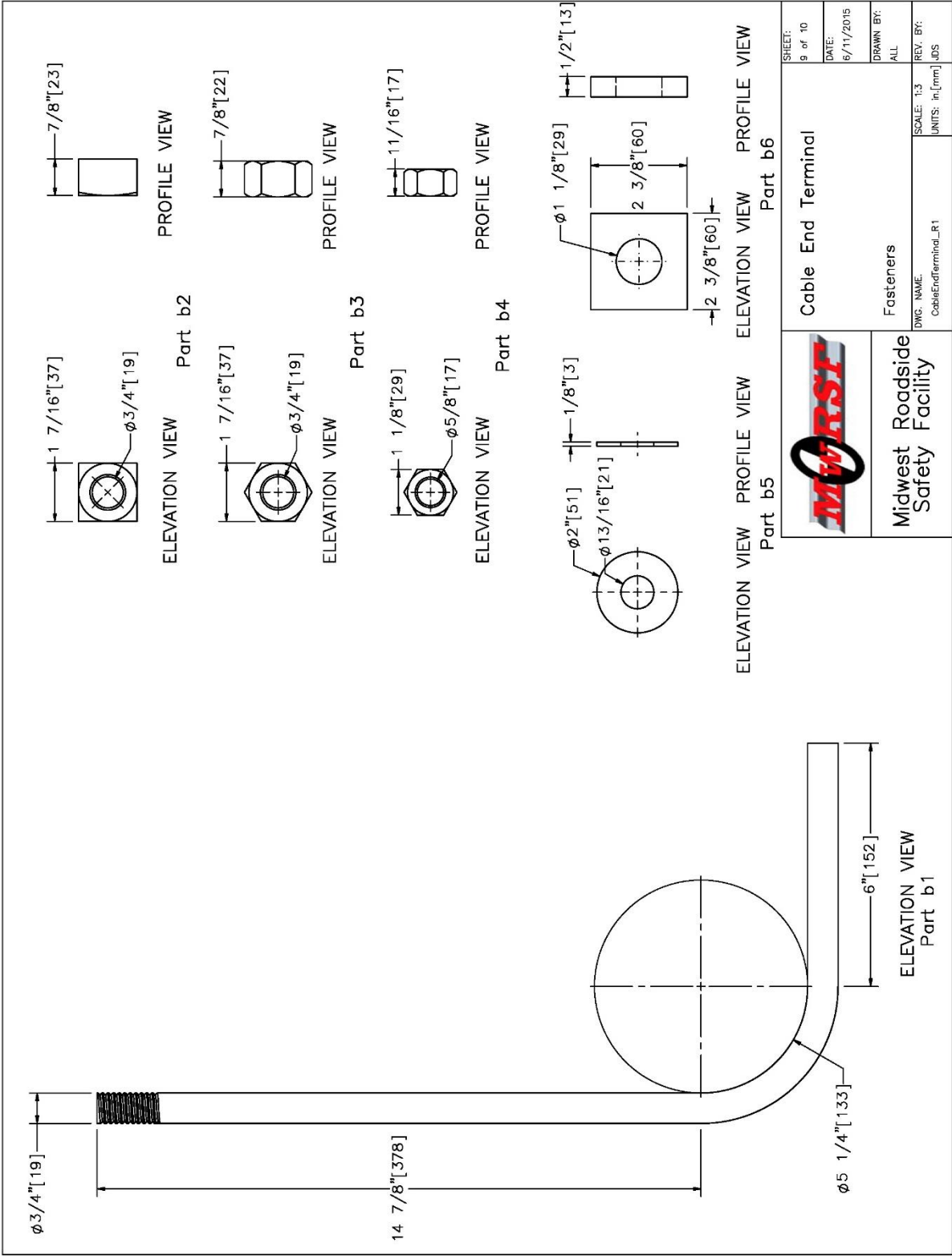
Figure 14. Cable Anchor Bracket Fasteners

Item No.	QTY.	Description	Material Spec	Hardware Guide
a2	4	Bennet Cable End Fitter	ASTM A47	RCE03
a3	4	Cable End Threaded Rod	ASTM A449	RCE03
b1	7	3/4" [19] Dia. UNC J–Hook Anchor	J–Hook ASTM A449	FRJ16a
b2	4	7/8" [22] Dia. Square Nut	SAE J429 Gr. 5	FNS20
b3	8	7/8" [22] Dia. Hex Nut	ASTM A563C	RCE03
b4	7	3/4" [19] Dia. UNC Hex Nut	ASTM A563A	FNX20a
b5	7	3/4" [19] Dia. Flat Washer	ASTM F844	FWC20a
b6	4	2 3/8"x2 3/8"x1/2" [60x60x13] Washer Plate	–	–
c1	2	19 9/16"x19 1/4"x1/2" [497x489x13] Bent Bracket Plate	ASTM A36	–
c2	4	Outside Gusset	ASTM A36	–
c3	6	Inside Gusset	ASTM A36	–
c4	6	Shelf Gusset	ASTM A36	–
c5	4	Release Lever Tube	ASTM A36	–
c6	1	Cable Bracket Plate	ASTM A36	–
c7	2	Release Lever Plate	ASTM A36	–

Cable End Terminal
Bill of Materials
Midwest Roadside Safety Facility
SHEET: 10 of 10
DATE: 6/11/2015
DRAWN BY: ALL
REV. BY: JDS
SCALE: 1:3
UNITS: in.[mm]
DWG. NAME: CableEndTerminal_R1

Figure 15. Cable Anchor Bracket Bill of Materials

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3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Terminals and crash cushions, including cable end terminals, must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the Federal Highway Administration (FHWA) for use on the National Highway System (NHS). For new hardware, these safety standards consist of the guidelines and procedures published in MASH [15]. According to TL-3 of MASH, end terminals must be subjected up to nine full-scale vehicle crash tests, as summarized in Table 1. Test no. 3-36 is not required as it is designed to examine the behavior of terminals and redirective crash cushions when attached to rigid barriers or other very stiff features, which does not occur in the cable median barrier.

Table 1. MASH TL-3 Crash Test Conditions for Terminals and Crash Cushions

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight, lb (kg)	Impact Conditions		Evaluation Criteria [1]
				Speed, mph (km/h)	Angle, deg.	
Terminals and Crash Cushions	3-30	1100C	2,425 (1,100)	62 (100)	0	C,D,F,H,I,N
	3-31	2270P	5,000 (2,270)	62 (100)	0	C,D,F,H,I,N
	3-32	1100C	2,425 (1,100)	62 (100)	5/15	C,D,F,H,I,N
	3-33	2270P	5,000 (2,270)	62 (100)	5/15	C,D,F,H,I,N
	3-34	1100C	2,425 (1,100)	62 (100)	15	C,D,F,H,I,N
	3-35	2270P	5,000 (2,270)	62 (100)	25	A,D,F,H,I
	3-36	2270P	5,000 (2,270)	62 (100)	25	A,D,F,H,I
	3-37 [2]	2270P	5,000 (2,270)	62 (100)	25	C,D,F,H,I,N
	3-38	1500A	3,300 (1,500)	62 (100)	0	C,D,F,H,I,N

[1] Evaluation criteria explained in Table 2.
[2] In MASH 2016, test 3-37 will be test 37a and 37b conducted with 2270P and 1100C vehicles

3.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the end terminal to contain and redirect impacting vehicles. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 2 and defined in greater detail in MASH. In lieu of conducting several full-scale crash tests to evaluate the cable end terminal system, a computer simulation effort was conducted first to evaluate the potential performance of the redesigned end terminal.

Table 2. MASH Evaluation Criteria for Terminals and Crash Cushions

Structural Adequacy	A.	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.
	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.
Occupant Risk	D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.
	F.	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
	H.	Occupant Impact Velocity (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:

Occupant Impact Velocity Limits		
Component	Preferred	Maximum
Longitudinal and Lateral	30 ft/s (9.1 m/s)	40 ft/s (12.2 m/s)

	I.	The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:

Occupant Ridedown Acceleration Limits		
Component	Preferred	Maximum
Longitudinal and Lateral	15.0 g's	20.49 g's

Vehicle Trajectory	N.	Vehicle trajectory behind the test article is acceptable.

4 COMPUTER SIMULATION

LS-DYNA finite element analysis software was employed to evaluate the performance of the system in a 0-degree and 15-degree impact on the end of the system and in a 25-degree reverse direction impact near the end of the system, similar to MASH test designation nos. 3-30, 3-32, and 3-37.

4.1 Cable End Terminal Model

A 96-ft (29.3-m) long 9-post cable end terminal system model was created, as shown in Figure 16. Post nos. 1 and 9 consisted of the new cable anchor bracket presented in Chapter 2. The brackets were anchored with ¾-in. (19-mm) diameter rigid steel bolts that were constrained from motion in all directions. Because these bolts did not have any pre-stress, several nodes around each bolt hole in the cable anchor bracket base plate were constrained from motion in all directions.

Post nos. 2 and 8 were slip base posts spaced at 8 ft (2.4 m) from post nos. 1 and 9, respectively. The slipbase post assemblies were previously developed by Hiser [19] and modified by Terpsma [16] to have 4 cables. The primary purpose of the post was to support the cables as they transitioned from the horizontal, guardrail section, down to the anchor bracket. The cables rest in notches in the cable hanger bracket. Small bolts at the base of the post fracture when impacted and allow the upper post structure to disengage. The lower post structure is rigid and constrained from motion in all directions. Post components and a complete description of the development of the model were detailed by Hiser [19]. The slip base post model is shown in Figure 17.
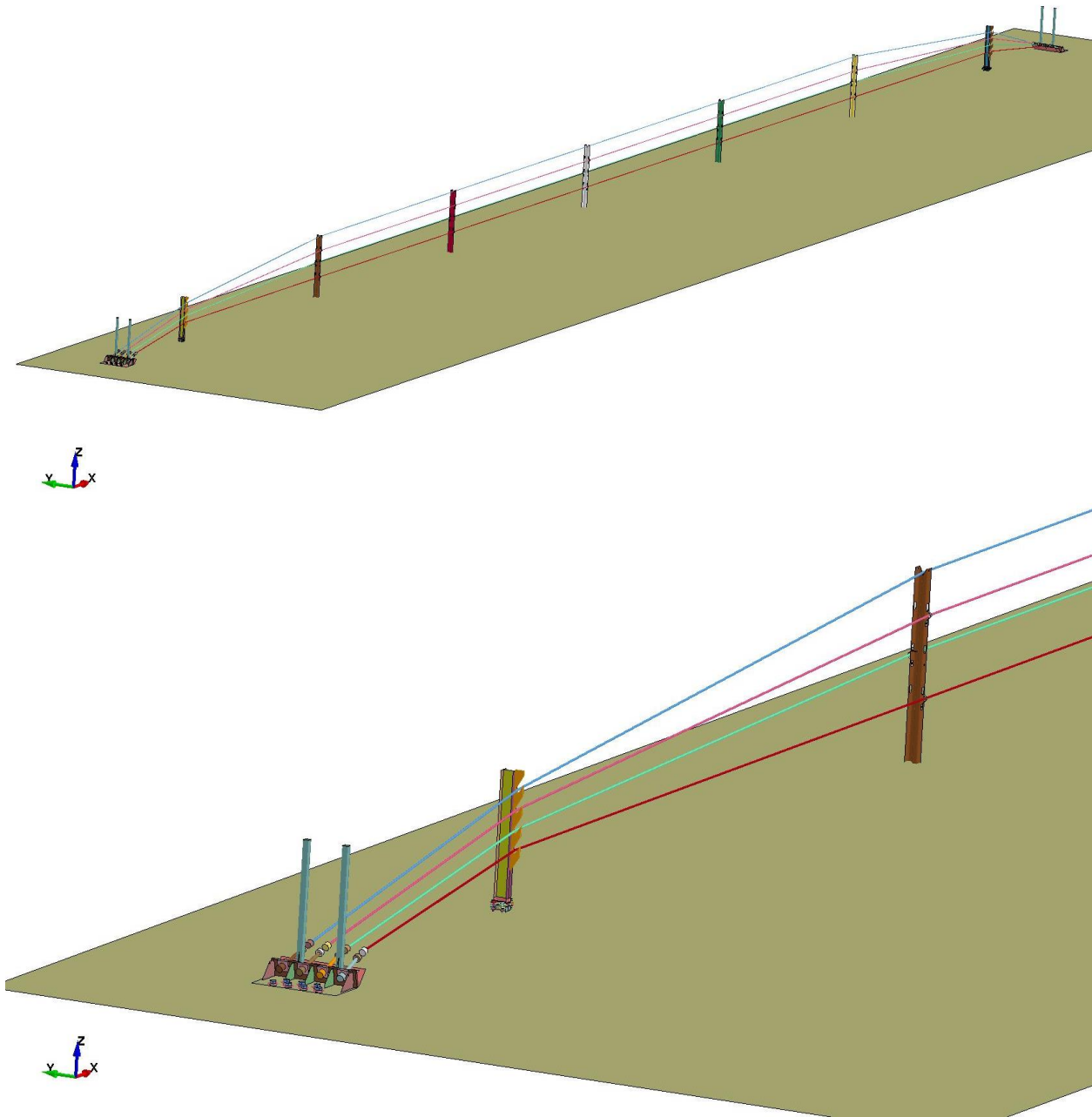
Figure 16. Cable End Terminal System Model
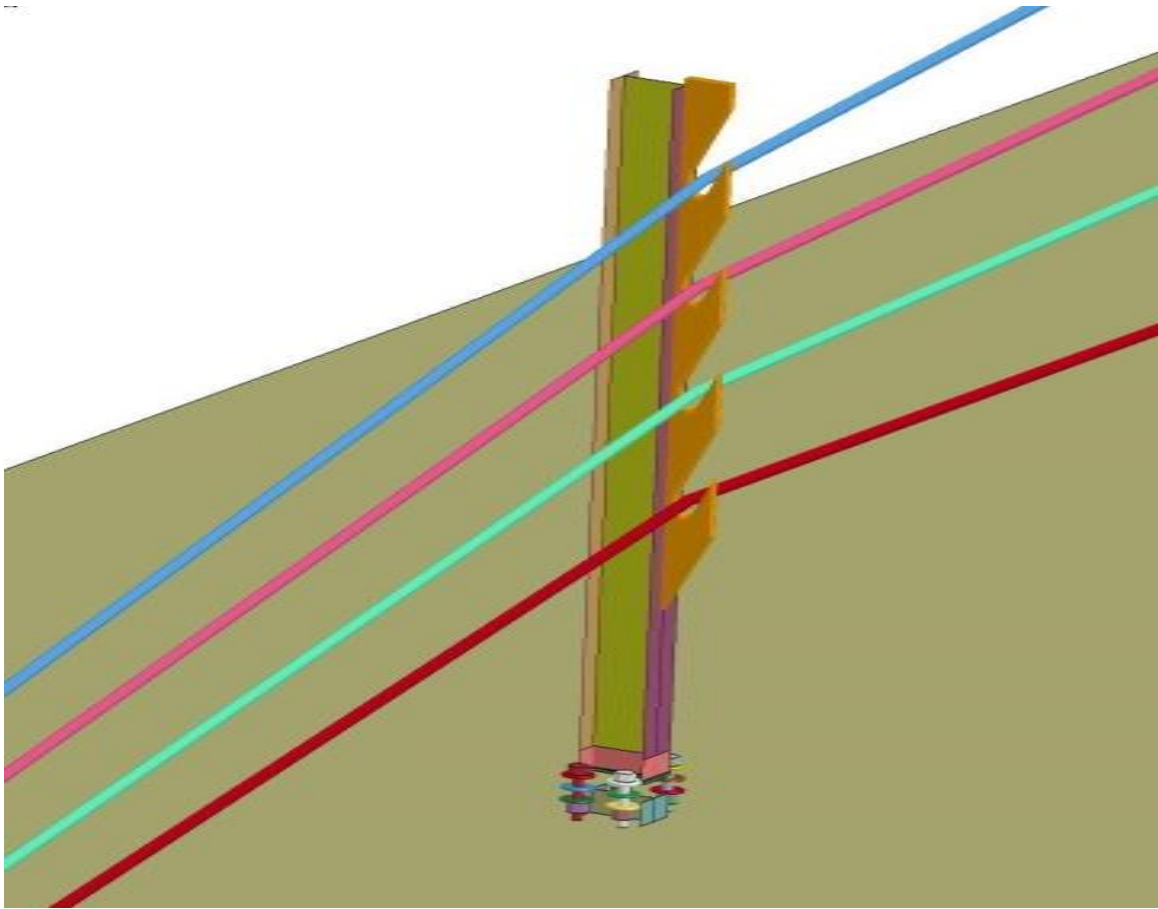
Figure 17. Post nos. 2 and 8

Post nos. 3 through 7 were MWPs spaced at 16 ft (4.9 m) apart. The MWP model was developed by Bielenberg and provided an accurate prediction of the performance of the strong- and weak-axis behavior of the MWP [9]. The MWP model is shown in Figure 18. Energy absorbed by the post in simulations was nearly identical in the strong axis and slightly lower in the weak axis when compared to component tests with the same impact conditions. The full-scale crash tests on the end terminal system are weak-axis impacts (0 degrees) and impacts up to 25 degrees. Therefore, the weak-axis performance of the posts is most important for the end terminal system. The overall energy absorption of the post is not as important as the bending and yielding behavior that could lead to vehicle instabilities and/or excessive occupant risk values. Since the initial MWP model was developed, the width of the post increased from 1⅝ in. (41

mm) to 1¾ in. (44 mm). Component tests did not exist to compare the new post model's performance against. However, it is believed that the new MWP model should still accurately predict the post's performance.
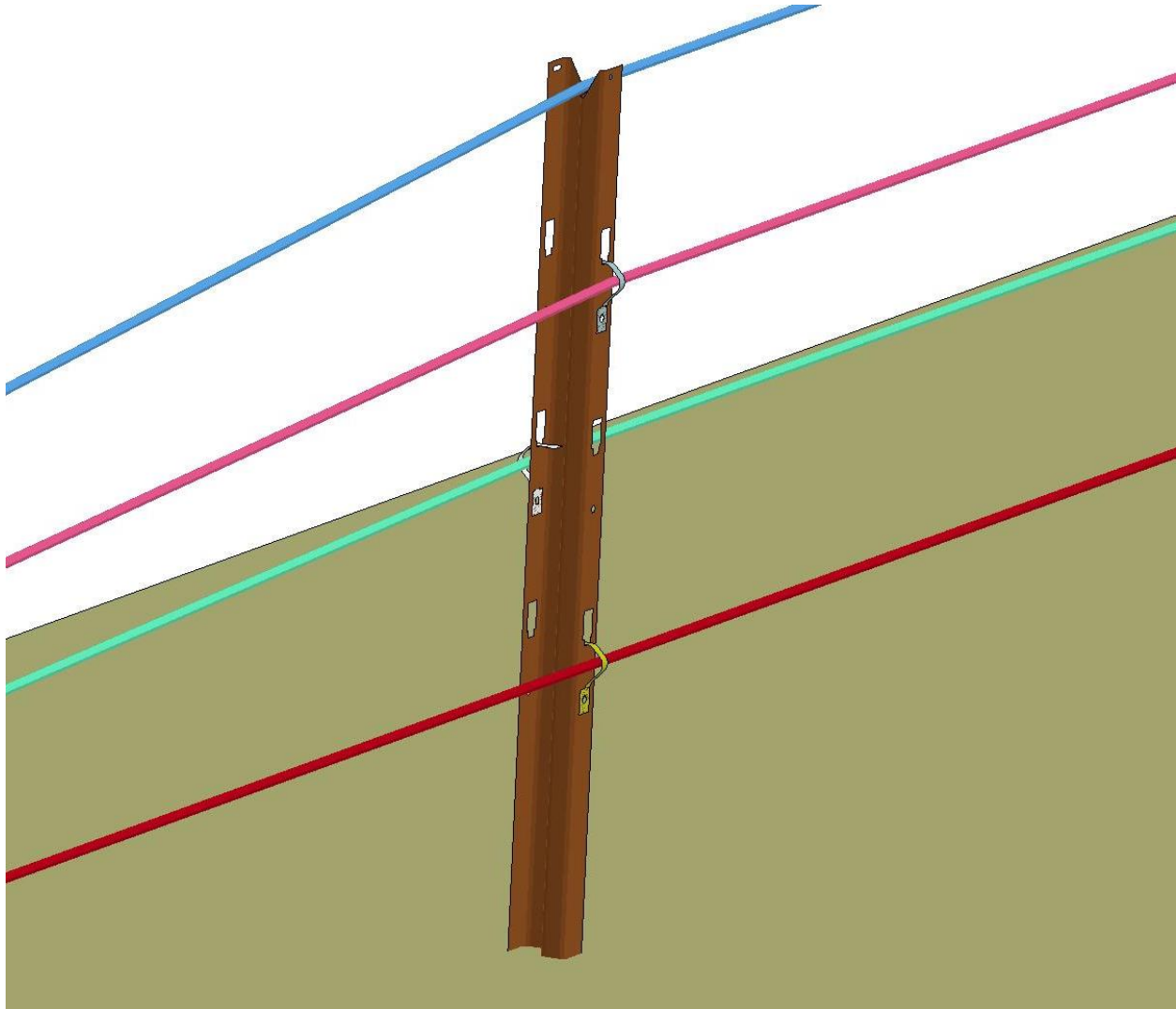
Figure 18. Post nos. 3 through 7

Since the MWP is a weak post that easily yields and displaces little soil upon impact, soil was not modelled around these posts. Instead, the bottom two-thirds of the posts below groundline were constrained from motion in all directions. This allows the post to displace minimally and yield at groundline, which replicates real world performance.

The cables were connected to post nos. 3 through 7 with tabbed brackets that the lower portion is bolted through the post and the upper tabbed portion fits into a keyway in the post. The tabbed brackets have not been validated, but the tabbed brackets should have minimal effect on the system performance in the 0- and 15-degree impacts as their primary objective is to maintain cable height. In the 25-degree reverse direction impact, the performance of the tabbed brackets and whether they release the cables in the vertical or lateral directions may be more important than the end-on impacts. However, the overall behavior can still be examined.

The wire rope model was developed by Stolle, et al. [20], and replicated many of the characteristics of physical wire rope used in cable barrier systems very well, including tension, moment-bending, and dynamic bending wave propagation. The cables were pre-stressed to 2,500 lb (11.1 kN) before the impact to simulate a 100 degree Fahrenheit day or 5,000 lb (22.2 kN) to simulate a cold day. The default time step was decreased to minimize mass scaling in the small elements in the cable anchor bracket.

4.2 Vehicle Models

4.2.1 Bogie

The cable release mechanism was evaluated with a bogie vehicle model impacting at 0- and 15-degree impacts. The bogie has a mass of 1,735 lb (787 kg) and is constructed of rigid tubes and tubes and tires, as shown in Figure 19. The impact head is constructed of an 8⅝-in. (219-mm) diameter rigid steel tube with a neoprene pad on the impact side and is mounted 19 in. (483 mm) above the ground.

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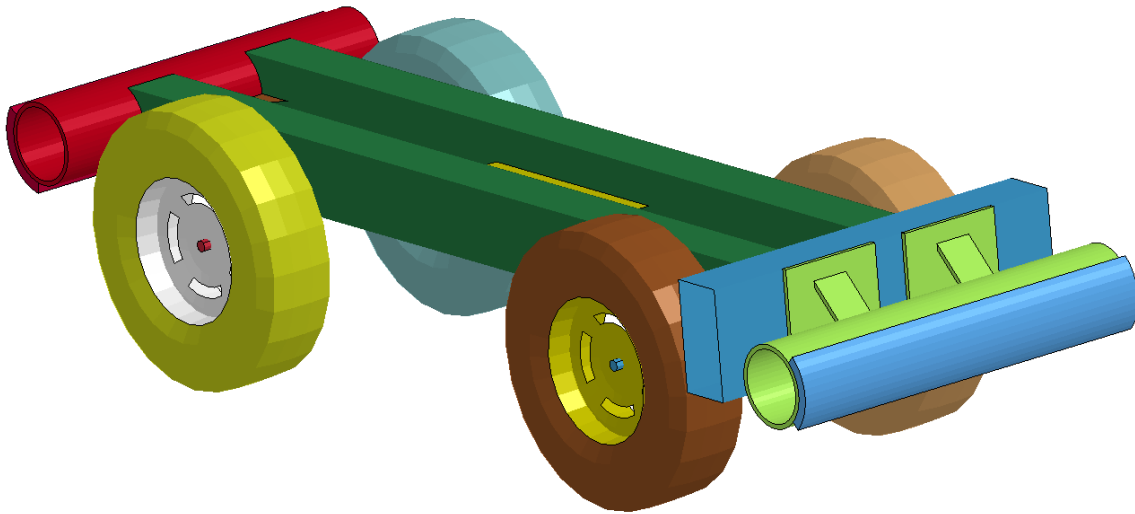
Figure 19. Bogie Vehicle Model

4.2.2 Toyota Yaris

The end terminal system performance was also evaluated with the Toyota Yaris model impacting at 25 degrees in the reverse direction. The Yaris vehicle model is representative of the 1100C MASH test vehicle with simulated passengers. The Toyota Yaris was originally developed and validated by the National Crash Analysis Center (NCAC) [21] and later modified by MwRSF. The Yaris model has a mass of 2,776 lb (1,259 kg), and is shown in Figure 20.

4.2.3 Geo Metro

The end terminal system performance was also evaluated with the Geo Metro model impacting at 25 degrees in the reverse direction. The Geo vehicle model is representative of the 820C NCHRP Report 350 test vehicle with a simulated passenger. The Geo Metro was originally developed by NCAC, was improved upon and obtained from Politecnico di Milano, Italy. This model was later modified by MwRSF personnel for use in roadside safety applications. The Geo model has a mass of 1,984 lb (900 kg), and is shown in Figure 21.
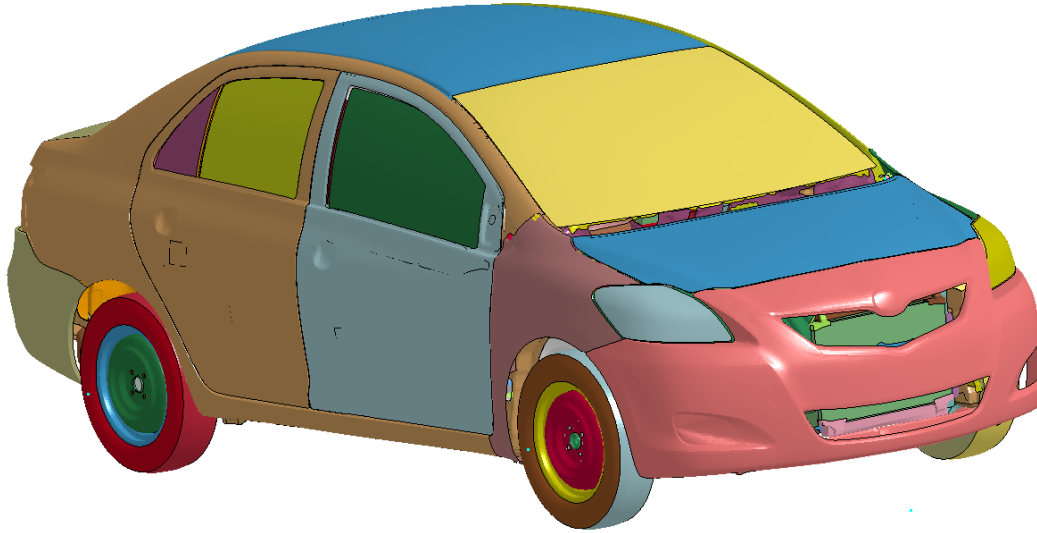
Figure 20. 1100C Yaris Vehicle Model
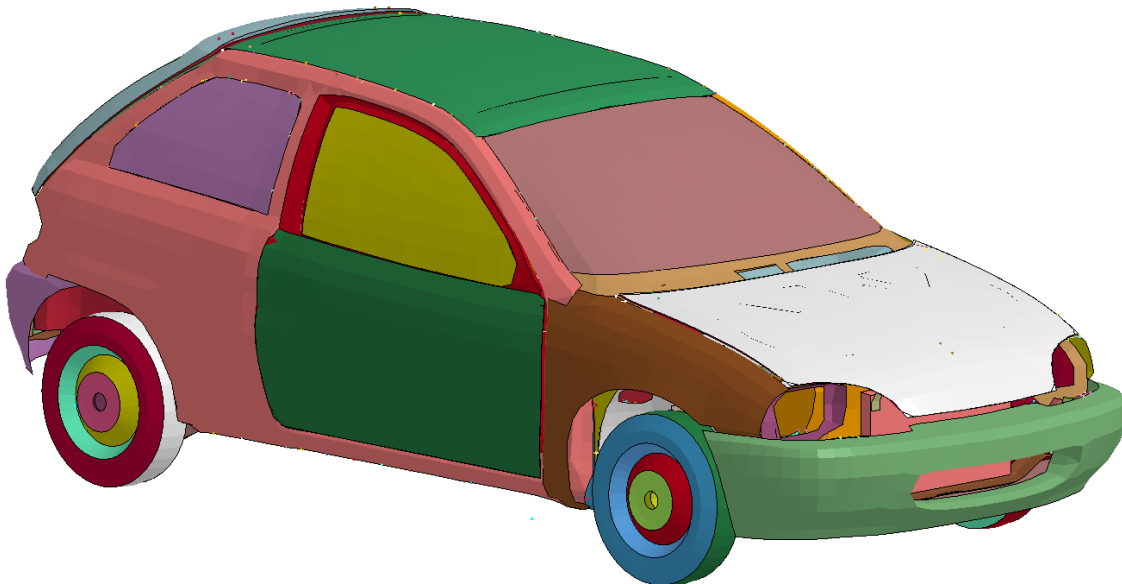
Figure 21. 820C Geo Vehicle Model

4.3 Bogie Vehicle Impact Simulations

4.3.1 0-degree End Impact

The 1,735-lb (787-kg) bogie vehicle model impacted the end terminal with the centerline of the bogie aligned with the centerline of the cable release lever at a speed of 45 mph (20.1

mm/ms) and at an angle of 0 degrees. Sequential photographs are shown in Figures 22 through 24. The cable release lever began rotating upon impact and all the cables were fully released within 13 ms, and the bogie continued without a significant change in velocity. The cable release lever experienced minor permanent deformations during the initial impact with bogie impact head, and the cable anchor bracket components experienced no permanent deformation. However, the cable release lever was not constrained with a cable, as would be expected in real world installations, so the lever subsequently contacted the bottom of the bogie, was drug downstream, and experienced significant deformation.

Due to the ease in which the cables released from the cable anchor bracket, significant damage to an actual vehicle was not expected. This simulation was only intended to evaluate the initial impact with the cable anchor bracket and post no. 2. The end terminal line posts will need to be evaluated in the future to ensure that the posts do not cause vehicle instabilities or cause excessive occupant compartment intrusion or penetration, such as floorboard penetration. There was no indication that occupant impact velocities or occupant ridedown accelerations would exceed the limits established in MASH.

Figure 22. Sequential Photographs, Simulated Test No. 3-30

Figure 23. Sequential Photographs, Simulated Test No. 3-30

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Figure 24. Sequential Photographs, Simulated Test No. 3-30

4.3.2 15-degree End Impact

The 1,735-lb (787-kg) bogie vehicle model impacted the centerline of the cable release lever at a speed of 45 mph (20.1 mm/ms) and at an angle of 15 degrees. Sequential photographs are shown in Figures 25 through 27. The cable release lever began rotating upon impact and all the cables were fully released within 16 ms, and the bogie continued without a significant change in velocity. The bogie gated behind the system and did not contact post no. 2. The cable release lever experienced permanent deformations during the initial impact with bogie impact head, and the cable anchor bracket components experienced no permanent deformation. However, the cable release lever was not constrained with a cable, as would be expected in real world installations, so the lever subsequently contacted the bottom of the bogie, was drug downstream, and experienced significant deformation.

Due to the ease in which the cables released from the cable anchor bracket, significant damage to the vehicle is not expected. This simulation was only intended to evaluate the initial impact with the cable anchor bracket. There was no indication that occupant impact velocities or occupant ridedown accelerations would exceed the limits established in MASH.
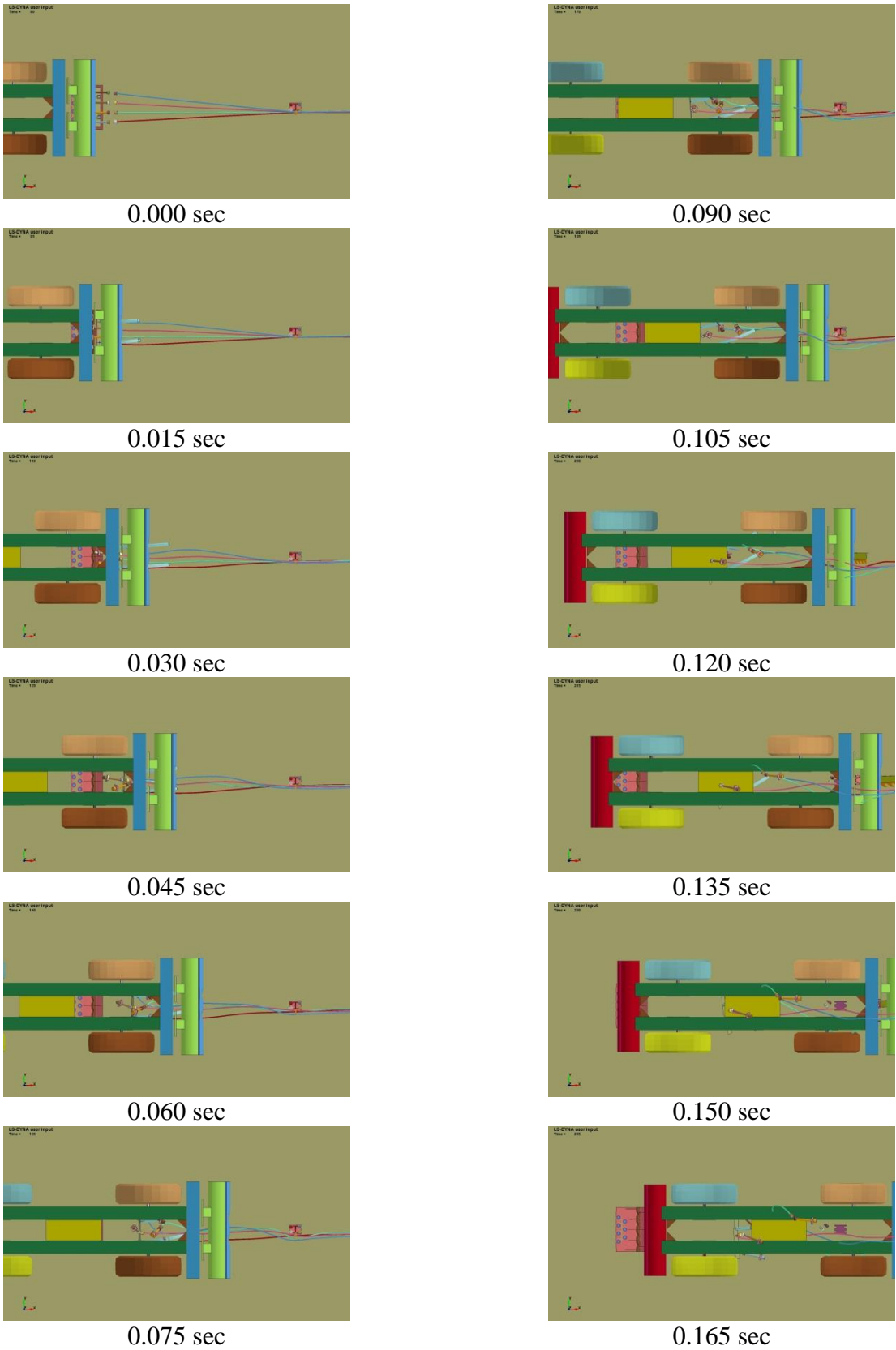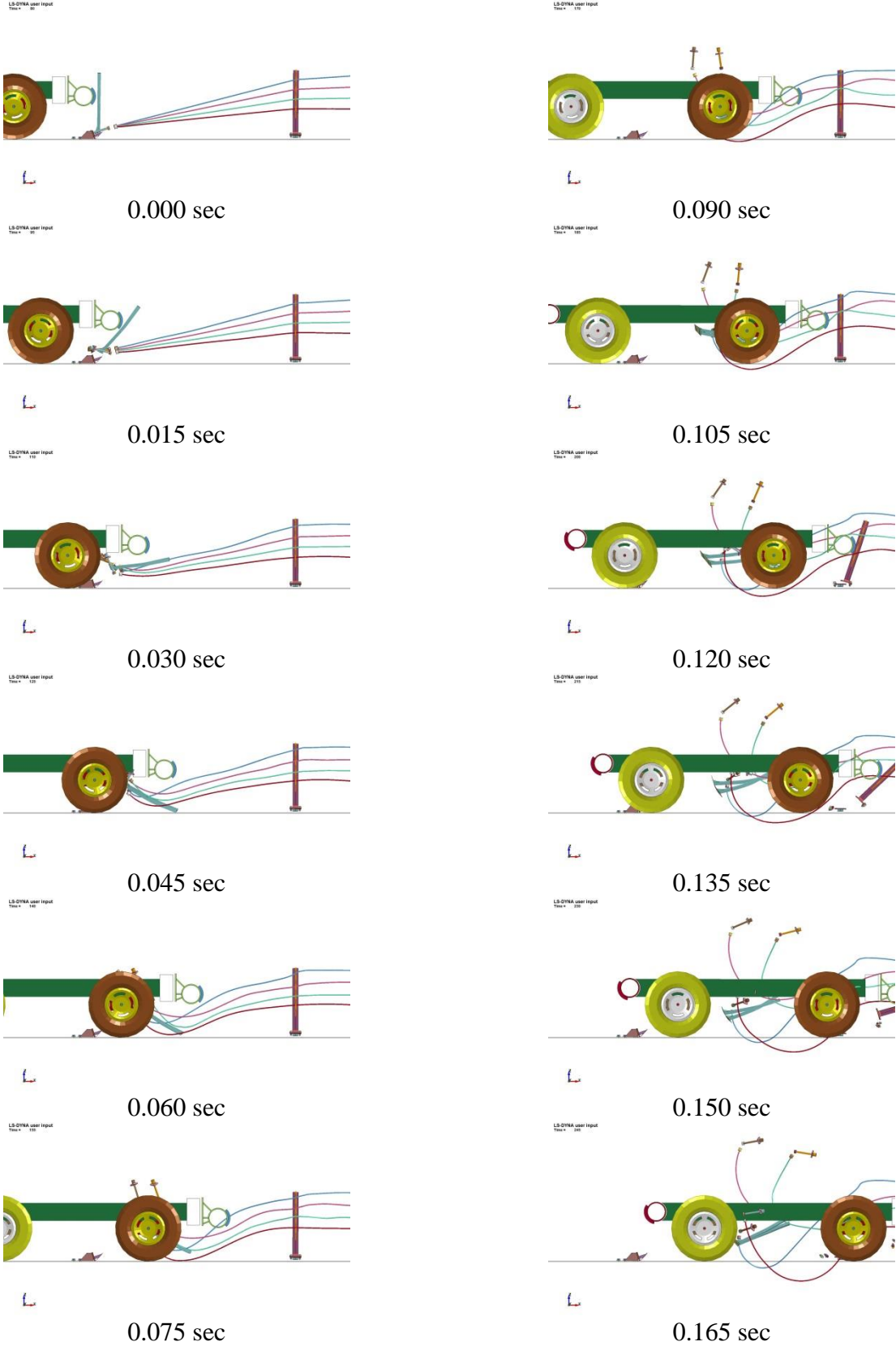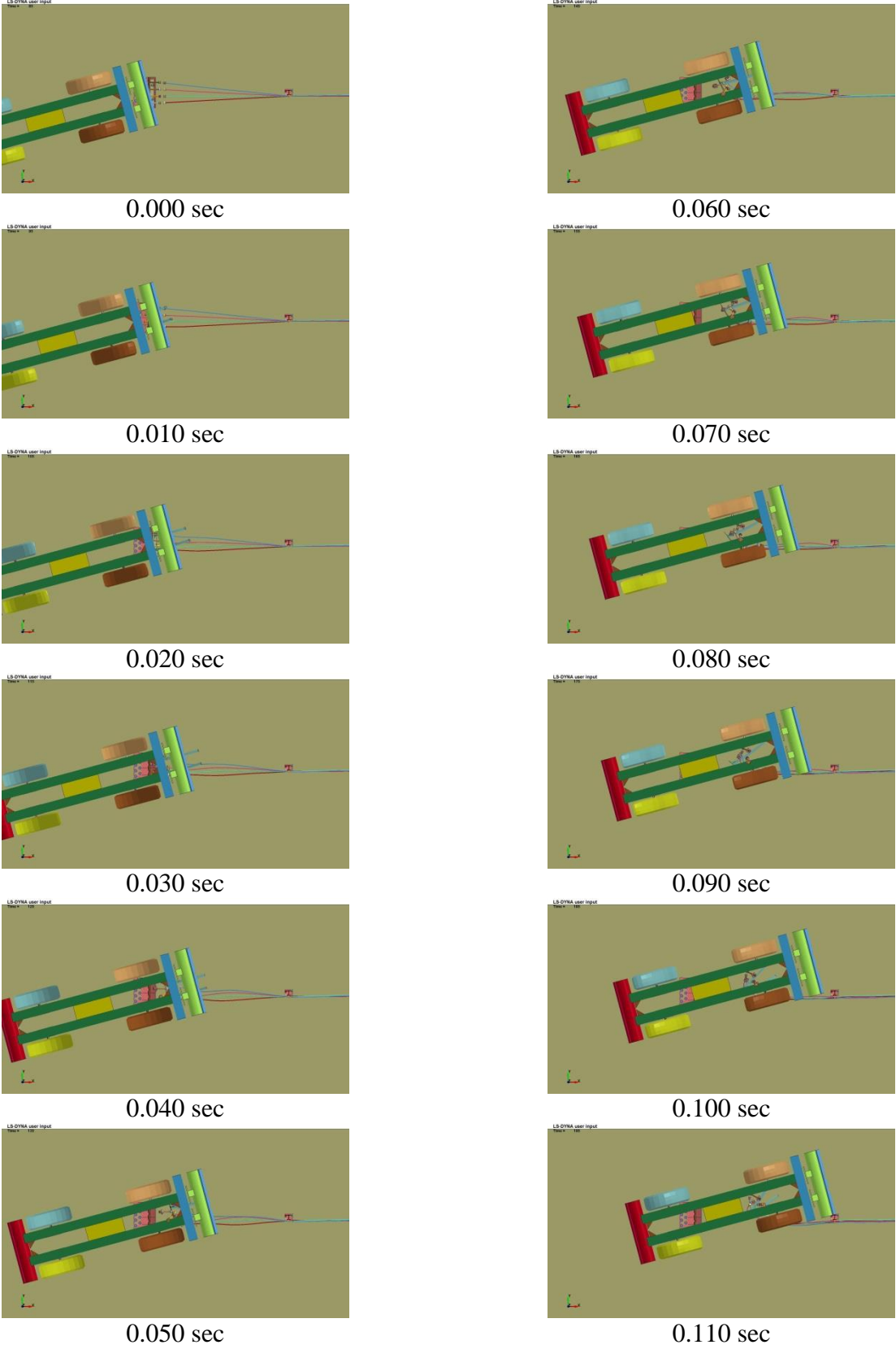
Figure 25. Sequential Photographs, Simulated Test No. 3-32
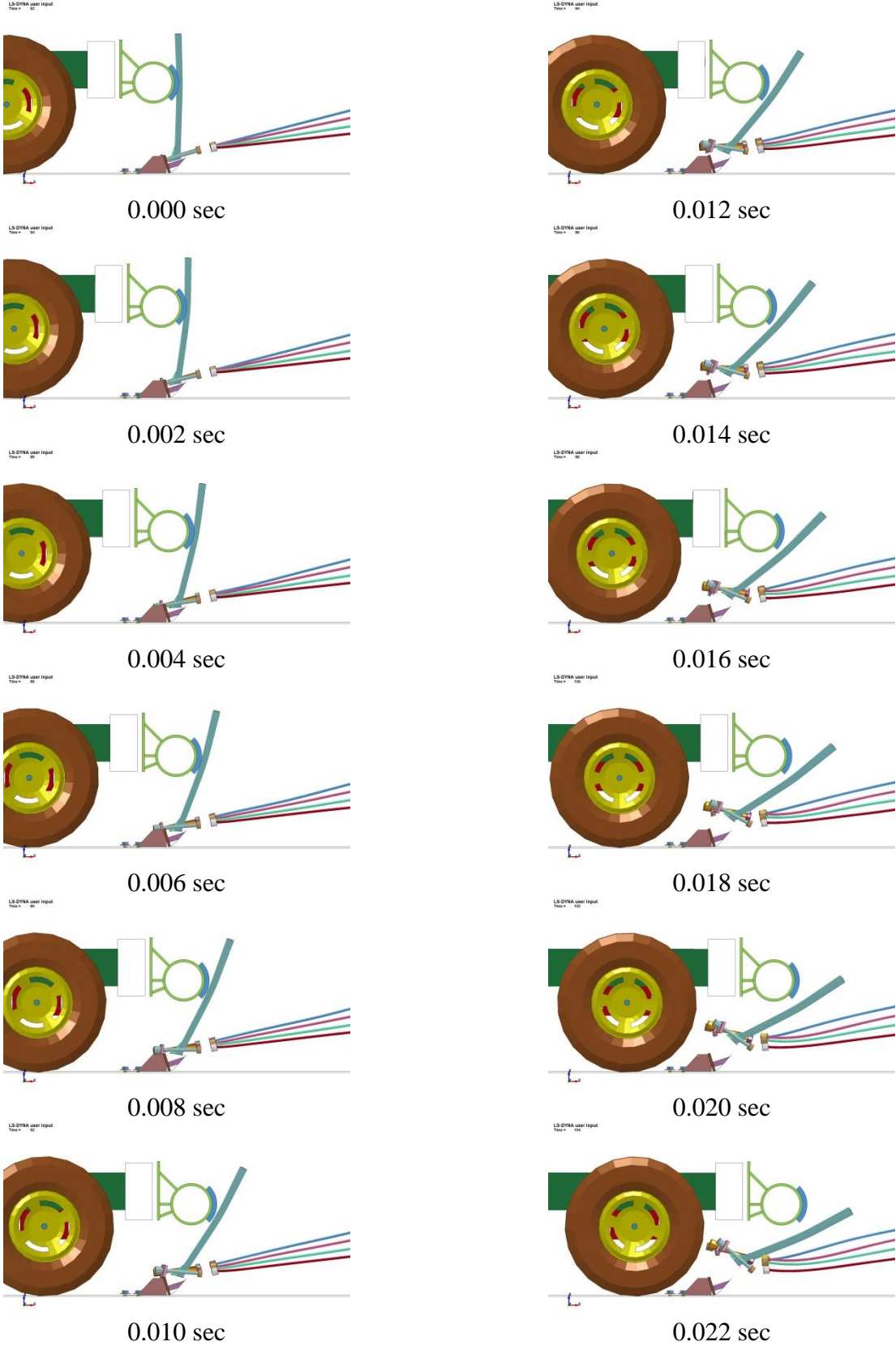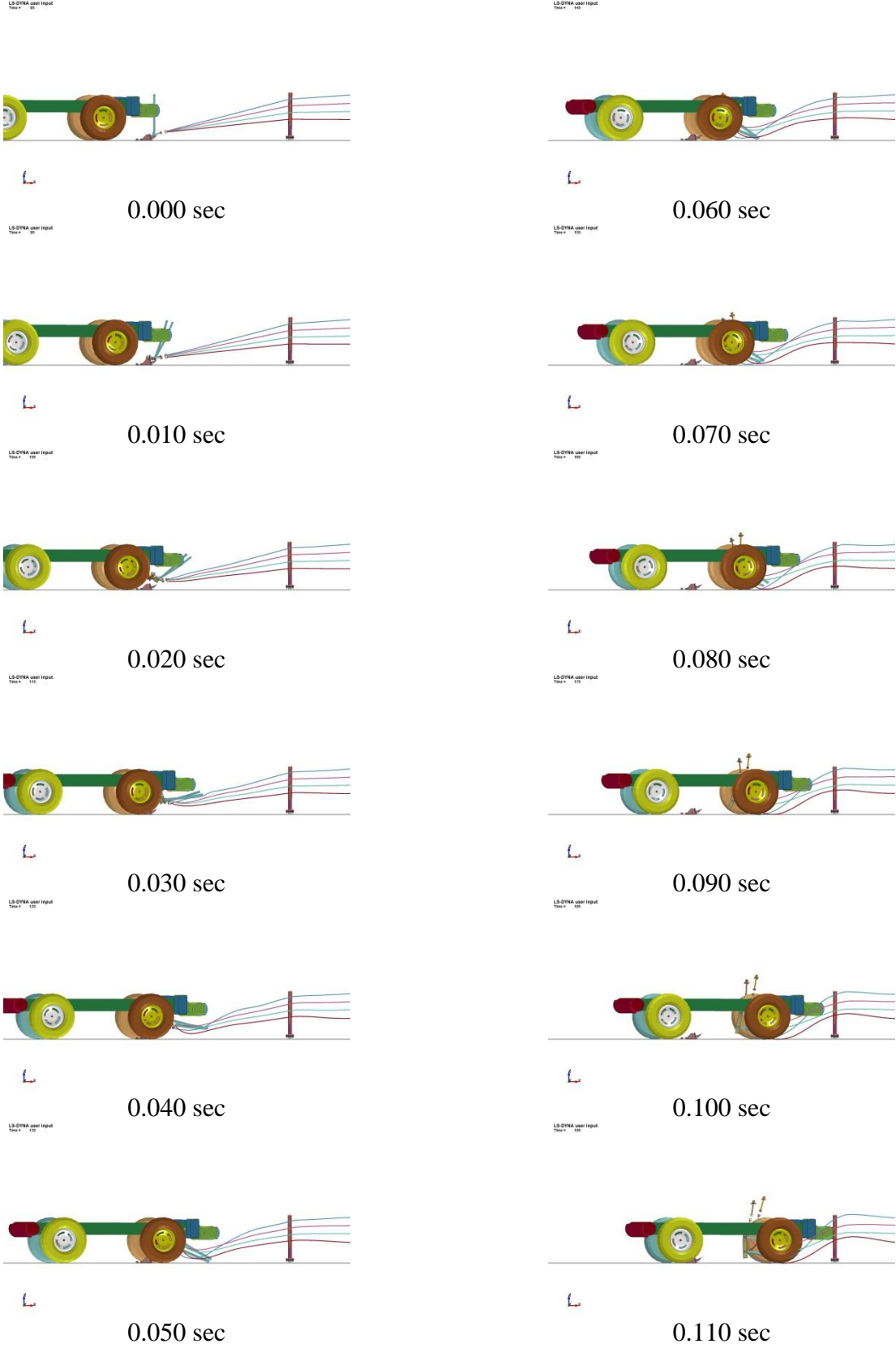
Figure 26. Sequential Photographs, Simulated Test No. 3-32
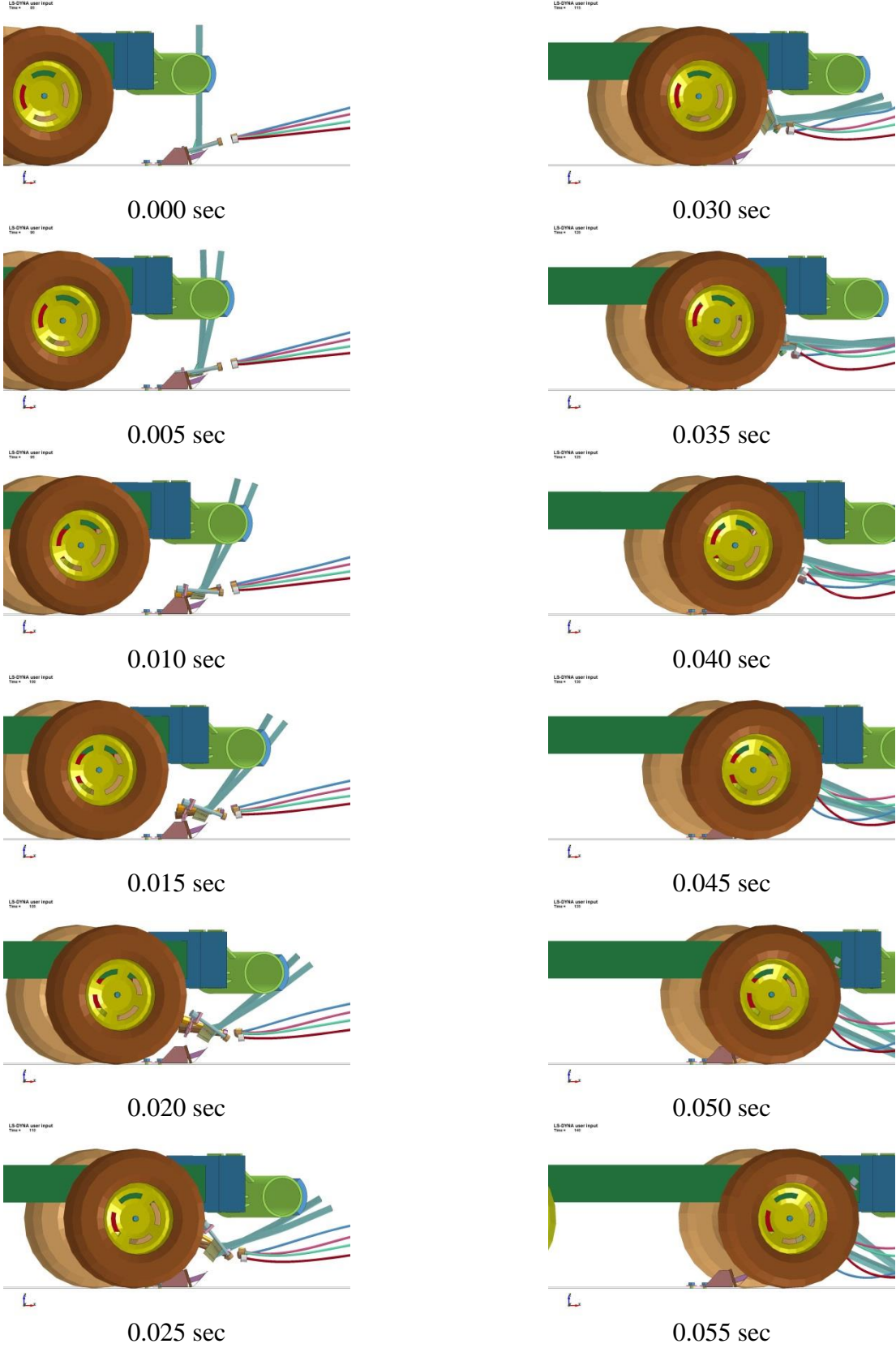
Figure 27. Sequential Photographs, Simulated Test No. 3-32

4.4 Vehicle Impact Simulations

4.4.1 25-degree Reverse Impact

The reverse direction impact utilized an 1100C small car instead of a 2270P pickup truck as it was believed to be more critical to cause vehicle instability, occupant compartment deformation and penetration, and increased occupant risk measures. These simulations were conducted using a MASH 1100C Toyota Yaris model as well as the NCHRP Report 350 820C Geo Metro model due to some model instabilities that occurred with the Yaris. The impact point selected for the initial simulations was at the mid-span between post no. 2 (slip base) and post no. 3 (the first MWP). The impact velocity was 62 mph (27.8 mm/ms) and at an angle of 25 degrees in the reverse direction.

The same end terminal system as the 0-degree and 15-degree end impacts was utilized initially for the reverse direction impact. Early on in the event, the simulation with the 1100C Yaris became unstable. When modeled with the 820C Geo model, the simulation had an error 140 ms after the initial vehicle impact. As shown in Figure 28 with the Geo model, the right front corner of the car became entrapped as the cables pulled down on the front of the car. Cable no. 1 went under the vehicle, cable no. 2 became embedded above the bumper, and cable nos. 3 and 4 were on top of the hood. Both of the models with the 1100C and 820C vehicle models exhibited the right front of the car becoming entrapped, and this entrapment likely led to model instabilities. This behavior was not desired as it could likely lead to excessive occupant risk measures and occupant compartment deformations if the car does not redirect.

The system was then updated to reflect the changes made throughout the development of the 4-cable, high-tension median barrier system. As mentioned previously, the cable heights and spacings changed during the period of this project. Therefore, these modifications were implemented in the model to accommodate the new cable heights, as the cable heights were more

likely to affect the results of the reverse direction impact rather than the results of the end-on

impacts. The cable locations at post no. 2 were also modified so that the cables were evenly

distributed on both sides of the post, rather than being located solely on one side of the post. This

post configuration is shown in Figure 29.
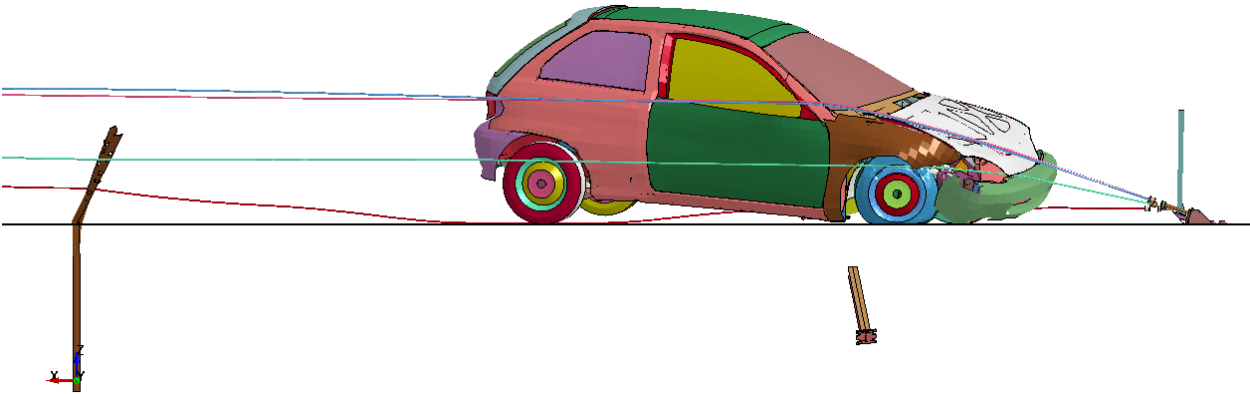
Figure 28. Initial Simulation, Modified MASH Test Designation 3-37
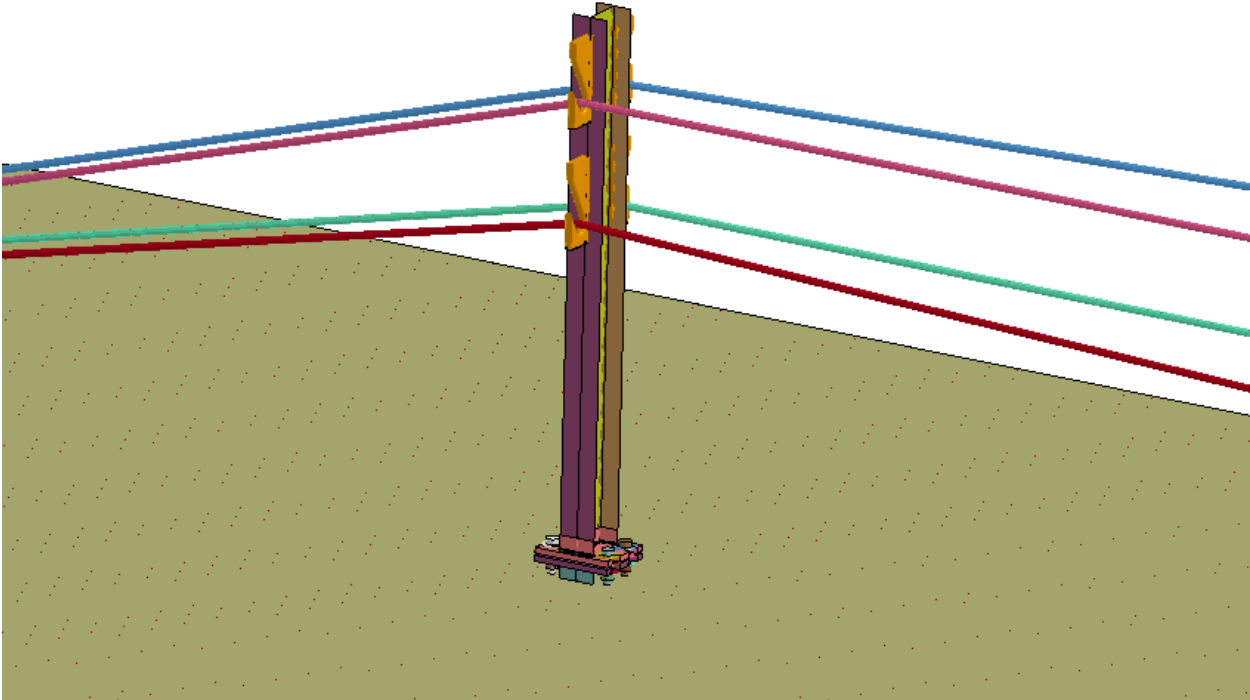
Figure 29. New Cable Configuration at Post No. 2

Further simulations were conducted with the 1100C Yaris model impacting the modified system at the midspan between post nos. 2 and 3. As shown in Figures 30 through 32, the right front of the car becomes entrapped by the cables. Shortly after impact, cable nos. 1 and 2 traversed behind the top of the right-front tire, cable no. 3 became embedded in the right-front headlight area, and cable no. 4 was on top of the hood. Post no. 2 released from the slip base, but no cables released from the cable anchor bracket. The model terminated 90 ms after the initial impact, likely due to the complex contacts in the right-front car with the cables becoming trapped in the car.

Further simulations were conducted with the 820C Geo model impacting the modified system at the midspan between post nos. 2 and 3 to further investigate vehicle interactions the terminal when impacted in the reverse direction. As shown in Figures 33 through 35, the right front of the car became entrapped by the cables. Shortly after impact, cable nos. 1 and 2 traversed behind the top of the right-front tire, and cable nos. 3 and 4 were on top of the hood. Post no. 2 released from the slip base, and cable nos. 4, 2, and 3 released at approximately 110 ms, 155 ms, and 165 ms after impact from the cable anchor bracket. Despite several of the cables releasing tension in the system, the right-front of the car became entrapped, which is likely what led to model instabilities. This behavior was not desired as it could likely lead to excessive occupant risk measures and occupant compartment deformations if the car does not redirect. Further simulations were not conducted to determine the CIP, as the impact point selected appeared to be very critical.

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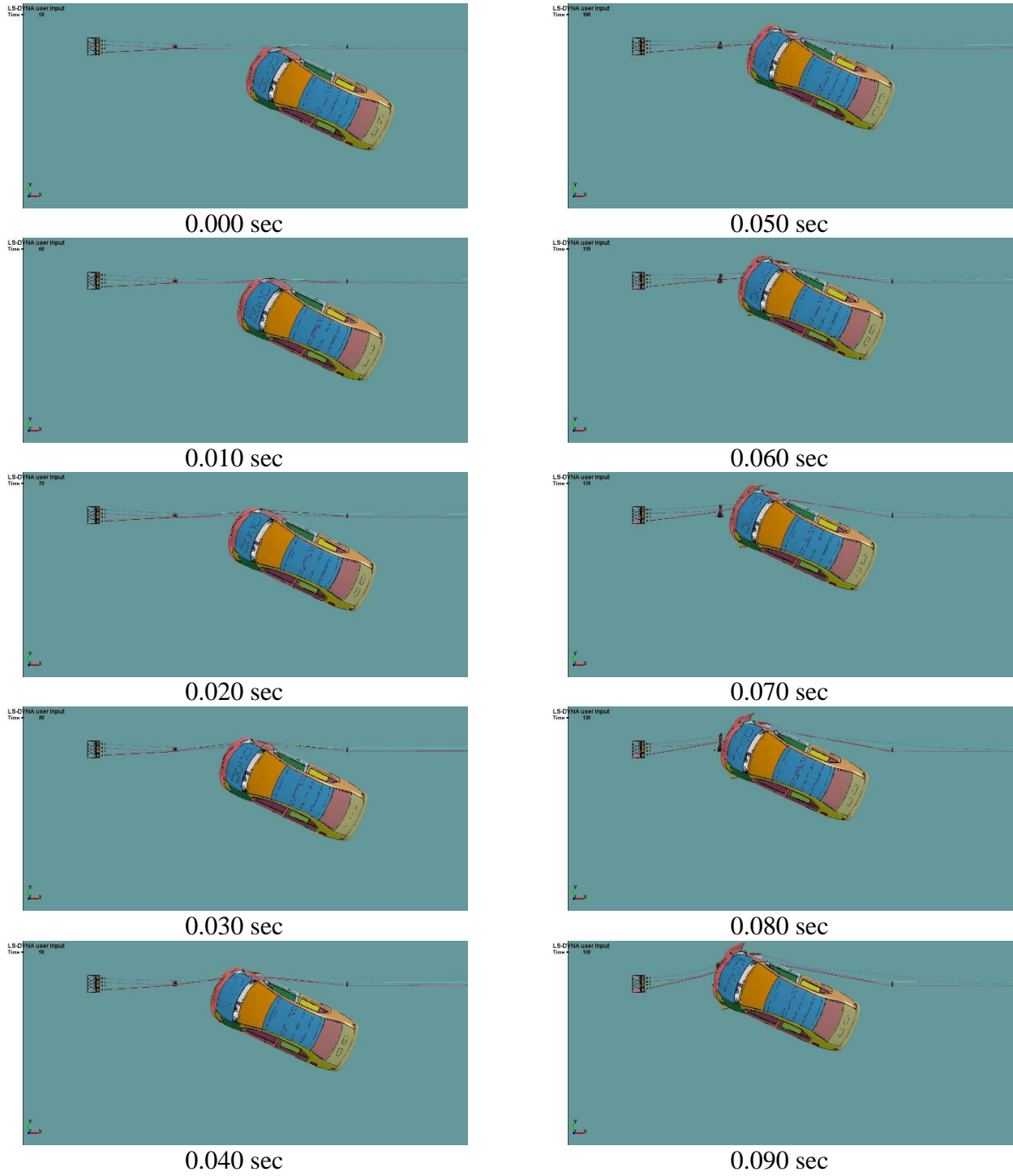
Figure 30. Sequential Photographs, Simulated Test No. 3-37, 1100C Yaris

41
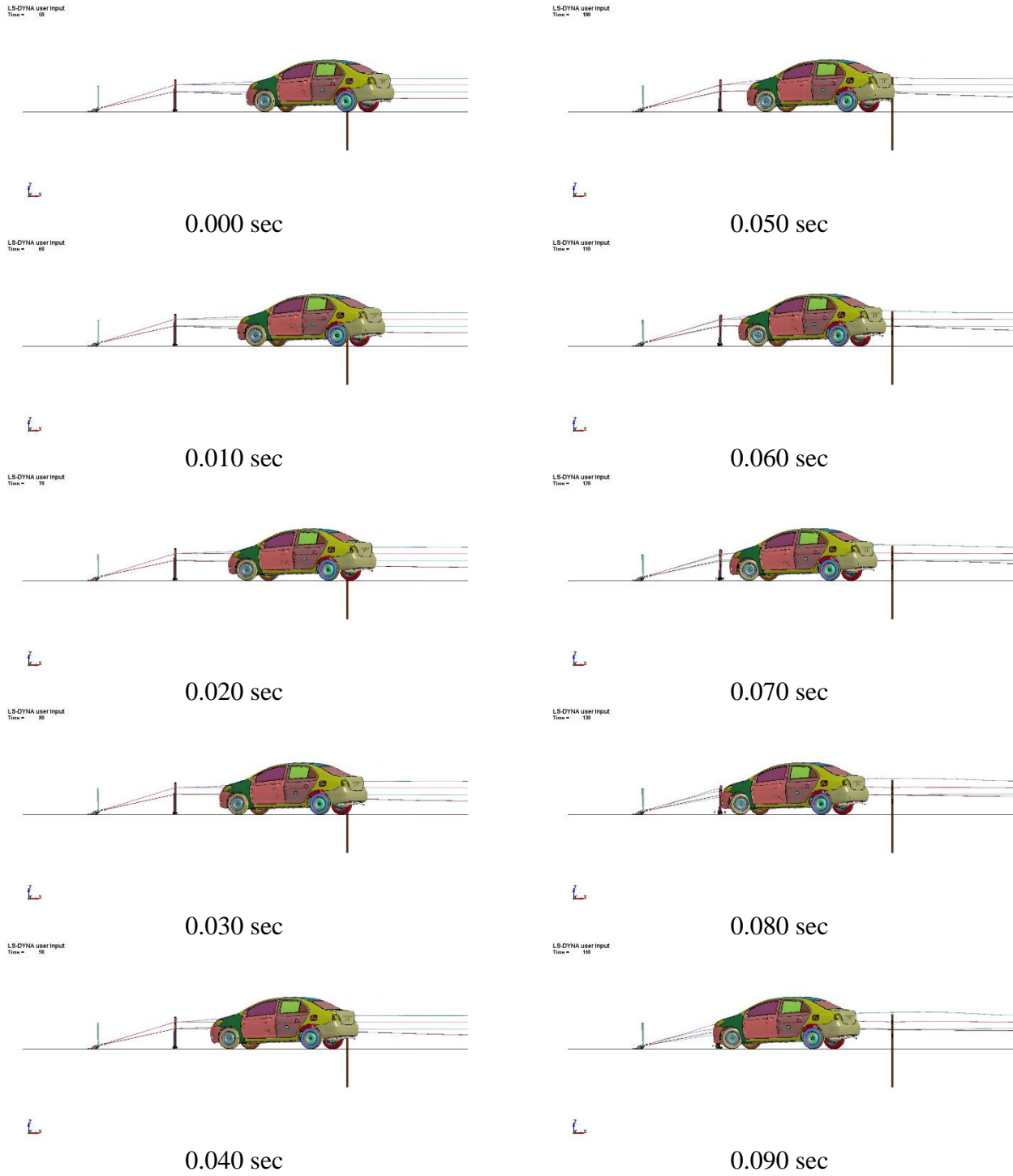
Figure 31. Sequential Photographs, Simulated Test No. 3-37, 1100C Yaris
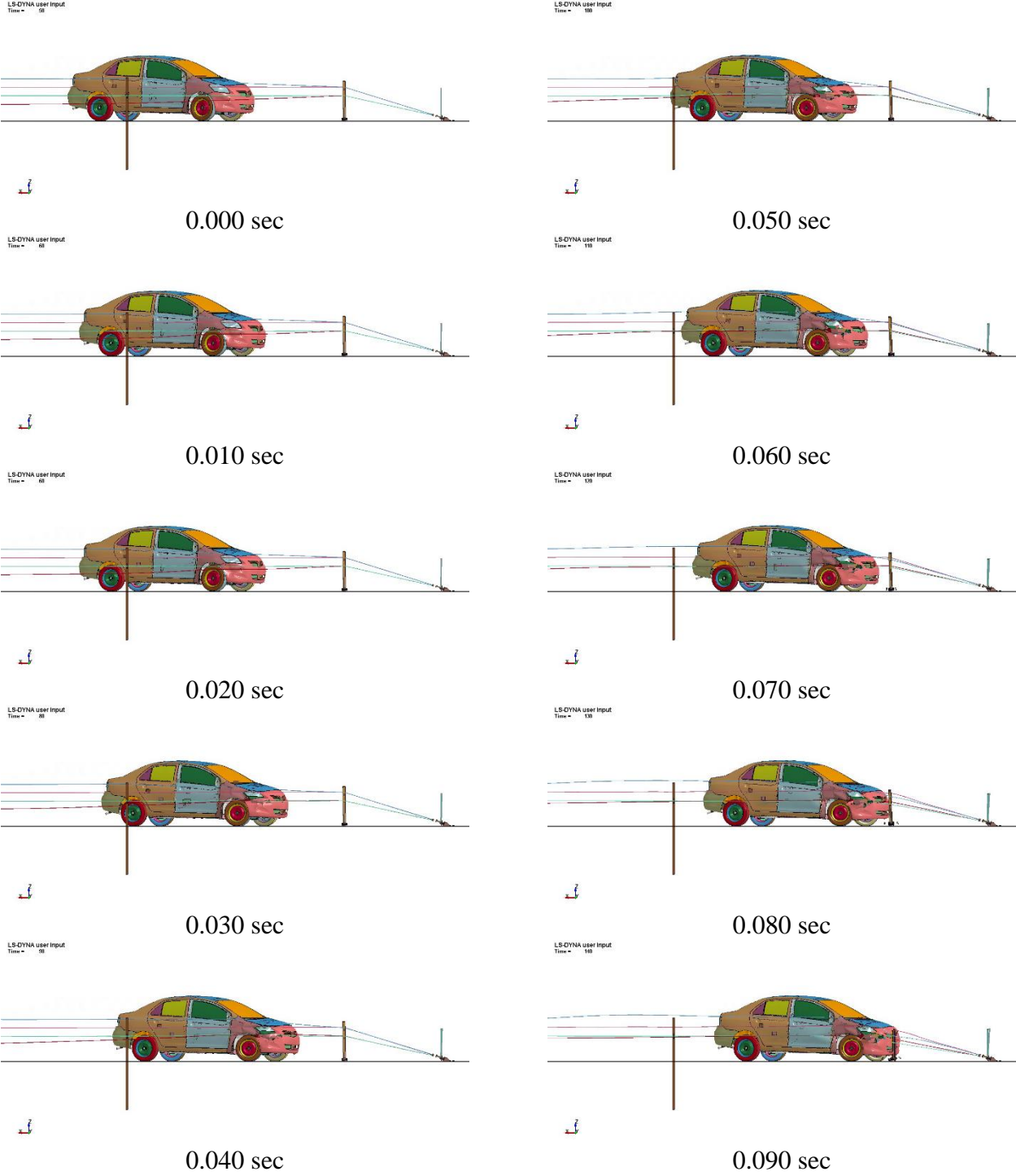
Figure 32. Sequential Photographs, Simulated Test No. 3-37, 1100C Yaris

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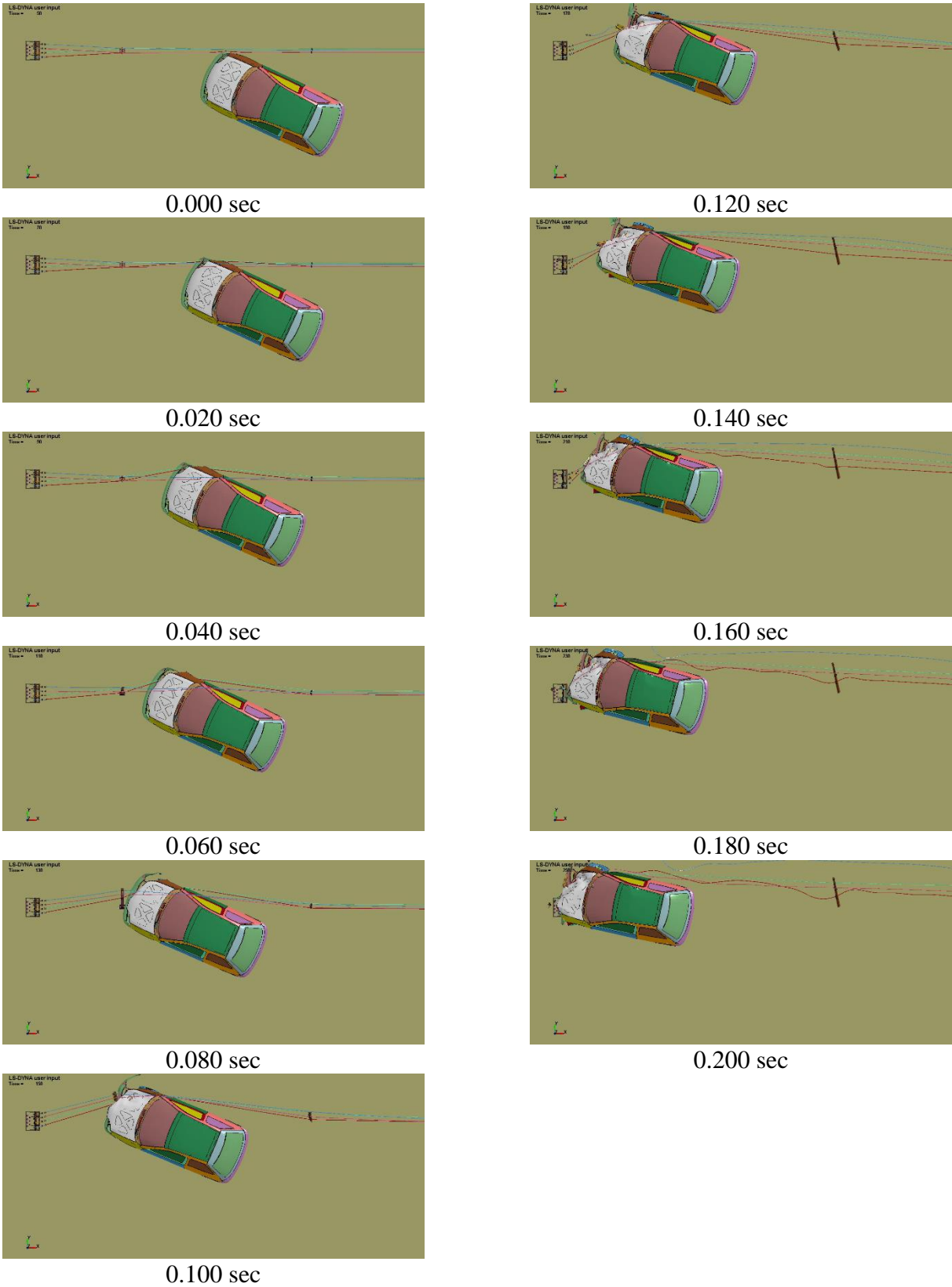
Figure 33. Sequential Photographs, Simulated Test No. 3-37, 820C Geo

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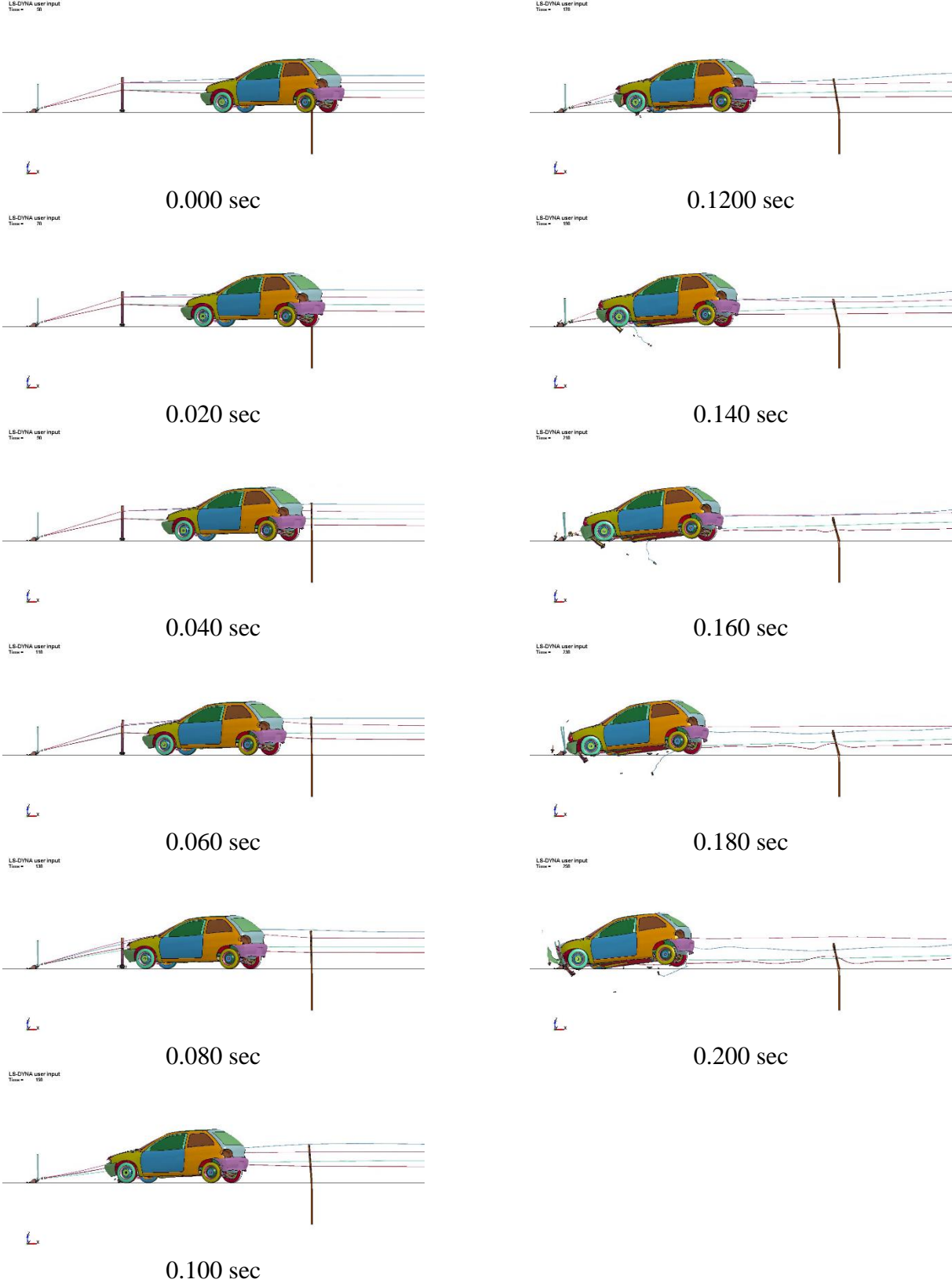
Figure 34. Sequential Photographs, Simulated Test No. 3-37, 820C Geo

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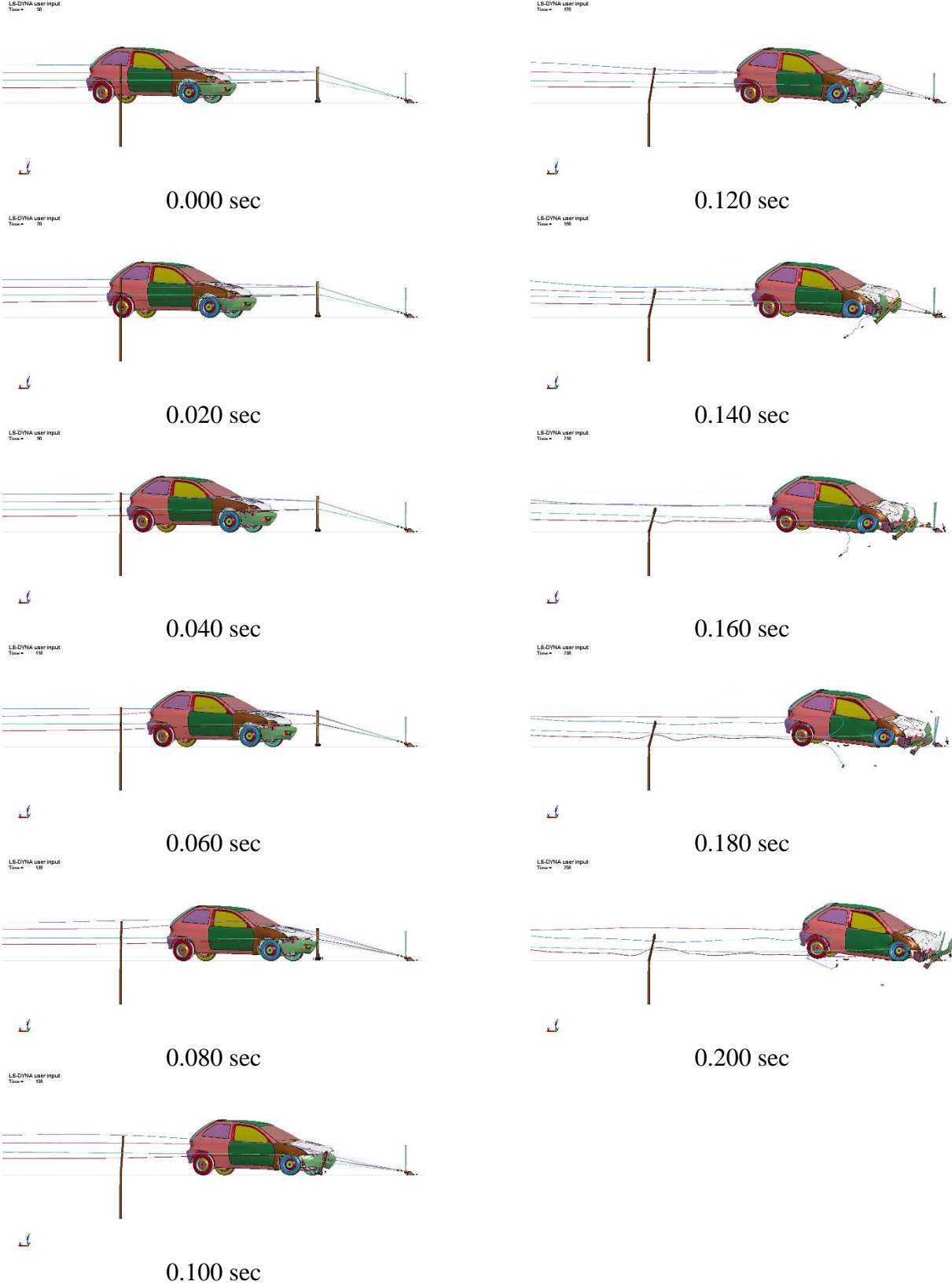
Figure 35. Sequential Photographs, Simulated Test No. 3-37, 820C Geo

4.5 Evaluation of Line Posts

Previous full-scale crash testing of the low-tension, three-cable end terminal had indicated a potential for vehicle instability due to impact with the weak axis of line posts downstream of the terminal after the cables had been released from the cable anchor bracket [1]. During test no. CT-3, the cable release mechanism performed as designed by releasing the cables. However, after the vehicle engaged the S3x5.7 (S76x8.5) posts downstream of the anchor, the front corner of the vehicle became elevated, resulting in vehicle rollover. The solution to the instability caused by the vehicle interaction with the line posts was to replace the first eight standard line posts with S3x5.7 (S76x8.5) posts with breakaway slip bases. Subsequent full-scale crash testing in tslip baseest no. CT-4 demonstrated that the use of the slip base post reduced vehicle instability and allowed for acceptable safety performance. Thus, while the S3x5.7 (S76x8.5) and MWP posts are typically termed a "weak" post, the line posts in a cable end terminal system have been shown to adversely affect vehicle stability.

In order to investigate the potential for the MWP posts in the current terminal design to cause similar instabilities, the researchers compared the section properties of the S3x5.7 (S76x8.5) post, the most recent version of the MWP post with the 1¾-in. (44.5-mm) wide flange, and modified versions of the MWP post. The modified versions of the MWP post consisted of the placement of ¾-in. (19.1-mm) diameter and 3/8-in. (9.5-mm) diameter holes in both of the webs of the post at groundline to weaken the section. The standard and modified MWP posts are shown in Figure 36.

Comparison of the section properties of the three MWP post versions and the S3x5.7 (S76x8.5) post is shown in Table 3. Examination of the post section properties led to several conclusions. First, while the MWP post was designed to have lower strong-axis (lateral) strength and similar weak-axis (longitudinal) strength to the S3x5.7 (S76x8.5), modifications to the

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design such as increasing the flange width resulted in a post with a 43 percent reduction in strong-axis section modulus, but a 14.9 percent increase in weak axis section modulus. This indicated that the potential for the MWP post to induce vehicle instability may be equal to or greater than the S3x5.7 (S76x8.5) post previously evaluated with the low-tension, three-cable end terminal. The modified MWP posts with holes in the web provided for some improvement in the weak-axis capacity of the post while maintaining most of the lateral capacity of the post section. The addition of the ¾-in. (19.05-mm) diameter and 3/8-in. (9.5-mm) diameter holes to the MWP post resulted in a reduction in strong-axis section modulus of 45.7 and 49.7 percent, respectively, as compared to the S3x5.7 (S76x8.5) post. This would correspond to a reduction in strong-axis section modulus of 4.7 and 11.7, respectively, as compared to the standard MWP post. Weak-axis capacity of the modified MWP posts was reduced more drastically. The weak-axis section modulus of the MWP post with ¾-in. (19.1-mm) diameter and 3/8-in. (9.5-mm) diameter holes were reduced 2.5 and 23.26 percent, respectively, as compared to the S3x5.7 (S76x8.5) post.

Based on this comparison of the various post section properties further investigation of the dynamic impact performance of the posts was done in LS-DYNA to determine if similar reductions could be expected during a vehicle impact. The simulations would provide performance comparisons of the standard and modified MWP post sections with to the S3x5.7 (S76x8.5) post used in the original cable end terminal design. A post design with similar strong-axis strength to the MWP post used in the current cable median barrier design and reduced weak-axis strength to reduce potential vehicle instability were desired.

a) Standard MWP Post

b) MWP Post with 3/8-in. diameter holes
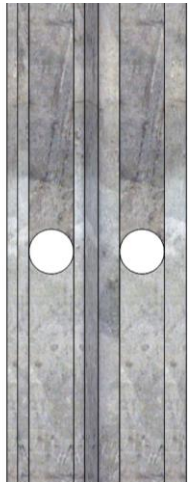
c) MWP Post with 3/4-in. diameter holes

Figure 36. Standard and Modified MWP Posts

Table 3. Post Section Properties

Post Type	Width (in.)	Depth (in.)	Thickness (in.)	A (in.^{2})	I_x (in.^{4})	S_x (in.^{3})	I_y (in.^{4})	S_y (in.^{3})	% reduction x	% reduction y
S3x5.7 Post	2.33	3.00	Varies	1.67	2.52	1.68	0.45	0.39	-	-
MWP Post - 7 gauge No Hole	1.75	3.00	0.18	1.26	1.44	0.96	0.39	0.45	43.04	-14.88
MWP Post - 7 gauge With One 3/8-in. Hole	1.75	3.00	0.18	1.13	1.37	0.91	0.33	0.38	45.70	2.45
MWP Post - 7 gauge With One 3/4-in. Hole	1.75	3.00	0.18	0.99	1.27	0.85	0.26	0.30	49.68	23.26

x = strong/lateral axis
y = weak/longitudinal axis

4.5.1 Simulation of Dynamic Post Performance

Finite element models were developed for all four of the post sections described in the previous section. A model of the S3x5.7 (S76x8.5) post was developed using solid elements with Type 2 element formulation. Type 2 solid elements were used because initial models with shell elements were not able to correctly capture the post behavior due to the varying thickness and cross-section of the "S" section post. Models of the MWP post with and without holes were created using Type 2 shell elements. The material for the S3x5.7 (S76x8.5) was specified as an ASTM A992 steel, while the MWP posts were modeled with an ASTM A1011 Grade 50 steel. All models used the MAT_PIECEWISE_LINEAR_PLASTICITY material model in LS-DYNA. All four of the simulated posts are shown in Figure 37.

A simulation model of the standard MWP post had previously been compared with dynamic component testing during its development [9], and was found to provide good correlation with physical testing. Similar comparisons were made with the S3x5.7 (S76x8.5) post and available test data. No data was available at the time of this research for comparison of the weak-axis behavior of the model. However, comparison of the force and energy versus deflection data taken from previous strong-axis testing of S3x5.7 (S76x8.5) posts, as shown in Figure 38, found that the model of the S3x5.7 (S76x8.5) post correlated well with the physical test. Because both the standard MWP and S3x5.7 (S76x8.5) post models correlated well with previous physical tests, it was believed that they could be used to investigate the weak-axis performance of the posts.

To evaluate and compare the dynamic performance of the post sections, simple impact models were made using a cylindrical impact head mounted at a 27-in. (686-mm) height, as shown in Figure 39. The impact head height, mass, and geometry corresponded with the bogie testing setup typically used at MwRSF for the evaluation of cable barrier posts. The bases of the

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posts were installed in rigid sleeves in the model to constrain their motion during impact. All of the posts were impacted at a speed of 20 mph (8.94 mm/ms).

The results from the cable terminal post simulation models are shown in sequential images in Figures 40 through 47. Comparison of the force versus deflection for the strong- and weak-axis impact simulations is shown in Figures 48 and 50, respectively. Energy versus deflection for the strong- and weak-axis impact simulations is shown in Figures 49 and 51, respectively. Finally, the tabulated results for the average forces at various deflections from the simulations of the four post types in the strong and weak-axis are shown in Table 4.

Review of the simulation results found the standard and modified MWP posts provided reductions in both the strong and weak-axis capacities of the post that corresponded well with the reductions anticipated from the comparison of the post section properties. The strong-axis simulations found that all four post sections hinged at the groundline, and the presence of the holes in the webs of two of the post sections did not change the hinging of the post. The S3x5.7 post demonstrated roughly twice the force and energy levels displayed by the standard and modified MWP posts. The strong axis of the modified MWP posts with holes did display slightly lower strong-axis forces and energies as compared to the standard MWP post, but the reductions were minor. This would suggest that incorporation of the holes in the web of the MWP post would have minimal effect on the lateral stiffness of the cable median barrier.

Comparisons were also made regarding the weak-axis post simulations. Similar to the strong-axis simulations, all four post sections hinged about the groundline as expected, and the presence of the holes in the webs of two of the post sections did not change the hinging of the post. The standard MWP post exhibited average forces and energies that were only slightly lower than the S3x5.7 (S76x8.5) post. Incorporation of the 3/8-in. (9.5-mm) diameter holes in the web of the MWP post only moderately reduced the weak-axis average force and energy levels as

compared to the S3x5.7 (S76x8.5) post and the standard MWP post. The addition of 3/4-in.

(19.1-mm) diameter holes provided a more significant drop with average forces dropping

approximately 20 to 25 percent levels as compared to the S3x5.7 (S76x8.5) post and the standard

MWP post. Thus, it appeared that the modified MWP with 3/4-in. (19.1-mm) diameter holes in

the web may provide the best combination of maintaining a lateral strength similar to the

standard MWP post while reducing the weak-axis capacity to improve vehicle stability.

a) S3x5.7   b) Standard MWP

c) MWP with 3/8-in. Hole   d) MWP with 3/4-in. Hole
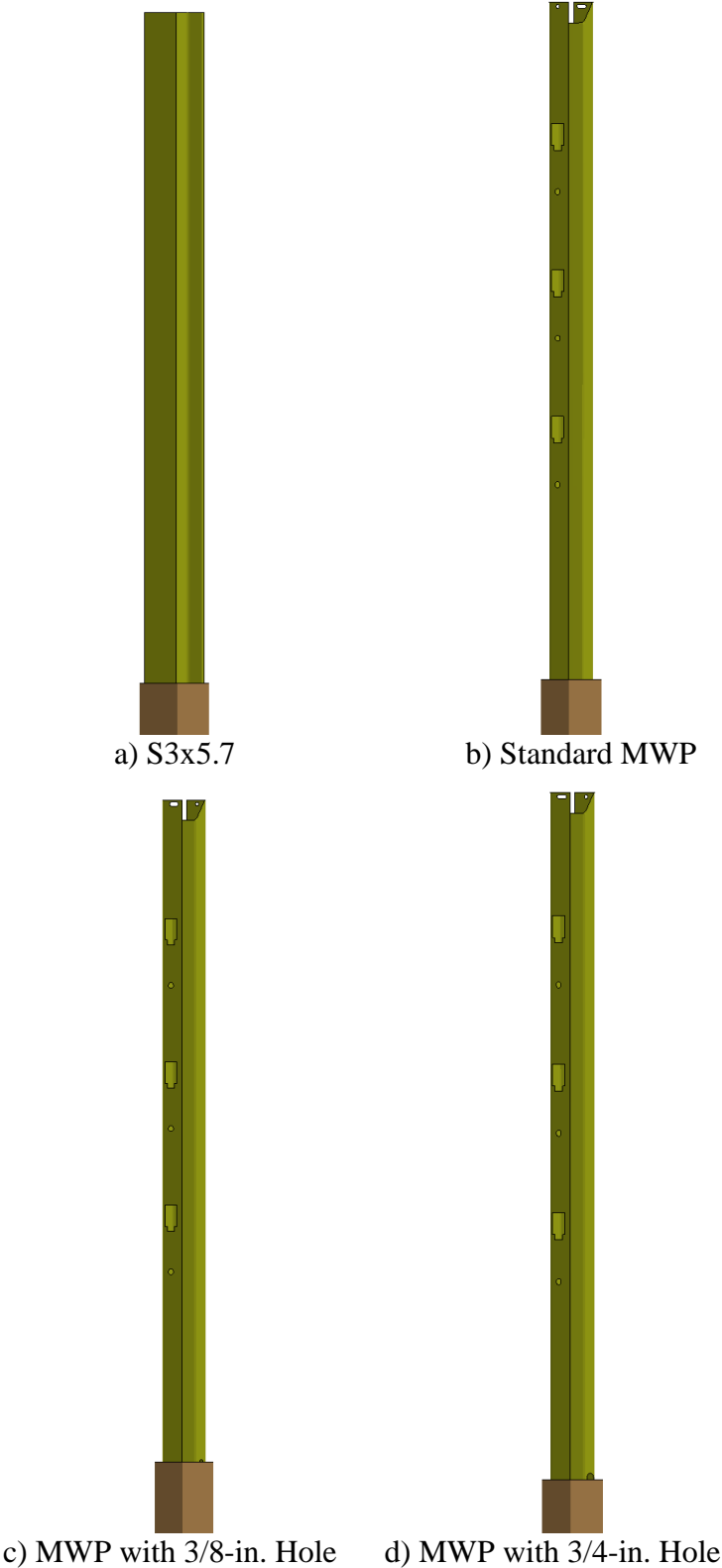
Figure 37. Cable End Terminal Post Models
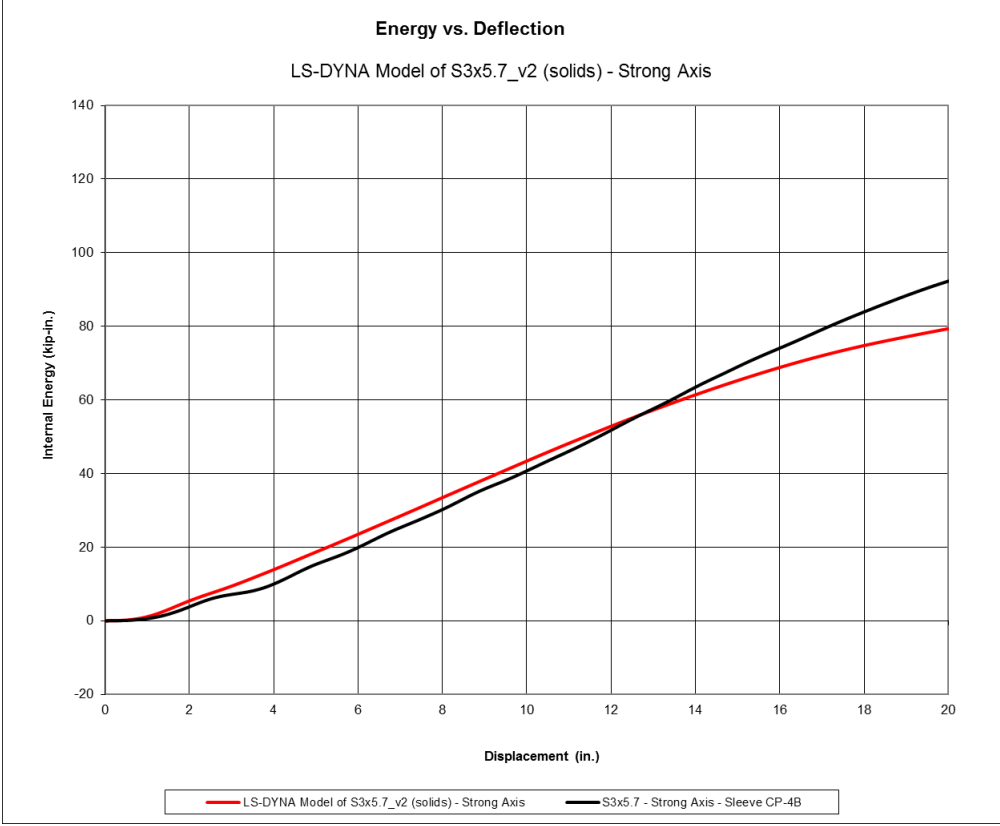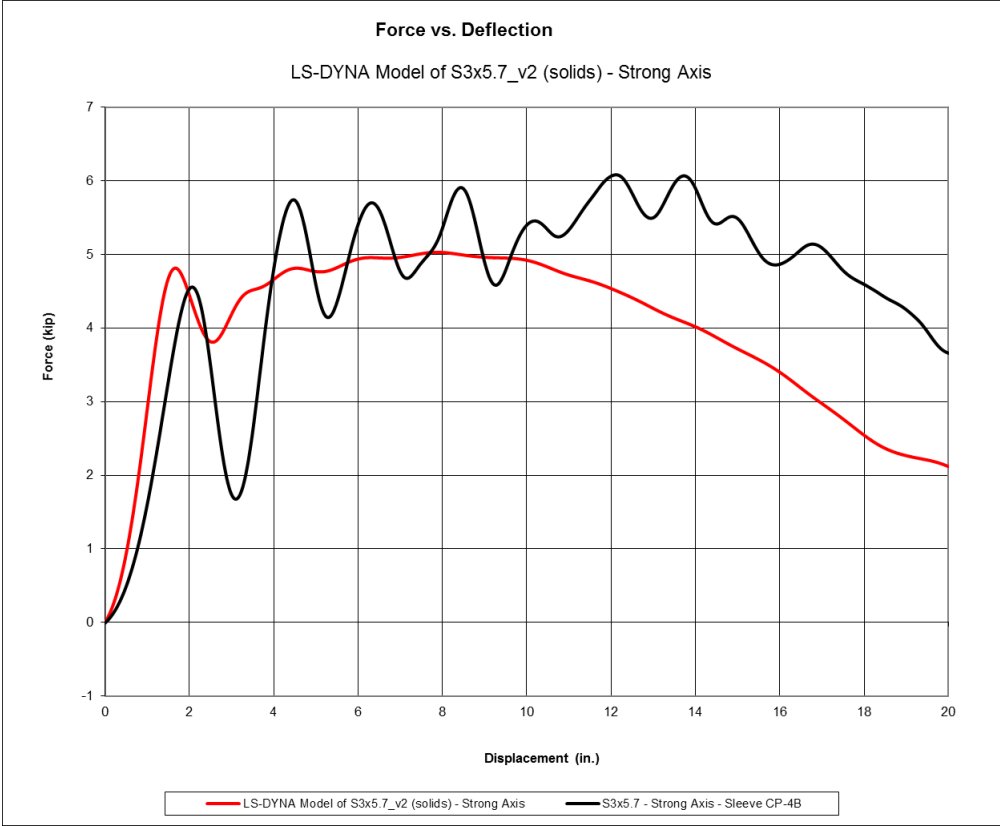
Figure 38. Comparison of S3x5.7 Post with Dynamic Test Data
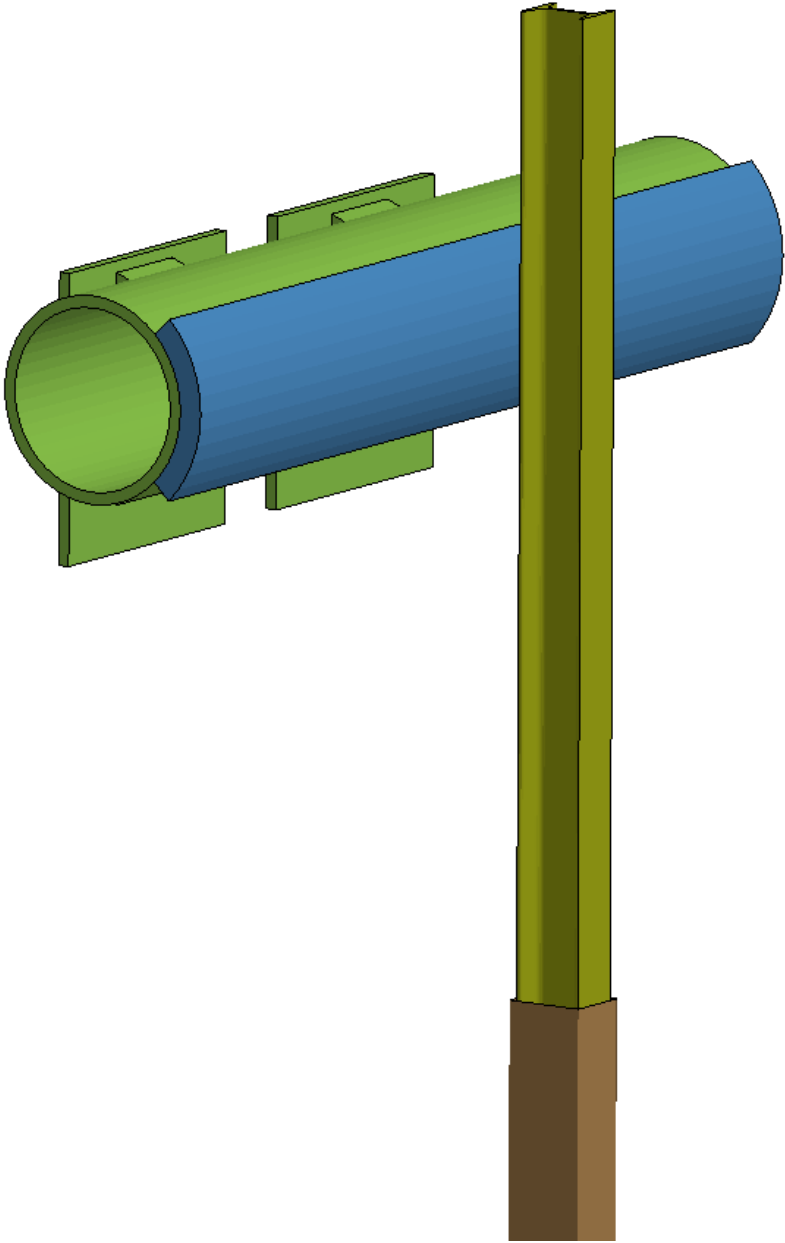
Figure 39. Cable End Terminal Posts, Typical Dynamic Impact Model Configuration
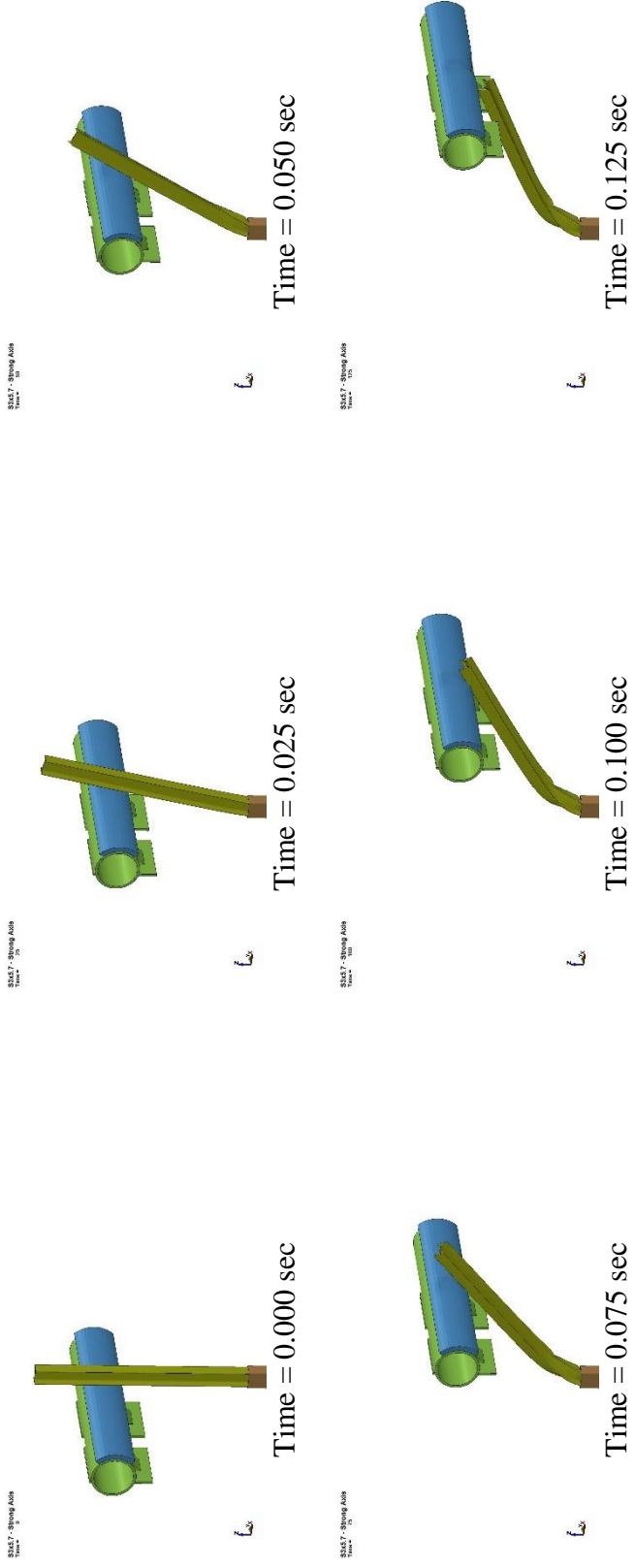
Figure 40. Sequential Images, S3x5.7 Strong-Axis Post Impact Simulation

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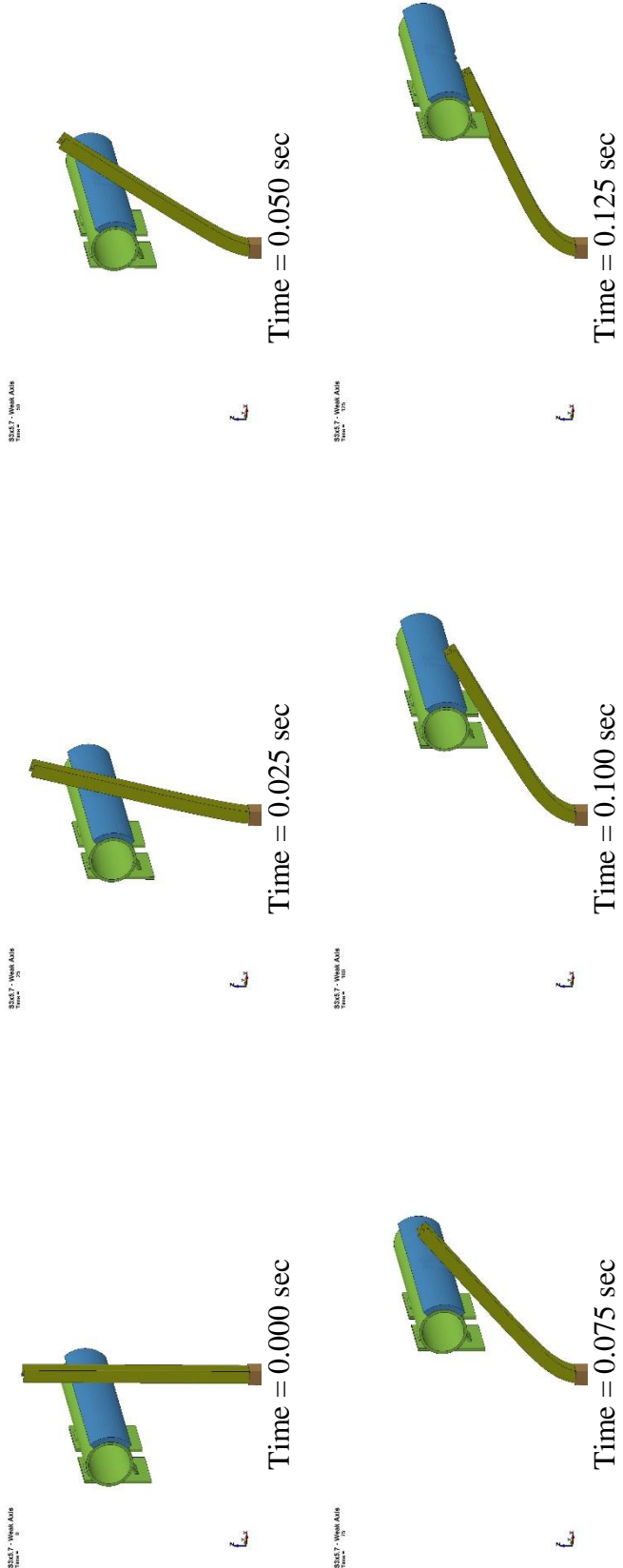
Figure 41. Sequential Images, S3x5.7 Weak-Axis Post Impact Simulation
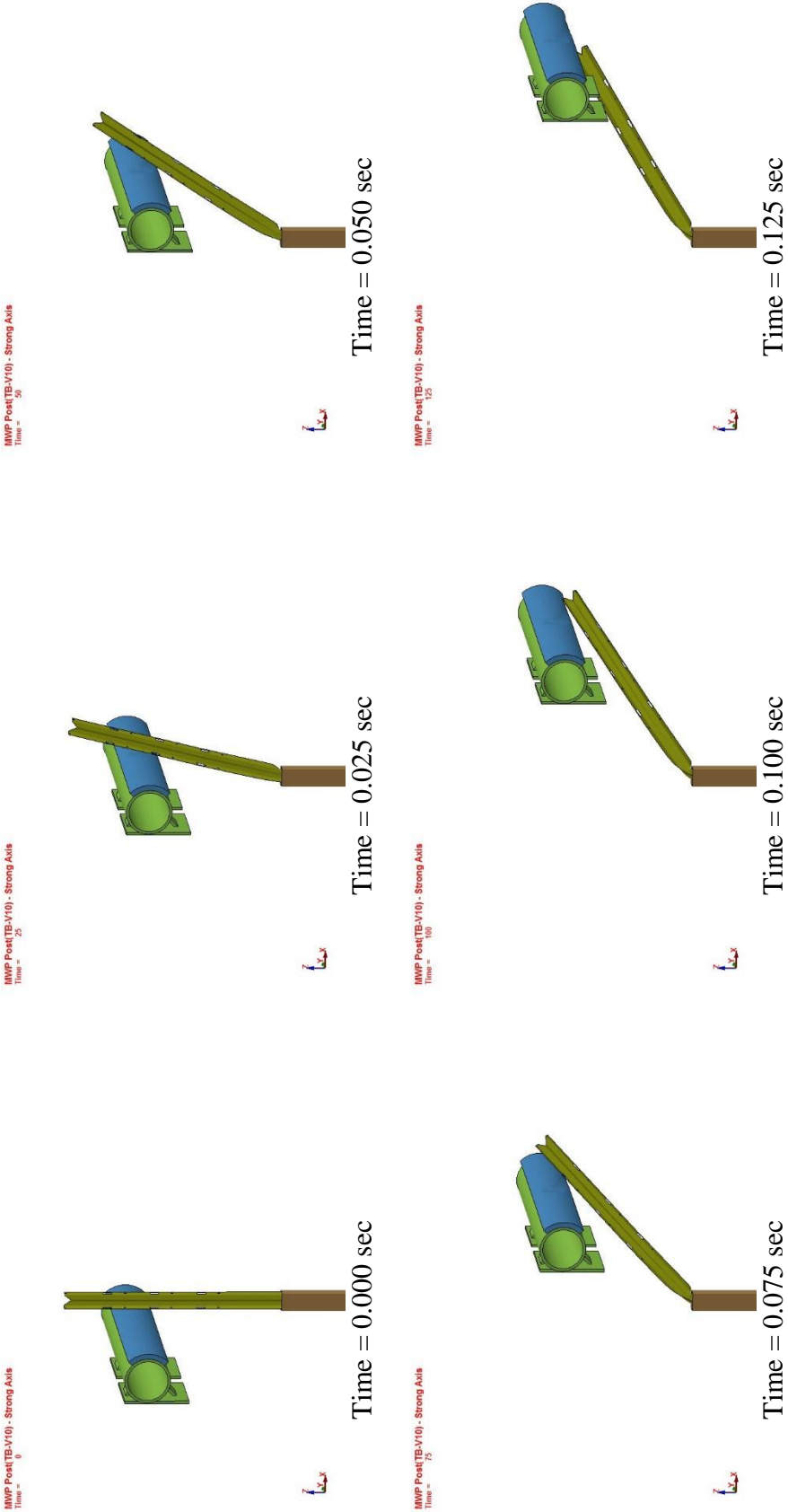
Figure 42. Sequential Images, MWP Strong-Axis Post Impact Simulation
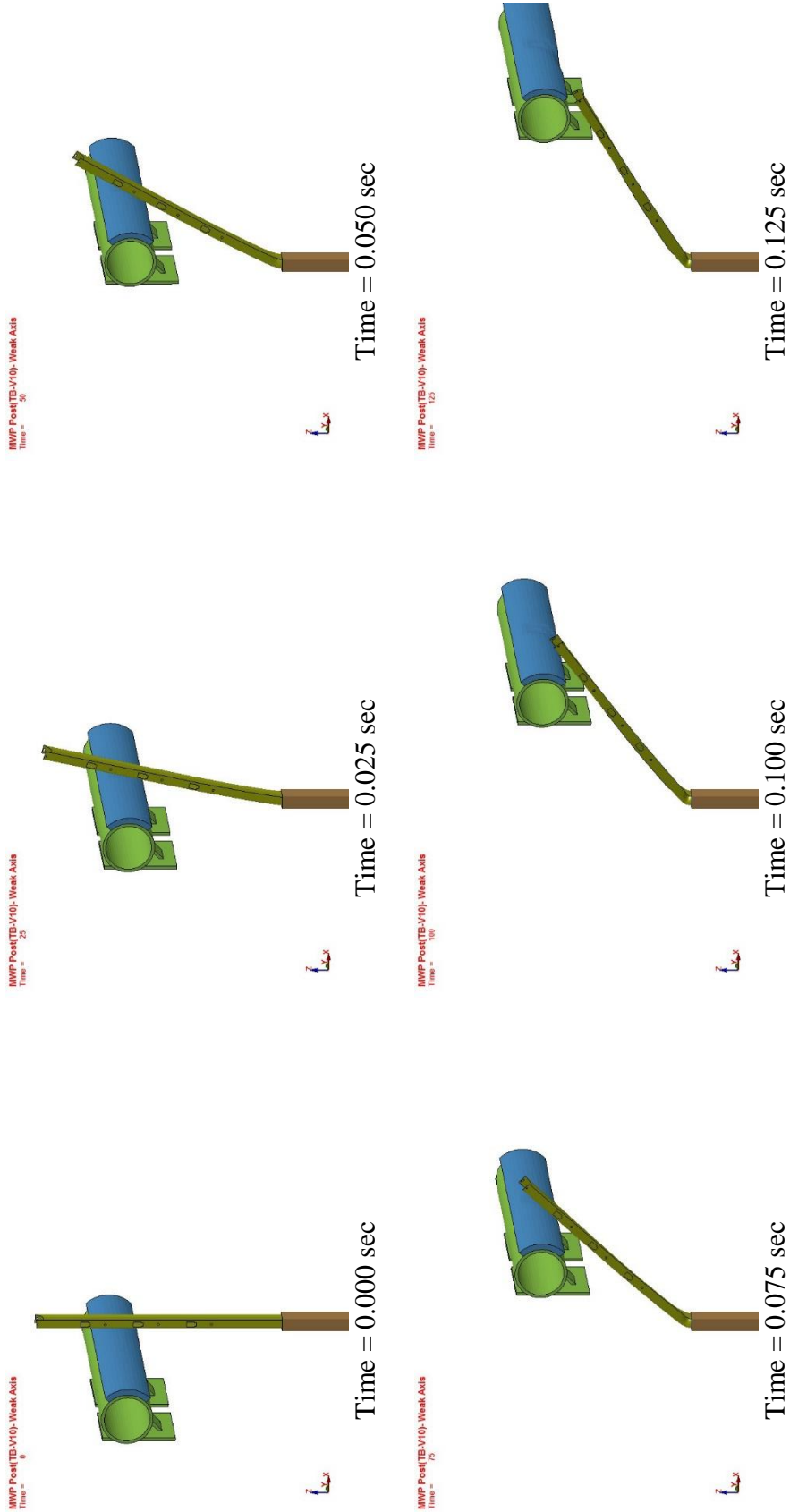
Figure 43. Sequential Images, MWP Weak-Axis Post Impact Simulation
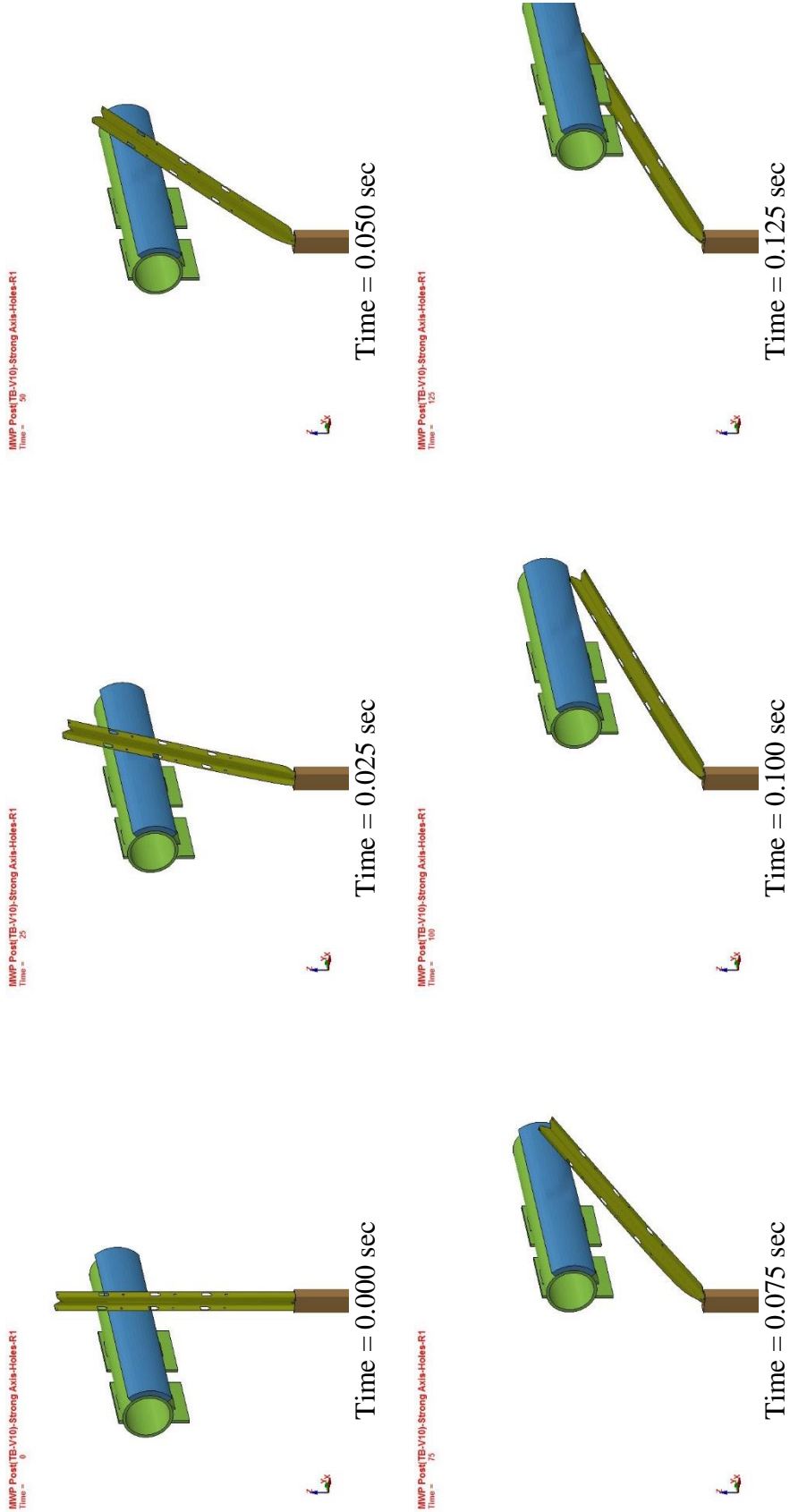
Figure 44. Sequential Images, MWP with 3/8-in. Hole Strong-Axis Post Impact Simulation
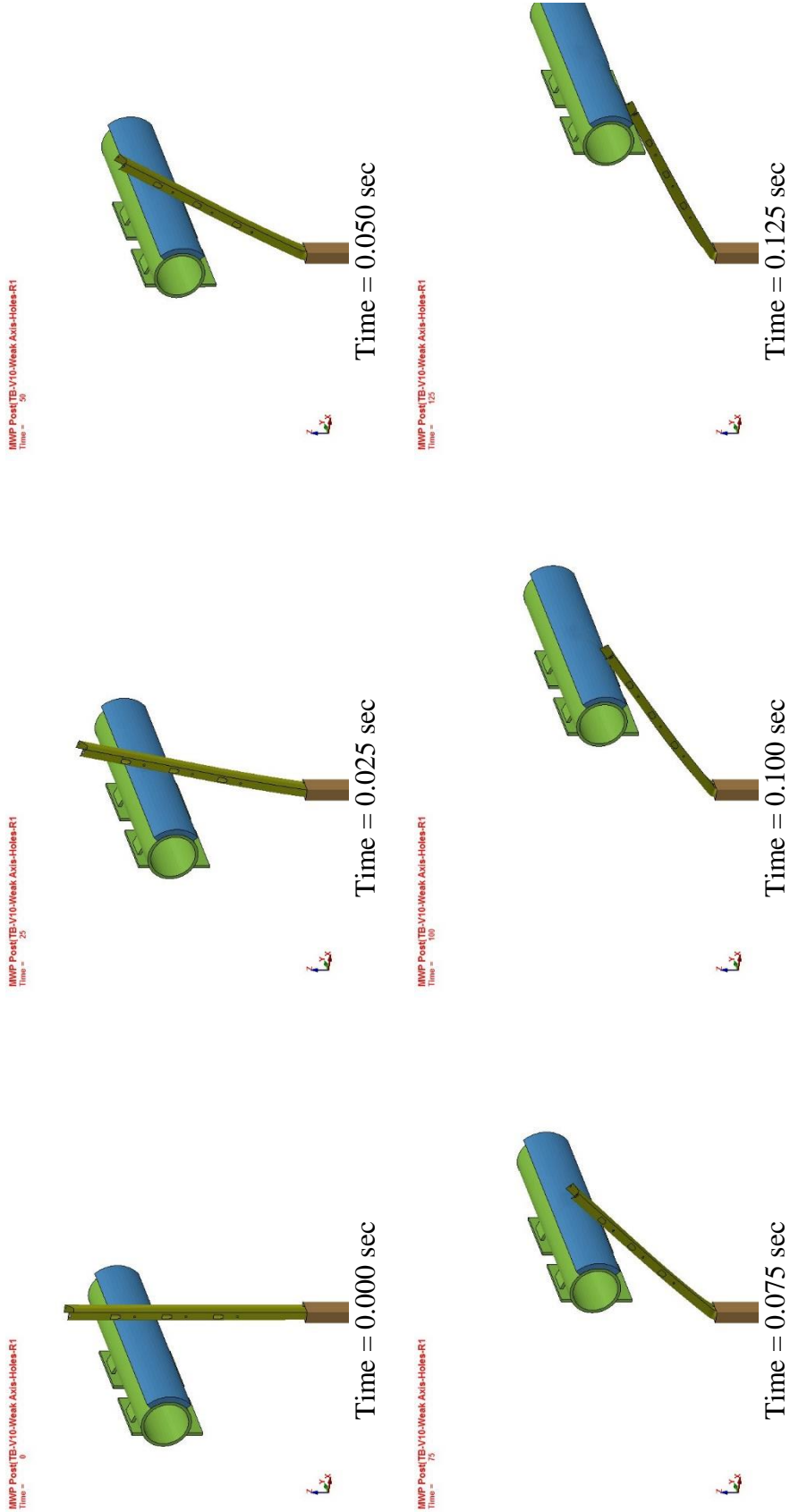
Figure 45. Sequential Images, MWP with 3/8-in. Hole Weak-Axis Post Impact Simulation
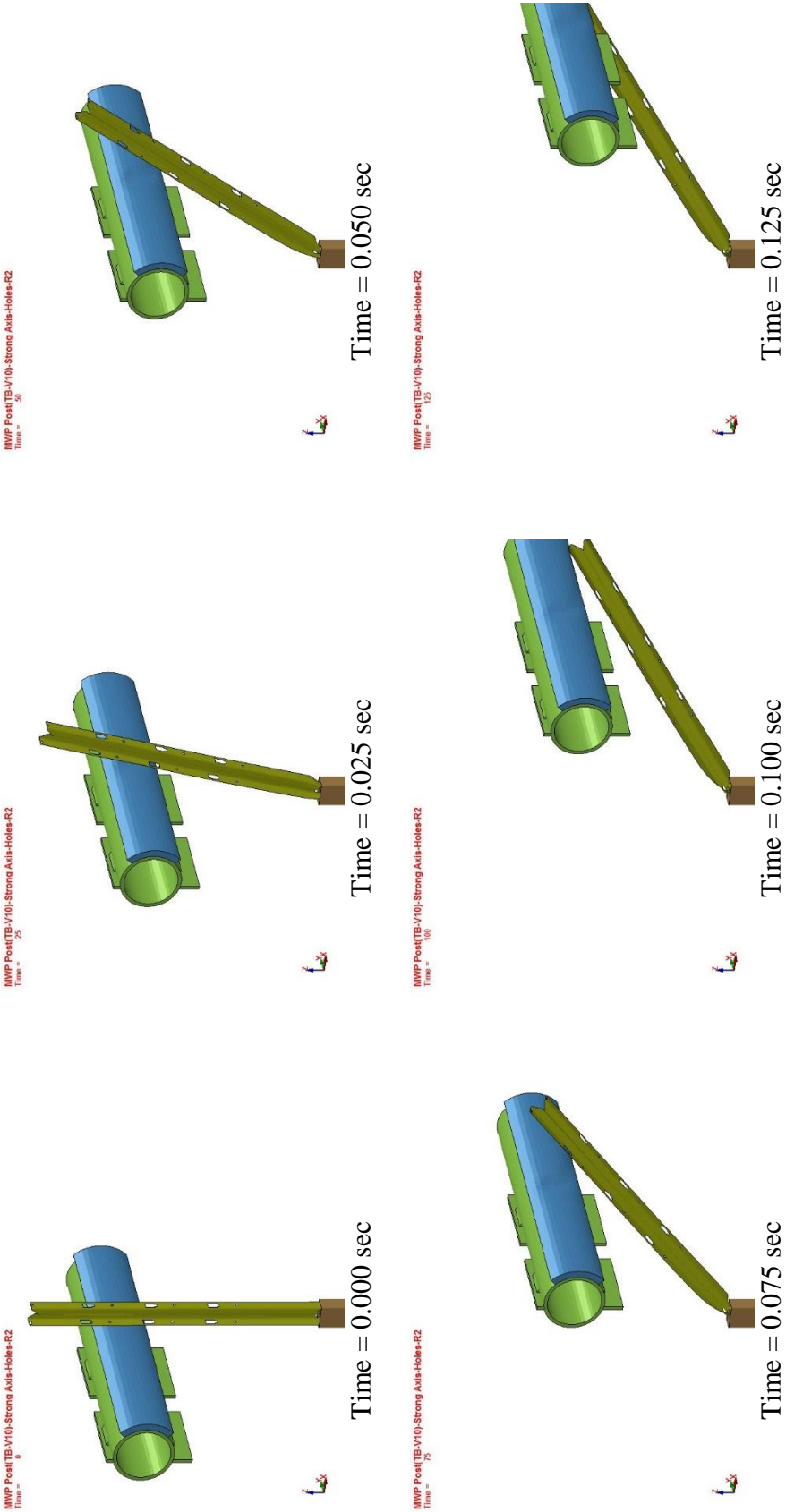
Figure 46. Sequential Images, MWP with 3/4-in. Hole Strong-Axis Post Impact Simulation
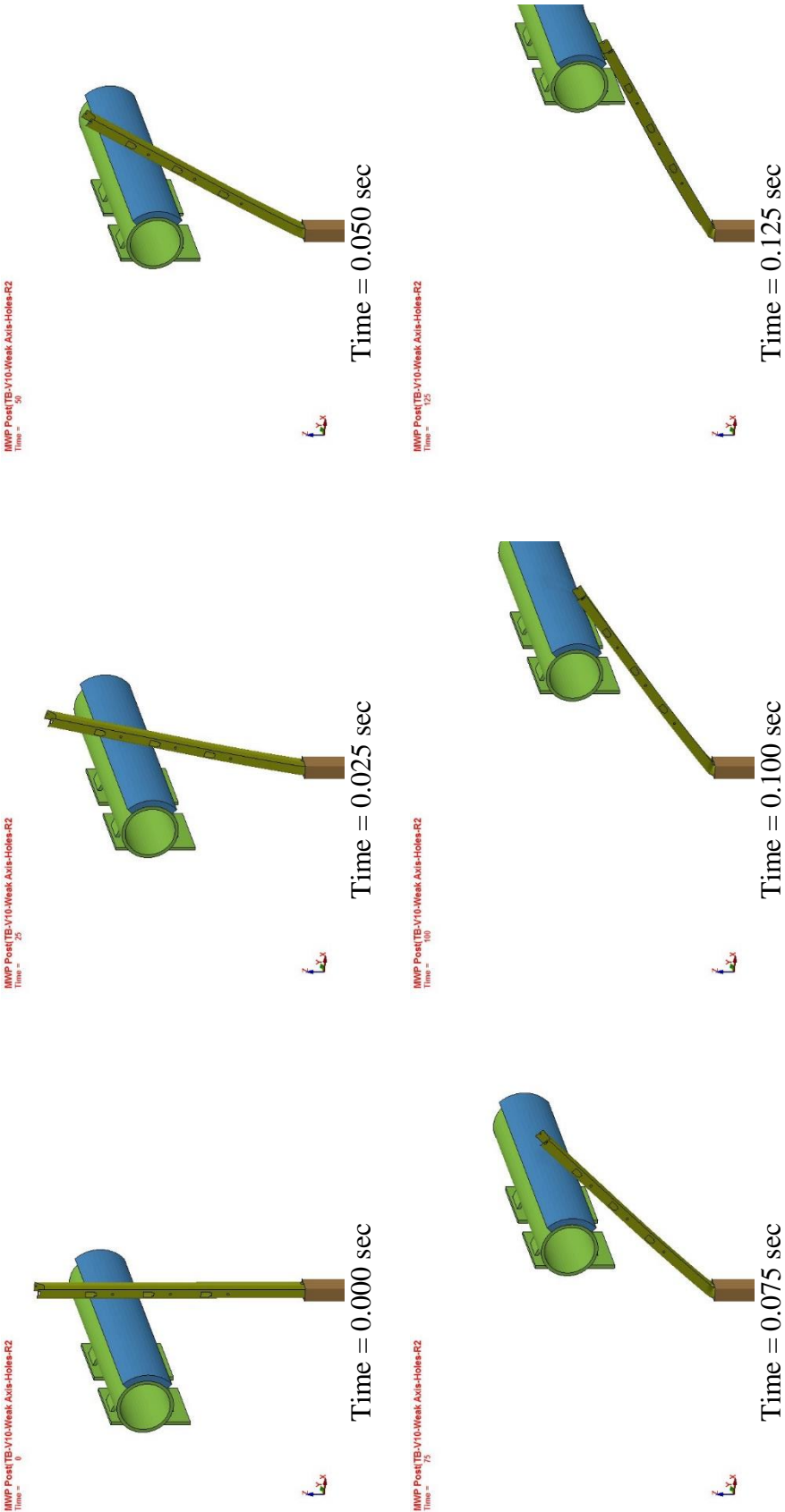
Figure 47. Sequential Images, MWP with 3/4-in. Hole Weak-Axis Post Impact Simulation
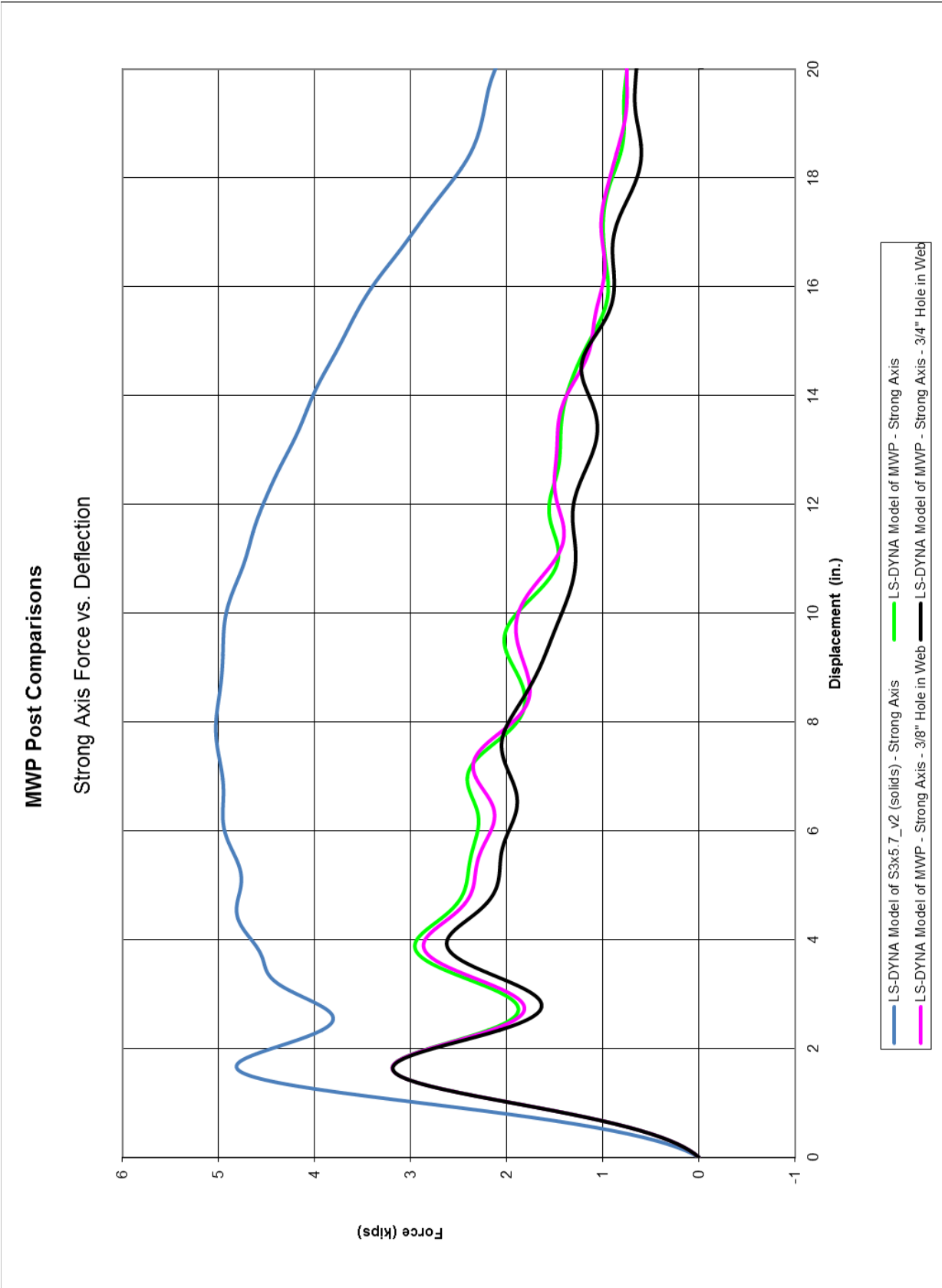
Figure 48. Cable End Terminal Post Strong-Axis Force vs. Deflection
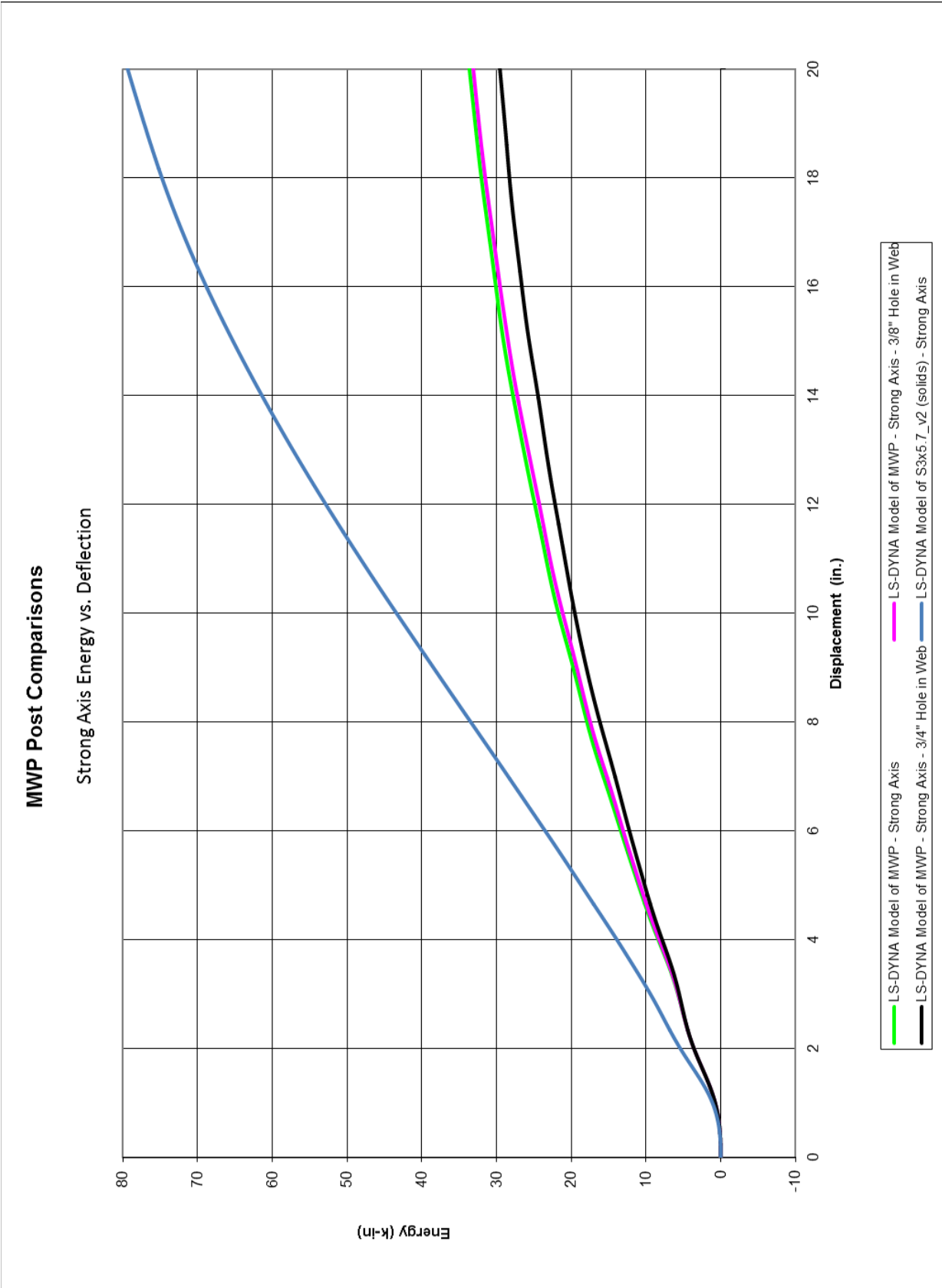
Figure 49. Cable End Terminal Post Strong-Axis Energy vs. Deflection
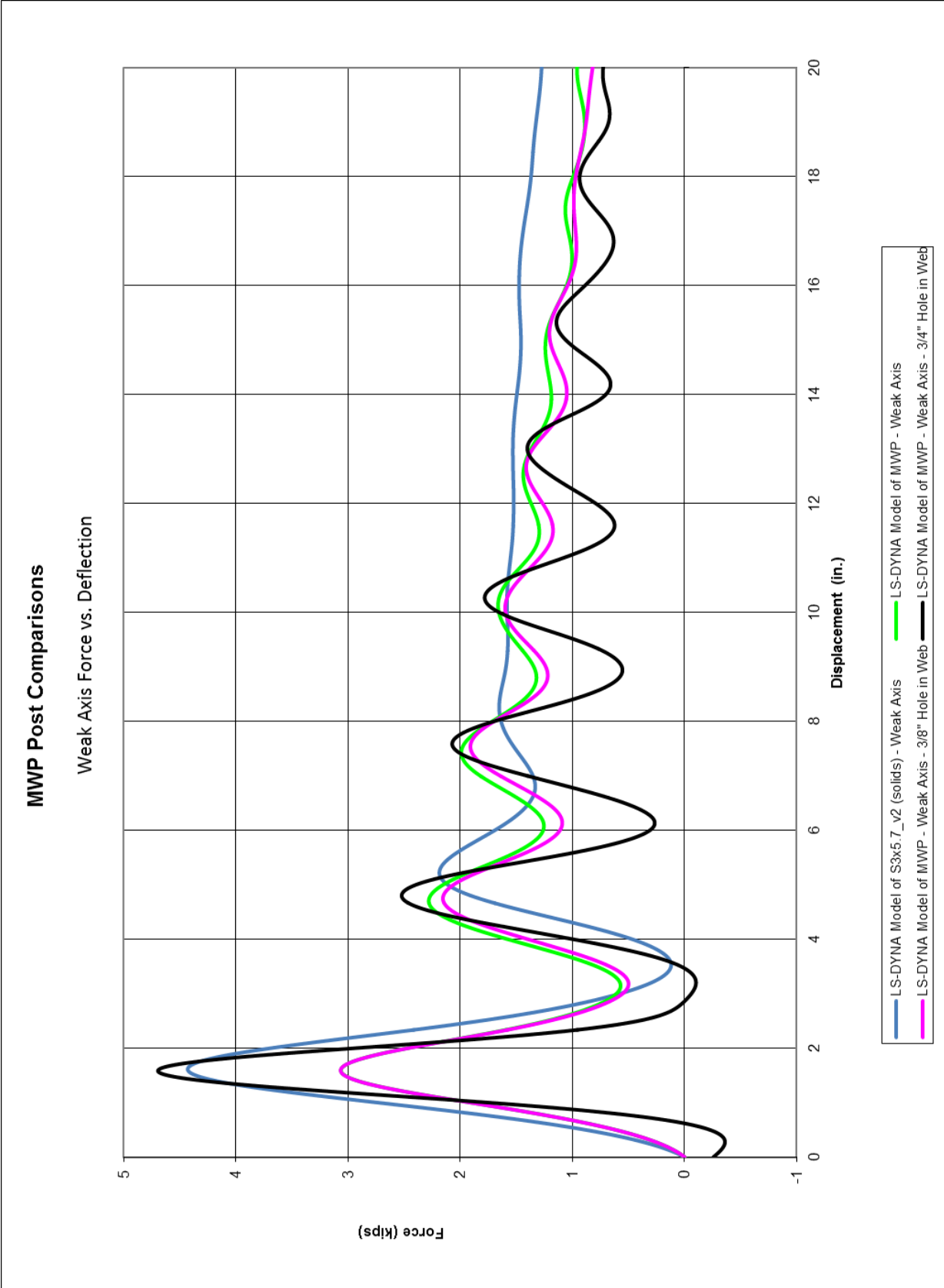
Figure 50. Cable End Terminal Post Weak-Axis Force vs. Deflection
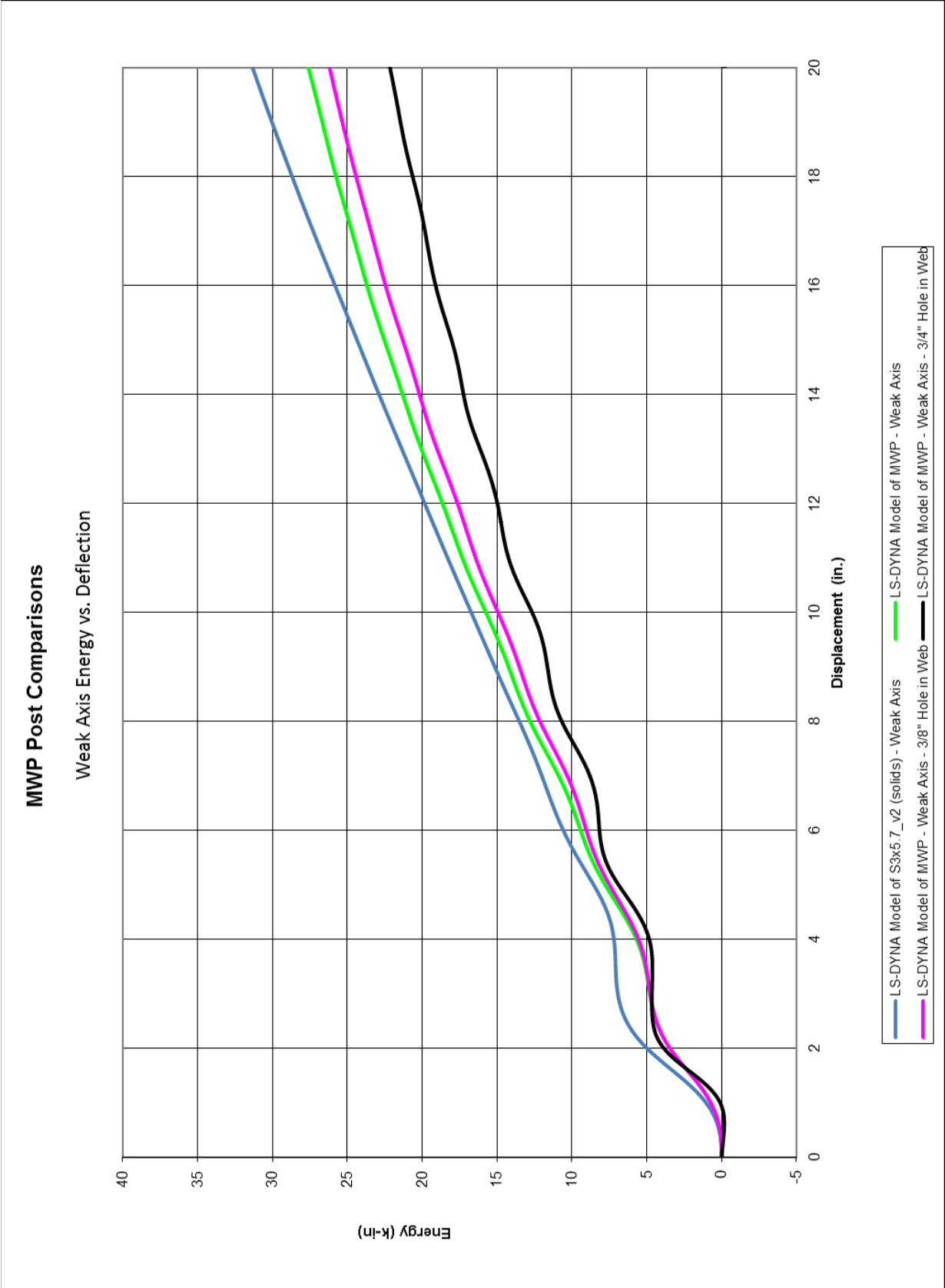
Figure 51. Cable End Terminal Post Weak-Axis Energy vs. Deflection

Table 4. Cable End Terminal Post Simulation Average Forces

			Cable End Terminal Post Average Forces – Strong Axis					
Post Type	Impact Axis	Bumper Height (in.)	Average Force @ 5" (kips)	% Difference	Average Force @ 10" (kips)	% Difference	Average Force @ 15" (kips)	% Difference
S3x5.7	Strong	27	3.73	-	4.34	-	4.35	-
MWP	Strong	27	2.20	-41.07	2.17	-49.91	1.94	-55.45
MWP 3/8" Hole	Strong	27	2.16	-42.24	2.11	-51.27	1.90	-56.39
MWP 3/4" Hole	Strong	27	2.04	-45.48	1.95	-54.99	1.71	-60.70

			Cable End Terminal Post Average Forces – Weak Axis					
Post Type	Impact Axis	Bumper Height (in.)	Average Force @ 5" (kips)	% Difference	Average Force @ 10" (kips)	% Difference	Average Force @ 15" (kips)	% Difference
S3x5.7	Weak	27	1.71	-	1.67	-	1.62	-
MWP	Weak	27	1.56	-8.95	1.58	-5.87	1.50	-7.48
MWP 3/8" Hole	Weak	27	1.50	-12.33	1.49	-10.71	1.42	-12.55
MWP 3/4" Hole	Weak	27	1.38	-19.44	1.27	-24.29	1.20	-25.94

4.5.1 Vehicle Stability Simulations

In order to further evaluate the performance of the cable end terminal posts, the researchers attempted to conduct simulations of small car passenger vehicles overriding a line of posts with a ¼-point offset similar to MASH test designation 3-30. The purpose of the simulation of the vehicle overriding these posts would demonstrate the potential for inducing vehicle instability posed by various end terminal posts.

The simulation investigation began with both the Toyota Yaris 1100C and Geo Metro 820C vehicles impacting a line of S3x5.7 (S76x8.5) posts at 16 ft (4.88 m) post spacing. The line of posts was impacted at a speed of 62.1 mph (100 km/h) and an angle of 0 degrees with a ¼-point offset from the centerline of the bumper. S3x5.7 (S76x8.5) posts were selected for the initial simulations because they had demonstrated the ability to induce vehicle instability during the three-cable, low-tension end terminal development. Thus, simulation of impacts into a line of the S3x5.7 (S76x8.5) posts should demonstrate similar induced instability in the small car vehicles provide a baseline for comparison with the other post types.

The results from the simulation of both the Yaris and Geo Metro vehicle models impacting a line of S3x5.7 (S76x8.5) posts are shown in sequential images in Figure 52 and Figure 53, respectively. Neither vehicle demonstrated any significant vehicle instability when impacting the line of S3x5.7 (S76x8.5) posts. This was problematic as the results did not correlate with the excessive roll and vehicle instability induced by these posts in test no. CT-3. The reasons for the inability of the simulation model to induce vehicle instability were not able to be identified during this study. Thus, further investigation of the standard and modified MWP post was not attempted, and conclusions regarding their ability to reduce vehicle instability were not able to be made.
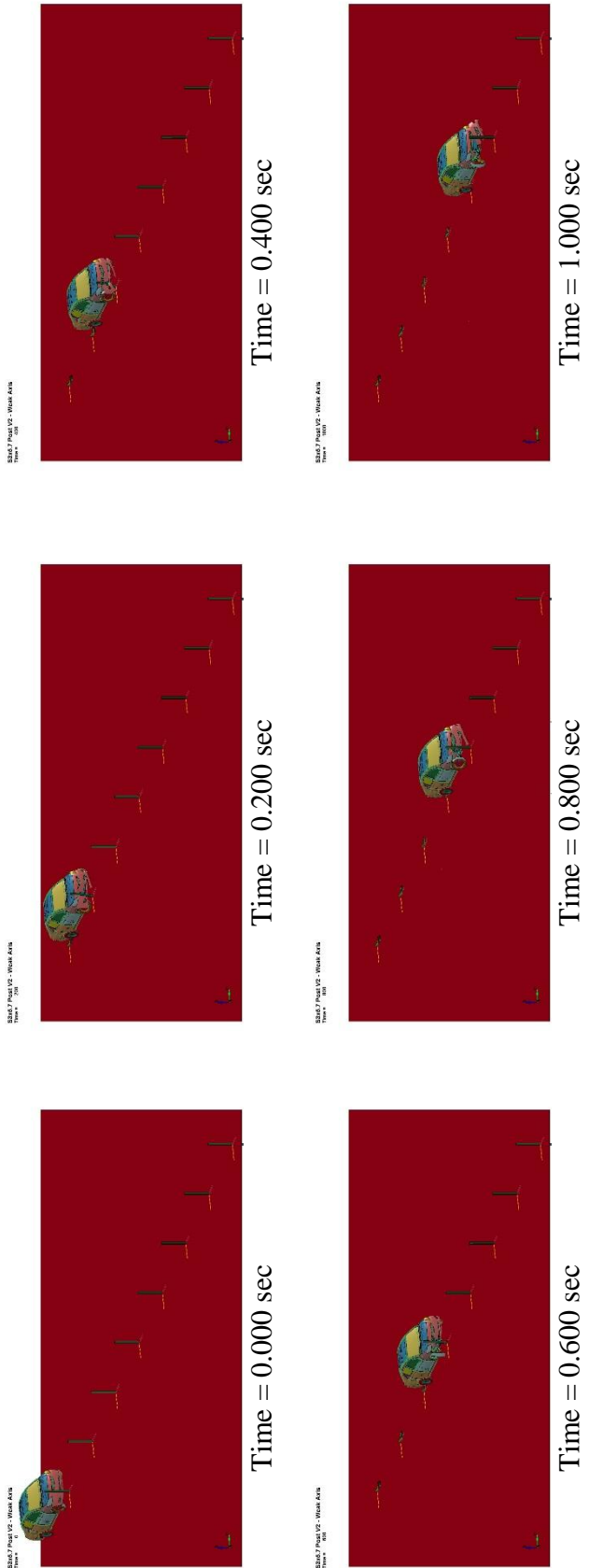
Figure 52. Sequential Images, Yaris Impact with S3x5.7 Posts
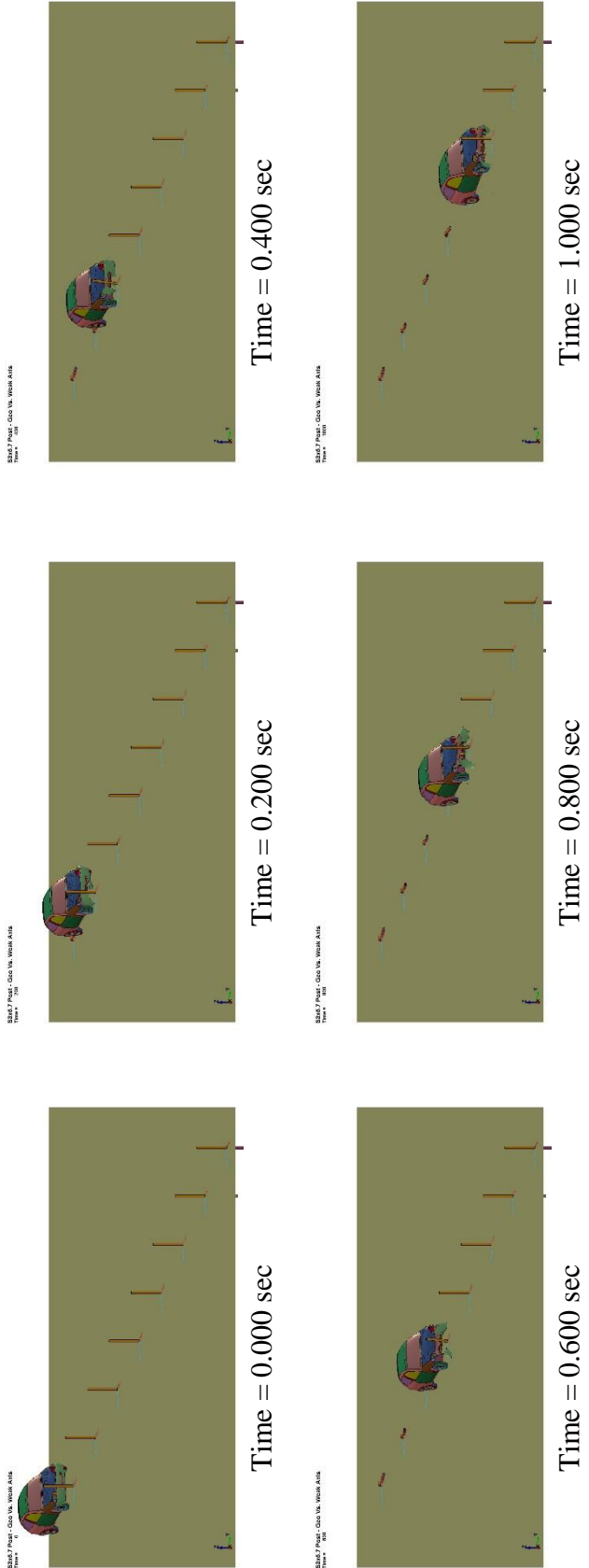
Figure 53. Sequential Images, Geo Metro Impact with S3x5.7 Posts

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5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Several modifications were made to the cable end terminal system after delayed cable release and vehicle rollover occurred in bogie test nos. HTCT-2 and HTCT-3 [18]. The design cable tension for the longitudinal barrier was decreased from 4,213 lb (18.7 kN) to 2,500 lb (11.1 kN) per cable at 100 degrees Fahrenheit [10]. The cable heights were changed, and the current design has cable heights at 15½ in. (394 mm), 23 in. (584 mm), 30½ in. (775 mm), and 38 in. (965 mm) above the groundline. The median system previously had S3x5.7 line posts and now has Midwest Weak Posts (MWPs) [9-10]. It was desired that the end terminal posts 3 through the end of the end terminal system maintain the MWP parts to minimize the number of unique parts required.

The cable anchor bracket was to be modified to be similar to the 3-cable, low-tension cable anchor bracket and cable release lever rotation. Due to adjustments in the cable heights on the longitudinal barrier, the angle to which the cables anchored in the bracket was also modified. Overall geometry was optimized to reduce the number of parts, material, and welds. The design changes simplified end terminal design, improved constructability, and reduced stub height to be below 4 in. (102 mm).

The new cable anchor bracket was evaluated using LS-DYNA computer simulation with a bogie model impacting the centerline of the cable anchor bracket at 0 and 15 degrees. All four cables easily released from the cable anchor bracket within 16 ms in both the 0- and 15-degree impacts. Due to the ease in which the cables released from the cable anchor bracket, significant damage to the vehicle is not expected. This simulation was only intended to evaluate the initial impact with the cable anchor bracket and post no. 2. The end terminal line posts will need to be evaluated in the future to ensure that the posts do not cause vehicle instabilities or cause excessive occupant compartment intrusion or penetration, such as floorboard penetration. There

was no indication that occupant impact velocities or occupant ridedown accelerations would exceed the limits established in MASH. Simulations of the impacts on the end of the system indicated that the revised design quickly and effectively disengaged the cables and allowed the bogie to pass over the cable anchor bracket safely.

A 25-degree reverse direction impact with both an 1100C Yaris model and an 820C Geo Metro model was simulated. The cars impacted at the midspan between post nos. 2 and 3 in the reverse direction. Errors occurred in the simulations which were believed to occur when the right-front corner of the cars became trapped by the cables.

The cable system was modified to incorporate the new cable heights from the continued development of the cable barrier median system. The location of the cables at post no. 2 was modified to incorporate cables on both sides of the post.

Further simulations were conducted with the 1100C Yaris model impacting the modified system at the midspan between post nos. 2 and 3. The cables trapped the right-front corner of the car, and none of the cables released from the cable anchor bracket. The model errored out 90 ms after the initial impact, likely due to the complex contacts in the right-front car with the cables becoming trapped in the car.

Further simulations were conducted with the 820C Geo model impacting the modified system at the midspan between post nos. 2 and 3 to determine if less errors would occur in the model. Shortly after impact, cable nos. 1 and 2 traversed behind the top of the right-front tire, and cable nos. 3 and 4 were on top of the hood. Post no. 2 released from the slip base, and cable nos. 4, 2, and 3 released at approximately 110 ms, 155 ms, and 165 ms after impact from the cable anchor bracket. Despite several of the cables releasing tension in the system, the right-front corner of the car became entrapped, which is likely what led to model instabilities.

In all of the simulations involving reverse-direction impacts, the small cars became entangled with the cables, which trapped the right-front corner of the cars with a large change in longitudinal velocity and prevented them from redirecting. This behavior was not desired as the potential exists for excessive occupant risk measures, increased vehicle instability, and occupant compartment deformations if the car does not redirect. However, fracture and failure of many of the components were not enabled in the computer model, and the behavior during full-scale crash testing is unknown as physical testing of this system has yet to be conducted. Previous full-scale crash testing with an 1100C small car impacting a W-beam guardrail trailing end terminal indicated substantial snag on the downstream end anchorage, which contributed to a longitudinal OIV value close to the maximum acceptable MASH limit [22]. The snag observed in the trailing end terminal test was in part due to the impacting tire sliding under the anchor cable and becoming entrapped by the cable until further post fracture and vehicle suspension failure occurred. While the cable end terminal simulation results and previous trailing-end terminal testing indicate the potential for hazardous snag, the results of the simulation cannot be confirmed without verification through full-scale crash testing.

The changes to the cable end terminal simplified the design and constructability of the system and enhanced cable release during simulated impacts on the end of the system. The reverse-direction simulation impacts indicated a potential for the cables to be retained by the end terminal rather than released and for interlock and rapid vehicle deceleration as it approached the cable anchor bracket. Simulations of various line post designs found that the MWP and weakened MWP have lower forces and energies during impact than the S3x5.7 (S76x8.5) posts used in previous three-cable end terminals. This finding would suggest improved performance with respect to vehicle override and instability. However, vehicle simulations with multiple line posts impacted were inconclusive. Therefore, further design, analysis, and testing is

recommended to improve the performance of the system during reverse-direction impacts near

the end of the system and to evaluate the potential for vehicle instability due to override of

multiple line posts during end-on impacts.

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