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DESIGN AND EVALUATION OF HIGH-TENSION CABLE MEDIAN BARRIER HARDWARE

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16. Abstract (Limit: 200 words)

Static and dynamic testing of components for use in the high-tension cable median barrier, accompanied by results and conclusions, are presented in this report. Components tested included cable-to-post attachments, end-fittings, and cable splices.

The cable-to-post attachment selected for use in the high-tension cable median barrier is a curved keyway bracket. This attachment was found capable of sustaining the target load of approximately 6,000 lbs when loaded laterally, while releasing the cable under vertical loads of approximately 1,000 lbs. These loads were selected as they develop the full capacity of the posts used in the median barrier and ensure that all of the cables are not pulled under the impacting vehicle as the posts deflect.

The Bennett Bolt Works, Inc. low-tension end-fitting with a 0.875-in. threaded rod and the Armor Flex cable splice were selected for use in the cable median barrier. These components were required to develop the full capacity of the 0.75-in. diameter, 3x7 wire rope used in the barrier, or a load of approximately 39 kips. Both of these components were found capable of meeting this criterion.

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1 INTRODUCTION

1.1 Background

The Midwest Roadside Safety Facility (MwRSF) was contracted to develop a non-proprietary, high-tension, cable median barrier. This barrier was to be developed for use at any point in a median with up to a 4:1 sloped V-ditch. Due to the nature of this type of design, the cable barrier hardware used in the system needed to be re-evaluated when compared to traditional cable barrier hardware. Traditional cable-to-post attachments were not feasible. Roadside cable barriers load the posts by pushing the cables toward the post when they are impacted. However, for a median cable system, the vehicle interaction with the cable can potentially pull the cable away from the post or push the cable towards the post. Thus, the cable attachment must be capable of developing the full moment capacity of the post when loaded laterally in order to ensure that the posts effectively function in the impact event. Additionally, the cable attachments must release the cable vertically under much lower loads in order to ensure that the cables do not remain attached to the post as it bends over, which would compromise the cable position and capture of the vehicle. The cables must also release vertically to ensure that they are not locked down on the A-pillar of small passenger vehicles, thus creating a potential for a cable to cut through the A-pillar and into the occupant compartment. Thus, a new cable attachment design was needed for the high-tension, cable median barrier.

Cable end-fitting and cable splice designs are also affected when one transitions from traditional cable barrier hardware to a high-tension cable median barrier. Many current end-fittings and splice designs are based on previous low-tension cable hardware. This hardware may not be sufficient to deal with the increased loads expected in a high-tension barrier due to the higher cable preload and lower deflections. As such, it was necessary to evaluate and verify the capacity of the end-fitting and splice hardware to ensure it was sufficient.

Beginning in June 2005, the MwRSF designed and tested a variety of cable attachment hardware for a high-tension, 4-cable median barrier to be placed at any point across a V-ditch with a 4-to-1 slope. Additionally, dynamic tests were performed to identify a cable end-fitting and cable splice with sufficient capacity for use with the high-tension cable barrier system. The end-fittings and cable splices were required to develop the ultimate load capacity of the 0.75-in. diameter, 3x7 wire rope used in the barrier.

1.2 Objective

The first objective of the research was to design a cable attachment for the high-tension cable median barrier that would satisfy predetermined loading conditions. These loading conditions differed between the lateral and vertical directions. To allow the post to develop its strength, the attachment had to withstand a lateral load of 6,000 lbs before failure. In the vertical direction, it was required that the attachment fail under a load of only 1,000 lbs or less.

Other desired aspects in the attachment were affordability and constructability. Additionally, the attachment system had to be designed without infringing on current cable-to-post connection patents.

To meet the design requirements, two basic attachment concepts were conceived: slotted brackets and U-bolt connections. Several different styles of each concept were designed. Each attachment underwent a static load test, in which a tensile testing machine applied an increasing load until the attachment failed. Each attachment was statically tested for both lateral and vertical load capacities. Once static testing had identified a candidate design, dynamic component testing was conducted to insure proper function of the connection.

The second objective of the research was to identify cable end-fittings and splices that could be used in the high-tension, cable median barrier. These components were required to have sufficient strength to fully develop the capacity of the cable, or approximately 39,000 lbs. Existing cable end-fittings designed by Bennett Bolt and Armor Flex and splices designed by Bennett Bolt and Armor Flex were tested dynamically to evaluate their potential performance in the median barrier system.

2 LITERATURE REVIEW

2.1 Patented Attachment Systems

As several proprietary, high-tension cable barrier systems have previously been designed, it was deemed appropriate to review current patents to avoid any possible infringements. The existing relevant barrier designs that were found and their corresponding patents are presented in this section.

2.1.1 Trinity Highway Safety Products, Inc.

Trinity Highway Safety Systems currently produces the Cable Safety System (CASS). Two attachments from the CASS were considered relevant to the development of a new system.

The first connection, used in line posts, utilizes a steel member that serves as the post. Sections used for the post are typically C-shaped or I-shaped, but the relevant patents also claim N-shaped, Z-shaped, V-shaped, and M-shaped members. A slot is cut into the post that begins at its top and extends downward into the post. The width of the slot is either uniform or varies between three wider sections, through which the cables pass, and three narrow sections. Plastic spacers are used to keep the cables separated, and plastic caps are placed over the tops of posts that hold the cables and spacers in place. The Trinity Corporation has claim to this connection in U.S. Patent No. 6,962,328 B2 and U.S. Patent Application No. 2005/0284695 A1. Figure 1 shows the CASS slot connection (images taken from Patent No. 6,962,328 B2).

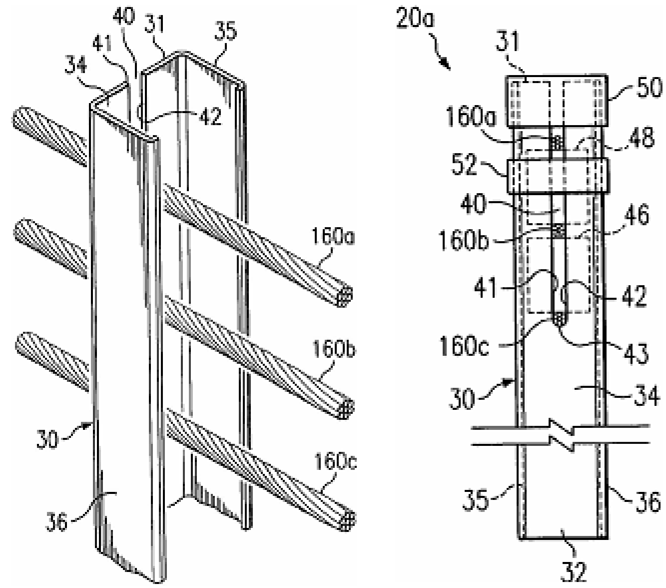


Figure 1. CASS Web-Slot Connection

The second connection, used in terminal posts, consists of a locking hook bolt that attaches the cable to the post. The locking hook bolts are U-shaped with one arm bent at a 90-degree angle that passes through the post to hold the bolt in place. The other arm of the bolt is threaded and also passes through the post, where it is held in place by a nut. Texas A&M University holds claim to the locking hook bolt attachment in U.S. Patent No. 6,948,703 B2. Figure 2 shows the locking hook bolt connection (images taken from Patent No. 6,948,703 B2).

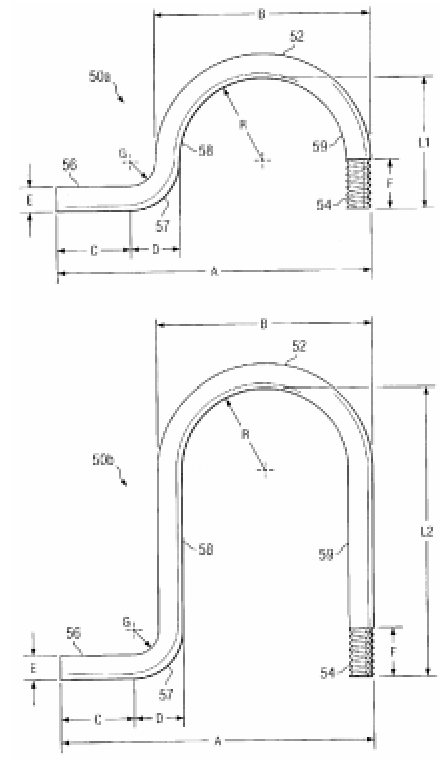


Figure 2. CASS Locking Hook Bolt Attachment (Texas A&M Patent)

2.1.2 Gibraltar Cable Barrier Systems, L.P.

The Gibraltar Cable Barrier System consists of a C-shaped post that is attached to the cable through a hairpin and lock-plate connection. The hairpin is a bent rod that features three U-shaped portions through which the cables pass. In between, the U-shaped sections are straight segments. The hairpin is positioned through a slot in the post such that the U-shaped portions are to the exterior of the post, housing the cables, while the straight portions are held within the post by a lock-plate apparatus. This lock plate spans the opening in the post, bearing against the post on either side. At the top of the hairpin, an additional bent section allows the hairpin to rest on top of the post on the side opposite the cables. Gibraltar has applied for a U.S. patent for the hairpin and lock-plate assembling in U.S. Patent Application 2007/0007501 A1. Figure 3 shows the Gibraltar hairpin and lock-plate attachment (image taken from Patent Application No. 2007/0007501 A1).

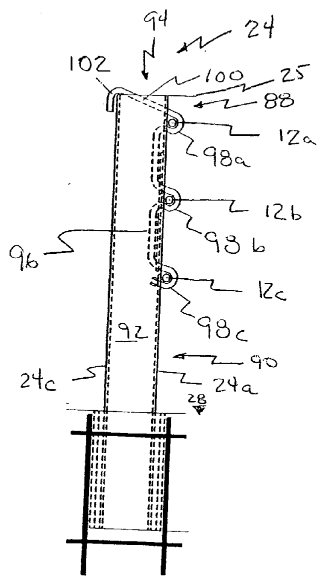


Figure 3. Gibraltar Hairpin and Lock-plate Attachment

The Gibraltar System uses a different connection for the posts near the terminals of the barrier. These connections consist of a J-shaped bolt that passes through the entire post, bent at a right angle on the cable-side of the post. The bolt is held in place by a nut on the opposite side. This connection is also claimed in U.S. Patent Application 2007/0007501 A1. Figure 4 shows the Gibraltar J-bolt connection (image taken from Patent Application No. 2007/0007501 A1).

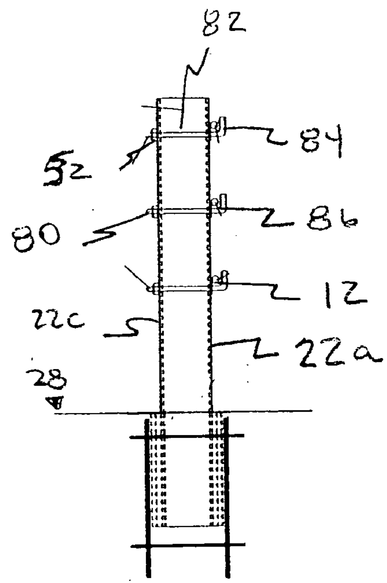


Figure 4. Gibraltar J-Bolt Attachment

2.1.3 Nucor Marion Steel, Inc.

Nucor Marion Steel currently manufactures the U.S. High Tension Cable Barrier System. The post used in the system is a U-shaped, flanged channel that is connected to the cables through locking hook bolts. The locking hook bolts are U-shaped with one arm bent at a 90-degree angle that passes through the post to hold the bolt in place. The other arm of the bolt is threaded and also passes through the post, where it is held in place by a nut. A bolt with a larger hook is used to fasten the cable to the non-impact side of the post while a bolt with a smaller hook is used to fasten the cable to the impact side of the flange. The locking hook bolts are proprietary technology of Texas A&M University, claimed in U.S. Patent No. 6,948,703 B2. Figure 5 shows the locking hook bolt attachment (image taken from Patent No. 6,948,703 B2).

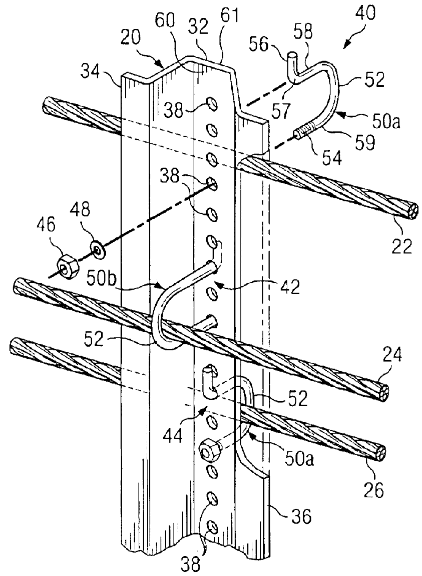


Figure 5. Nucor Marion Locking Hook Bolt Attachment (Texas A&M Patent)

2.1.4 Blue Systems AB

Blue Systems developed the Safence Barrier that is currently marketed in America by Impact Absorption, Inc. The system uses several different attachments to attach the cables to the posts.

The first connection consists of a channel-shaped or tube-shaped post with two slots cut through the upper end. Cables pass through these slots with spacers inserted between them to maintain separation distance. This connection is claimed in U.S. Patent Application No. 2002/0014620 A1. Figure 6 shows this connection in a channel application (image taken from Patent Application No. 2002/0014620 A1).

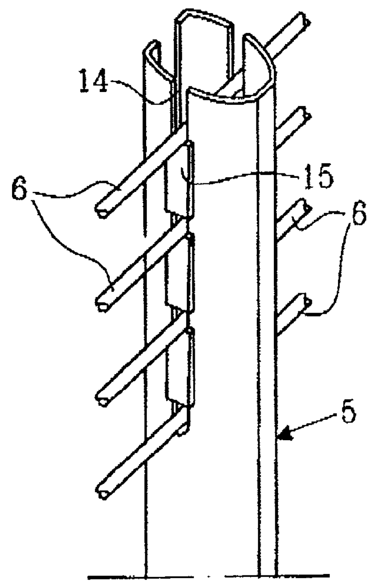


Figure 6. Blue Systems Safence Channel Connection

Another connection in the Safence Barrier connects the cable to channel-shaped or tube-shaped posts via slots cut into the posts at the height of the cable. These slots have an angled opening at their upper end and are used to support U-shaped hooks through which the cable passes. The ends of these hooks are bent approximately 90 degrees, such that when the hook is positioned to support the cable, the ends are parallel to the cable. The ends are bent in perpendicular directions, allowing the hook to be inserted into the post and through the keyway-slot with a twisting motion. This connection is claimed in U.S. Patent Application No. 2002/0014620 A1. Figure 7 shows the bent hook connection (images taken from Patent Application No. 2002/0014620 A1). Blue Systems also has applied a similar connection under the same patent application, differing slightly by the shape of the hook (not shown).

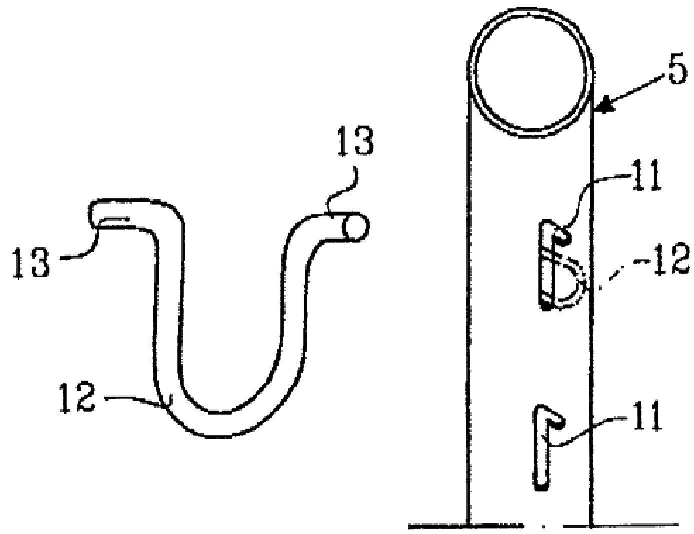


Figure 7. Blue Systems Safence Bent Hook Connection

Another Safence connection utilizes openings cut into the posts that are larger and keyway-shaped at their upper end and smaller at their lower end. U-shaped attachments with balled ends that capture the cable are inserted into the keyways and pushed downward such that the smaller openings prevent the hooks from releasing the cable when loaded laterally. This connection is claimed in U.S. Patent Application No. 2002/0014620 A1. Figure 8 shows the keyway connection (images taken from Patent Application No. 2002/0014620 A1).

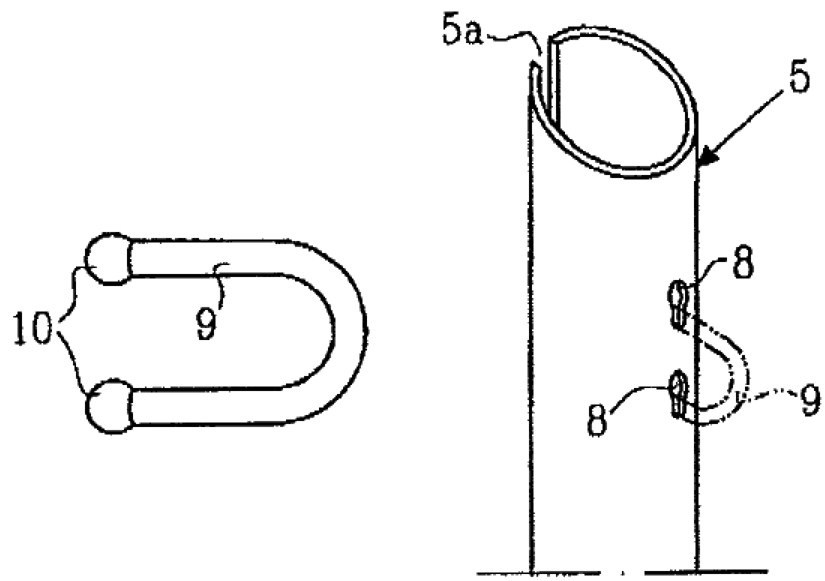


Figure 8. Blue Systems Hook and Keyway Connection

Blue Systems also uses a connection in their barrier that is formed by cutting a curved, angled slot into the cable-side of the post. The cable is then inserted into this slot, which is shaped such that it prevents the cable from being released unless a vertical force is applied on it. This connection is claimed in U.S. Patent Application No. 2002/0014620 A1. Figure 9 shows the curved, angled slot connection (image taken from Patent Application No. 2002/0014620 A1).

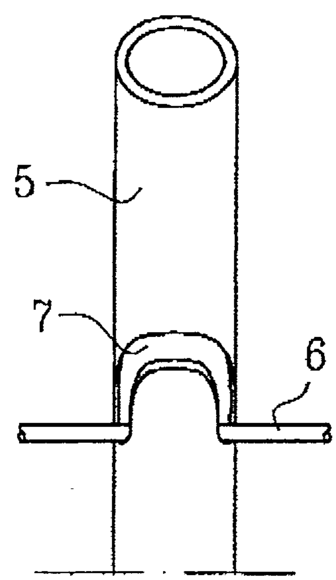


Figure 9. Blue Systems Curved, Angled Slot Connection

The Safence Barrier also has a connection design used for end posts. This design consists of an I-shaped member, which is used as the post, which has a slot cut through its web at its upper end. The cables are passed through this slot and separated by spacers. This connection is claimed in U.S. Patent No. 6,902,151 B1. Figure 10 shows the I-shaped post slot connection (image taken from Patent No. 6,902,151 B1).

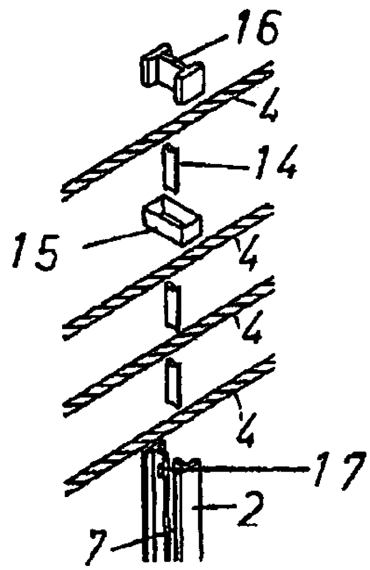


Figure 10. Blue Systems Safence I-Shaped Post Connection

2.1.5 Brifen USA, Inc.

Brifen USA manufactures the Wire Rope Safety Fence (WRSF). The WRSF uses either S-shaped or Z-shaped members as posts. Cables are attached to the posts through one of several methods. The top cable passes through slots cut into the top of the posts, with a cap placed over the top of the member to close the slot. Lower cables are held in place on the post either by pegs that the cables rest upon or by other means. Brifen claims these connections in U.S. Patent No. 5,039,066. Figure 11 shows the Brifen connection system (image taken from Patent No. 5,039,066).

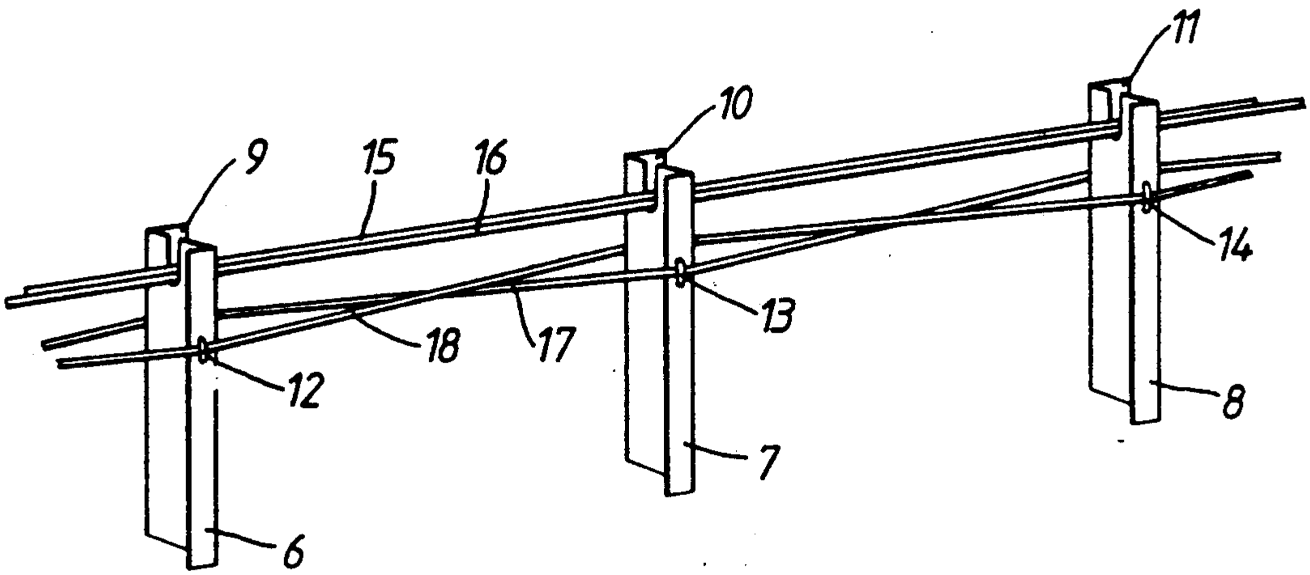


Figure 11. Brifen Attachment System

3 CABLE ATTACHMENT DESIGN DETAILS

3.1 Introduction

Development of a cable attachment for the high-tension, cable median barrier system required design and evaluation of several attachment concepts. The design of the cable attachment was required to develop 6,000 lbs of load laterally in order to fully develop the lateral resistance of the line posts. The attachment also needed to be able to release the cable under loads of 1,000 lbs or less to prevent the cable from being pulled down by deformed posts or cutting through the A-pillar of the vehicle.

The cable attachment concepts fell into two main categories; (1) Slotted brackets; and (2) U-bolt attachments. The following sections detail the various concepts that were developed, and subsequent sections of the report detail the testing and evaluation of the concepts.

3.2 S3x5.7 Steel Post Jigs

The standard post used in the high-tension cable median barrier is an S3x5.7 section. The post is manufactured from ASTM A36 steel and has a cross section in accordance with A6M standards. The post primarily consists of three major components: two flanges and the connecting web. The flanges are 2.33-in. wide and 0.26-in. thick, while the web is 0.17-in. thick.

The cables used in the barrier are attached to the flanges of the posts with the previously described attachments. Four cables are used, with two cables attached to the impact side and two cables attached to the non-impact side of each post. The cables utilize 0.75-in. diameter, 3x7 wire rope.

Test jigs, fabricated from S3x5.7 posts, were used for all tests performed in this study. Several different jigs were used in the tests to provide for the different connections between the cable attachments and the post.

3.3 Slotted Bracket Attachments

This section describes the different attachment designs that were developed and tested. A summary of slotted bracket concepts and tests performed is presented in Table 1.

Table 1. Slotted Bracket Concepts and Test Numbers

	Slotted Brackets Designs				
	Uniform Slots	**Flat Keyways**	**Angled Slots**	**Bent Keyways**	**Curved Keyways**
Test No.	SB-1	SB-19	SB-23	SB-27	SB-31
	SB-2	SB-20	SB-24	SB-28	SB-32
	SB-3	SB-21	SB-25	SB-29	SB-33
	SB-4	SB-22	SB-26	SB-30	SB-34
	SB-5				
	SB-6				
	SB-7				
	SB-8				
	SB-9				
	SB-10				
	SB-11				
	SB-12				
	SB-13				
	SB-14				
	SB-15				
	SB-16				
	SB-17				
	SB-18				

3.3.1 Uniform Slot Brackets

Tests of the first slotted bracket concept utilized slots of uniform width. Bolts passed through these slots to fasten the bracket to the post, and the cable passed through a curved section at the middle of the bracket. The design intent was for the bracket to only release the cable upon rupture near the bolts under lateral loading, while vertical loading would cause the bracket to release the bolt through the slot, thus resulting in a lesser failure load. All brackets were cut from A36 plate steel. Several different variations were investigated using different bracket thicknesses and slot widths and lengths. All brackets were fastened to the test jig with 0.375-in. diameter, Grade 5 bolts, tightened with a torque wrench set to 275 lb-in. A total of nine uniform slotted brackets were tested for both lateral and vertical strength. Table 2 summarizes test information for the uniform slot bracket concept, and Figure 12 shows a typical uniform slot bracket.

Table 2. Uniform Slot Bracket Test Information

Test No.	Width (in.)	Length (in.)	Gage	Thickness (in.)	Slot Width (in.)	Slot Length (in.)	Load Direction	Torque (lb-in.)
SB-1	1.01	5.55	12	0.101	0.3845	1.364	Horizontal	275
SB-2	1.01	5.546	12	0.102	0.4375	1.485	Horizontal	275
SB-3	1.034	5.6	10	0.1345	0.375	1.37	Horizontal	275
SB-4	1.033	5.58	10	0.135	0.4825	1.495	Horizontal	275
SB-5	1.01	5.58	12	0.1015	0.39	1.425	Vertical	275
SB-6	1.0065	5.55	12	0.1015	0.482	1.4945	Vertical	275
SB-7	1.035	5.56	10	0.1345	0.3765	1.393	Vertical	275
SB-8	1.032	5.57	10	0.13425	0.474	1.495	Vertical	275
SB-9	1.02	5.53	16	0.0605	0.5065	1.53	Horizontal	275
SB-10	1.02	5.54	16	0.0605	0.515	1.54	Vertical	275
SB-11	1.016	5.57	16	0.0605	0.49	1.547	Horizontal	275
SB-12	1.017	5.55	16	0.0605	0.494	1.55	Vertical	275
SB-13	1.017	5.43	14	0.745	0.49	1.565	Horizontal	275
SB-14	1.012	5.58	14	0.74	0.483	1.55	Vertical	275
SB-15	1.02	5.58	14	0.74	0.494	0.1545	Horizontal	275
SB-16	1.015	5.54	14	0.74	0.496	1.55	Vertical	275
SB-17	1.272	5.6	14	0.74	0.748	1.54	Horizontal	275
SB-18	1.267	5.57	14	0.74	0.75	1.51	Vertical	275

Figure 12. Uniform Slot Bracket, Test No. SB-8

3.3.2 Flat Keyway Brackets

The second slotted bracket concept was similar to the uniform slotted brackets but featured keyways instead of uniform slots. The keyways were located immediately to the interior of the fastening bolts and were intended to facilitate the release of the bolts under vertical loading, with a minimal decrease in lateral strength. All brackets were fastened to the test jig with 0.375-in. diameter, Grade 5 bolts. These bolts were tightened with a torque of 275 lb-in. for two of tests and were not tightened for two tests. Two vertical and two lateral tests were performed on flat keyway brackets. Table 3 summarizes test information for the flat keyway bracket concept, and Figure 13 shows a typical keyway bracket.

Table 3. Keyway Bracket Test Information

Test No.	Width (in.)	Length (in.)	Gage	Thickness (in.)	Slot Width (in.)	Slot Length (in.)	Load Direction	Torque (lb-in.)
SB-19	1.3125	5.5	10	0.1354	Keyway 0.375" - 0.75"	0.625 center to center	Vertical	275
SB-20	1.3125	5.5	10	0.1354	Keyway 0.375" - 0.75"	0.625 center to center	Vertical	0
SB-21	1.3125	5.5	10	0.1354	Keyway 0.375" - 0.75"	0.625 center to center	Horizontal	275
SB-22	1.3125	5.5	10	0.1354	Keyway 0.375" - 0.75"	0.625 center to center	Horizontal	0

Figure 13. Flat Keyway Bracket

3.3.3 Angled Slot Brackets

The next series of bracket tests were performed on brackets featuring angled slots through which bolts passed to fasten the bracket to the post. The slots were inclined at an angle of 60 degrees from the bracket's vertical orientation and extended through the edge of the bracket. They were intended to release the bolt under vertical loading without requiring the bracket to rupture. These openings were located on opposite sides of the bracket. All brackets were fastened to the test jig with 0.375-in. diameter, Grade 5 bolts. These bolts were tightened with a torque of 275 lb-in. for two tests and were not tightened for two tests. A total of four tests were performed on the slotted brackets, with two tests performed in each loading orientation. Table 4 summarizes test information for the angled slot bracket concept, and Figure 14 shows a typical angled slot bracket.

Table 4. Angled Slot Bracket Test Information

Test No.	Width (in.)	Length (in.)	Gage	Thickness (in.)	Slot Width (in.)	Slot Length (in.)	Load Direction	Torque (lb-in.)
SB-23	1.3125	5.5	10	0.1354	0.375" wide x 60 deg. angled slot	NA	Vertical	275
SB-24	1.3125	5.5	10	0.1354	0.375" wide x 60 deg. angled slot	NA	Vertical	0
SB-25	1.3125	5.5	10	0.1354	0.375" wide x 60 deg. angled slot	NA	Horizontal	275
SB-26	1.3125	5.5	10	0.1354	0.375" wide x 60 deg. angled slot	NA	Horizontal	0

Figure 14. Angled Slot Bracket

3.3.4 Bent Keyway Brackets

Another bracket concept that was tested also consisted of a bracket with keyway openings. These keyways were positioned on the bent portion of the bracket through which the cable passed and were intended to further facilitate the release of the bolt under vertical loading. Bolts also fastened these brackets to the post, near the exterior edge of the keyway portion. These bolts were 0.375-in. diameter, Grade 5 bolts that were fastened snugly but not tightened down with a torque wrench. Four tests were performed on this concept. Table 5 summarizes test information for the bent keyway bracket concept, and Figure 15 shows a typical bent keyway bracket.

Table 5. Bent Keyway Bracket Test Information

Test No.	Width (in.)	Length (in.)	Gage	Thickness (in.)	Slot Width (in.)	Slot Length (in.)	Load Direction	Torque (lb-in.)
SB-27	1.4375	3.5464	10	0.1354	Keyway 0.375"-1.0"	0.5762	Vertical	0
SB-28	1.4375	3.5464	10	0.1354	Keyway 0.375"-1.0"	0.5762	Horizontal	0
SB-29	1.4375	3.5464	10	0.1354	Keyway 0.375"-1.0"	0.5762	Horizontal	0
SB-30	1.4375	3.5464	10	0.1354	Keyway 0.375"-1.0"	0.5762	Vertical	0

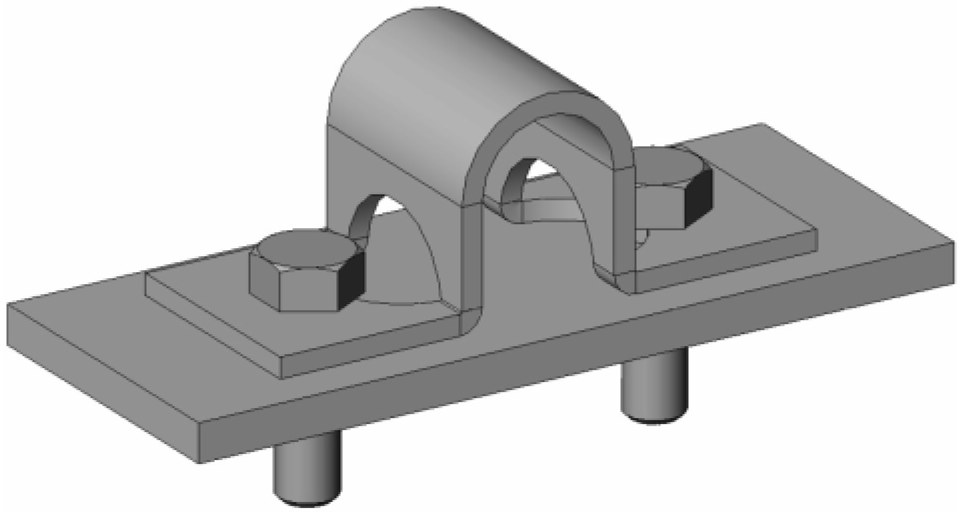


Figure 15. Bent Keyway Bracket

3.3.5 Curved Keyway Brackets

The final bracket concept to be tested was the curved keyway bracket, which differed from the bent keyway bracket by utilizing a smooth curve to accommodate the cable rather than a 90-degree bend. The curved design was chosen to reduce the deformation required for the bracket to reach its peak load and to aid in the release of the cable under vertical loading. These brackets were connected to the test jig with 0.375-in. diameter, Grade 5 bolts that passed through the brackets near the exterior edge of the keyway portion. The bolts were not tightened past snug with any torque. The curved keyway bracket concept was tested twice laterally and twice vertically. Table 6summarizes test information for the curved keyway bracket concept, and Figure 16 shows a typical curved keyway bracket.

Table 6. Curved Keyway Bracket Test Information

Test No.	Width (in.)	Length (in.)	Gage	Thickness (in.)	Slot Width (in.)	Slot Length (in.)	Load Direction	Torque (lb-in.)
SB-31	1.5	4	10	0.1354	Keyway 0.375"-1.0"	NA	Vertical	0
SB-32	1.5	4	10	0.1354	Keyway 0.375"-1.0"	NA	Vertical	0
SB-33	1.5	4	10	0.1354	Keyway 0.375"-1.0"	NA	Horizontal	0
SB-34	1.5	4	10	0.1354	Keyway 0.375"-1.0"	NA	Horizontal	0

Figure 16. Curved Keyway Bracket

3.4 U-Bolt Attachments

This section describes the different U-bolt cable attachment designs that were developed and tested. A summary of U-bolt concepts and tests performed is presented in Table 7.

Table 7. U-Bolt Concepts and Test Numbers

	U-Bolt Attachment Designs							
	Welded, Notched Bolts	Nut Combinations	Keyways	Slotted Top Holes	Spacers	Double Slots	Oversized Holes	Bolts w/ Clips
Test No.	UBLSH (1)	UB-1	UB-11	UB-13	UB-16	UB-18	UB-27	UB-43
	UBLMH (2)	UB-2	UB-12	UB-13B	UB-17		UB-28	UB-44
	UBLLH (3)	UB-3		UB-14	UB-19		UB-29	UB-45
	UBHSH (4)	UB-4		UB-15	UB-20		UB-30	UB-46
	UBHMH (5)	UB-5			UB-21		UB-31	UB-47
	UBHLH (6)	UB-6			UB-22		UB-32	UB-48
	UBLSV (7)	UB-7			UB-23			UB-49
	UBLMV (8)	UB-8			UB-24			UB-50
	UBLLV (9)	UB-8B			UB-25			UB-51
	UBHSV (10)	UB-9			UB-26			UB-52
	UBHMV (11)	UB-9B			UB-33			UB-53
	UBHLV (12)				UB-34			
					UB-35			
					UB-36			
					UB-37			
					UB-38			
					UB-39			
					UB-40			
					UB-41			
					UB-42			

3.4.1 Welded and Notched J-Bolts

Testing of the first U-bolt concept consisted of two J-bolts welded together such that they resembled a U-bolt with the threaded portion of each bolt forming a leg of the U-shape. Holes in the post were offset to accommodate the bolts which were fastened in place with nuts. Notches were cut into the interior threading of the bolts that were intended to localize the stress in the bolt when loaded vertically. It was hoped that this would result in failure at much lower loads than when loaded laterally. Bolt Grades C1018 and C1038 steel were used to create these connections. Material information on these grades of steel, as well as other grades mentioned later in the text, can be found in Appendix A. A total of twelve connections were tested that varied by both weld and notch sizes. Table 8 summarizes test information for the welded and notched J-bolts concept, and Figure 17 shows a typical welded and notched J-bolt.

Table 8. Welded and Notched J-Bolt Test Information

Test No.	Diameter (in.)	Grade	Weld Size	Notch Depth (in.)	Notch Width (in.)	Notch Depth (in.)	Notch Width (in.)	Load Direction
UBLSH (1)	0.375	C1038 (plain)	small	0.2365	0.216	0.221	0.212	Horizontal
UBLMH (2)	0.375	C1038 (plain)	medium	0.167	0.1905	0.2055	0.22	Horizontal
UBLLH (3)	0.375	C1038 (plain)	large	0.174	0.216	0.17	0.2175	Horizontal
UBHSH (4)	0.375	C1018 (red)	small	0.2165	0.2295	0.182	0.23	Horizontal
UBHMH (5)	0.375	C1018 (red)	medium	0.2005	0.211	0.1825	0.1815	Horizontal
UBHLH (6)	0.375	C1018 (red)	large	0.2235	0.229	0.204	0.2415	Horizontal
UBLSV (7)	0.375	C1038 (plain)	small	0.2315	0.314	0.2025	0.231	Vertical
UBLMV (8)	0.375	C1038 (plain)	medium	0.2025	0.23	0.2055	0.208	Vertical
UBLLV (9)	0.375	C1038 (plain)	large	0.1935	0.226	0.1985	0.227	Vertical
UBHSV (10)	0.375	C1018 (red)	small	0.214	0.215	0.209	0.213	Vertical
UBHMV (11)	0.375	C1018 (red)	medium	0.2455	0.219	0.214	0.208	Vertical
UBHLV (12)	0.375	C1018 (red)	large	0.2255	0.2035	0.2265	0.209	Vertical

Figure 17. Welded, Notched J-Bolts

3.4.2 U-Bolts with Nut Combinations

The next U-bolt concept consisted of U-bolts connected to the post with different combinations of nuts and washers. One nut was used on each end of the U-bolts to fasten them to the post. Additional nuts were used on the top arm of the U-bolts, on the cable-side of connection, to vary the stiffness and failure properties of the U-bolt. These additional nuts were intended to extend the moment arm on the top arm of the U-bolts when loaded vertically and to increase the bending stress in the bolt and cause failure at comparatively lower loads than when loaded laterally. These nuts were attached either individually or welded together. Twelve different tests were performed on U-bolt and nut combination connections. Table 9 summarizes test information for the U-bolts with nut combinations concept, and Figure 18 shows a typical U-bolt and nut combination connection.

Table 9. U-Bolts with Nut Combinations Test Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-1	0.25	C1018	Vertical	single nut bottom - 1+2 nut top
UB-2	0.25	C1018	Vertical	single nut bottom - 1+1 nut top
UB-3	0.25	C1018	Vertical	1+1 nut bottom - 1+1 nut top
UB-4	0.25	C1018	Vertical	1+1 nut bottom - 1+3 nut top
UB-5	0.25	C1018	Vertical	single nut bottom - 1+3 nut top
UB-6	0.25	C1018	Vertical	single nut bottom - 1+3 welded nut top
UB-7	0.25	C1018	Vertical	1+1 nut bottom - 1+3 welded nut top
UB-8	0.25	C1018	Horizontal	1+1 nut bottom - 1+1 nut top
UB-8B	0.25	C1018	Horizontal	1+1 nut bottom - 1+1 nut top
UB-9	0.25	C1018	Horizontal	single nut bottom - single nut top
UB-9B	0.25	C1018	Horizontal	single nut bottom - single nut top

Figure 18. U-Bolt with Nut Combination, Test UB-6

3.4.3 U-Bolts with Keyway Slots

The second U-bolt concept employed a keyway opening in the post through with the top arm of a U-bolt passed. This concept would allow the upper arm of the U-bolt to be released from the post, through the keyway, under lower vertical loads. Failure under lateral loading would require the bolt to fail in tension, presumably only possible with much higher loads. A standard bolt hole was used to attach the bottom leg of the U-bolt. Two different tests were performed on this concept. Table 10 summarizes test information for the U-bolts with keyways concept, and Figure 19 shows a typical U-bolt and keyway connection.

Table 10. U-Bolts with Keyways Test Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-11	0.25	C1018	Vertical	Keyway - single nut bottom - single nut top
UB-12	0.25	C1018	Vertical	Keyway - 1+1 nut bottom - 1+1 nut top

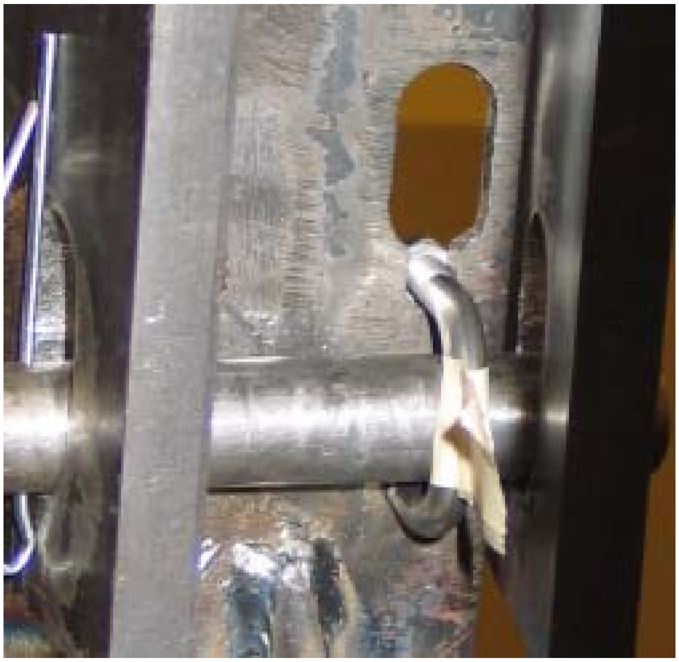


Figure 19. U-Bolt with Keyway

3.4.4 U-Bolts with Upper Slots

The next U-bolt concept utilized a slotted opening in the post through with the upper arm of a U-bolt passed. This slot was intended to release the bolt under vertical loading while preserving the lateral strength of the connection. A standard bolt hole was used for the bottom arm of the U-bolt. Two different tests were also performed on this concept. Table 11 summarizes test information for the U-bolts with upper slots concept, and Figure 20 shows a typical U-bolt and upper slot arrangement.

Table 11. U-Bolts with Upper Slots Test Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-13	0.25	C1018	Vertical	Notched top hole - single nut bottom - single nut top
UB-13B	0.25	C1018	Vertical	Notched top hole - single nut bottom - single nut top
UB-14	0.25	C1018	Vertical	Notched top hole - single nut bottom - single nut top
UB-15	0.25	C1018	Vertical	Notched top hole - single nut bottom - single nut top

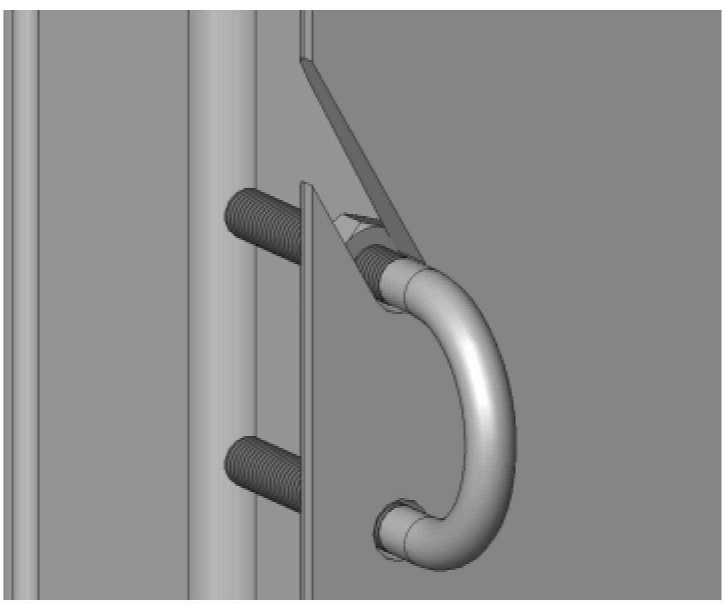


Figure 20. U-Bolt with Upper Slot

3.4.5 U-Bolts with Spacers

The next U-bolt concept also consisted of U-bolts attached to the post with nuts, but utilized spacers that intended to keep the cable near the curved end of the U-bolt. This concept attempted to use the tensile strength of the bolt to satisfy the lateral load requirement while reducing the vertical load capacity by increasing the moment arm of the cable on the bolt. This larger moment arm would create a larger moment in the bolt, resulting in higher bending stresses and lower failure loads. The materials used for the spacer blocks included wood and high-density polyethylene (HDPE). A total of 20 different tests were performed on this concept. Table 12 summarizes test information for the U-bolts with spacers concept, and Figure 21 shows a typical U-bolt and spacer connection.

Table 12. U-Bolts with Spacers Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-16	0.25	C1018	Vertical	5/8" spacer - single nut bottom - single nut top
UB-17	0.25	C1018	Vertical	5/8" spacer - single nut bottom - single nut top
UB-19	0.25	C1018	Vertical	3/4"x1" spacer - single nut bottom - single nut top
UB-20	0.25	C1018	Vertical	3/4"x1" spacer - single nut bottom - single nut top
UB-21	0.25	C1018	Vertical	3/4"x1" spacer - 1+1 nut bottom - 1+1 nut top
UB-22	0.25	C1018	Vertical	3/4"x1" spacer - 1+1 nut bottom - 1+1 nut top
UB-23	0.25	C1018	Vertical	1"x1" spacer - single nut bottom - single nut top
UB-24	0.25	C1018	Vertical	1"x1" spacer - single nut bottom - single nut top
UB-25	0.25	C1018	Vertical	1"x1" spacer - single nut bottom - single nut top
UB-26	0.25	C1018	Vertical	1"x1" spacer - 1+1 nut bottom - 1+1 nut top
UB-33	0.25	C1038	Vertical	1"x1" spacer - single nut bottom - single nut top
UB-34	0.25	C1018	Vertical	1"x1" HDPE spacer - single nut bottom - single nut top
UB-35	0.25	C1018	Vertical	1"x1" HDPE spacer - single nut bottom - single nut top
UB-36	0.25	C1018	Vertical	1"x1" HDPE spacer - single nut bottom - single nut top
UB-37	0.25	C1018	Vertical	1"x1" HDPE spacer - single nut bottom - single nut top
UB-38	0.25x3.5x1.5	Grade 2	Vertical	2" HDPE spacer - single nut bottom - single nut top
UB-39	0.25x3.5x1.5	Grade 2	Vertical	2" HDPE spacer - single nut bottom - single nut top
UB-40	0.25x3.5x1.5	Grade 2	Horizontal	2" HDPE spacer - single nut bottom - single nut top
UB-41	0.25x3.5x1.5	Grade 2	Vertical	2"X2.5"X.875" HDPE spacer - single nut bottom - single nut top
UB-42	0.25x3.5x1.5	Grade 2	Vertical	2"X2.5"X.875" HDPE spacer - single nut bottom - single nut top

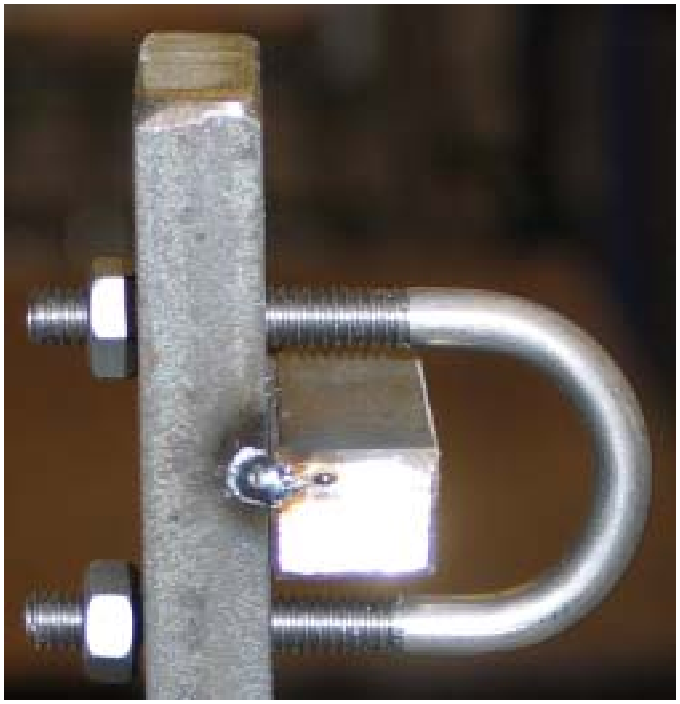


Figure 21. U-Bolt with Spacer

3.4.6 U-Bolts with Double Slots

Another concept that was tested consisted of a U-bolt attached to a post through two slots angled at 60 degrees. These slots extended through the end of the post and were designed to release the bolts when loaded vertically while preserving the connection's lateral load capacity. One test was performed on this concept. Table 13 summarizes test information for the U-bolt with double slots concept, and Figure 22 shows a U-bolt with double slots connection.

Table 13. U-Bolt with Double Slots Test Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-18	0.25	C1018	Vertical	double slots in post flange

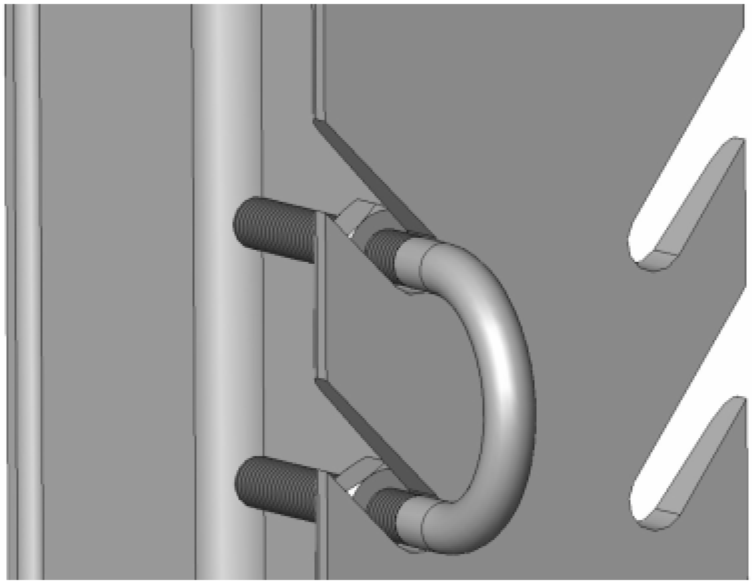


Figure 22. U-Bolt with Double Slots

3.4.7 U-Bolts with Oversized Upper Holes

The next U-bolt concept consisted of a U-bolt attached to the post through an oversized upper bolt hole and a lower standard bolt hole. Nuts were used at each hole to hold the bolts in place, with the nut at the upper hole partially supported by the post and partially overhanging the hole. The size of the hole was varied. In two of the tests, a washer was used at the top hole to better anchor the U-bolt. A total of six tests were performed on this concept. Table 14 summarizes test information for the U-bolts with oversized upper holes concept, and Figure 23 shows a the U-bolt with oversized upper hole connection.

Table 14. U-Bolts with Oversized Upper Holes Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-27	0.25	C1018	Horizontal	large hole prototype - 0.5625 dia. - single nut bottom - single nut top
UB-28	0.25	C1018	Horizontal	large hole prototype - 0.625 dia. - single nut bottom - single nut top
UB-29	0.25	C1018	Horizontal	large hole prototype - 0.625 dia. - single nut + washers bottom & top
UB-30	0.25	C1018	Vertical	large hole prototype - 0.625 dia. - single nut + washers bottom & top
UB-31	0.25	C1038	Vertical	large hole prototype - 0.5625 dia. - single nut bottom - single nut top
UB-32	0.25	C1038	Vertical	large hole prototype - 0.625 dia. - single nut bottom - single nut top

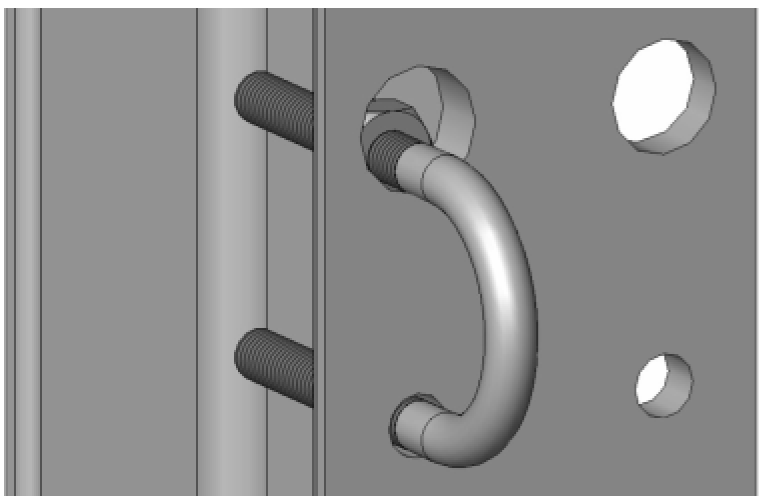


Figure 23. U-Bolt with Oversized Upper Hole

3.4.8 Bolts with Clips

Two different bolt and clip arrangements were tested. The first consisted of a clip that was attached to the post with a single bolt. Slot-like openings at either end of the clip allowed a U-bolt to pass through, which was held in place with nuts. These openings extended to the edge of the clip to allow the cable to be released under vertical loads while preserving the lateral capacity of the connection. A total of eleven tests were performed on this concept. Table 15 summarizes U-bolt clip test information, and Figure 24 and Figure 25 show typical U-bolt clips for both of the aforementioned styles.

Table 15. U-Bolt Clip Information

Test No.	Diameter (in.)	Grade	Load Direction	Attachment
UB-43	0.25	C1018	Vertical	U-Bolt Clip
UB-44	0.25	C1018	Vertical	U-Bolt Clip
UB-45	0.25	C1018	Vertical	U-Bolt Clip
UB-46	0.25	C1018	Horizontal	U-Bolt Clip
UB-47	0.25	C1018	Horizontal	U-Bolt Clip
UB-48	0.25	Grade 5	Vertical	U-Bolt Clip Plate with two 0.25" dia. x 2.0" long grade 5 bolts
UB-49	0.25	Grade 5	Vertical	U-Bolt Clip Plate with two 0.25" dia. x 2.5" long grade 5 bolts
UB-50	0.25	Grade 5	Vertical	U-Bolt Clip Plate with two 0.25" dia. x 2.5" long grade 5 bolts
UB-51	0.25	Grade 5	Vertical	U-Bolt Clip Plate with two 0.25" dia. x 2.5" long grade 5 bolts
UB-52	0.25	Grade 5	Horizontal	U-Bolt Clip Plate with two 0.25" dia. x 2.5" long grade 5 bolts
UB-53	0.25	Grade 5	Horizontal	U-Bolt Clip Plate with two 0.25" dia. x 2.5" long grade 5 bolts

Figure 24. U-Bolt Clip, Style 1

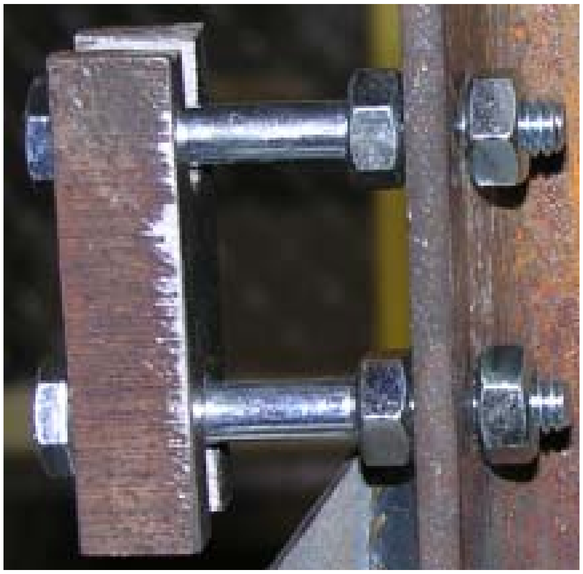


Figure 25. U-Bolt Clip, Style 2

4 CABLE ATTACHMENT STATIC TESTING

4.1 Test Facility

Static testing was performed at the University of Nebraska-Lincoln's Mechanical Engineering Materials Lab, located in the Walter Scott Engineering Center.

4.2 Data Acquisition Systems

A self-contained material testing system was utilized for static testing. This system was equipped with a load cell and displacement transducer that collected the data needed to evaluate the attachment systems. Additionally, cameras were used to collect visual documentation of the tests.

4.2.1 MTS 810

The Material Testing System (MTS) 810 was used to test the cable attachments under static loads. A 20-kip load cell measured the force placed on each attachment, while displacement transducers measured the corresponding deflection. Most of the tests that were performed loaded the attachments at a rate of 0.2 in./min, but for several systems, the machine was used to simulate dynamic loading. This was done by setting the MTS to its maximum speed of approximately 8 in./sec to demonstrate how the attachments would behave in releasing the cable in dynamic situations.

4.2.2 Digital Photography

Digital photographs were taken of the samples before and after static testing. These were taken with a Nikon Coolpix 8800 digital camera.

Video footage of the static tests was also collected. A Canon Mini digital video camera was used to capture video onto tape, which was later converted into digital format.

5 CABLE ATTACHMENT STATIC TESTING RESULTS

5.1 Results

The instrumentation used in the tests produced data for the force and corresponding displacement until failure for each cable attachment system. Concepts were tested both vertically and laterally, and the results were compared to the target loads of 1,000 lbs for vertical load-orientation and 6,000 lbs for lateral load-orientation.

5.2 Slotted Bracket Attachments

Thirty-four static tests were conducted on the various slotted bracket concepts, as detailed below.

5.2.1 Uniform Slot Brackets

Test nos. SB-1 through SB-18 demonstrated that uniform slot brackets were capable of satisfying the lateral load requirements but not the vertical load requirements. In several tests, the brackets actually demonstrated a higher vertical strength than lateral strength. The first group of tests, nos. SB-1 through SB-9, demonstrated high lateral strength as the brackets held until fracture. However, the brackets were unable to properly release the bolt for the corresponding vertical tests and failed in fracture, thus creating much higher loads than desired. Test nos. SB-9 through SB-18, which featured larger slots, were more successful at releasing the bolt under vertical loads, but were unable to resist the required lateral loads. Table 16 shows uniform slot bracket test results, and the corresponding force-deflection curves are presented in Figure 26 through Figure 29.

Table 16. Uniform Slot Bracket Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
SB-1	Horizontal	4566	fractured on side of slot
SB-2	Horizontal	2655	fractured on side of slot (both slots)
SB-3	Horizontal	6966	fractured on side of slot
SB-4	Horizontal	5769	fractured on side of slot
SB-5	Vertical	8047	bent/fractured top bolt
SB-6	Vertical	4554	bolt head slipped out of slot
SB-7	Vertical	7836	bent/fractured top bolt
SB-8	Vertical	5461	bent/fractured top bolt
SB-9	Horizontal	1158	Fractured clip on side of slot
SB-10	Vertical	1688	Bolt pullout of top slot
SB-11	Horizontal	1309	Bolt pullout with partial tear of clip on side of slot
SB-12	Vertical	2174	Bolt pullout of top slot
SB-13	Horizontal	1728	Fractured clip on side of slot
SB-14	Vertical	2062	Bolt pullout of top slot
SB-15	Horizontal	1662	Fractured clip on side of slot
SB-16	Vertical	2478	Bolt pullout of top slot
SB-17	Horizontal	-	Couldn't test because slots wouldn't contain the bolts
SB-18	Vertical	2319	Bolt pullout of top slot

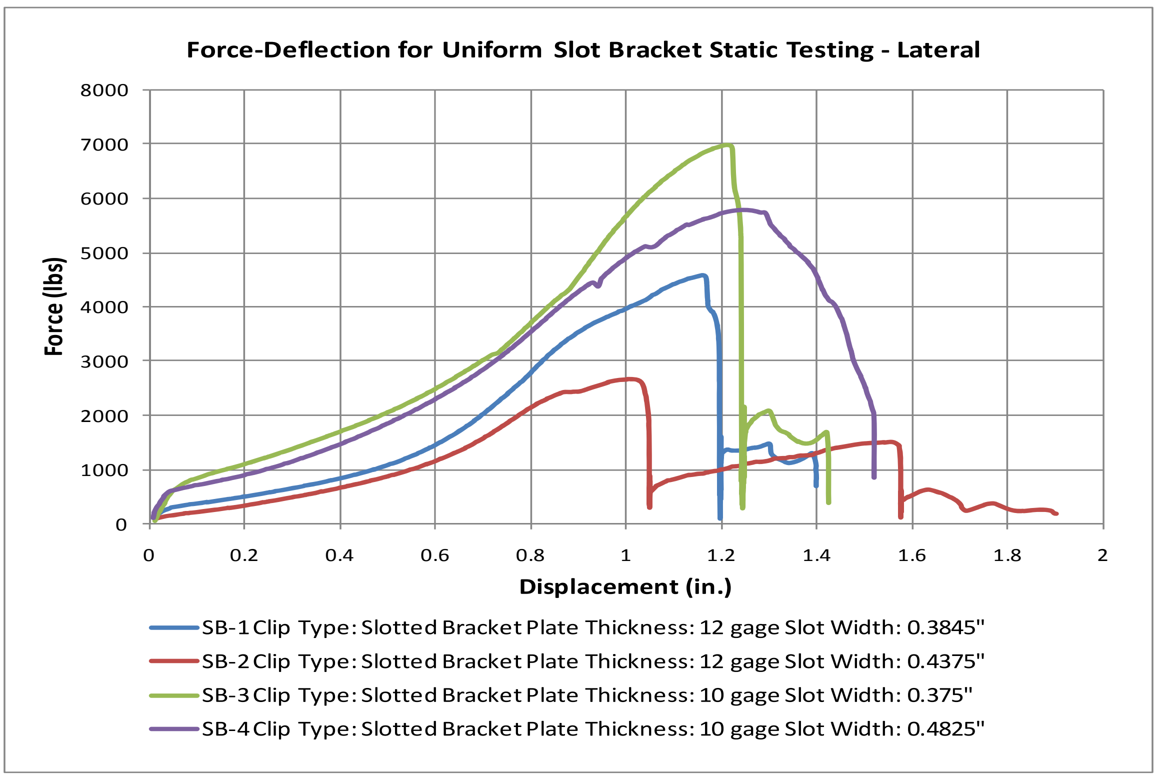


Figure 26. Lateral Testing Force-Deflection Curves for Uniform Slot Brackets

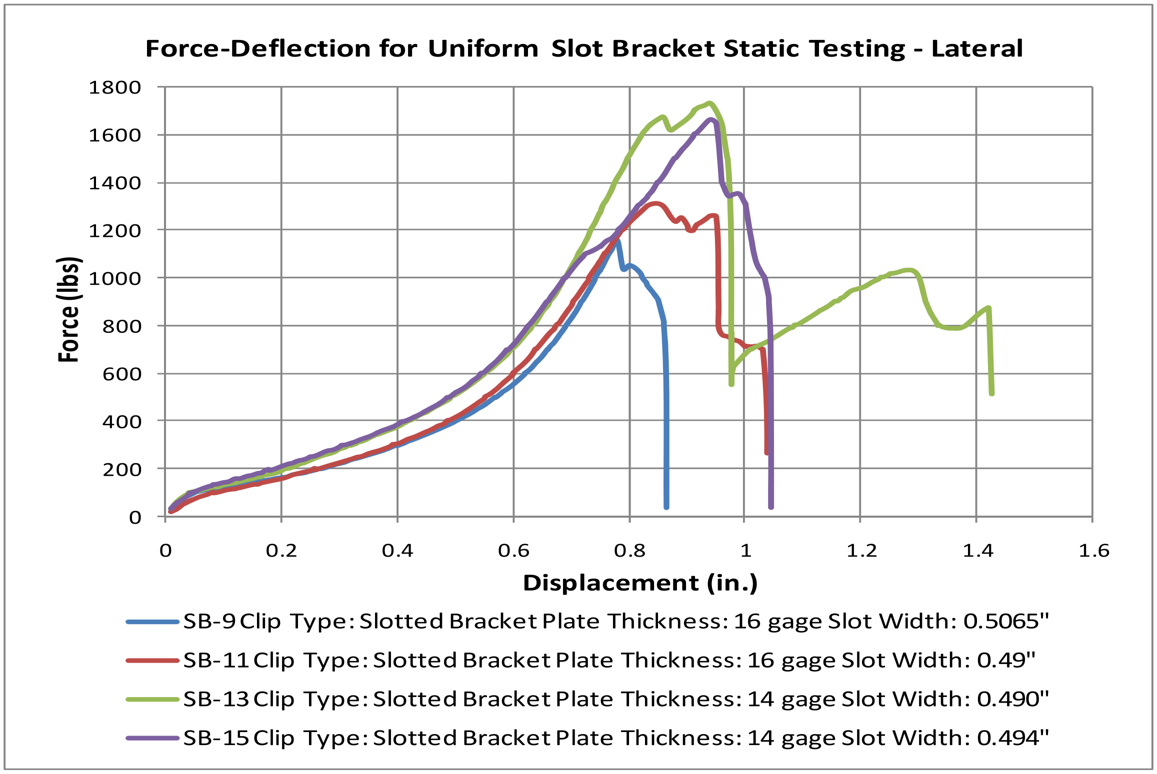


Figure 27. Lateral Testing Force-Deflection Curves for Uniform Slot Brackets, Continued

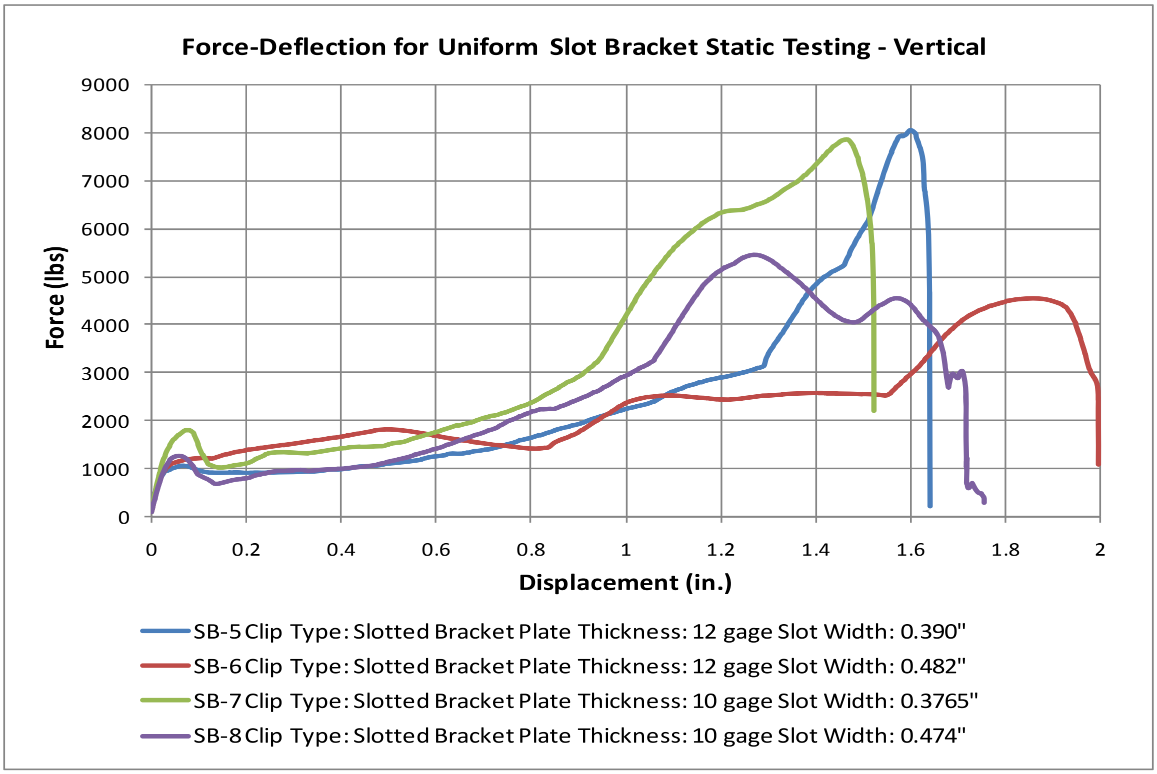


Figure 28. Vertical Testing Force-Deflection Curves for Uniform Slot Brackets

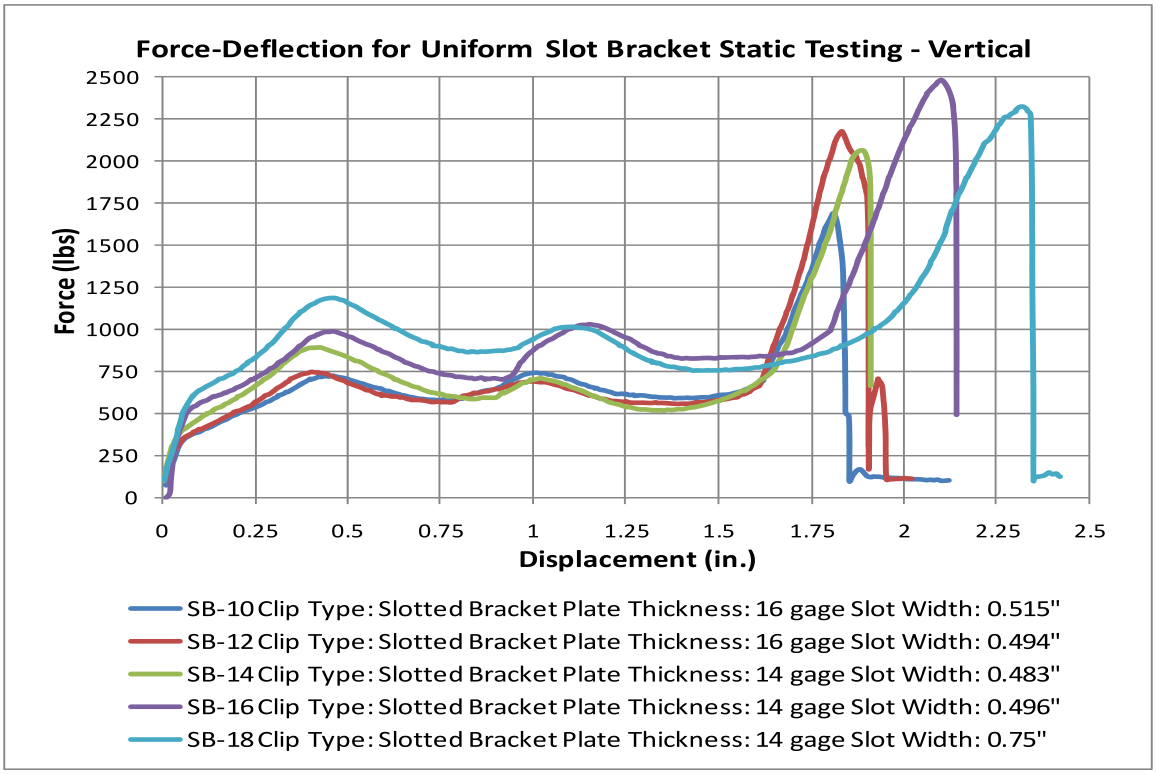


Figure 29. Vertical Testing Force-Deflection Curves for Uniform Slot Brackets, Continued

5.2.2 Flat Keyway Brackets

The flat keyway brackets investigated in test nos. SB-19 through SB-22 met the lateral load requirements, and did so more consistently than the uniform slot brackets. Test nos. SB-21 and SB-22 each withstood the required load of 6,000 lbs before failure. The vertical tests showed mixed results. In test no. SB-19, the bolt did not exit through the keyhole until the load was far greater than the desired 1,000-lb load. Test no. SB-20 performed much better, failing as the bolt exited the keyway under a loading of 971 lbs, but the bolts were loose prior to loading. These results suggested that the behavior of the bracket under vertical loading was highly dependent on bolt torque and preloading. Lower torque and preloading levels enabled the brackets to release under lighter loads while not adversely affecting the lateral capacity of the bracket. Table 17 presents flat keyway bracket test results, and Figure 30 and Figure 31 present the corresponding force-deflection curves.

Table 17. Flat Keyway Bracket Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
SB-19	Vertical	6207	Bolt head did not slide down initially, but did exit keyway
SB-20	Vertical	971	Loose bolts, head slid cleanly out of keyway
SB-21	Horizontal	6646	Bracket fractured on the side
SB-22	Horizontal	6511	Bolt tore through the bracket in bearing failure

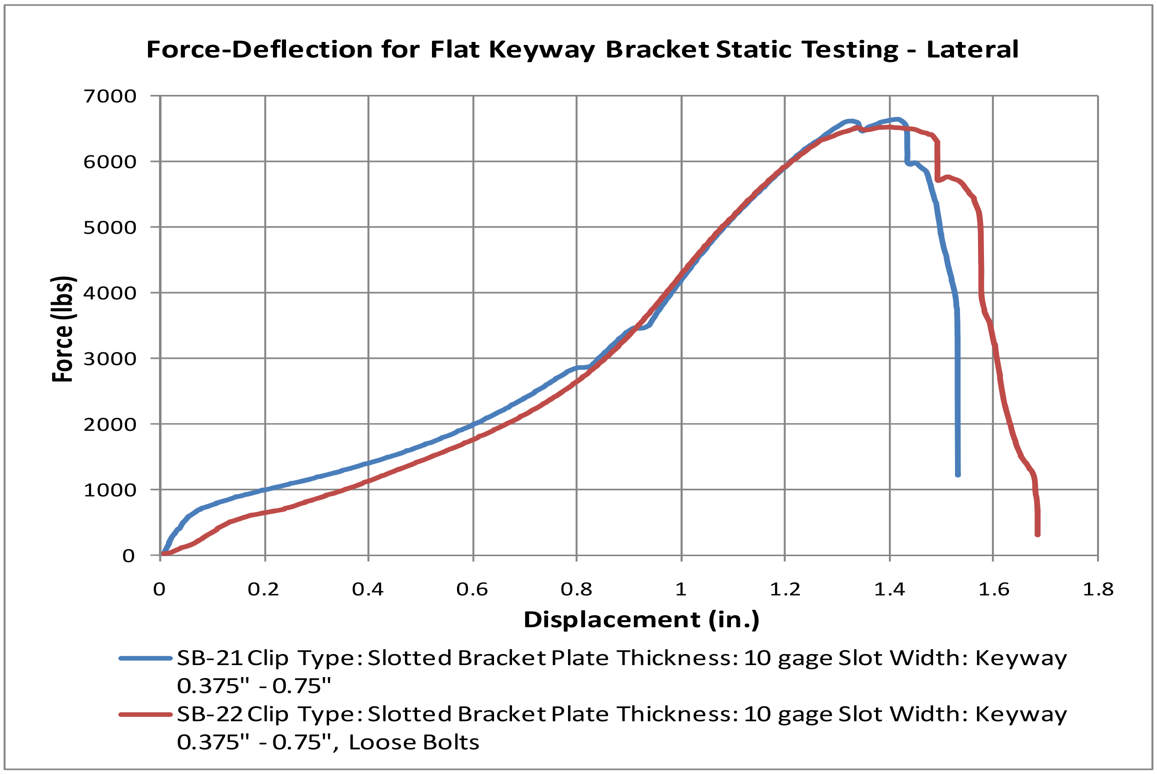


Figure 30. Lateral Force-Deflection Curves for Flat Keyway Brackets

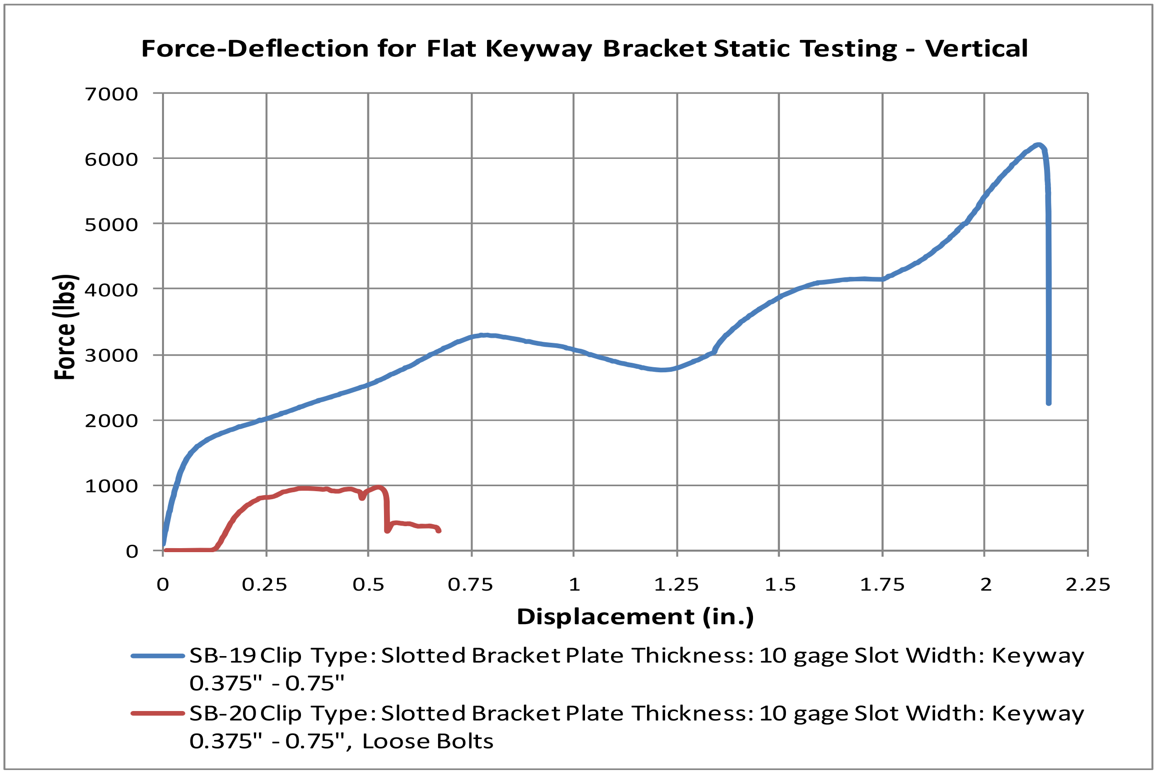


Figure 31. Vertical Force-Deflection Curves for Flat Keyway Brackets

5.2.3 Angled Slot Brackets

The angled slot brackets failed to meet either load requirement. When laterally loaded, test nos. SB-25 and SB-26 fractured under loads well short of the 6,000-lb requirement. The brackets also developed more strength when vertically loaded than was desired. Table 18 summarizes the angled slot bracket test results, and Figure 32 and Figure 33 present corresponding force-deflection curves.

Table 18. Angled Slot Bracket Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
SB-23	Vertical	1917	Bottom leg of bracket bent around bolt head and fractured
SB-24	Vertical	1555	Bolt exited slot but still tore the bottom leg
SB-25	Horizontal	2069	Bracket fractured on both sides
SB-26	Horizontal	1825	Bracket fractured on both sides

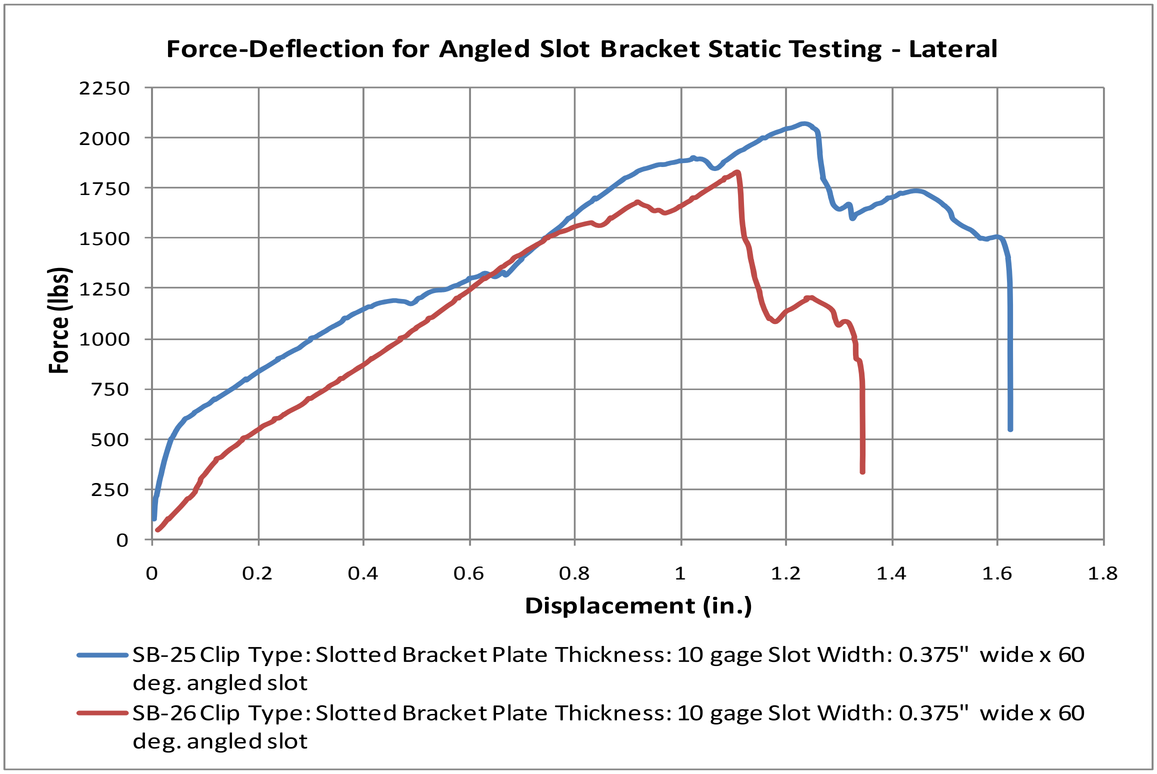


Figure 32. Lateral Force-Deflection Curves for Angled Slot Brackets

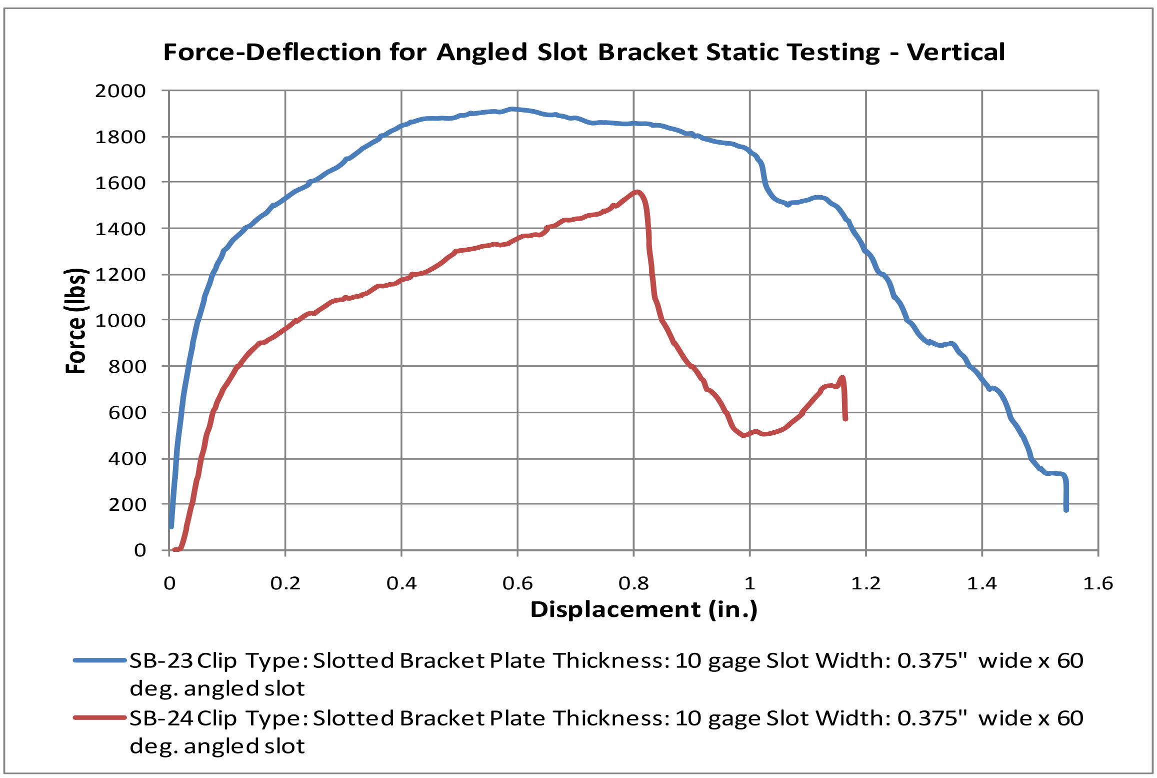


Figure 33. Vertical Force-Deflection Curves for Angled Slot Brackets

5.2.4 Bent Keyway Brackets

Test nos. SB-27 through SB-30 evaluated the bent keyway brackets with moderate success. When loaded vertically, the brackets in test nos. SB-27 and SB-30 each failed by releasing the bolt at loads of less than 1,000 lbs. However, in each test, the bar then became caught between the bracket and the cable, causing the load to increase to at least 1,700 lbs. This snagging on the bolt upon exit was not believed to be representative of the behavior of an actual cable, but it did suggest that the release could be made cleaner. In the lateral load tests, the brackets withstood a moderate load, but fell short of the requirement to develop the full strength of the post. It was believed that the lateral load could easily be increased by increasing the tensile area of the bracket. Table 19 summarizes bent keyway bracket test results, and Figure 34 and Figure 35 present corresponding load-deflection curves.

Table 19. Bent Keyway Bracket Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
SB-27	Vertical	1700	Bolt exited the keyway cleanly with approx. 640 lbs, but the cable then got caught sliding between the bracket and bolt casuing a load increase
SB-28	Horizontal	3200	Bracket fracture at miniumum tensile area at the bend
SB-29	Horizontal	4334	Dynamic - Bracket fracture at miniumum tensile area at the bend
SB-30	Vertical	1860	Dynamic - Bolt exited the keyway cleanly with approx. 780 lbs, but the cable then got caught sliding between the bracket and bolt casuing a load increase

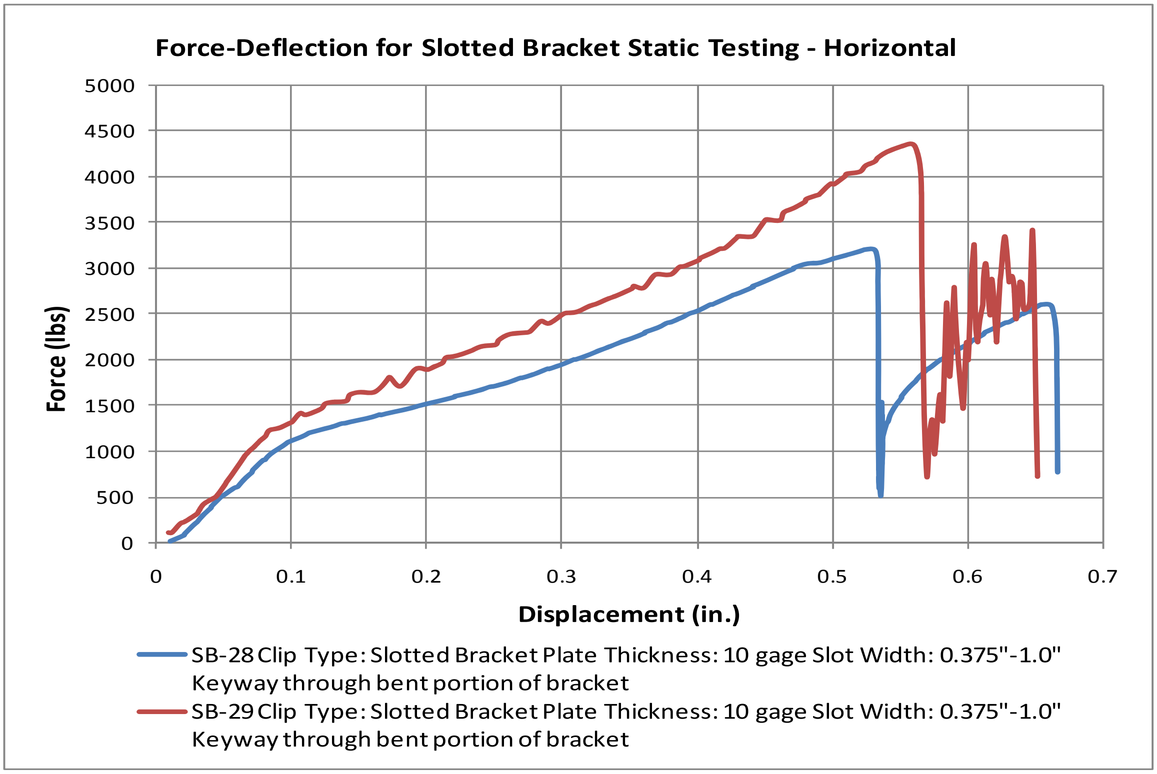


Figure 34. Lateral Force-Deflection Curves for Bent Keyway Brackets

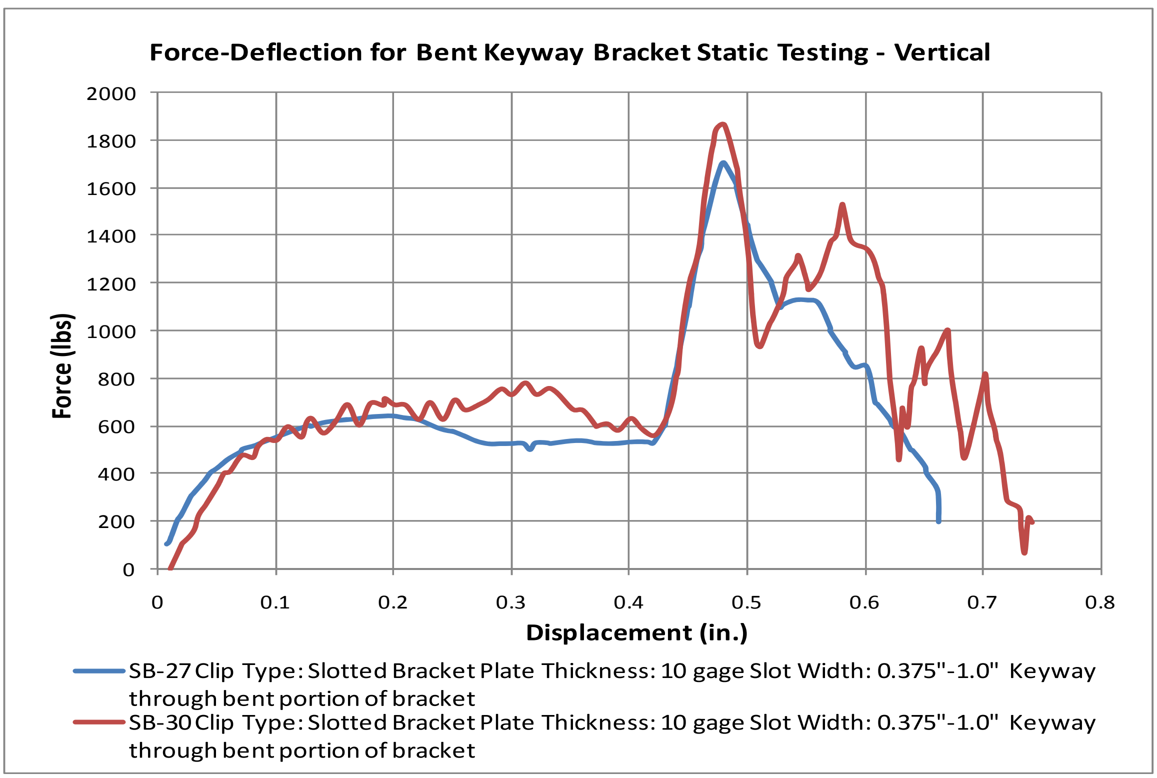


Figure 35. Vertical Force-Deflection Curves for Bent Keyway Brackets

5.2.5 Curved Keyway Brackets

The curved keyway brackets were designed to provide cleaner vertical release and more lateral capacity than the bent keyway brackets. As such, the curved keyway brackets displayed the best performance of all slotted bracket concepts tested. When vertically loaded, test nos. SB-31 and SB-32 released the bolts at a 775-lb load. While the bar was then caught between the bracket and the bolt, thus causing a load increase, it was believed that this would not occur in service as the cable would be able to rotate and slip free. Laterally, the keyways developed the desired strength before fracturing. Table 20 summarizes curved bracket test results, and Figure 36 and Figure 37 present corresponding load-deflection curves.

Table 20. Curved Keyway Bracket Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
SB-31	Vertical	1870	Bolt exited the keyway cleanly with approx. 775 lbs, but the cable then got caught sliding between the bracket and bolt casuing a load increase
SB-32	Vertical	2550	Dynamic - Bolt exited the keyway cleanly with approx. 775 lbs, but the cable then got caught sliding between the bracket and bolt casuing a load increase
SB-33	Horizontal	6200	Bracket fracture at miniumum tensile area
SB-34	Horizontal	6630	Dynamic - Bracket fracture at miniumum tensile area

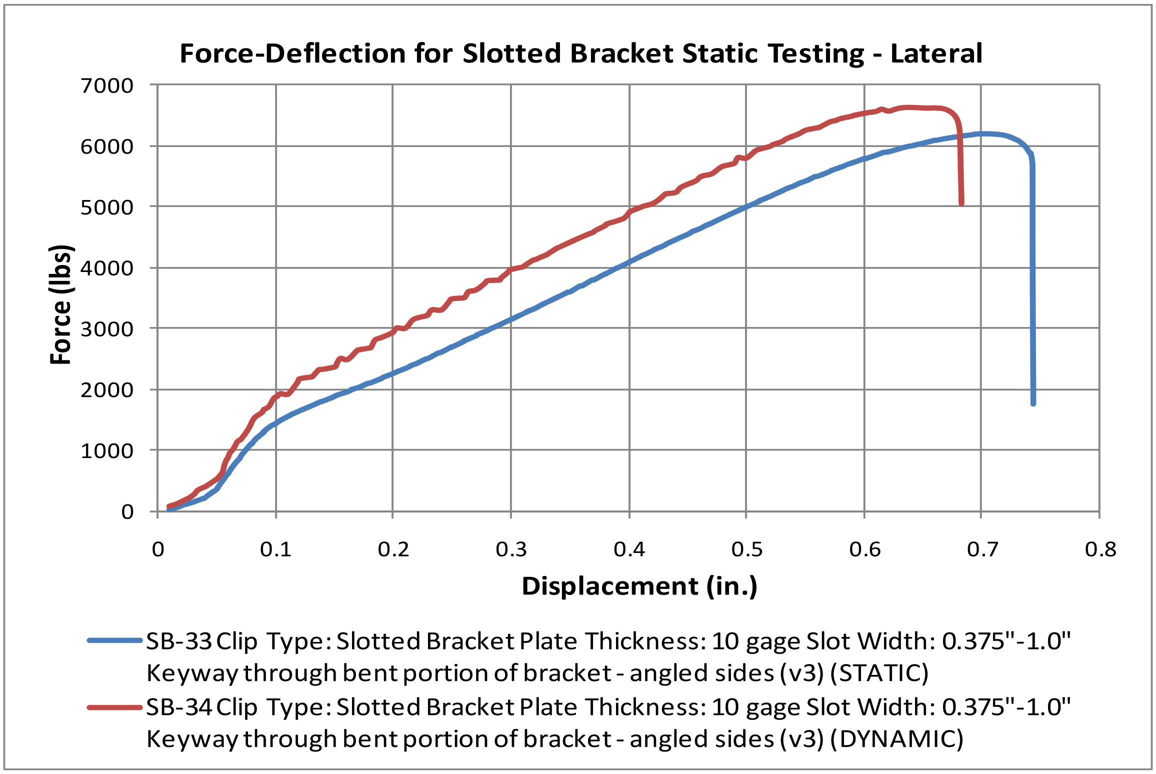


Figure 36. Lateral Force-Deflection Curves for Curved Keyway Brackets

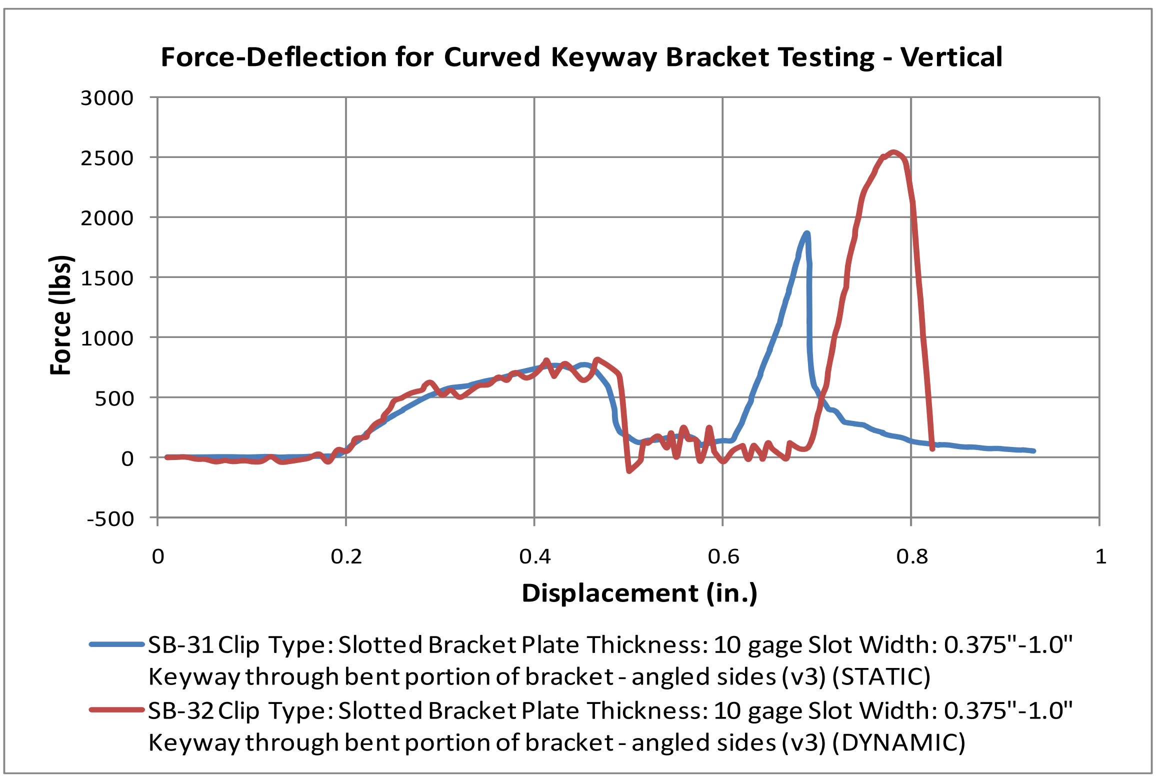


Figure 37. Vertical Force-Deflection Curves for Curved Keyway Brackets

5.3 U-Bolt Attachments

Sixty-seven different tests were conducted on the various U-bolt attachment concepts, as detailed below.

5.3.1 Welded and Notched J-Bolts

The first U-Bolt concept consisted of welded and notched J-bolts. Though these attachments could withstand large lateral loads, most of the tests did not reach the 6,000-lb requirement before fracturing at their notches. Additionally, the welded and notched J-bolts did not release the bar at 1,000 lbs of vertical load. In test no. UBLMV (8), the connection developed a vertical load of over 9,500 lbs, nearly ten times the required limit. Table 21 shows a summary of these attachments' performance, and Figure 38 and Figure 39 show the corresponding load-deflection curves.

Table 21. Welded, Notched U-Bolt Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UBLSH (1)	Horizontal	4002	fractured at notch
UBLMH (2)	Horizontal	5500	fractured at notch
UBLLH (3)	Horizontal	7400	fractured at notch
UBHSH (4)	Horizontal	4001	fractured at notch
UBHMH (5)	Horizontal	4700	fractured at notch
UBHLH (6)	Horizontal	3301	fractured at notch
UBLSV (7)	Vertical	6602	fractured at notch
UBLMV (8)	Vertical	9547	fractured at both notches
UBLLV (9)	Vertical	N/A	N/A
UBHSV (10)	Vertical	4500	fractured at notch
UBHMV (11)	Vertical	2100	fractured at notch
UBHLV (12)	Vertical	3128	fractured at notch

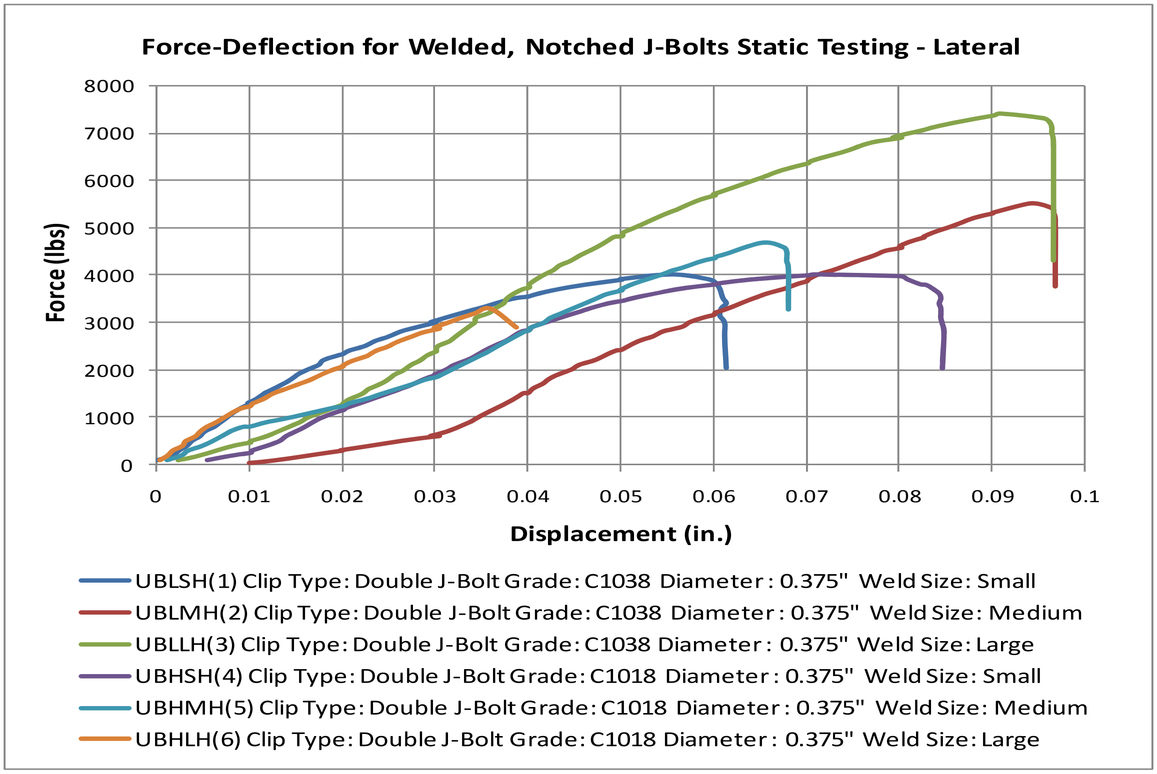


Figure 38. Lateral Force-Deflection Curves for Welded, Notched J-Bolts

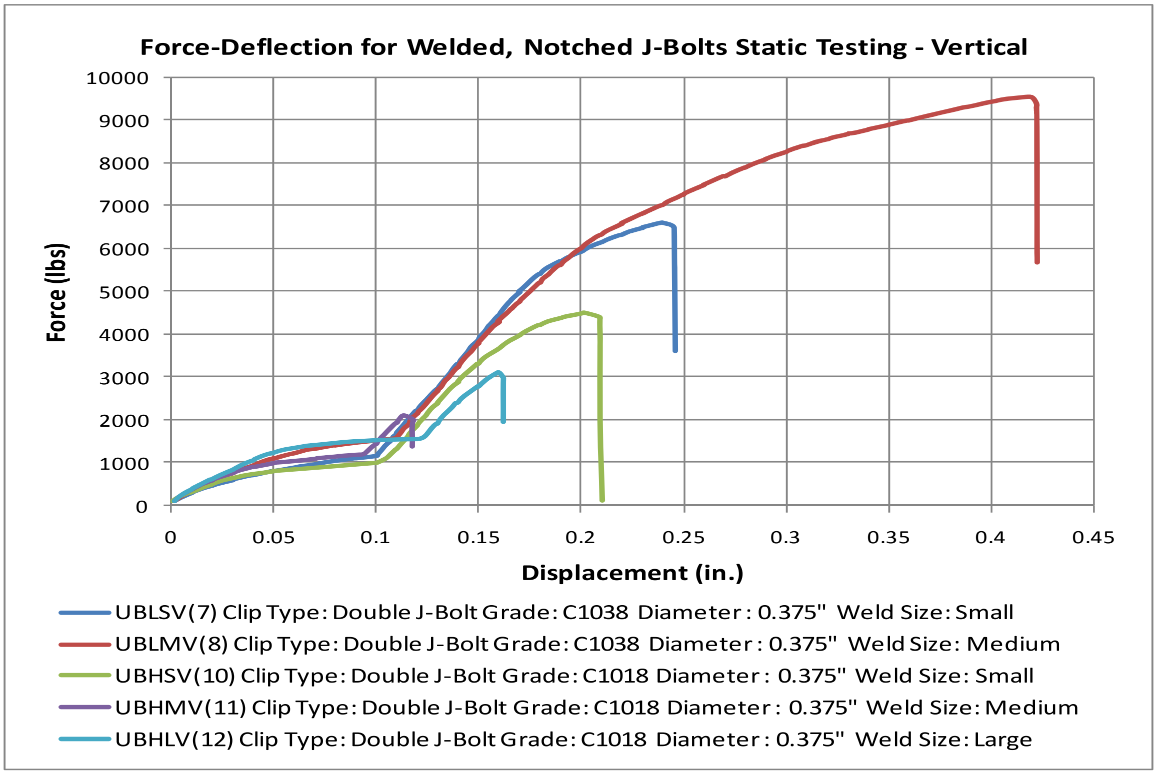


Figure 39. Vertical Force-Deflection Curves for Double J-Bolts

5.3.2 U-Bolts with Nut Combinations

The U-bolts with different combinations of nuts also failed to meet the design requirements of the attachments. These bolts were able to support a lateral load of over 6,000 lbs, but failed to release the bar when subjected to a 1,000-lb vertical load. The majority of tests required between 2,000 and 2,500 lbs of load before the cable was released. Results are presented in Table 22, and load-deflection curves are presented in Figure 40 and Figure 41.

Table 22. U-Bolts with Nut Combinations Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-1	Vertical	2400	fractured between two nuts on front
UB-2	Vertical	4300	fractured at base of the top nut
UB-3	Vertical	3600	fractured at base of the top nut
UB-4	Vertical	2500	fractured between the nut closest to the flange and the second nut on front
UB-5	Vertical	2250	fractured between the nut closest to the flange and the second nut on front
UB-6	Vertical	2455	fractured at base of the nut
UB-7	Vertical	2586	fractured at base of the nut
UB-8	Horizontal	6529	fractured at base of the nut
UB-8B	Horizontal		Bending test after fracture of the u-bolt
UB-9	Horizontal	6717	fractured at base of the nut
UB-9B	Horizontal		Bending test after fracture of the u-bolt

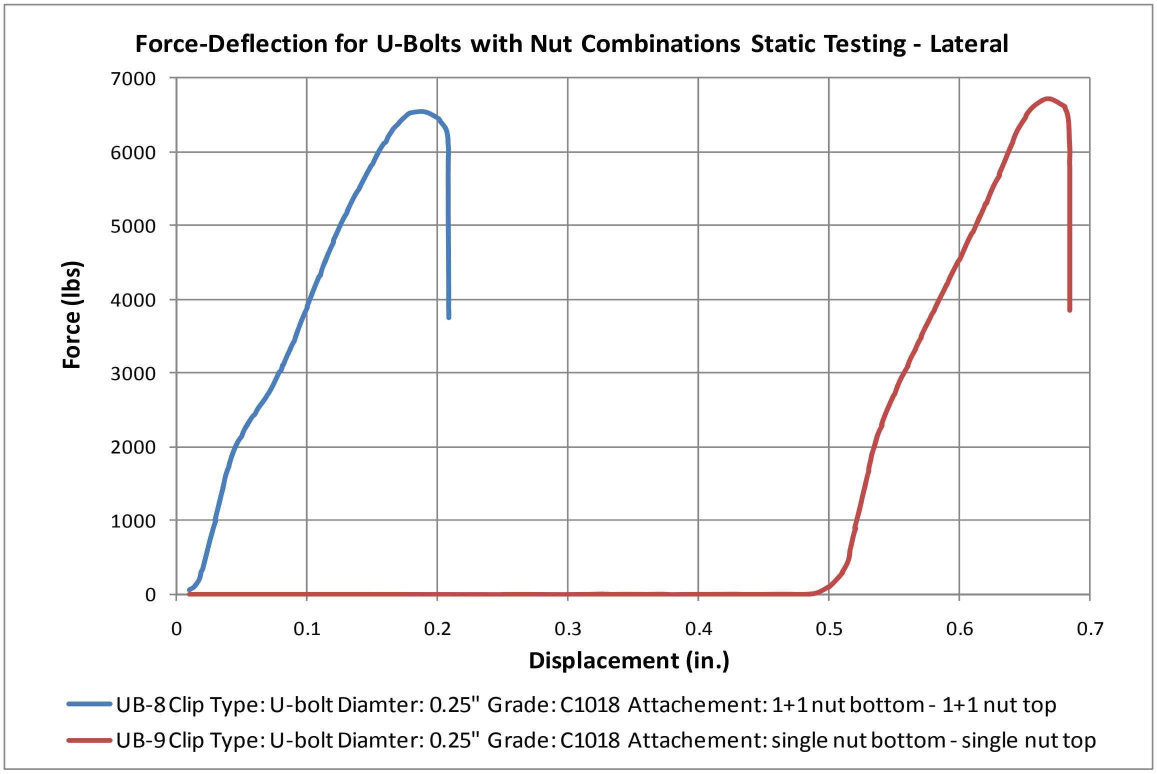


Figure 40. Lateral Force-Deflection Curves for U-Bolts with Nut Combinations

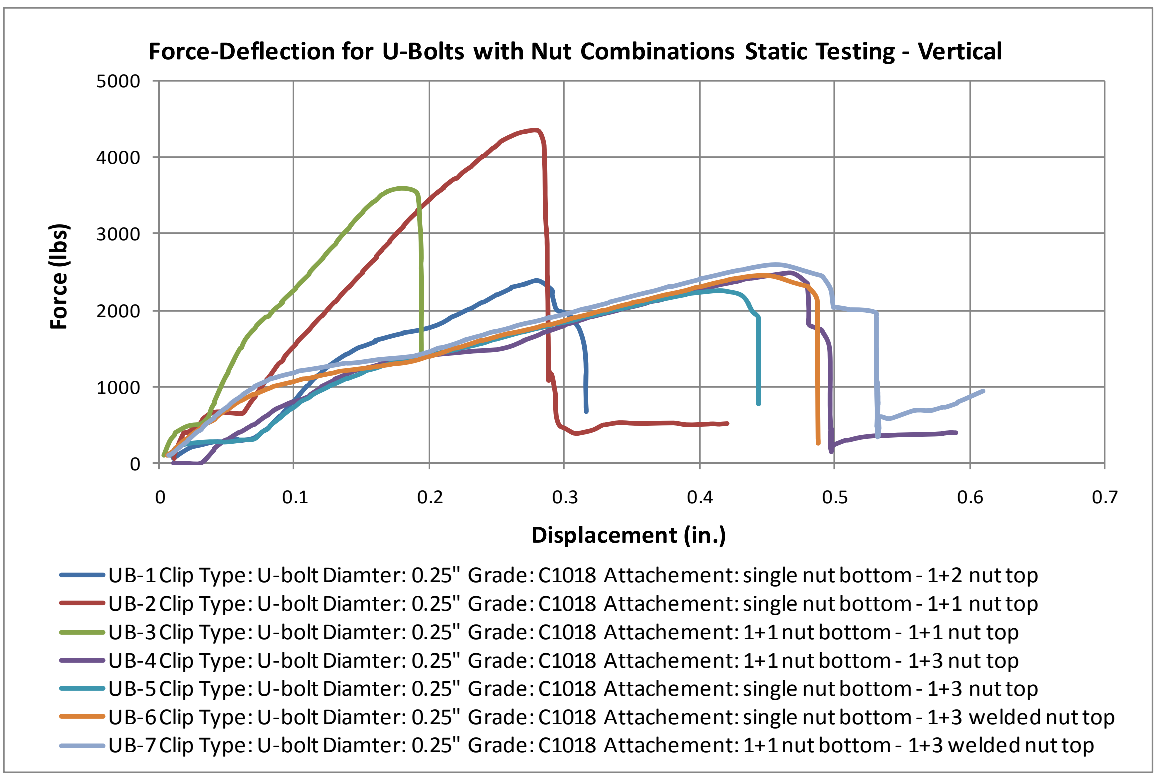


Figure 41. Vertical Force-Deflection Curves for U-Bolts with Nut Combinations

5.3.3 U-Bolts with Keyways

Test nos. UB-11 and UB-12 measured the vertical load capacity of the U-bolts with keyways concept. Lateral testing was not performed as the lateral capacity of the U-bolts had been demonstrated in test nos. UB-8 and UB-9. In both vertical tests, the connection failed when the U-bolt slipped through the keyway. Both bolts tested released the bar at loads of less than 500 lbs and were considered successful. Table 23 and presents test summary information, and Figure 42 presents the corresponding load-deflection curves.

Table 23. U-Bolts with Keyways Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-11	Vertical	454	bolt bent and slipped through keyway
UB-12	Vertical	490	bolt bent and slipped through keyway

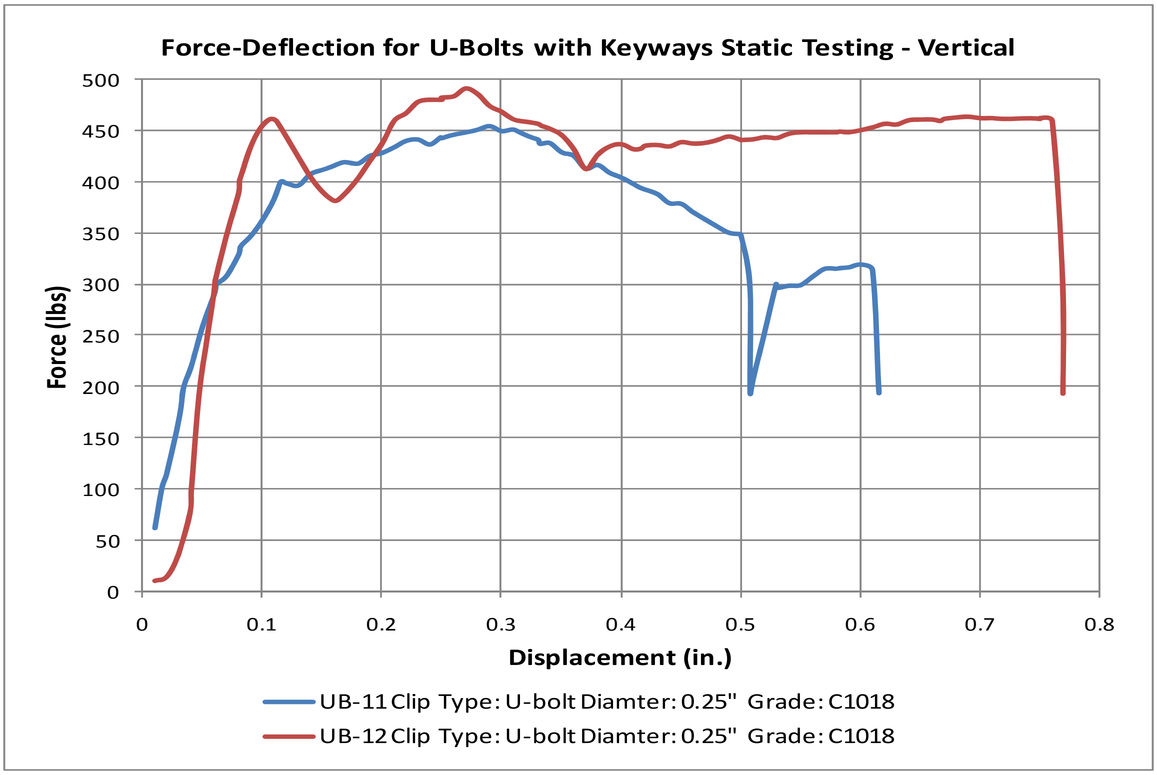


Figure 42. Vertical Force-Deflection Curves for U-Bolts with Keyways

5.3.4 U-Bolts with Upper Slots

The U-bolt concept that utilized slotted upper holes was tested in test nos. UB-13 through UB-15. Test no. UB-13 was deemed invalid as side plates on the test jig did not allow the bolt to exit the slot. Otherwise, all of these tests, which applied vertical loads to the U-bolts, failed when the upper end of the bolt cleanly exited the slot. The failure loads were approximately equal to the target load of 1,000 lbs. Table 24 presents summarized test results, and Figure 43 presents the corresponding load-deflection curves.

Table 24. U-Bolts with Upper Slots Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-13	Vertical	-	side plates on load jig did not allow bolt to exit cleanly rerun as 13B
UB-13B	Vertical	1100	reurn of 13 with only top of load jig (no side plates) - bolt slipped out end of slot
UB-14	Vertical	681	reurn of 13B with only top of load jig (no side plates) - bolt slipped out end of slot
UB-15	Vertical	900	reurn of 14 with only top of load jig (no side plates) - bolt slipped out end of slot

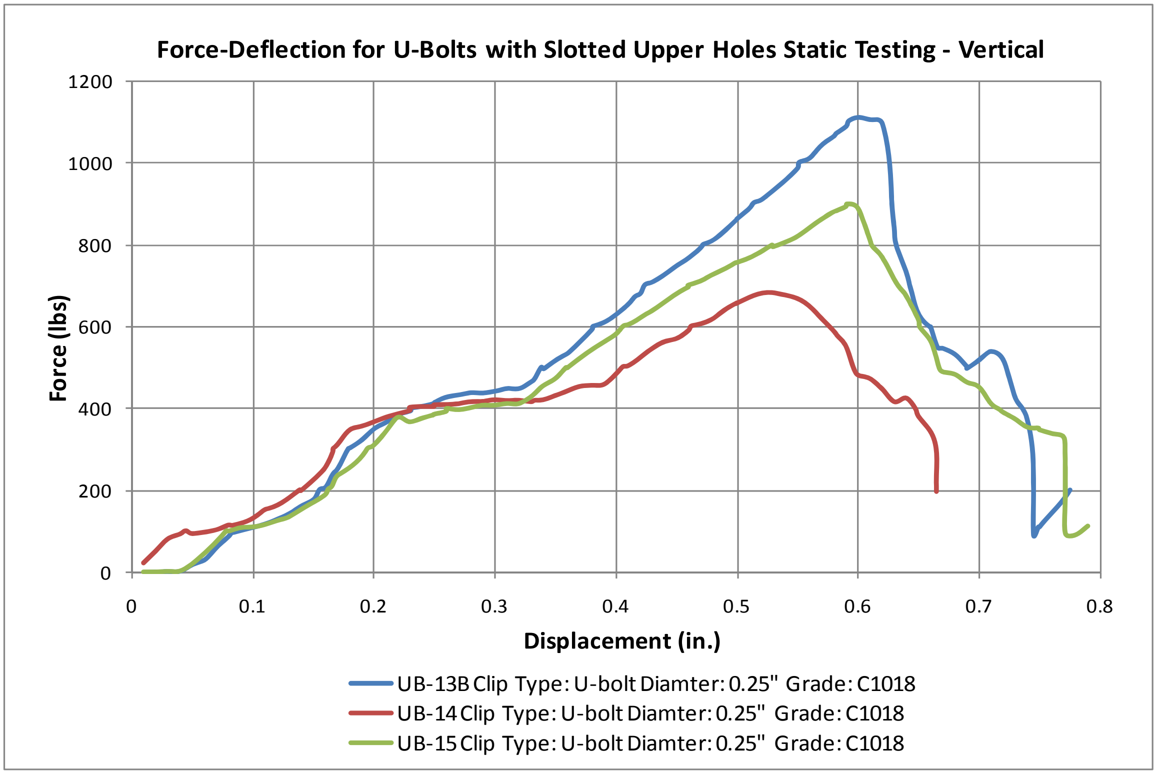


Figure 43. Vertical Force-Deflection Curves for U-Bolts with Nut Combinations

5.3.5 U-Bolts with Spacers

A large number of tests were performed on U-bolts with spacers. During the majority of these tests, the connection failed when the upper arm of the U-bolt fractured near the flange of the post. However, in some tests the bolt fractured at a greater distance from the post, and in several tests, the U-bolt partially or completely fractured at more than one location. Wooden spacers were used at first but were often crushed when the U-bolt deformed due to vertical loading. This allowed a reduction in the length of the moment arm that caused variation in the loads required for failure to occur, ranging from 1,018 lbs in test no. UB-26 to 2,170 lbs in test no. UB-17. The substitution of high density polyethylene spacers (HDPE) improved the uniformity of the test results. For the two tests that featured HDPE spacers, the failures occurred at loads of 1440 lbs and 1300 lbs. Table 25 presents a summary of the test results, and Figure 44 through Figure 50 show the corresponding force-displacement curves.

Table 25. U-Bolts with Spacers Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-16	Vertical	1241	spacer block welds broke
UB-17	Vertical	2170	spacer not welded - lost extended moment arm when cable deformed past the spacer width
UB-19	Vertical	1975	Bolt fractured at top arm
UB-20	Vertical	1882	Bolt fractured at top arm
UB-21	Vertical	1639	Bolt fractured at top arm outside of jam nut
UB-22	Vertical	1754	Bolt fractured at top arm outside of jam nut
UB-23	Vertical	1500	Bolt fractured near end of the thread, wooden spacer crushed significantly causing reduction of moment arm
UB-24	Vertical	1300	Bolt fractured near end of the thread - 1300 lbs - wooden spacer crushed significantly causing reduction of moment arm
UB-25	Vertical	1054	Bolt fractured near end of the thread, wooden spacer crushed significantly causing reduction of moment arm
UB-26	Vertical	1018	Bolt fractured near on outside of jam nut, wooden spacer crushed significantly causing reduction of moment arm
UB-33	Vertical	-	Bent vertical mounting jig - need to refabricate and reinforce
UB-34	Vertical	-	Bent vertical mounting jig - need to refabricate and reinforce - make out of S3x5.7 - stopped test
UB-35	Vertical	2030	Bolt fractured at top arm
UB-36	Vertical	2140	Bolt fractured at top arm
UB-37	Vertical	2300	Dynamic - Bolt fractured at top arm
UB-38	Vertical	1440	HDPE Spacer pivots on top edge - Top arm of bolt fractured at peak load
UB-39	Vertical	1300	HDPE Spacer pivots on top edge - Top arm of bolt fractured at peak load
UB-40	Horizontal	4850	Bent web prior to fracture of bolt due to torsion of section - Bolt fractured at peak load = 4850 lbs
UB-41	Vertical	-	Bottom arm of u-bolt fractured - Peak load = ??? - fracture of lower arm is in tension (both arms contributing so we are not isloating the bending enough to get the 6:1 ratio)
UB-42	Vertical	-	Bottom arm of u-bolt fractured - Peak load = ??? - fracture of lower arm is in tension (both arms contributing so we are not isloating the bending enough to get the 6:1 ratio)

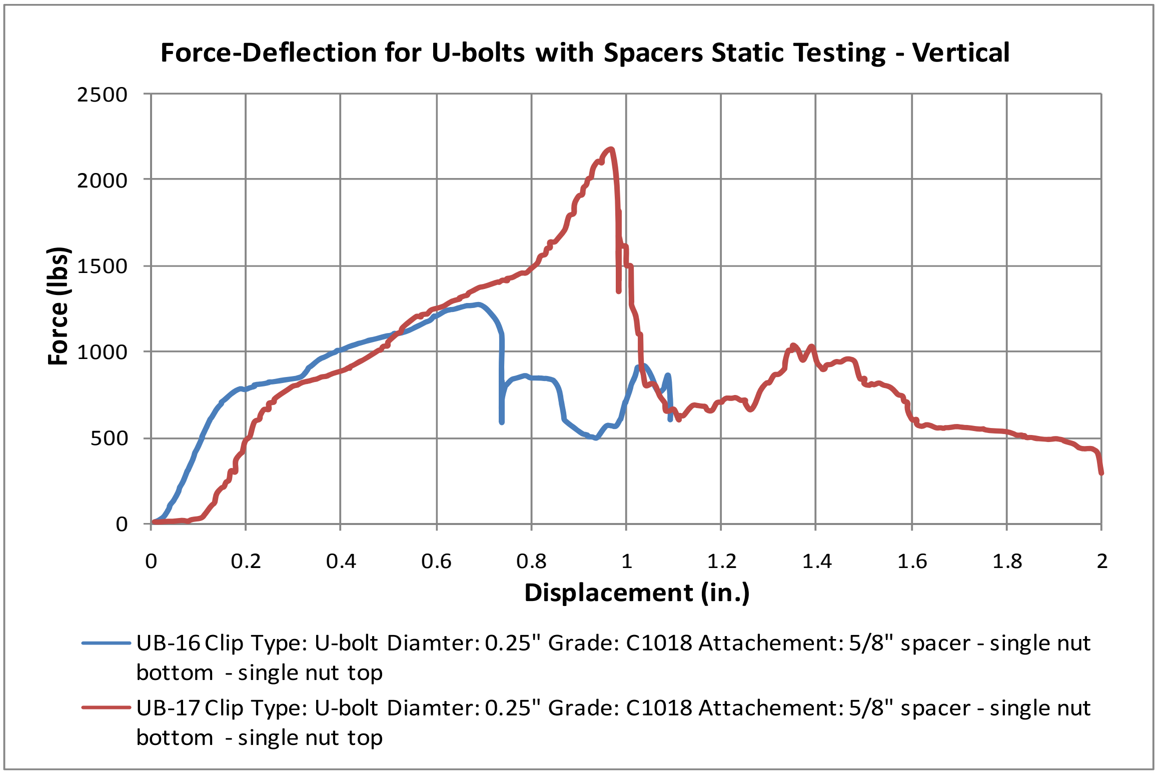


Figure 44. Vertical Force-Deflection Curves for U-Bolts with Spacers

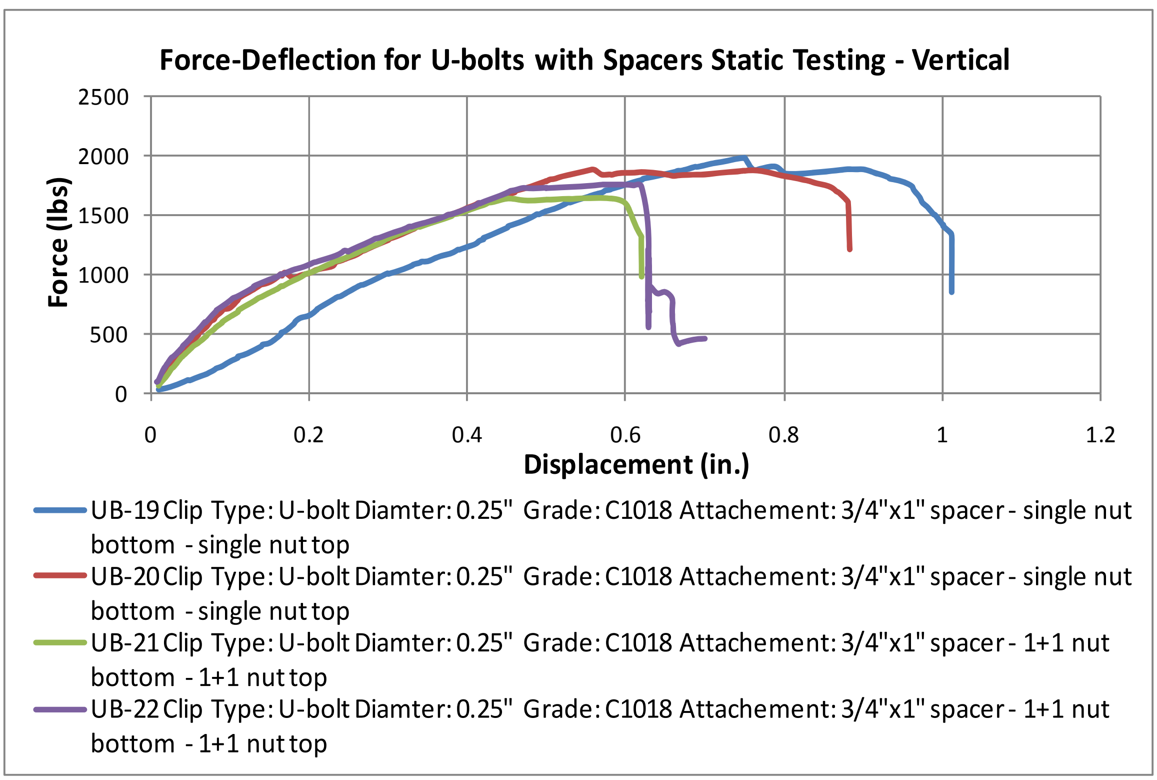


Figure 45. Vertical Force-Deflection Curves for U-Bolts with Spacers, Continued

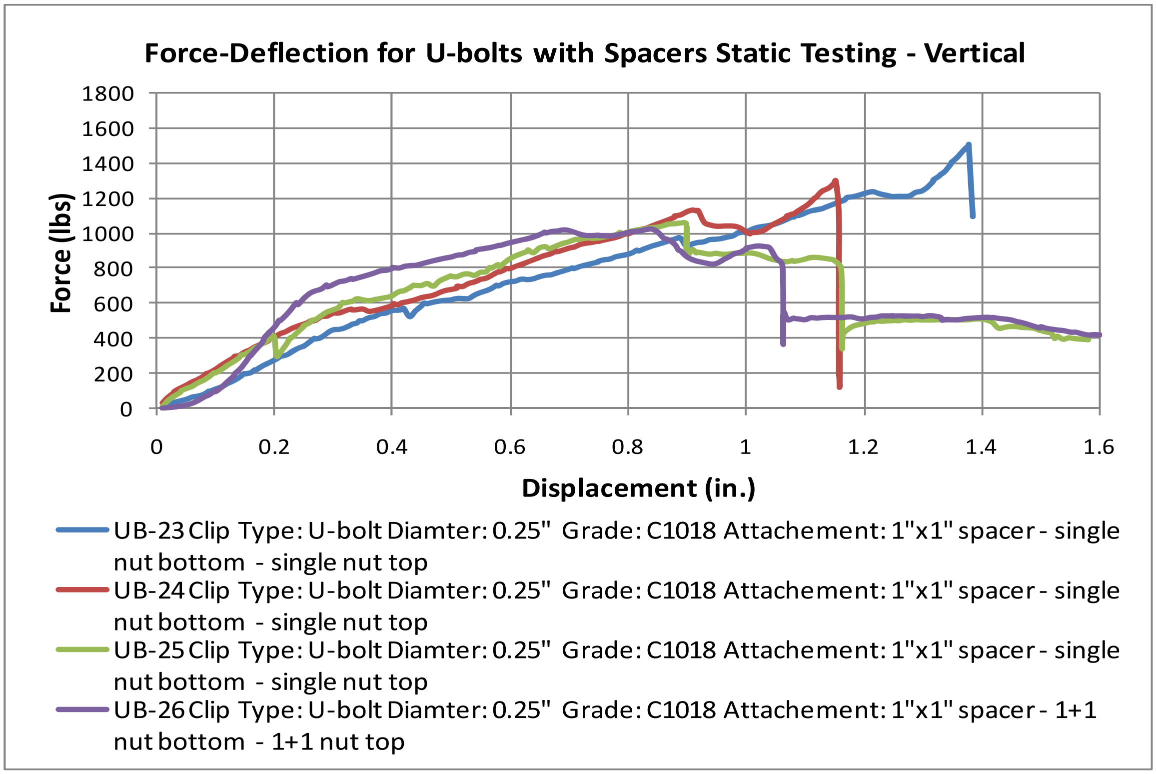


Figure 46. Vertical Force-Deflection Curves for U-Bolts with Spacers, Continued

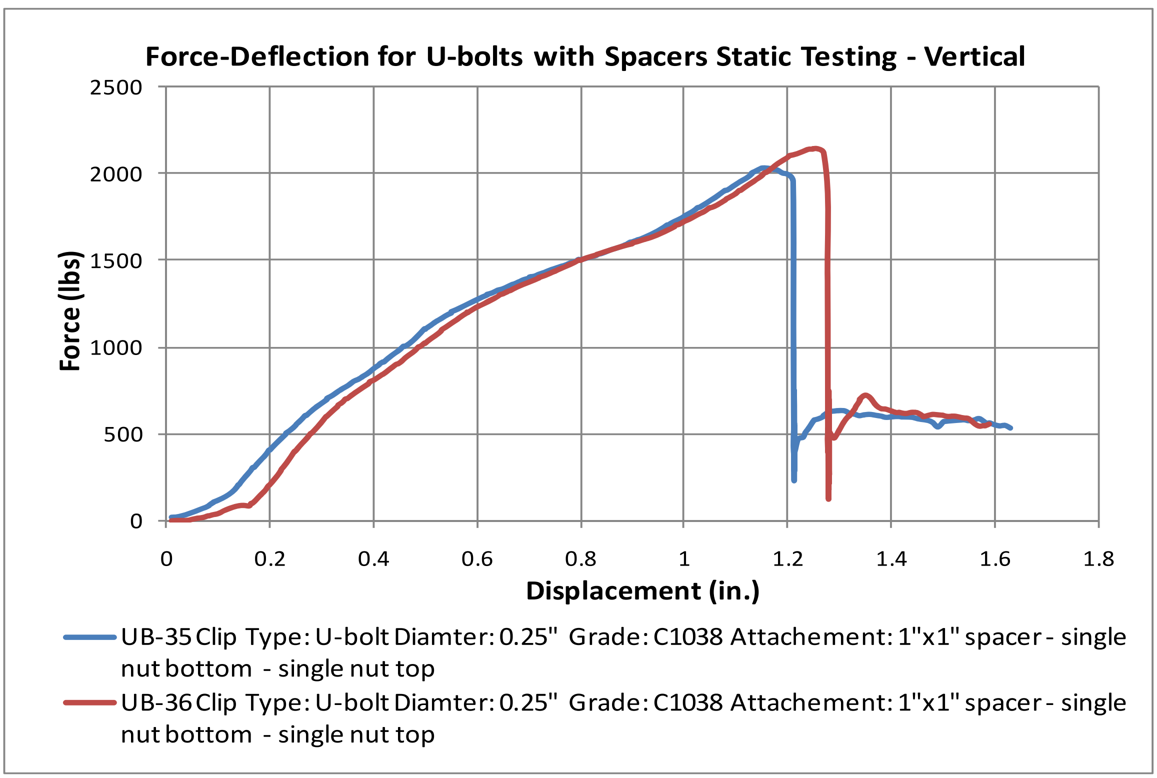


Figure 47. Vertical Force-Deflection Curves for U-Bolts with Spacers, Continued

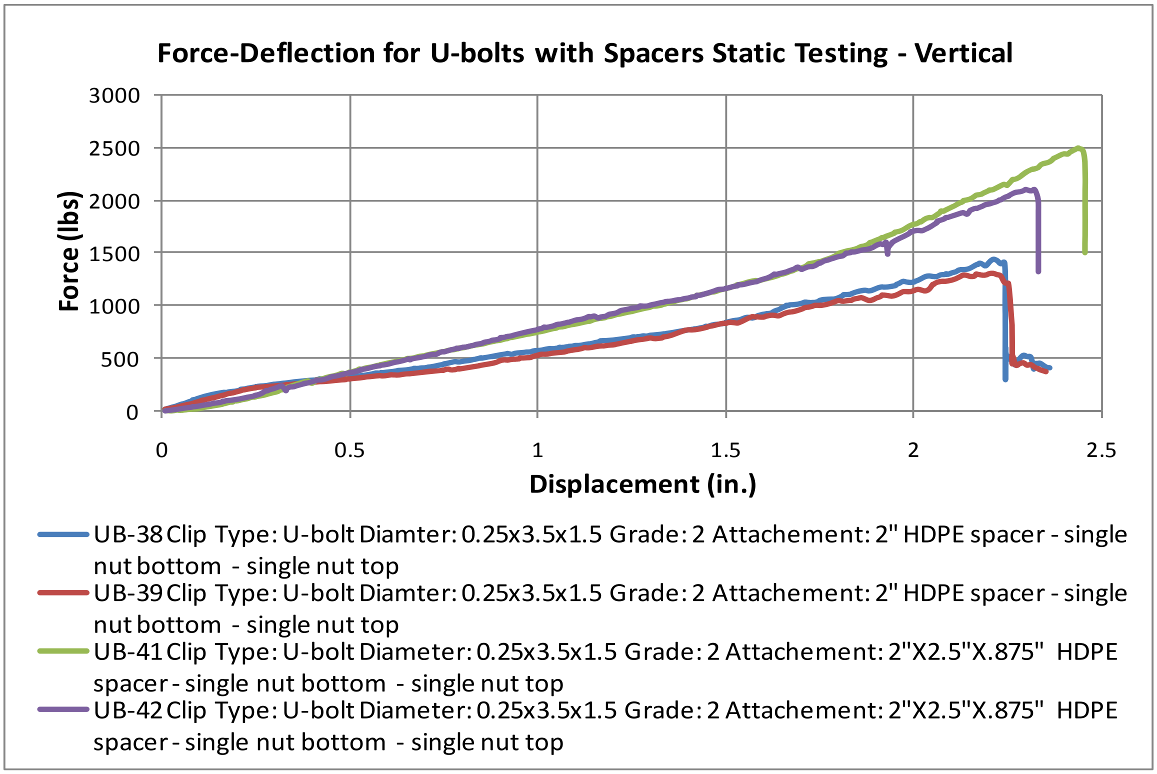


Figure 48. Vertical Force-Deflection Curves for U-Bolts with Spacers, Continued

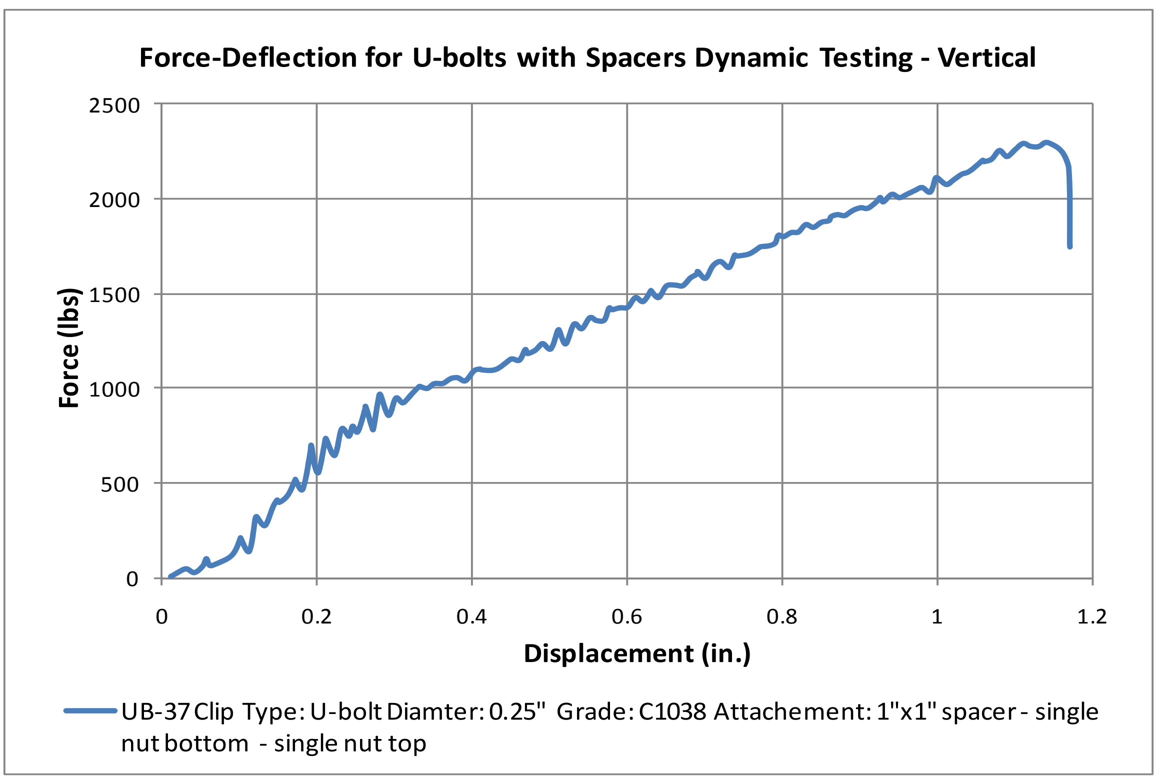


Figure 49. Vertical Force-Deflection Curves for U-Bolts with Spacers, Dynamic

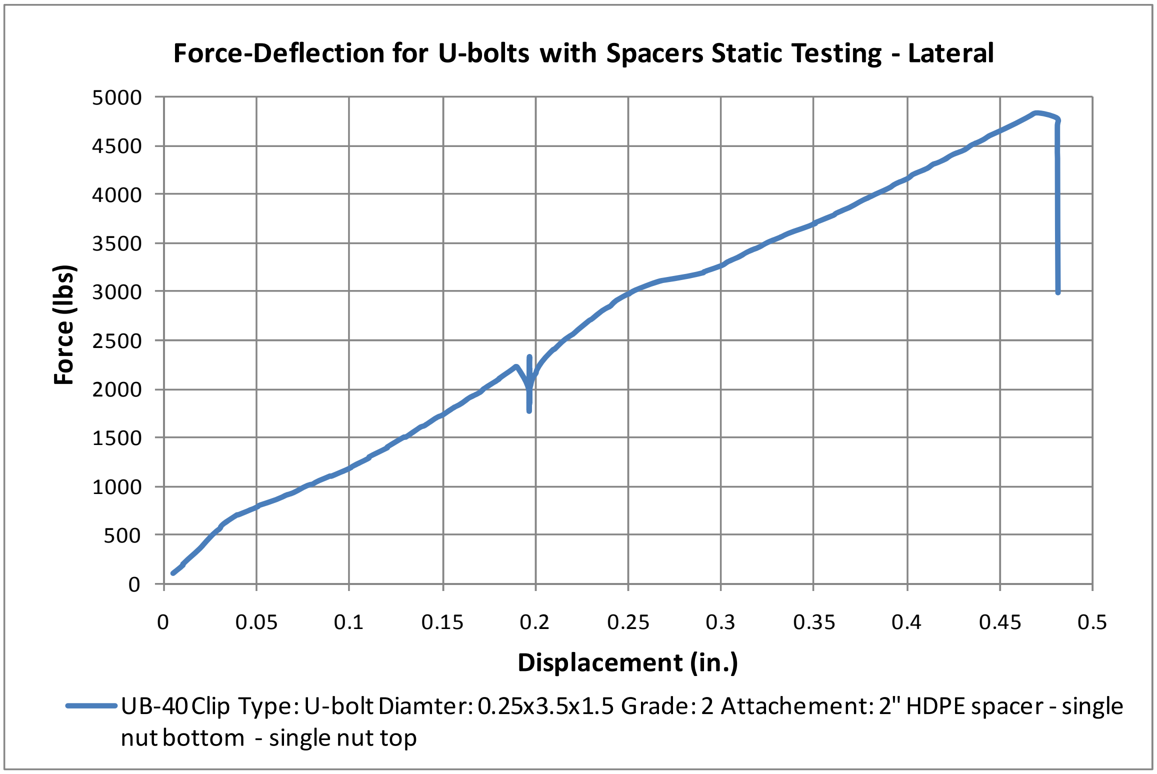


Figure 50. Lateral Force-Deflection Curves for U-Bolts with Spacers, Dynamic

5.3.6 U-Bolts with Double Slots

Only one test was performed on a U-bolt connected through double slotted holes in the post. Test no. UB-18 demonstrated that the connection was unable to develop any significant vertical load before failure. No further tests were conducted.

5.3.7 U-Bolts with Oversized Upper Holes

Test nos. UB-27 through UB-32 utilized U-bolts connections with oversized upper holes. Three tests were performed with lateral loads, and failure occurred when the bolt bent and allowed the nut to escape through the oversized upper hole. Three other tests were performed with vertically oriented loads. During these tests, the nuts did not exit cleanly through the oversized holes. Instead, failure occurred when the bolt fractured and allowed the bar to escape.

Table 26 shows summarized test results, and Figure 51 and Figure 52 show the corresponding load-deflection curves.

Table 26. U-Bolts with Oversized Upper Holes Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-27	Horizontal	1900	Bolt bent allowing nut to escape large hole on top
UB-28	Horizontal	2200	Bolt bent allowing nut to escape large hole on top
UB-29	Horizontal	2955	Bolt bent allowing nut to escape large hole on top
UB-30	Vertical	2669	Nut and washer could not exit hole - bolt fractured
UB-31	Vertical	3083	Nut did not exit hole cleanly, bolt fractured
UB-32	Vertical	2608	Nut did not exit hole cleanly, bolt fractured

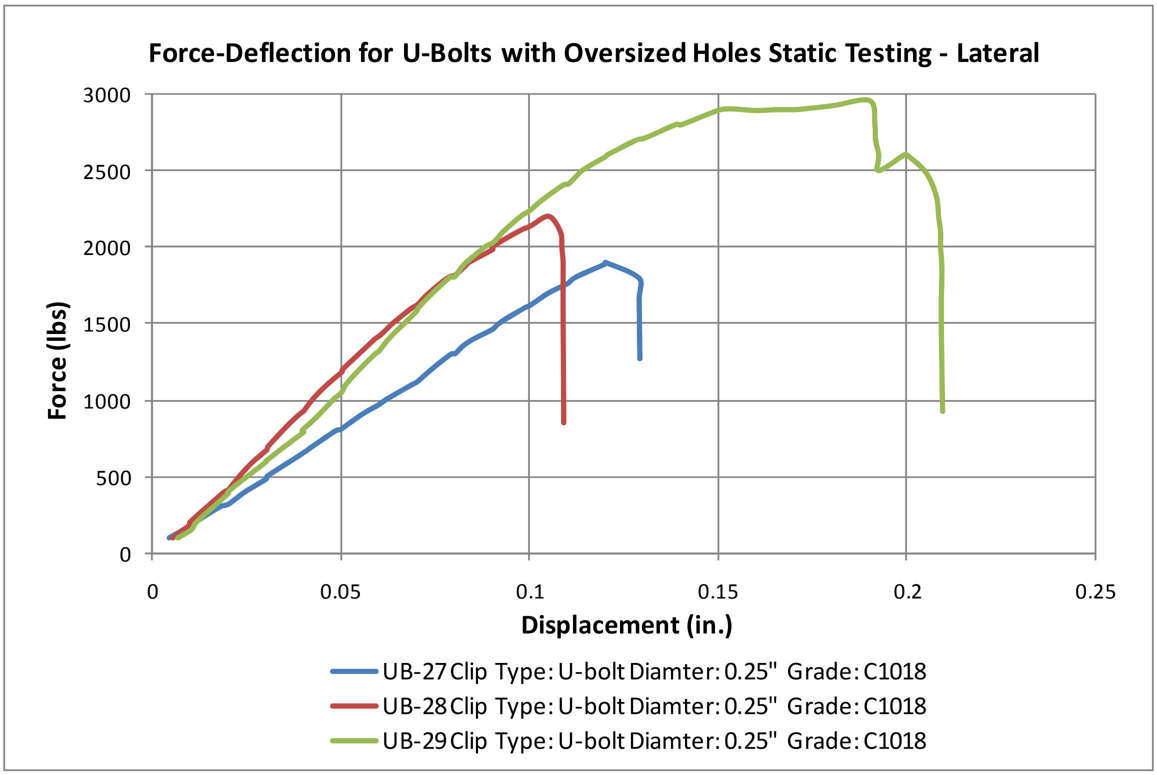


Figure 51. Lateral Force-Deflection Curves for U-Bolts with Oversized Holes

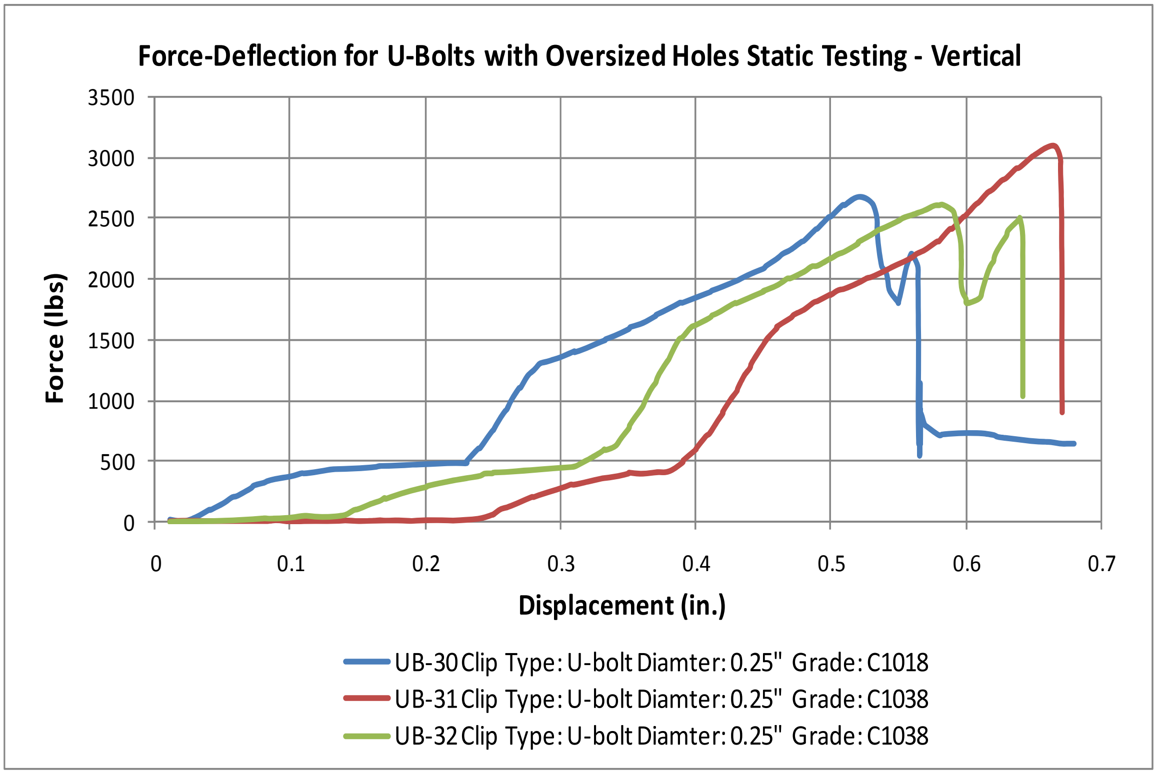


Figure 52. Vertical Force-Deflection Curves for U-Bolts with Oversized Holes

5.3.8 Bolts with Clips

Arrangements of U-bolt clips were tested last. The first set of tests, which used actual U-bolts, performed much like the U-bolts with keyways concept. When loaded laterally, the bolts fractured in tension, releasing the bar at loads of 6,530 lbs and 6,660 lbs. Under vertical loads, the U-bolts deflected through the side of the clip, allowing the bar to release at loads of less than 500 lbs. The second U-bolt concept, which consisted of two straight bolts connected by a clip, performed in a similar manner. When loaded laterally, the connections failed as the bolts either stripped their threads or fractured in tension, sustaining loads of over 5,000 lbs. Vertical loads caused the bolts to deflect, releasing the clips and the bar at loads of less than 1,000 lbs. Table 27 presents test results, and Figure 53 and Figure 54 present corresponding force-deflection curves.

Table 27. Bolts with Clips Test Results

Test No.	Load Orientation	Maximum Load (lbs)	Failure Notes/Other Notes
UB-43	Vertical	470	Smooth exit of top arm from clip
UB-44	Vertical	406	Smooth exit of top arm from clip
UB-45	Vertical	-	top arm snagged in the top hole on jig - problem with the jig - invalid test
UB-46	Horizontal	6530	Fracture of u-bolt in tension
UB-47	Horizontal	6660	Fracture of u-bolt in tension
UB-48	Vertical	3743	Bolt fractured due to shear
UB-49	Vertical	410	Started test with cable max distance from flange - Bolt bent releasing the clip plate and cable
UB-50	Vertical	968	Started test with cable next to flange - Bolt bent releasing the clip plate and cable
UB-51	Vertical	754	Started test with cable next to flange - Bolt bent releasing the clip plate and cable
UB-52	Horizontal	5400	Stripped threads - No clip plate deformatiion
UB-53	Horizontal	5264	Bolt broke in tension - No clip plate deformatiion

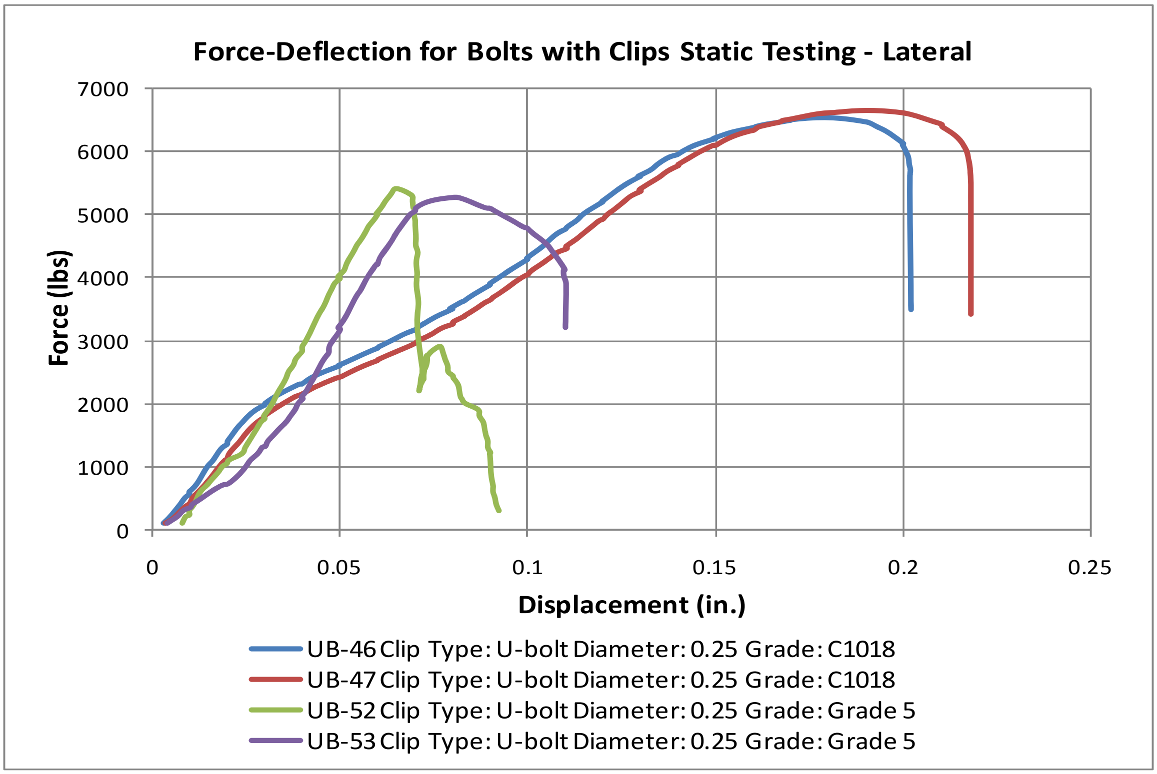


Figure 53. Lateral Force-Deflection Curves for Bolts with Clips

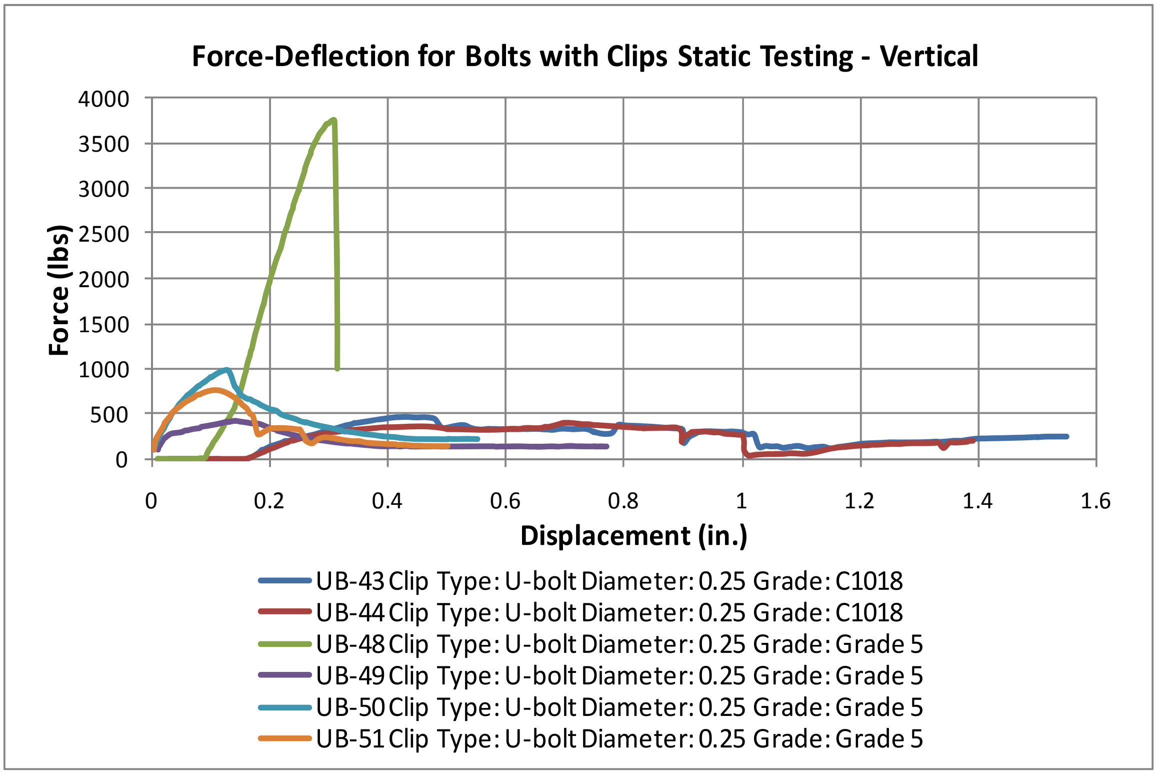


Figure 54. Vertical Force-Deflection Curves for Bolts with Clips

5.4 Discussion

Many of the concepts designed for the cable attachments proved incapable of developing the ideal lateral to vertical load ratio, 6,000 lbs to 1,000 lbs. The uniform slot brackets, the first tested concept, developed very similar lateral and vertical failure loads. Brackets featuring narrow slots satisfied the lateral load criteria but developed too much resistance when loaded vertically. Brackets with larger slots tended to satisfy the vertical load requirement better, but were unable to withstand large lateral loads.

The flat keyway bracket concept was an improvement over the uniform slot bracket, but was considered to be unreliable in meeting the vertical load requirement. Though both brackets tested laterally sustained loads over 6,000 lbs, the vertically tested brackets failed at loads of

6,207 lbs and 971 lbs. The larger load was caused by the bolt failing to slide into the bracket's keyway, and the smaller load was largely due to the bolts being installed loosely.

Brackets with angled slots failed to satisfy either loading criteria. The brackets failed under vertical loads that were larger than, but within reasonable range of the target loads. However, the brackets failed under lateral loads of approximately 2,000 lbs, or one-third the target load. As the brackets' failure ratio was not within reasonable limits of the design ratio, it was decided to abandon this concept.

The bent keyway brackets performed adequately, releasing the bar before vertical loads reached 1,000 lbs. The bar then became caught between the bracket and the bolt, resulting in an increased load. However, this was considered unimportant as in practice the cable will be free to rotate, increasing the likelihood that the cable can free itself from any snags. The bent keyway bracket's primary shortcoming was its inability to withstand the required lateral load. In the two tests performed, it failed under loads of 3,200 lbs and 4,334 lbs.

The final slotted bracket concept, the curved keyway bracket, improved on the lateral load capacity of the bent keyway bracket while maintaining its vertical load performance. Both tests performed using lateral loads surpassed the required 6,000 lb load, and in both vertical tests the brackets released the bar before the load reached 1,000 lbs. Though the load increased as the bar became caught between the bolt and the bracket, this was not considered an issue as a cable's ability to rotate would help prevent this from happening in actual field applications. The curved keyway bracket was deemed the overall best connection and was the only one to be subsequently tested under dynamic loading. A drawing of the final design of the curved keyway bracket is presented in Appendix D.

The first U-bolt concept tested, the welded and notched J-bolts, were unable to create the desired loading ratio. Under lateral loading, the capacities of the bolts varied widely and the average failure load, 4,818 lbs, was less than the requirement of 6,000 lbs. Additionally, the bolts developed more than the desired vertical strength, requiring much more than 1,000 lbs to release the bar.

Various U-bolts and nut combinations were tested next. Although these bolts were able to withstand the required lateral load, the bolts did not satisfy the vertical loading requirements. All of the vertical tests required loads of over 2,000 lbs to release the bar.

The U-bolt concepts which featured keyways and slotted upper holes in the post performed quite well. Testing confirmed that these concepts were consistent in releasing the cable within the desired load range. However, review of existing patent applications revealed a similar system, which created the possibility of future patent infringement if a patent were issued. As a result, these U-bolt concepts were discontinued in favor of other attachment systems.

A large number of tests were performed on U-bolt connections that utilized spacers, which were intended to increase the moment arm of the cable's force on the bolt. While some of the vertical tests did fail near the target load of 1,000 lbs, the tests did not demonstrate reliable results. When wood spacers were used, the deflection of the U-bolt tended to crush the block, allowing the cable to slide nearer to the post. This in turn reduced the moment arm, which lowered the bending stress in the bolt and increased the load required for failure. HDPE spacers were substituted to avoid this, but the deflection of the bolt still allowed the bar to move closer to the post. Larger spacers were used, including several that extended beyond the arms of the bolt, but they rotated about the bolt, also allowing the bar to move closer to the post. Overall, the U-bolts with spacers tended to satisfy the lateral load requirements, but most vertical tests required at least 1,500 lbs to fail. Due to the inconsistent failure of the connection when loaded vertically, it was eventually decided to discontinue the spacer concept.

Only one test was performed on the U-bolt concept that connected to the post through two inclined slots. In test no. UB-18, the bolt failed without developing any significant vertical load. Additionally, there was concern that this concept might infringe upon an existing patent. As a result, it was decided to not pursue this concept further.

The concept featuring oversized holes for the upper portion of the U-bolt connection was unable to develop the required load ratio. When loaded laterally, the bolt bent and allowed the nut to escape at loads of less than 3,000 lbs, far below the desired 6,000-lb load. Vertical tests showed that the nut and washer, when applicable, were unable to exit the hole cleanly. Failure occurred when the bolt fractured, which required over 2,500 lbs to occur. Additionally, this concept was thought to possibly infringe upon existing patent applications, so it was not pursued further.

The final U-bolt concepts tested, which utilized clips, were successful in creating the desired load ratio. The first clip concept tested, in which the U-bolts were fastened to a clip that was bolted to the post, developed lateral loads of over 6,000 lbs and failed under vertical loads of less than 1,000 lbs. However, the clip required for this concept had to be cast, which increased the price of each attachment. The second clip concept, which utilized two separate bolts connected by a clip, was developed to avoid this problem, as its clip could be inexpensively produced through stamping. Laterally, the tests showed that the attachment wasn't quite able to develop 6,000-lb loads but did sustain loads in the low 5,000-lb range. Vertical tests were largely successful as three of the four tests released the bar at loads of less than 1,000 lbs. One test, UB-

48, did not release the bar until the bolt fractured in shear, which occurred at a load of 3,743 lbs. While the second clip concept performed well, it was decided against based on serviceability issues. Though the clips were held in place by the bolts, they were allowed to move slightly due to space between the clips themselves and the bolts. There was concern that the clips might slip out due to this movement, rendering the attachment ineffective. It was decided, based on these reasons, to not further test the clip concepts.

6 CABLE ATTACHMENT DYNAMIC TESTING

6.1 Purpose

Upon completion of the static testing of the cable attachment concepts for the high-tension, cable median barrier, the curved keyway bracket was identified as the best option for the cable attachment. However, it was desired to evaluate the connection under dynamic load conditions prior to its use in a full-scale crash test. These tests would demonstrate the performance of the bracket when used with an actual cable and when loaded at speeds similar to those observed in full-scale tests.

6.2 Scope

A series of 14 dynamic tests were performed on the curved keyway bracket concept. These tests consisted of attaching one end of a cable to a bogie and the other end to the bracket, which was attached to an adjustable plate. The bogie was then set in motion, away from the bracket, placing a dynamic load on the on the bracket until failure. The tests were performed through different orientations relative to the bracket that simulated lateral, vertical, and inclined loads.

Two different styles of bolts were used to fasten the brackets to the plate. For the first nine tests, standard 0.375-in. diameter, Grade 5 bolts were used. These bolts fastened the brackets to the post but were only hand tightened to prevent the brackets from failing to release vertically due to bolt preload. Because specification of hand-tight torque is difficult for actual installation, 0.375-in. diameter, Grade 5 shoulder bolts were developed for use in the actual system. The heads of these bolts prevented the bracket from detaching from the post while the shoulders, which passed through the brackets, were tightened directly against the post, not impeding the vertical release of the cable. Simulated shoulder bolts were created by passing standard bolts through a short section of steel tube, which served as the shoulder, and tightening the entire apparatus against the post. The simulated shoulder bolts were tested in test SBB-10. Prototype shoulder bolts were later fabricated and tested in tests SBB-11 through SBB-14. Figure 55 shows the bracket and shoulder bolt installations, and a summary of the dynamic bracket tests is presented in Table 28. The test setups used for test nos. SBB-1 through SBB-10 and test nos. SBB-11 through SBB-14 are presented in Figure 56 and Figure 57, respectively.

Standard Bolts **Shoulder Bolts**

Figure 55. Standard and Shoulder Bolt Bracket Installation

Table 28. Dynamic Bracket Test Summary

Test No.	Angle* (deg)	Bolt Type	Method
SBB-1	0	Standard	Hand
SBB-2	90	Standard	Hand
SBB-3	90	Standard	Hand
SBB-4	45	Standard	Hand
SBB-5	45	Standard	Hand
SBB-6	0	Standard	Hand
SBB-7	30	Standard	Hand
SBB-8	30	Standard	Hand
SBB-9	15	Standard	Hand
SBB-10	90	Shoulder	Wrench
SBB-11	90	Shoulder	Wrench
SBB-12	90	Shoulder	Wrench
SBB-13	30	Shoulder	Wrench
SBB-14	0	Shoulder	Wrench

*Measured from bracket's vertical orientation

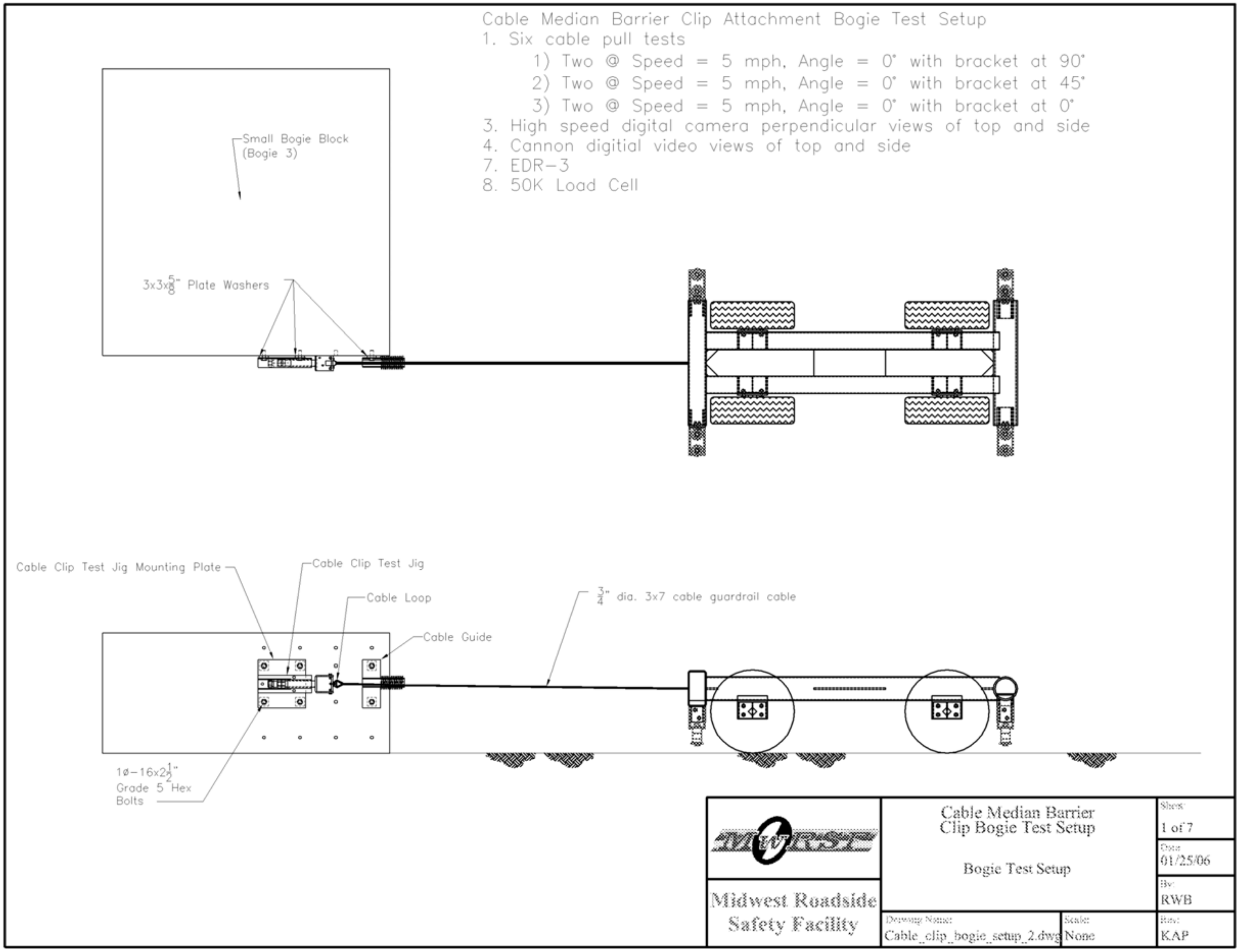


Figure 56. Test Setup for Test Nos. SBB-1 Through SBB-10

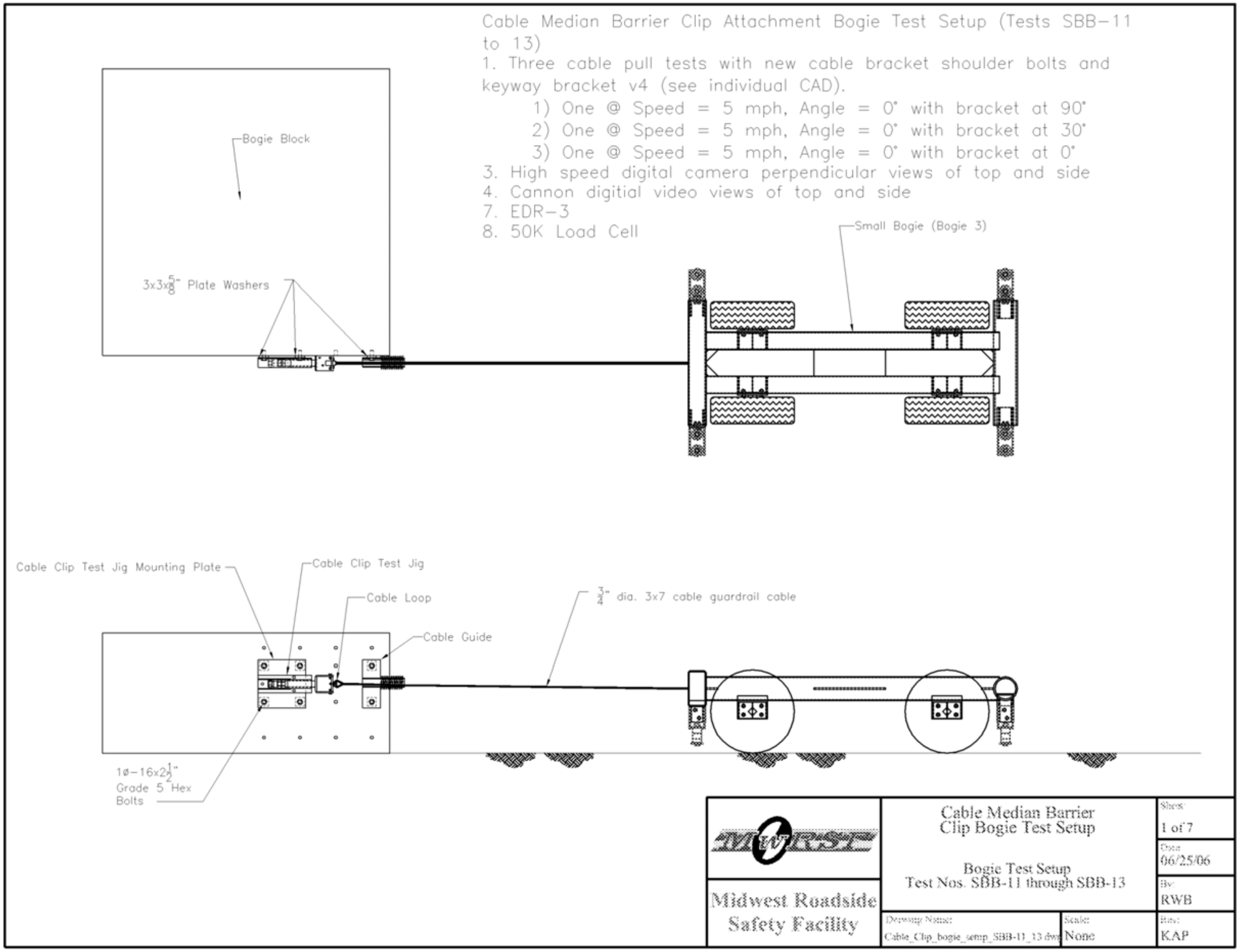


Figure 57. Test Setup for Test Nos. SBB-11 Through SBB-14

6.3 Test Facility

The testing facility is located at the Lincoln Air Park on the northwest (NW) side of the Lincoln Municipal Airport and is approximately 8.0 km (5 mi.) NW of the University of Nebraska-Lincoln.

6.4 Test Apparatus

The test apparatus consisted of a plate to which the attachments were fastened, which could be adjusted to incline the bracket at various angles. This plate was connected through a steel tube to a stationary barrier. The steel tube was attached to a mounting plate by a cylindrical joint which allowed a tension load cell to be used to measure loads. A cable was then looped through the attachment and tied to a bogie that was set in motion, away from the attachment, at a speed of approximately 6 mile per hour, placing a dynamic load on the attachment. Drawings of the test apparatus are presented in Appendix D.

6.5 Equipment and Instrumentation

A variety of equipment and instrumentation was used to record and collect data. It was important to gather correct data using accurate instrumentation in order to understand and derive meaningful conclusions from the dynamic tests. The main equipment and instruments used for the tests were:

- Bogie
- Accelerometer
- Load Cell
- Photography Cameras

6.5.1 Bogie

A rigid frame bogie, constructed under the direction of Dr. John Rohde, was used to test the attachments under dynamic loads. The weight of the bogie, not including the weight of the cable, was 1,353 lbs. The bogie is shown in Figure 58.

Figure 58. Bogie and Test Setup

6.5.2 Accelerometers

Two triaxial piezoresistive accelerometer systems, described below, were used to measure the acceleration in the longitudinal, lateral, and vertical directions. These were mounted on the bogie at approximately its center of gravity.

Principle EDR:

- Model EDR-4M6 – Instrumented Sensor Technology (IST) of Okemos, MI
- ± 200 g’s
- 10,000 Hz Sample Rate
- 3 Differential Channels, 3 Single-Ended Channels
- 6 MB RAM Memory
- 1,500 Hz low-pass filter

Secondary EDR:

- Model EDR-3 – Instrumented Sensor Technology (IST) of Okemos, MI
- ± 200 g's
- 3,200 Hz Sample Rate
- 256 kB RAM Memory
- 1,120 Hz low-pass filter

A laptop computer downloaded the raw acceleration data immediately following each test. Computer software "DynaMax 1 (DM-1)" and "DADiSP," was used to analyze and plot the accelerometer data. The data was processed as per the SAE J211/1 specifications.

6.5.3 Load Cell

A load cell was placed within the testing apparatus to measure the force exerted on the attachment until failure. This load cell was placed in tension, between the attachment and the stationary barrier, and had a maximum capacity of 50 kips.

6.5.4 High-Speed Digital Photography

Two high-speed AOS VITcam video cameras with operating speeds of 500 frames/sec, designated AOS-1 and AOS-2, were used to record video imagery of the dynamic testing. Camera AOS-1 was placed above of the attachment, facing downward, while camera AOS-2 was placed at the same height as the attachment, perpendicular to the test jig.

6.5.5 Digital Photography

Two JVC digital video cameras, designated JVC-1 and JVC-2, were used to film the dynamic tests. These cameras operated at a speed of 29.97 frames/sec. Camera JVC-1 was positioned at the same height as the attachment, perpendicular to the test jig, while camera JVC-2 was positioned above the attachment, facing downward.

A digital still camera was also used to record images of the dynamic tests. This camera was a Nikon D50.

7 ATTACHMENT DYNAMIC TESTING RESULTS AND DISCUSSION

7.1 Results

A series of fourteen dynamic tests were performed on the slotted bracket. Vertical, lateral, and inclined loads were applied to the brackets to test its load capacity under all load orientations. Standard bolts were used to fasten the bracket for the first nine tests, and shoulder bolts were used for the remainder of the tests. Results for all tests performed are presented in the following sections. A summary of these results is presented in Table 29.

Table 29. Dynamic Testing Results

Test No.	Angle (deg)	Peak Load (kips)	Release/ Failure Mode
SBB-1	0	0.805919	bolt head slid through keyway
SBB-2	90	6.838486	rupture of bracket near bolt head allowing bolt to release
SBB-3	90	6.885669	rupture of bracket near bolt head allowing bolt to release
SBB-4	45	5.33188	rupture of minimum tensile area
SBB-5	45	4.540741	rupture of minimum tensile area
SBB-6	0	0.872944	bolt head slid through keyway
SBB-7	30	no load cell	bolt head slid through keyway
SBB-8	30	1.966965	bolt head slid through keyway
SBB-9	15	0.882381	bolt head slid through keyway
SBB-10	90	7.028065	rupture of minimum tensile area
SBB-11	90	5.228548	bolt installed wrong - rupture of minimum tensile area
SBB-12	90	5.721919	bolt failed prior to failure of bracket
SBB-13	30	1.167267	bolt head slid through keyway
SBB-14	0	2.819096	bolt head slid through keyway - cable caught on bolt head causing extra load

7.1.1 Test No. SBB-1

For test no. SBB-1, the cable applied a load to the bracket along its vertical axis. The bracket was fastened using standard bolts and released the cable at a load of 806 lbs. The cable then became caught on the bolt, but rotated free. Pre-test and post-test photographs are presented in Figure 59. Sequential photographs for test no. SBB-1 are presented in Figure 60, and force-time data is presented in Figure 61.

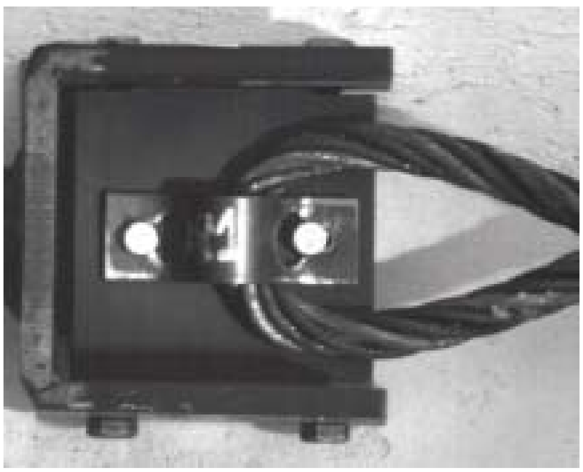
Pre-Test

Post-Test

Figure 59. Pre-Test and Post-Test Photographs for Test No. SBB-1

Time = 0ms

Time = 50ms



Time = 100ms

Time = 110ms

Time = 114ms

Time=130ms

Figure 60. Sequential Photographs, Test No. SBB-1

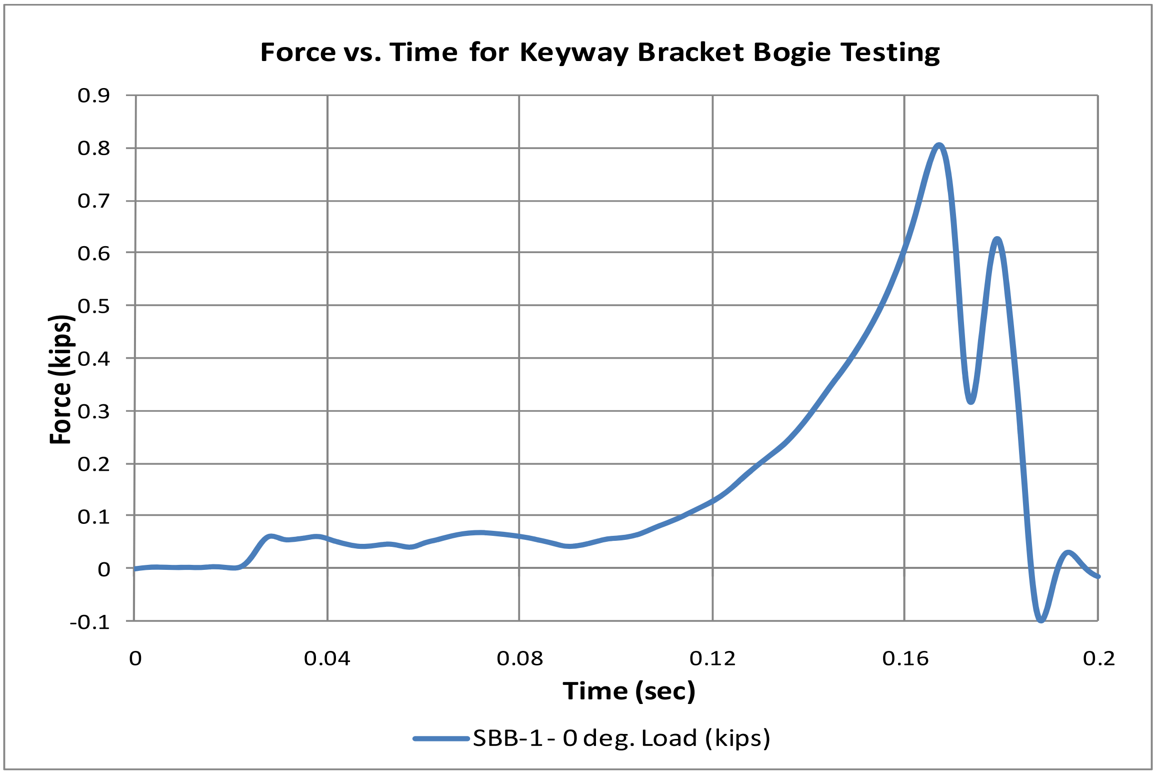
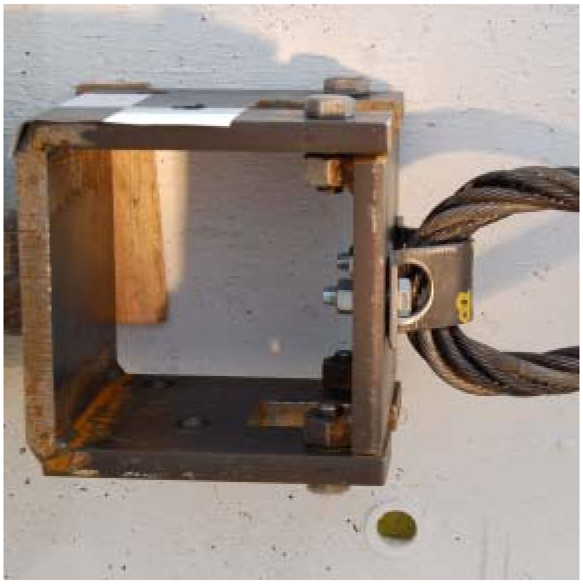


Figure 61. Force-Time Data for Test No. SBB-1

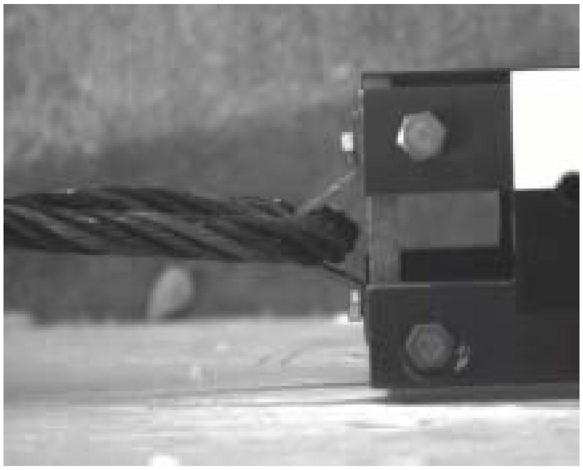
7.1.2 Test No. SBB-2

For test no. SBB-2, the cable applied a load to the bracket along its lateral axis. The bracket was fastened using standard bolts and released the cable when the bracket ruptured near the bolt connections at a load of 6,838 lbs. Pre-test and post-test photographs are presented in Figure 62. Sequential photographs for test no. SBB-2 are presented in Figure 63, and force-time data is presented in Figure 64.

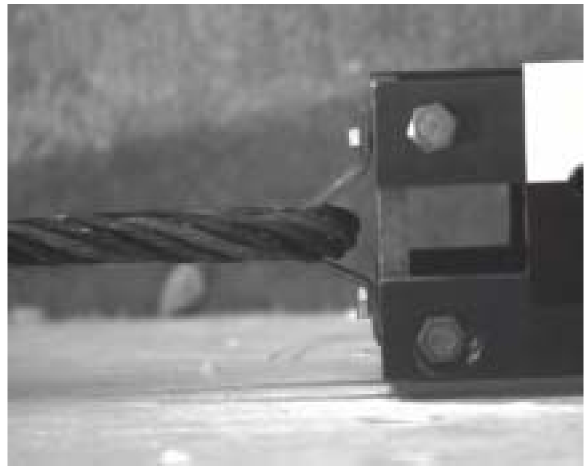


Pre-Test **Post-Test**

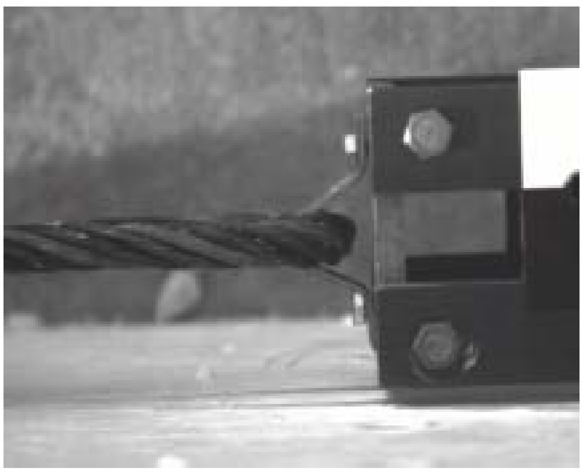
Figure 62. Pre-Test and Post-Test Photographs for Test No. SBB-2



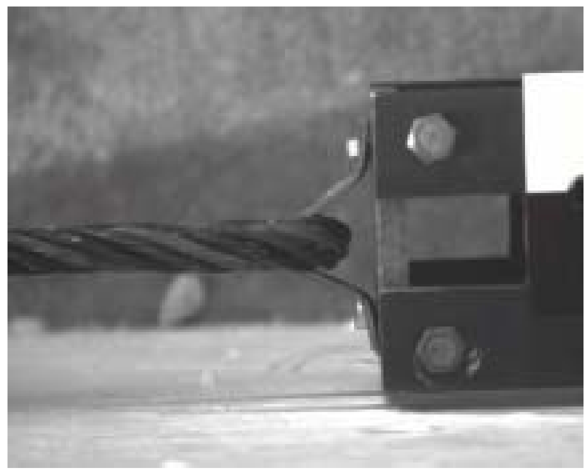
Time = 0ms



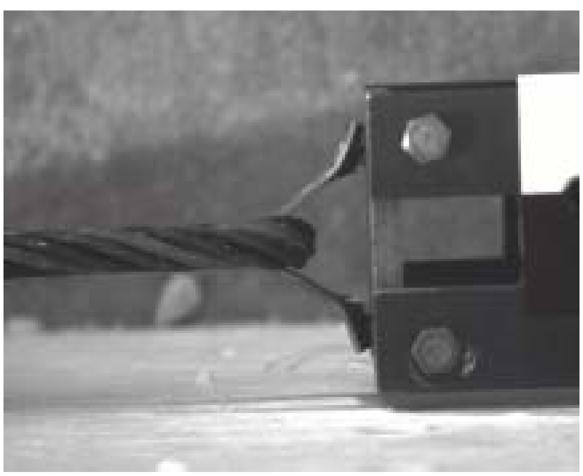
Time = 50ms



Time = 100ms



Time = 110ms



Time = 140ms

Time = 150ms

Figure 63. Sequential Photographs, Test No. SBB-2

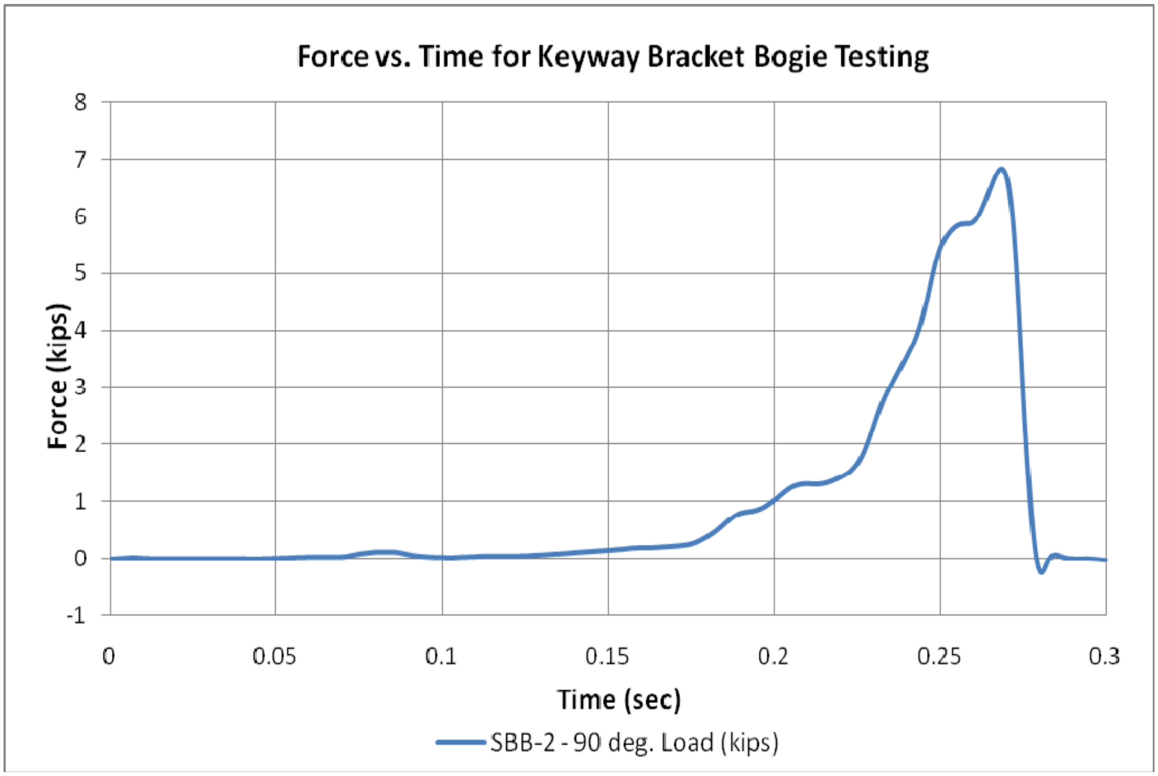
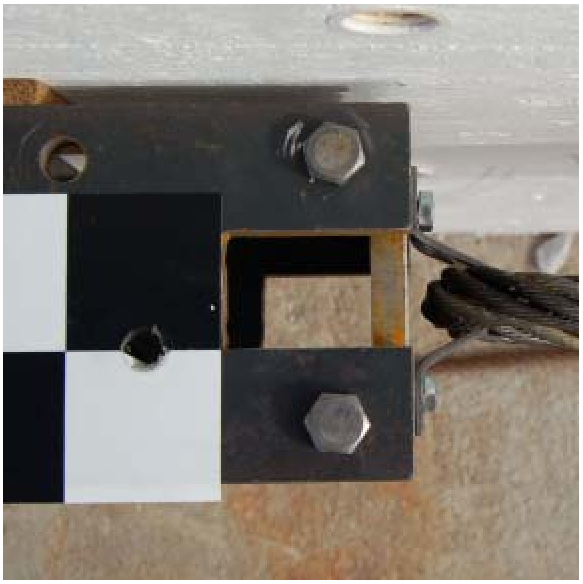


Figure 64. Force-Time Data for Test No. SBB-2

7.1.3 Test No. SBB-3

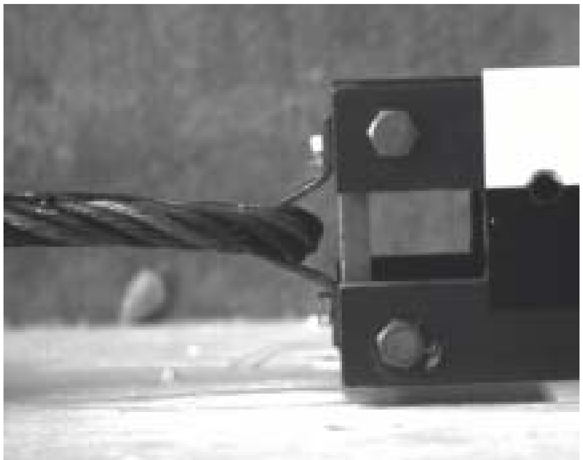
For test no. SBB-3, the cable applied a load to the bracket along its lateral axis. The bracket was fastened using standard bolts and released the cable when the bracket ruptured near the bolt connections at a load of 6,886 lbs. Pre-test and post-test photographs are presented in Figure 65. Sequential photographs for test no. SBB-3 are presented in Figure 66, and force-time data is presented in Figure 67.

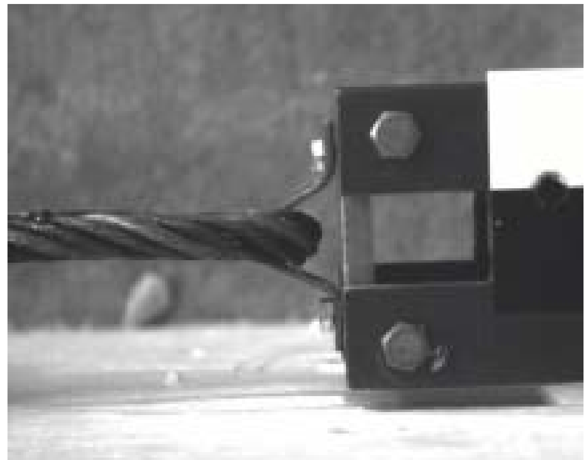


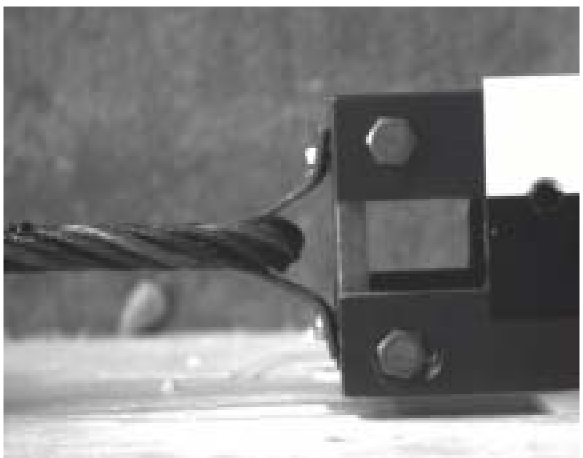
Pre-Test

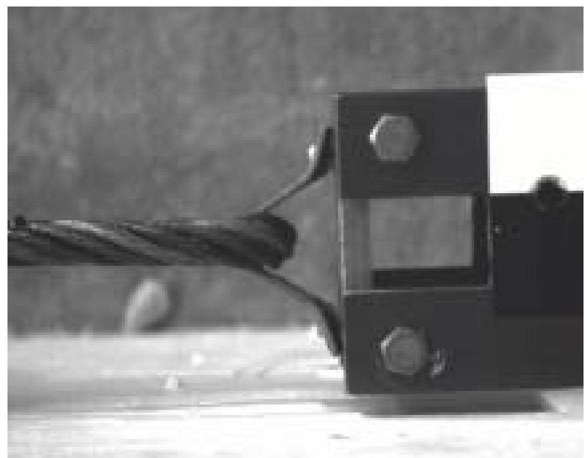
Post-Test

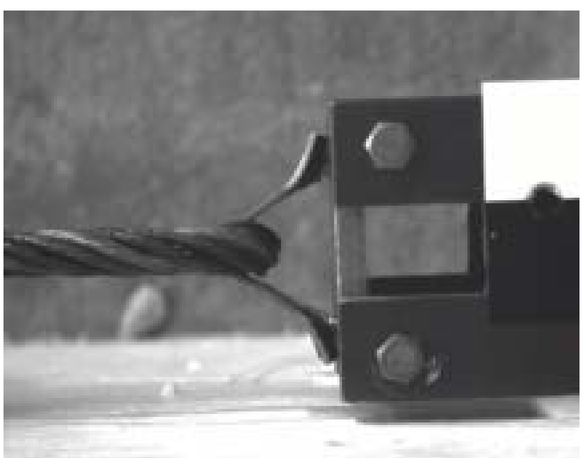
Figure 65. Pre-Test and Post-Test Photographs for Test No. SBB-3


Time = 0ms


Time = 50ms


Time = 90ms


Time = 100ms


Time = 110ms

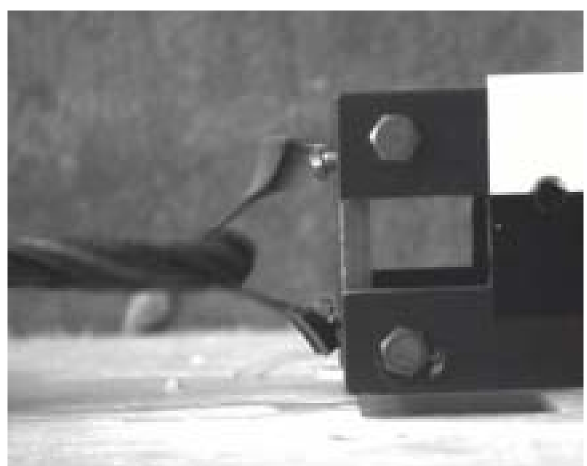

Time = 120ms

Figure 66. Sequential Photographs, Test No. SBB-3

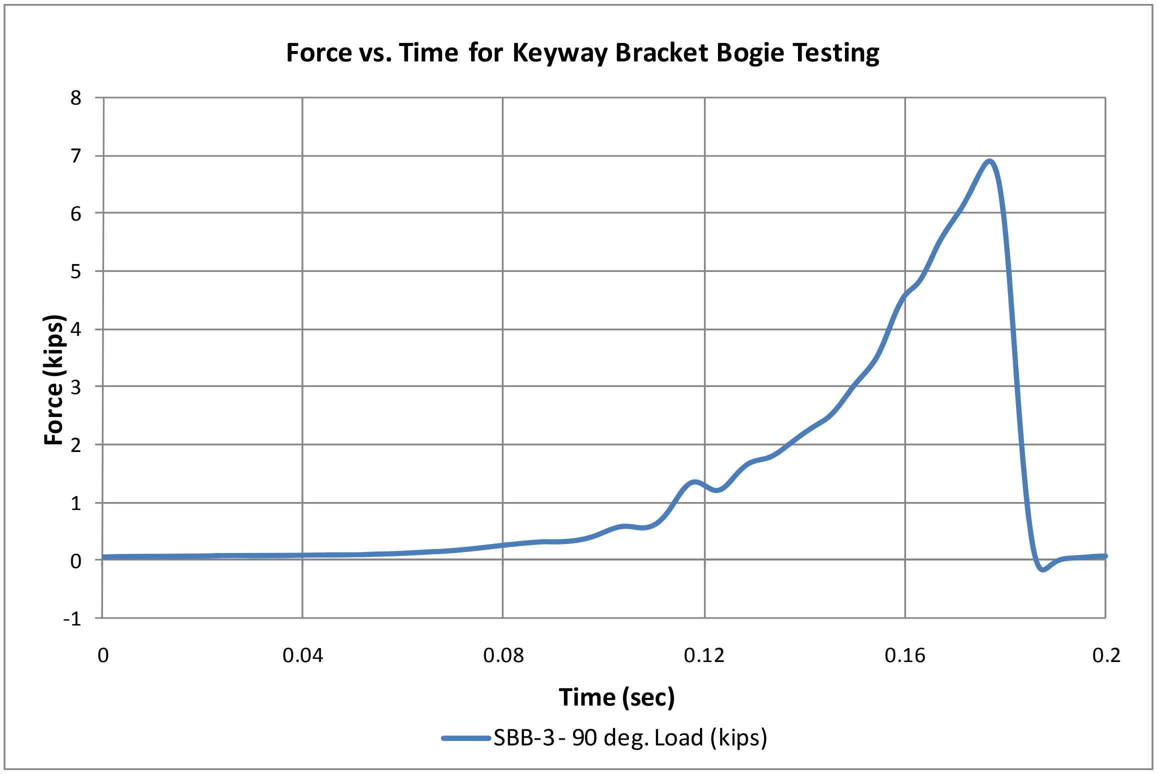


Figure 67. Force-Time Data for Test No. SBB-3

7.1.4 Test No. SBB-4

For test no. SBB-4, the cable applied a load at an angle of 45 degrees to the bracket's vertical axis. The bracket was fastened using standard bolts and released the cable when the bracket ruptured at the minimum tensile area, near the bolt connections, at a load of 5,332 lbs. Pre-test and post-test photographs are presented in Figure 68. Sequential photographs for test no. SBB-4 are presented in Figure 69, and force-time data is presented in Figure 70.

Pre-Test

Post-Test

Figure 68. Pre-Test and Post-Test Photographs for Test No. SBB-4

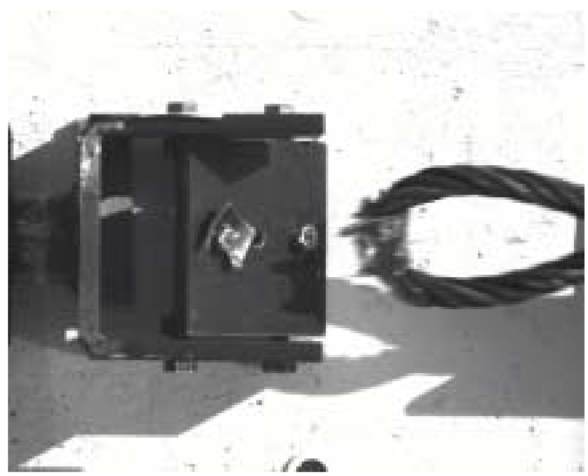
Time = 0ms

Time = 50ms

Time = 100ms

Time = 110ms

Time = 120ms



Time = 124ms

Figure 69. Sequential Photographs, Test No. SBB-4

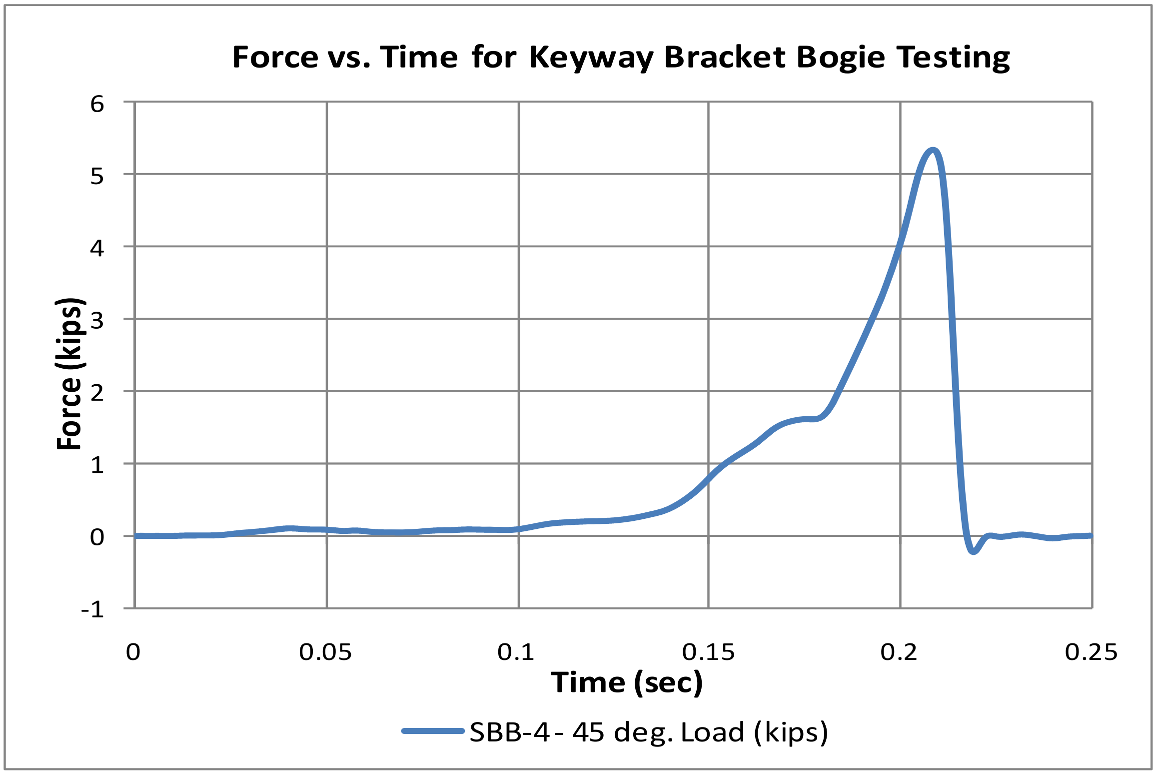


Figure 70. Force-Time Data for Test No. SBB-4

7.1.5 Test No. SBB-5

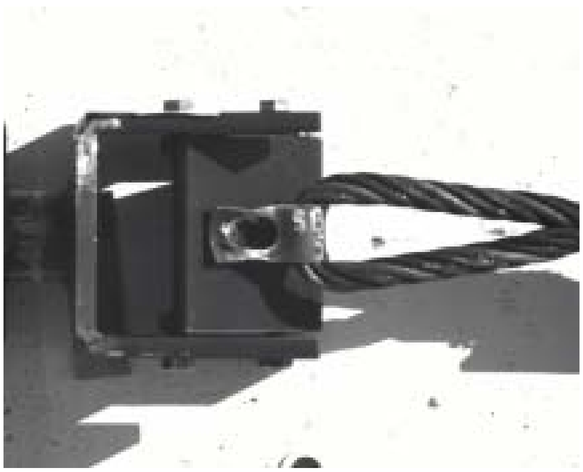
For test no. SBB-5, the cable applied a load at an angle of 45 degrees to the bracket's vertical axis. The bracket was fastened using standard bolts and released the cable when the bracket ruptured at the minimum tensile area, near the bolt connections, at a load of 4,541 lbs. Pre-test and post-test photographs are presented in Figure 71. Sequential photographs for test no. SBB-5 are presented in Figure 72, and force-time data is presented in Figure 73.

Pre-Test **Post-Test**

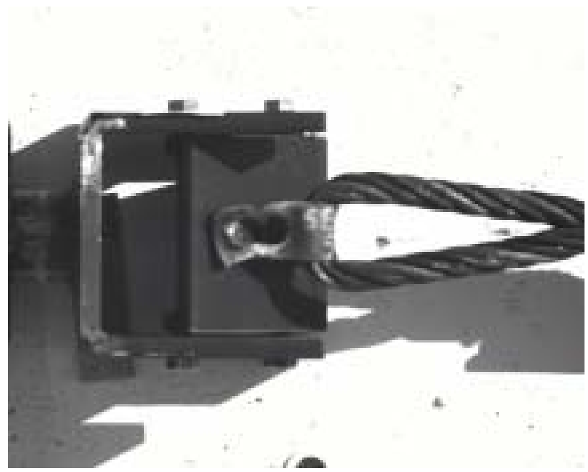
Figure 71. Pre-Test and Post-Test Photographs for Test No. SBB-5

Time = 0ms

Time = 100ms

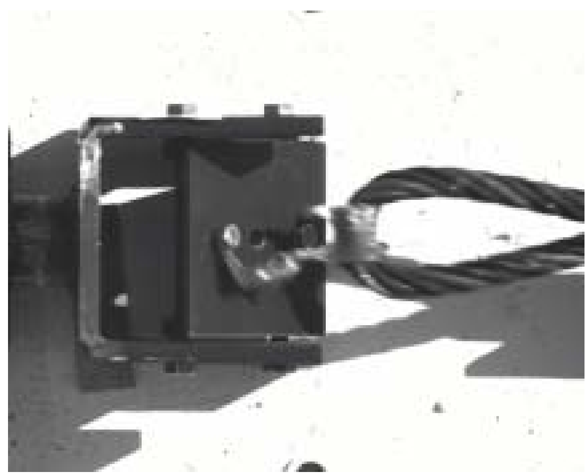


Time = 120ms



Time = 122ms

Time = 124ms



Time = 126ms

Figure 72. Sequential Photographs, Test No. SBB-5

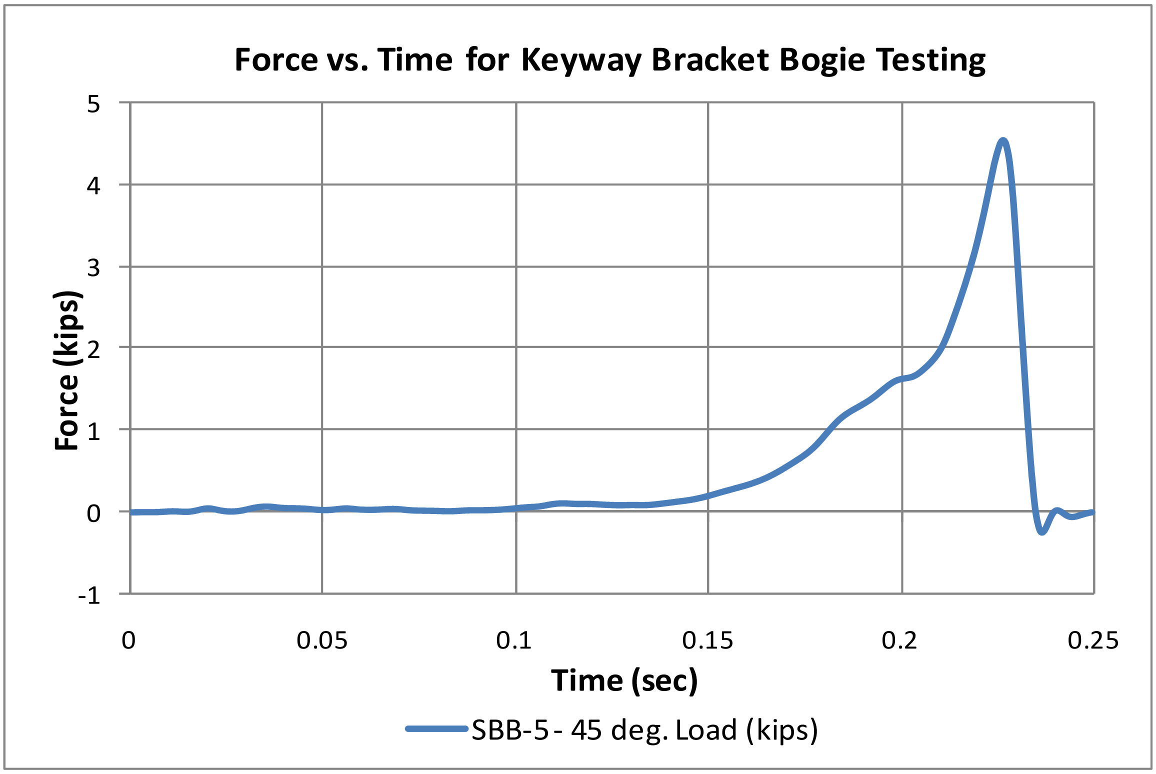


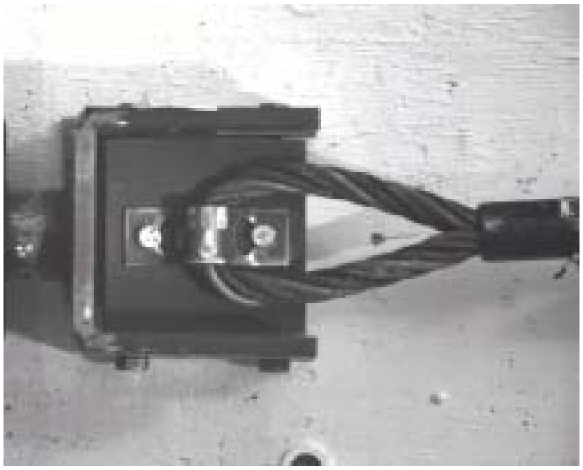
Figure 73. Force-Time Data for Test No. SBB-5

7.1.6 Test No. SBB-6

For test no. SBB-6, the cable applied a load to the bracket along its vertical axis. The bracket was fastened using standard bolts and released the cable which then became caught on the bolt, rotating free at a load of 873 lbs. Pre-test and post-test photographs are presented in Figure 74. Sequential photographs for test no. SBB-6 are presented in Figure 75, and force-time data is presented in Figure 76.

Pre-Test **Post-Test**

Figure 74. Pre-Test and Post-Test Photographs for Test No. SBB-6



Time = 0ms

Time = 110ms

Time = 116ms

Time = 124ms

Time = 130ms

Time = 140ms

Figure 75. Sequential Photographs, Test No. SBB-6

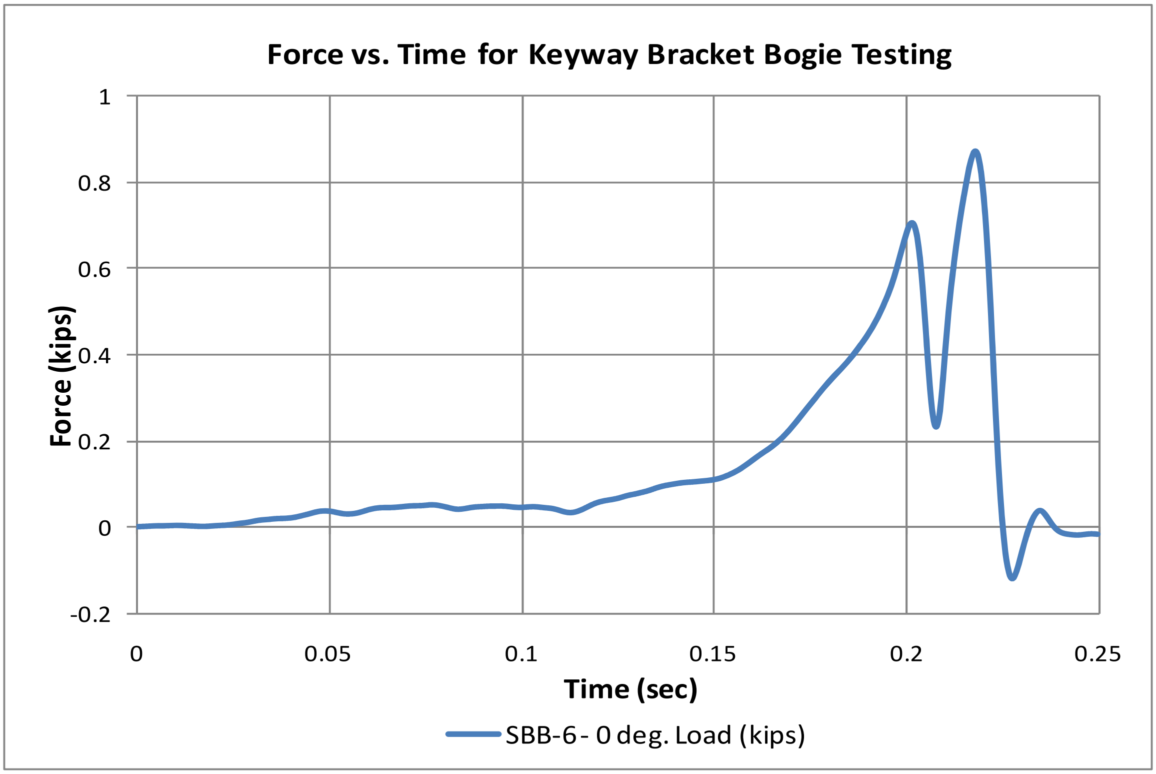


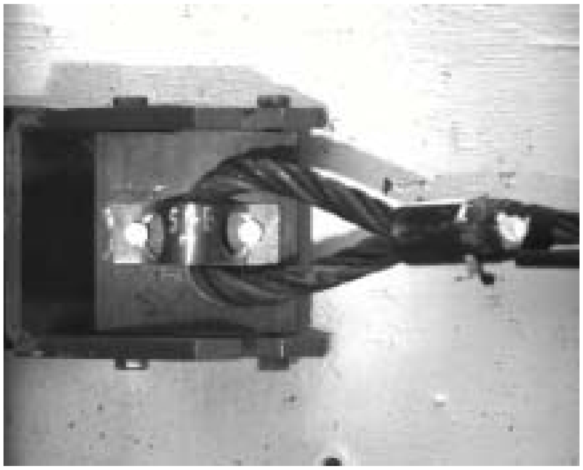
Figure 76. Force-Time Data for Test No. SBB-6

7.1.7 Test No. SBB-7

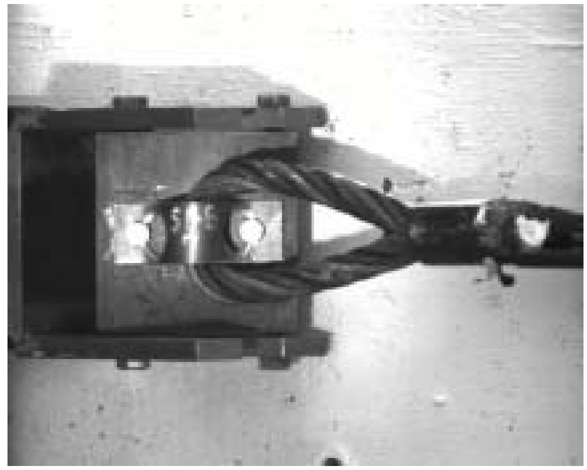
For test no. SBB-7, the cable applied a load to the bracket at an angle of 30 degrees relative to its vertical axis. The bracket was fastened using standard bolts and released the cable cleanly under the dynamic load. However, a load cell was not installed for this test, to the failure load is unknown. Pre-test and post-test photographs are presented in Figure 77. Sequential photographs for test no. SBB-7 are presented in Figure 78.

Pre-Test **Post-Test**

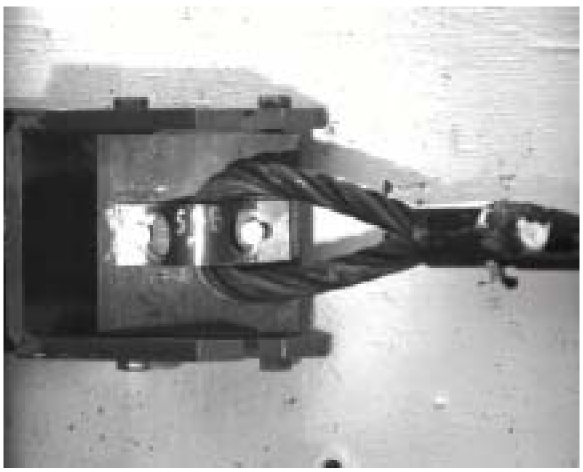
Figure 77. Pre-Test and Post-Test Photographs for Test No. SBB-7



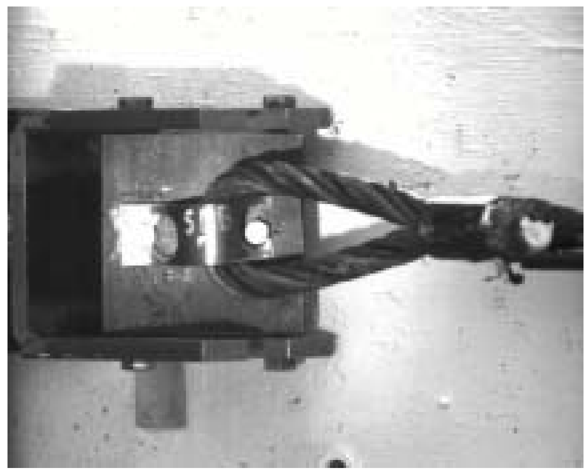
Time = 0ms



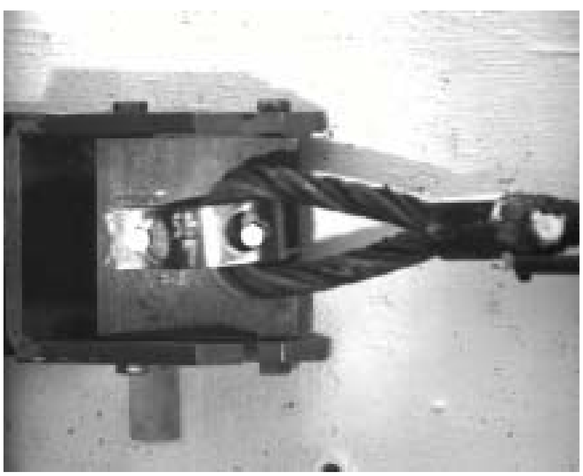
Time = 70ms



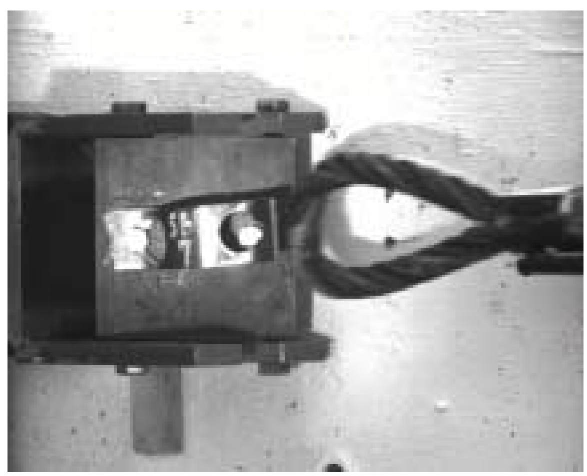
Time = 84ms



Time = 118ms



Time = 122ms



Time = 128ms

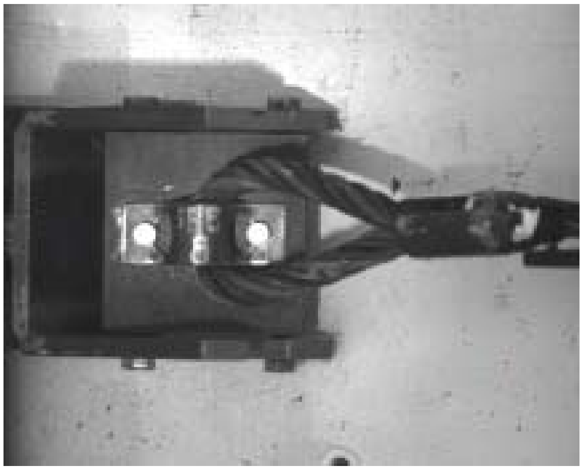
Figure 78. Sequential Photographs, Test No. SBB-7

7.1.8 Test No. SBB-8

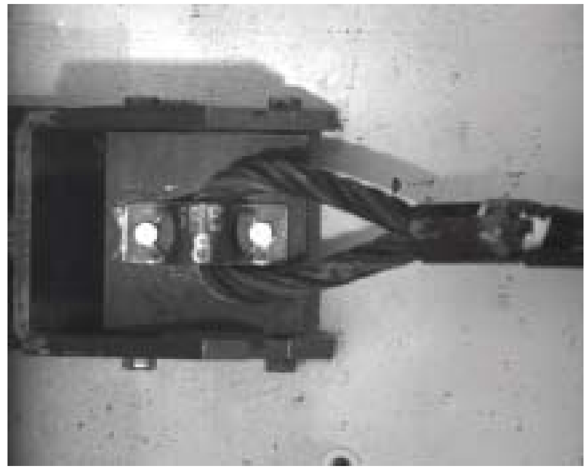
For test no. SBB-8, the cable applied a load to the bracket at an angle of 30 degrees relative to its vertical axis. The bracket was fastened using standard bolts and released the cable cleanly under a load of 1,967 lbs. Pre-test and post-test photographs are presented in Figure 79. Sequential photographs for test no. SBB-6 are presented in Figure 80, and force-time data is presented in Figure 81.

Pre-Test **Post-Test**

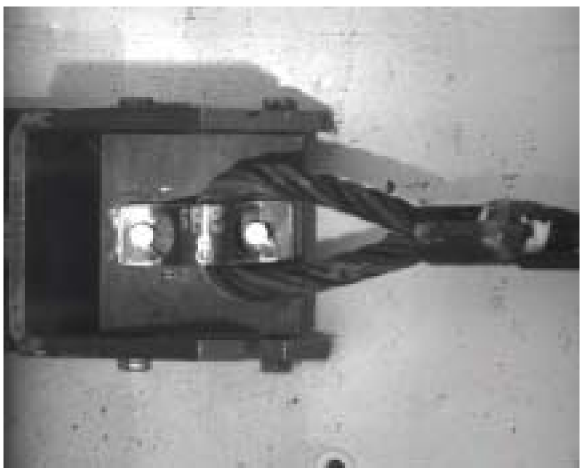
Figure 79. Pre-Test and Post-Test Photographs for Test No. SBB-8



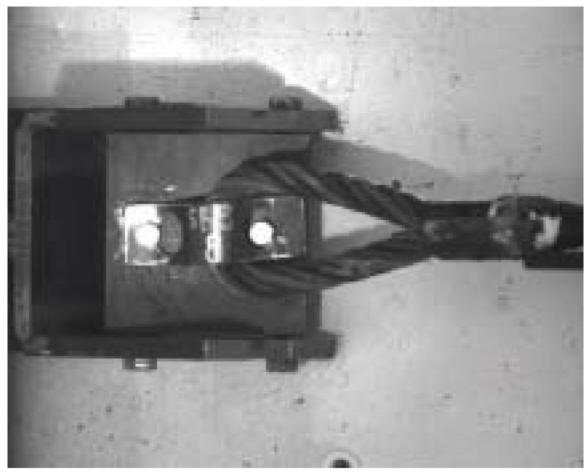
Time = 0ms



Time = 68ms

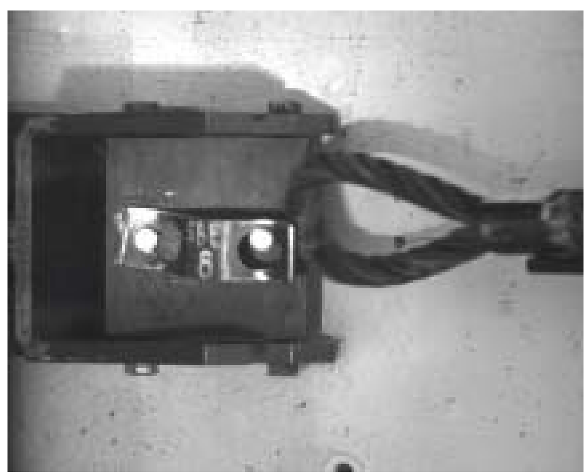


Time = 90ms



Time = 108ms

Time = 116ms



Time = 122ms

Figure 80. Sequential Photographs, Test No. SBB-8

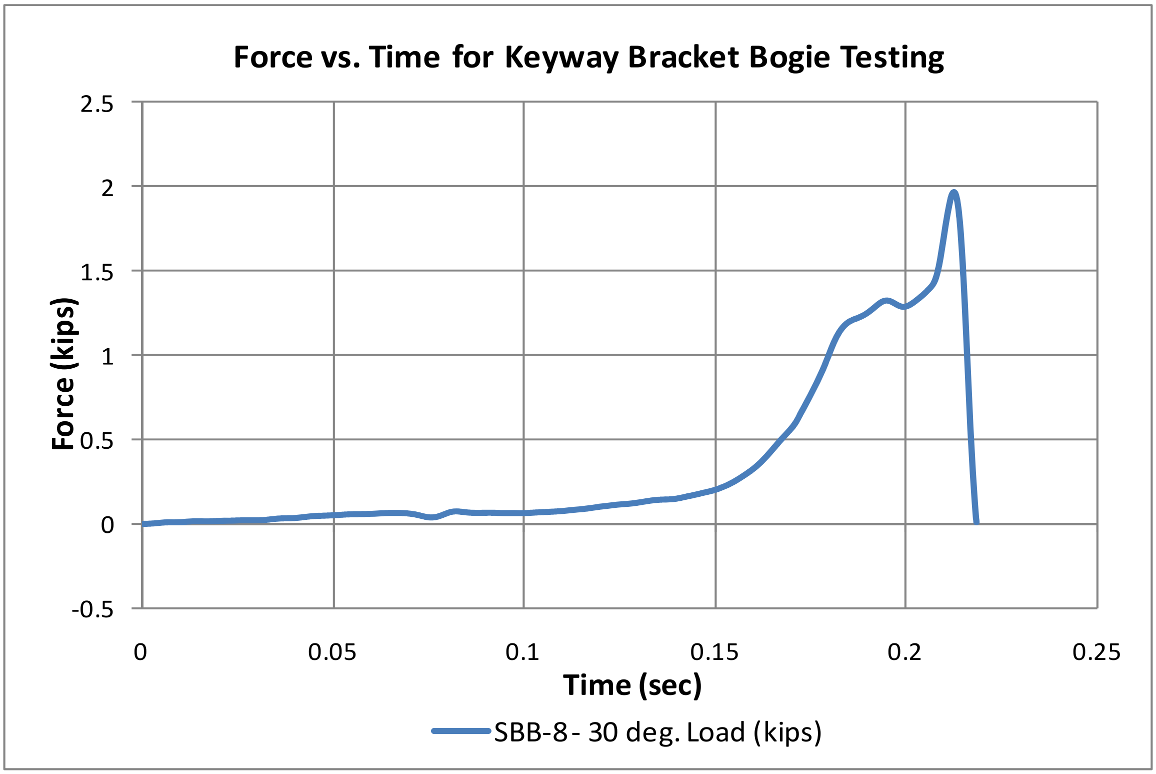


Figure 81. Force-Time Data for Test No. SBB-8

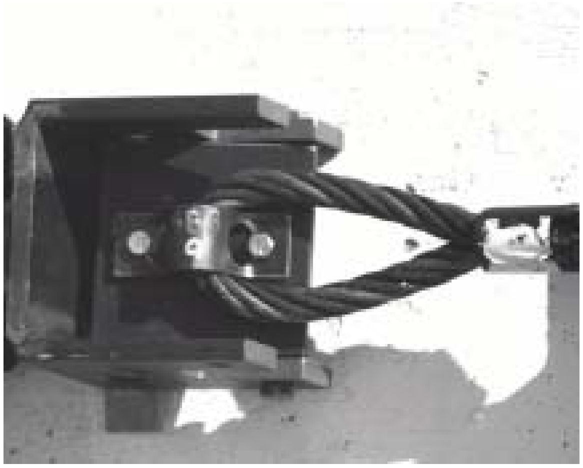
7.1.9 Test No. SBB-9

For test no. SBB-9, the cable applied a load to the bracket at an angle of 15 degrees relative to its vertical axis. The bracket was fastened using standard bolts and released the cable cleanly under a load of 882 lbs. Pre-test and post-test photographs are presented in Figure 82. Sequential photographs for test no. SBB-9 are presented in Figure 83, and force-time data is presented in Figure 84.

Pre-Test

Post-Test

Figure 82. Pre-Test and Post-Test Photographs for Test No. SBB-9

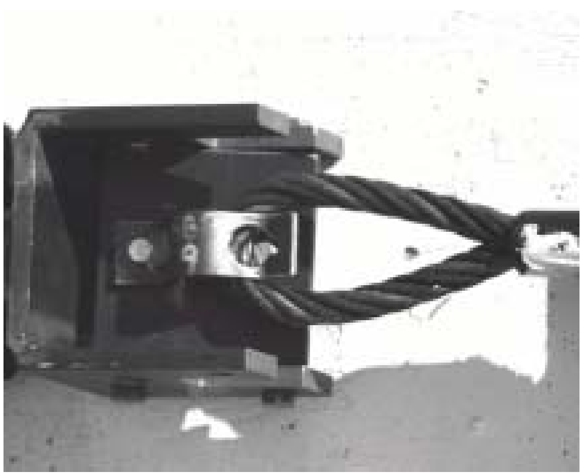


Time = 0ms

Time = 80ms

Time = 110ms

Time = 116ms



Time = 122ms

Time = 132ms

Figure 83. Sequential Photographs, Test No. SBB-9

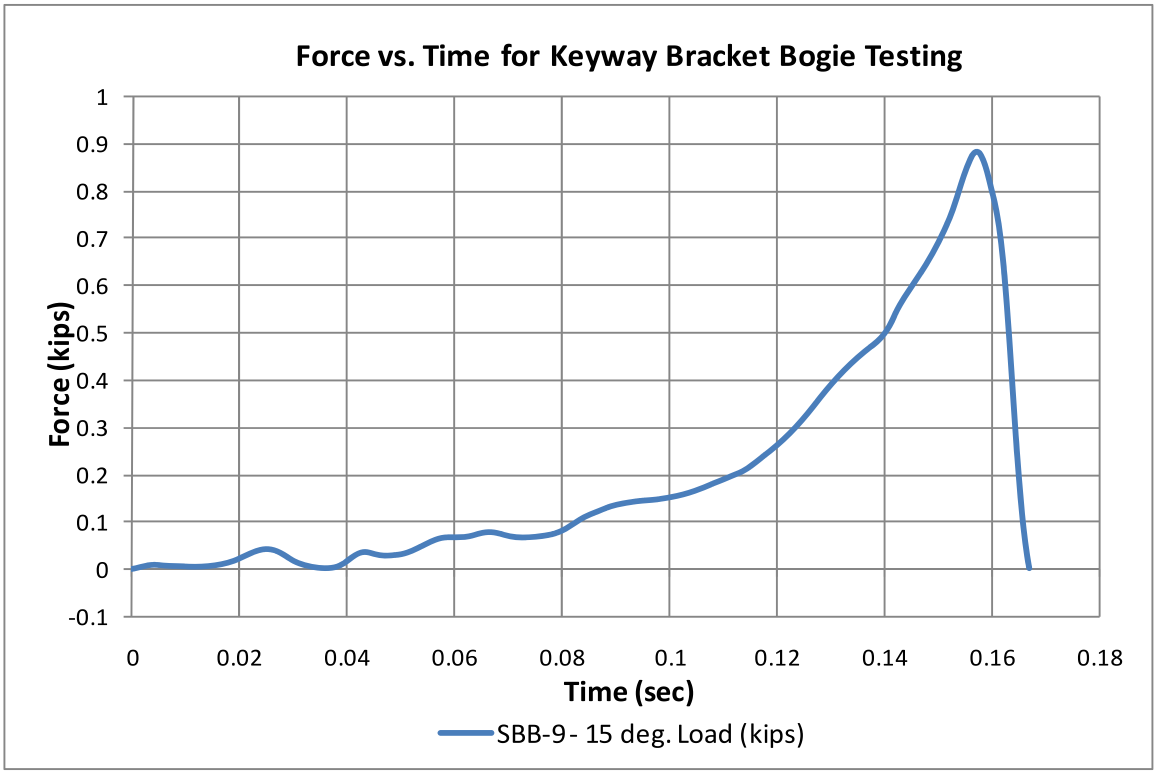


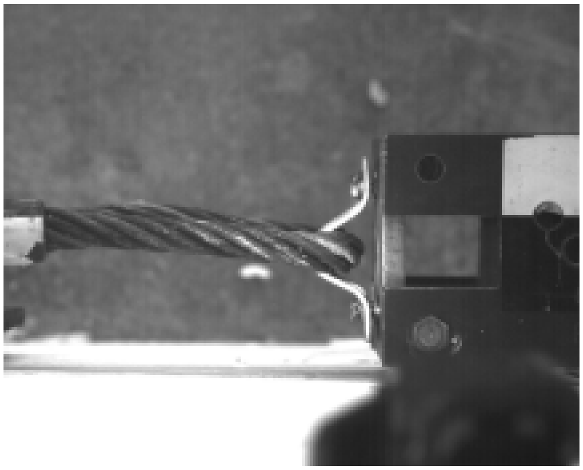
Figure 84. Force-Time Data for Test No. SBB-9

7.1.10 Test No. SBB-10

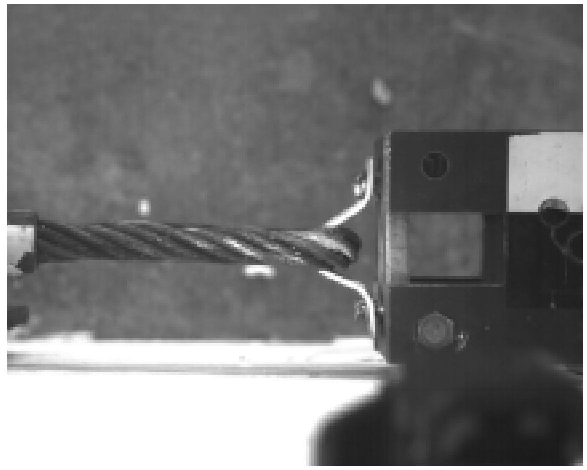
For test no. SBB-10, the cable applied a load to the bracket at an angle of 90 degrees relative to its vertical axis. The bracket was fastened using shoulder bolts and released the cable at a load of 7,028 lbs. Pre-test and post-test photographs are presented in Figure 85. Sequential photographs for test no. SBB-10 are presented in Figure 86, and force-time data is presented in Figure 87.

Pre-Test **Post-Test**

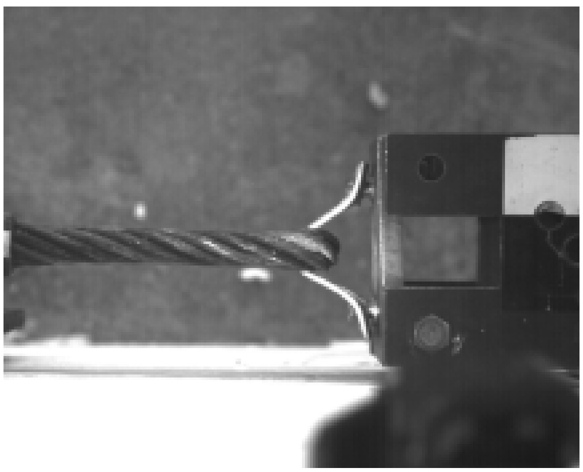
Figure 85. Pre-Test and Post-Test Photographs for Test No. SBB-10



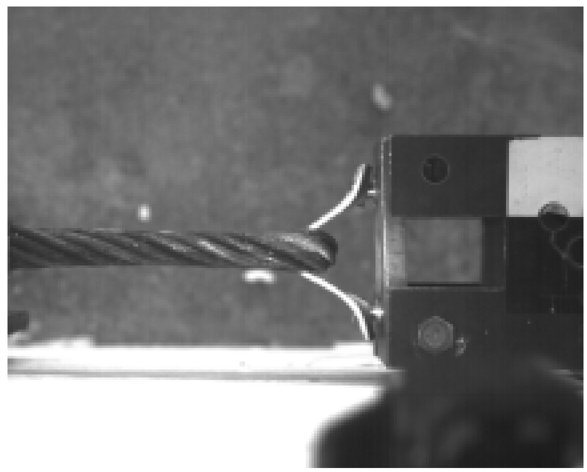
Time = 0ms



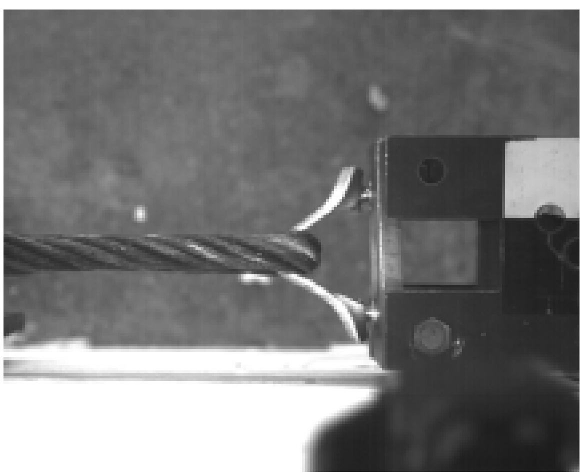
Time = 64ms



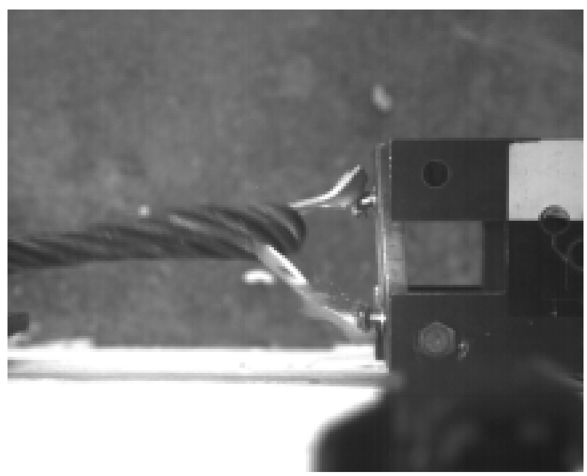
Time = 90ms



Time = 100ms



Time = 110ms



Time = 114ms

Figure 86. Sequential Photographs, Test No. SBB-10

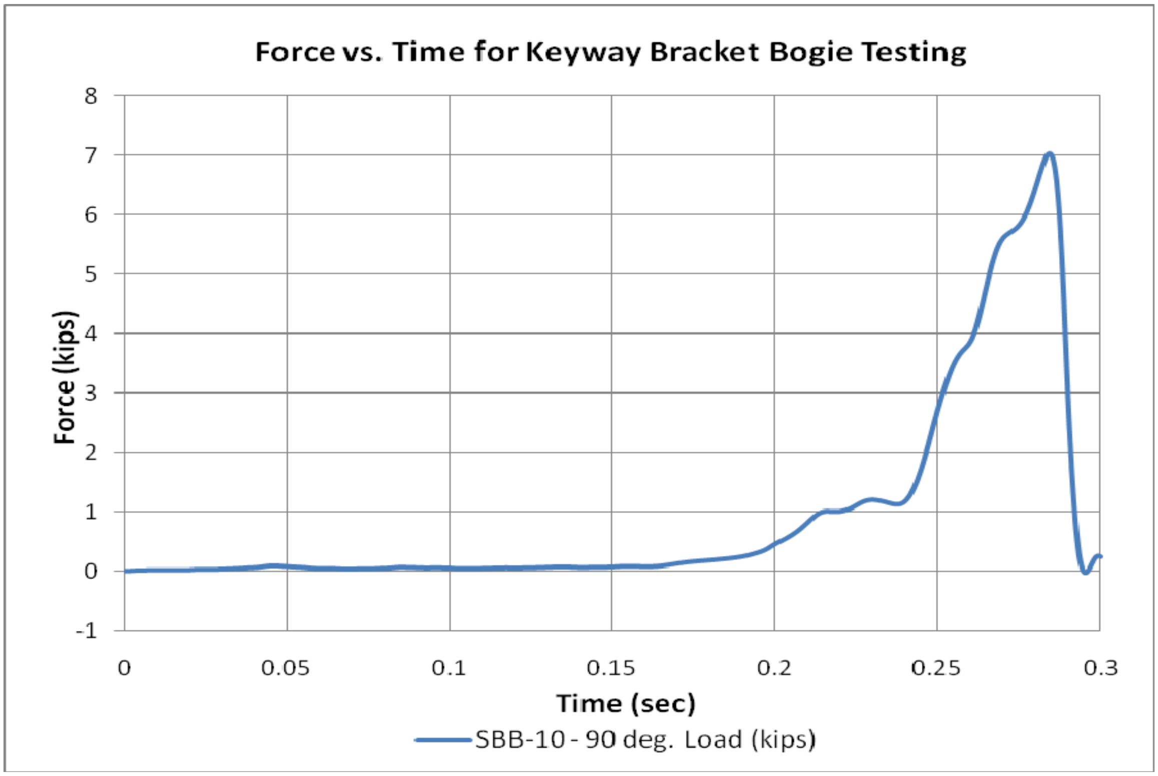


Figure 87. Force-Time Data for Test No. SBB-10

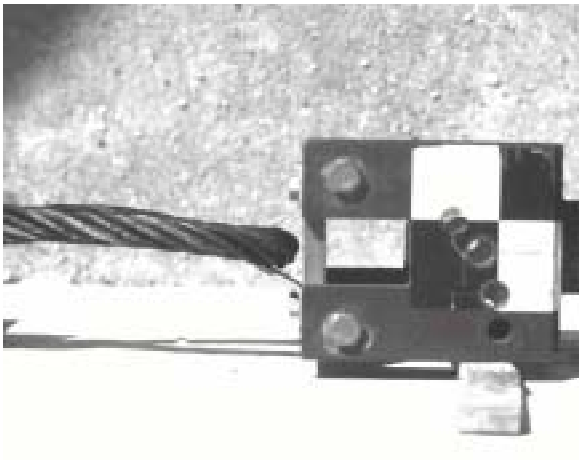
7.1.11 Test No. SBB-11

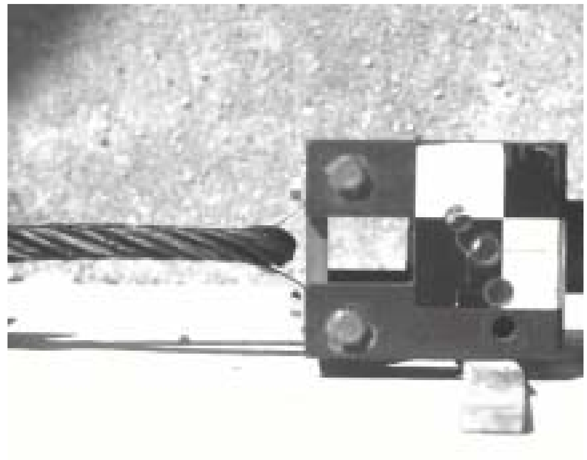
For test no. SBB-11, the cable applied a load to the bracket at an angle of 90 degrees relative to its vertical axis. The bracket was fastened using shoulder bolts; however, the bolts were installed incorrectly such that the shoulder entered the bolt hole and the bolt head applied a preload to the bracket. The cable was released when the bracket ruptured in tension at a load of 5,229 lbs. Pre-test and post-test photographs are presented in Figure 88. Sequential photographs for test no. SBB-11 are presented in Figure 89, and force-time data is presented in Figure 90. Note that the bracket is mislabeled as SBB-10.

Pre-Test

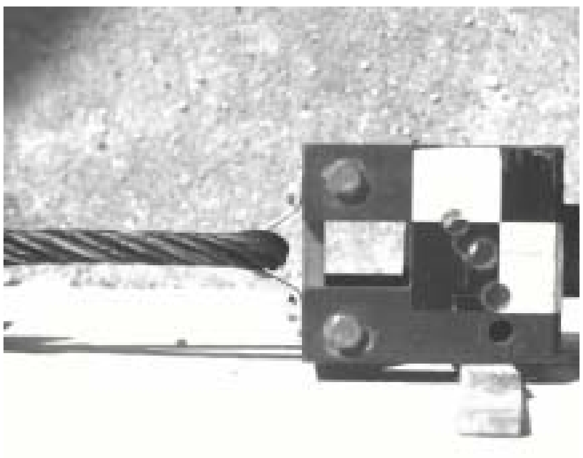
Post-Test

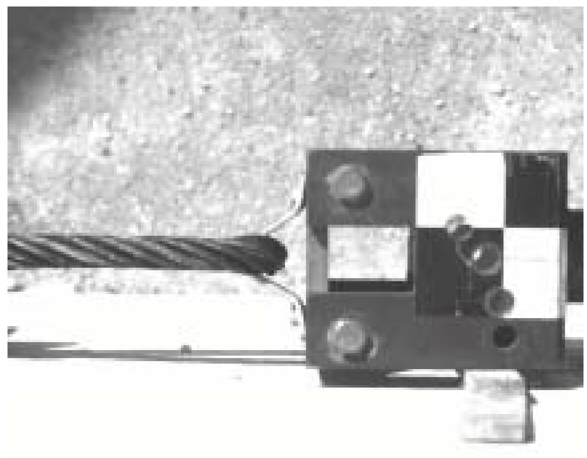
Figure 88. Pre-Test and Post-Test Photographs for Test No. SBB-11



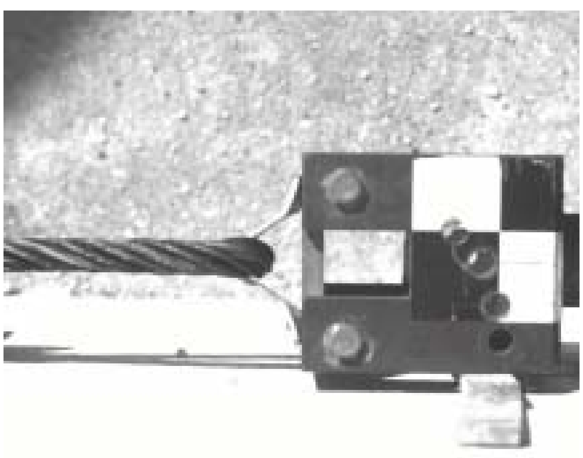


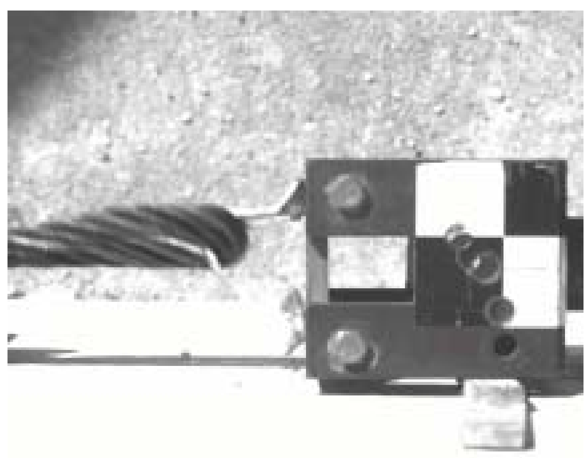
Time = 0ms Time = 92ms





Time = 100ms Time = 108ms





Time = 114ms Time = 120ms

Figure 89. Sequential Photographs, Test No. SBB-11

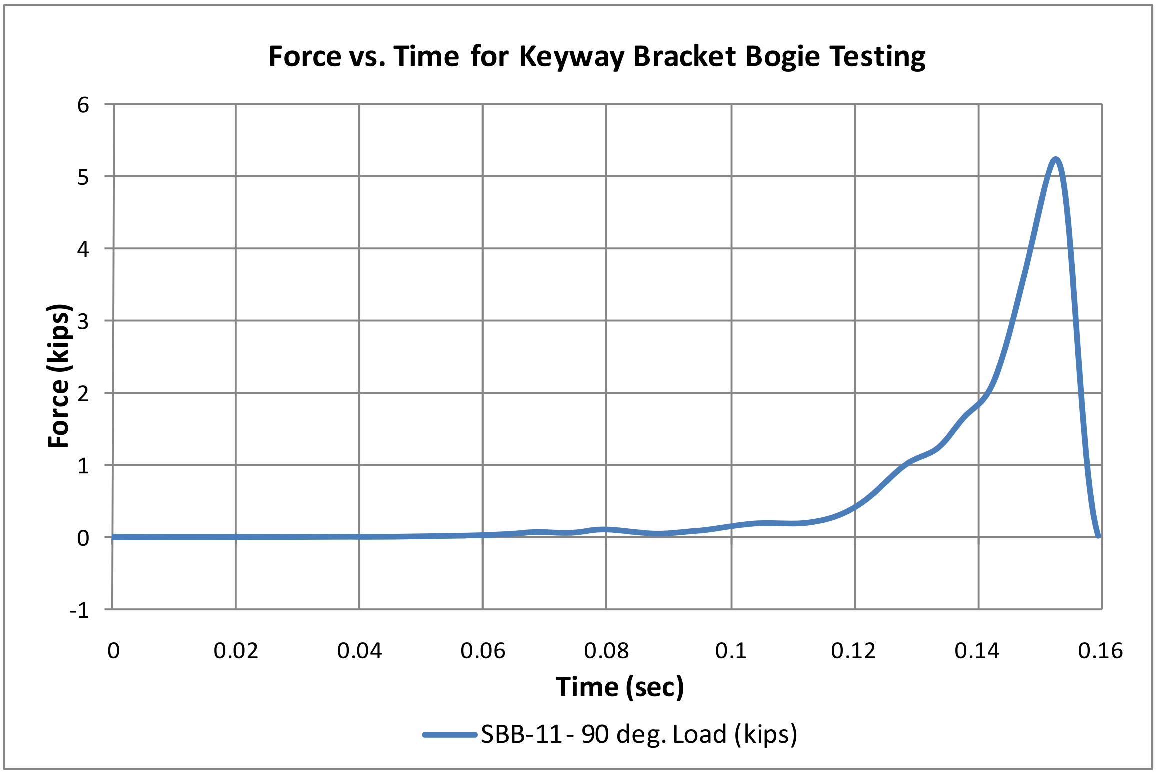


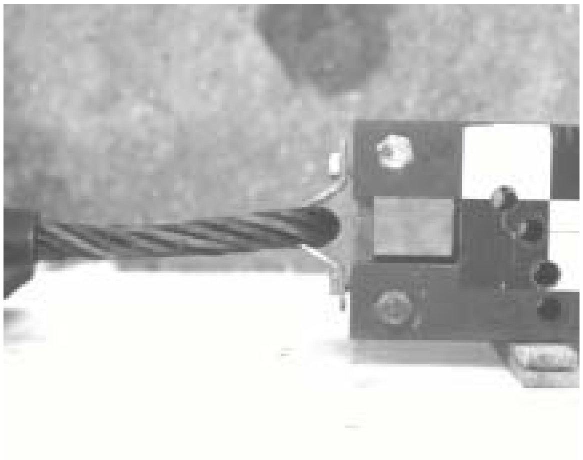
Figure 90. Force-Time Data for Test No. SBB-11

7.1.12 Test No. SBB-12

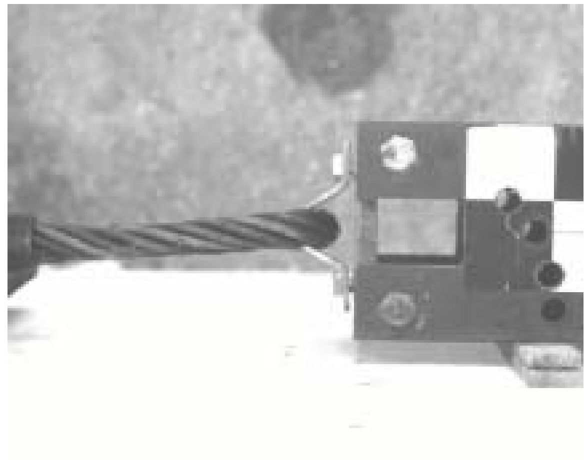
For test no. SBB-12, the cable applied a load to the bracket at an angle of 90 degrees relative to its vertical axis. The bracket was fastened using shoulder bolts and released the cable as one of the shoulder bolts fractured when the load reached 5,722 lbs. Pre-test and post-test photographs are presented in Figure 91. Sequential photographs for test no. SBB-12 are presented in Figure 92, and force-time data is presented in Figure 93.

Pre-Test **Post-Test**

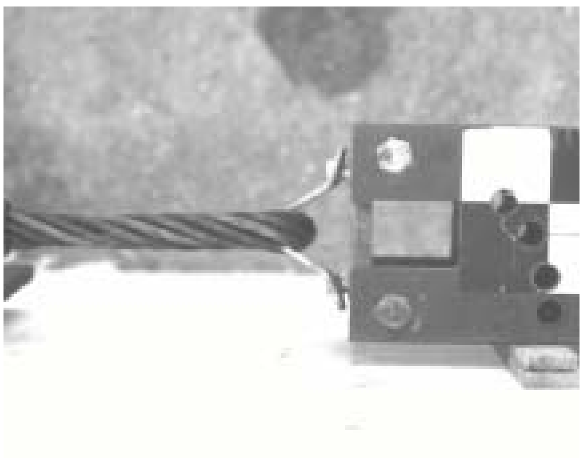
Figure 91. Pre-Test and Post-Test Photographs for Test No. SBB-12



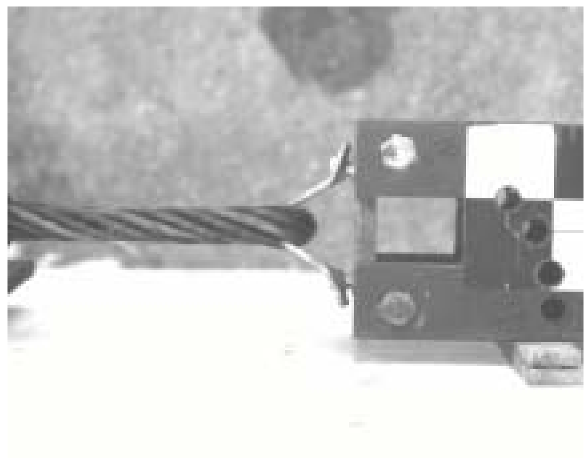
Time = 0ms



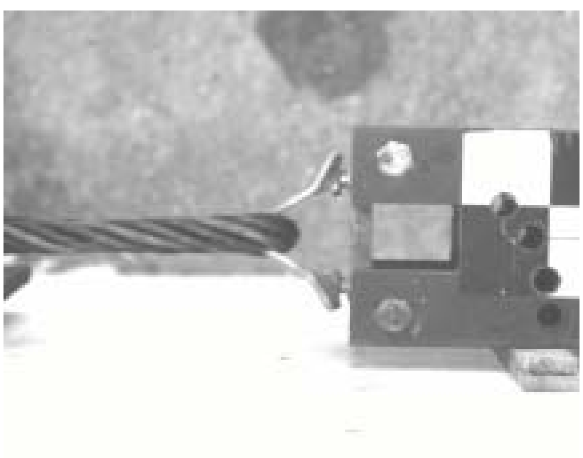
Time = 42ms



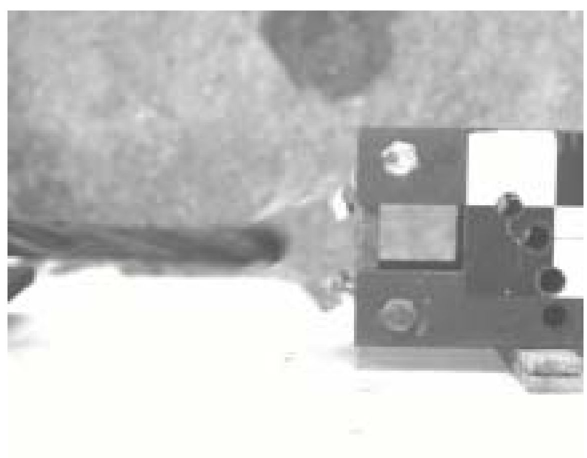
Time = 92ms



Time = 100ms



Time = 108ms



Time = 110ms

Figure 92. Sequential Photographs, Test No. SBB-12

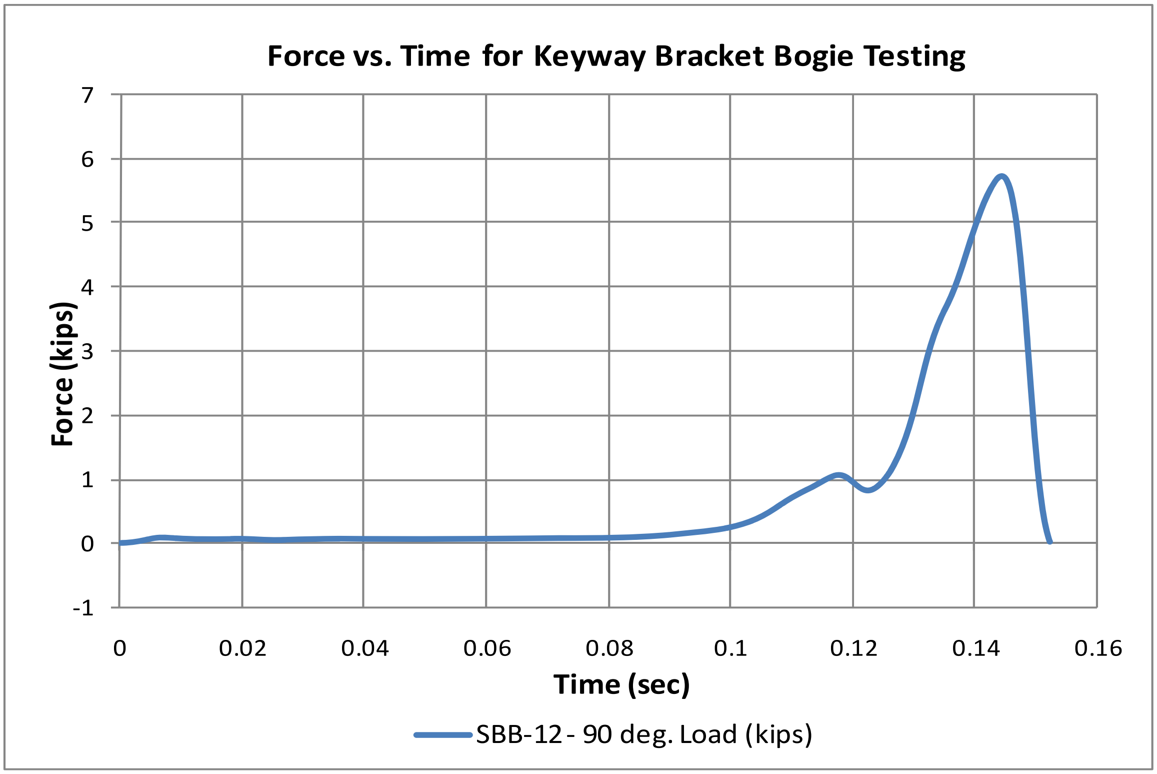
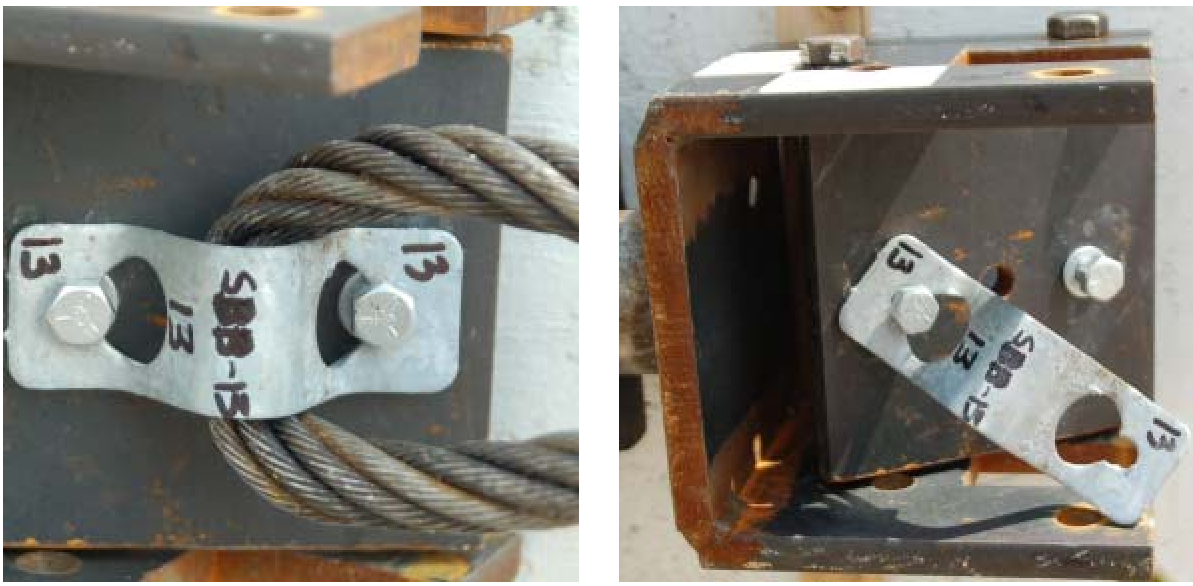


Figure 93. Force-Time Data for Test No. SBB-12

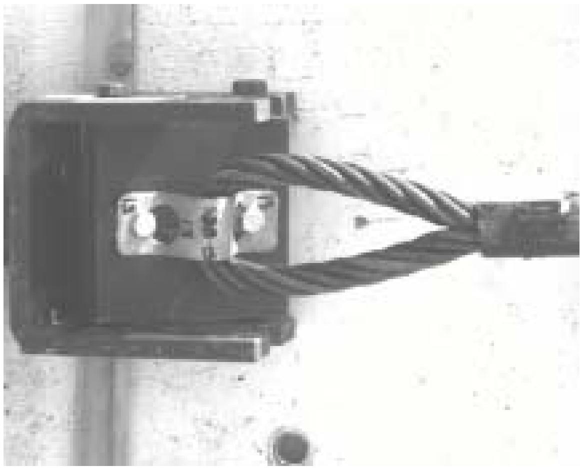
7.1.13 Test No. SBB-13

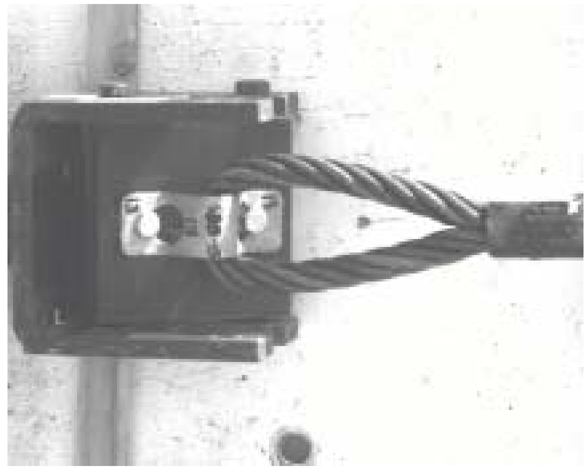
For test no. SBB-13, the cable applied a load to the bracket at an angle of 30 degrees relative to its vertical axis. The bracket was fastened using shoulder bolts and released the cable cleanly under a load of 1,167 lbs. Pre-test and post-test photographs are presented in Figure 94. Sequential photographs for test no. SBB-13 are presented in Figure 95, and force-time data is presented in Figure 96.

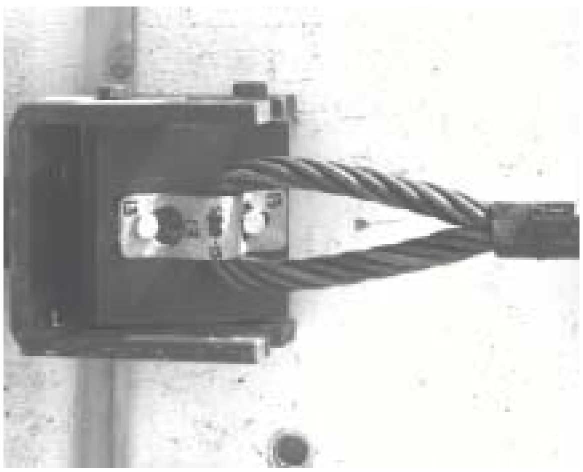


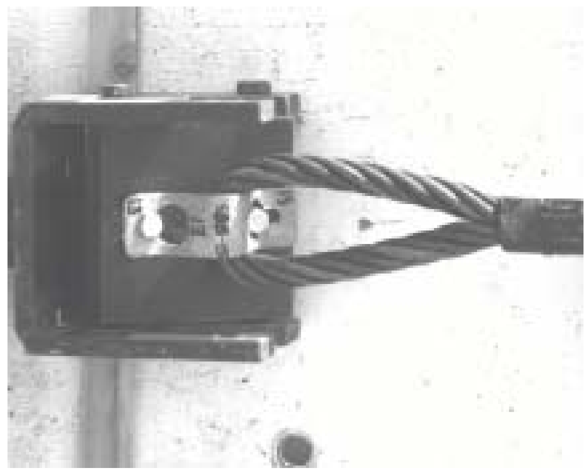
Pre-Test **Post-Test**

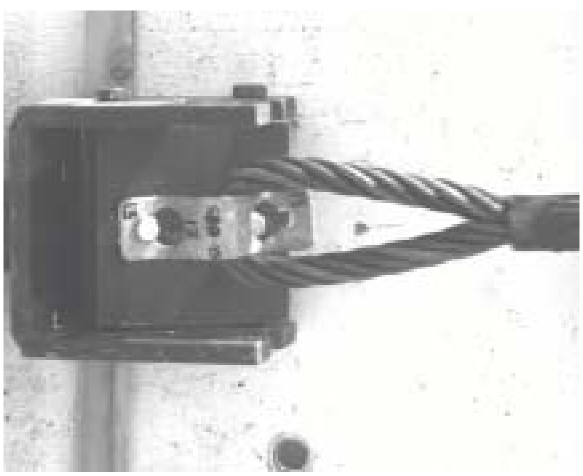
Figure 94. Pre-Test and Post-Test Photographs for Test No. SBB-13


Time = 0ms


Time = 60ms


Time = 76ms


Time = 100ms


Time = 104ms

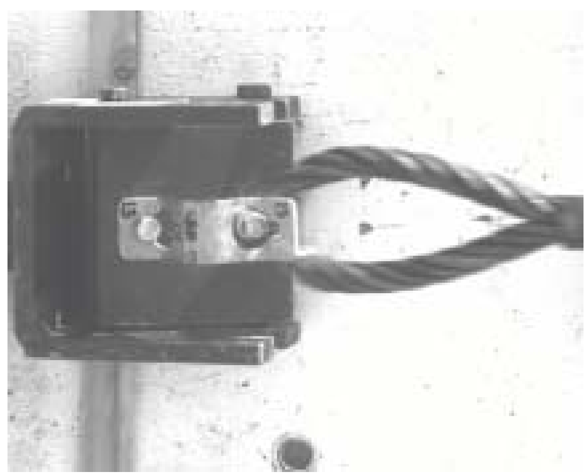

Time = 108ms

Figure 95. Sequential Photographs, Test No. SBB-13

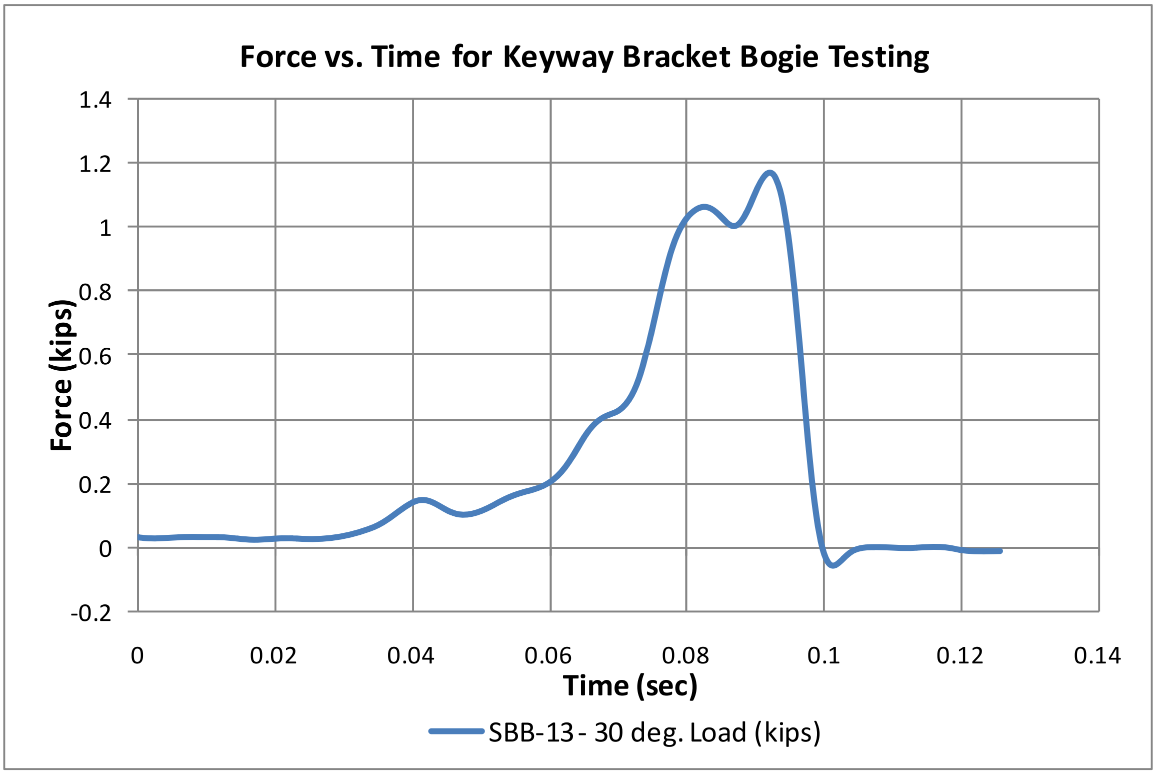


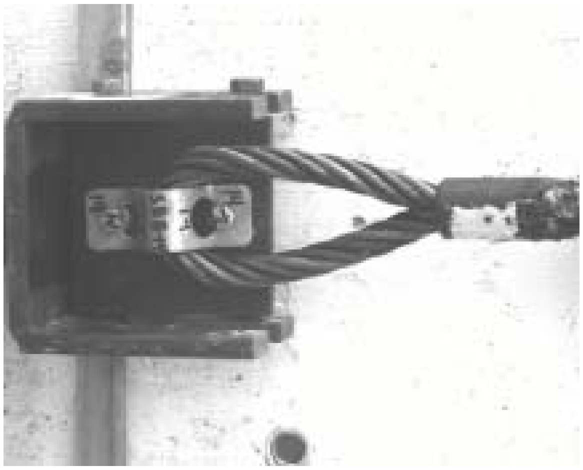
Figure 96. Force-Time Data for Test No. SBB-13

7.1.14 Test No. SBB-14

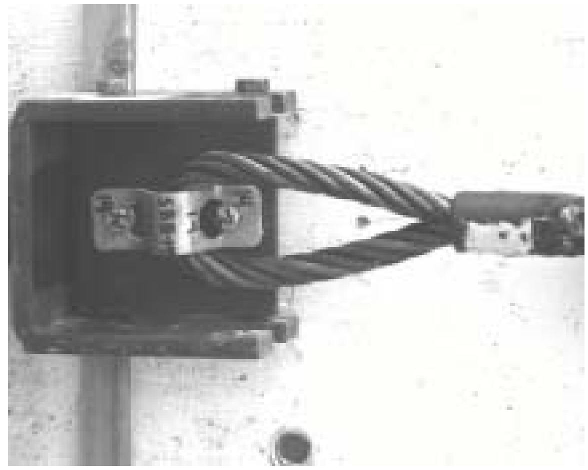
For test no. SBB-14, the cable applied a load to the bracket along its vertical axis. The bracket was fastened using shoulder bolts that allowed the bracket to behave as expected, releasing the cable under a vertical load of 1,169 lbs. However, the cable then snagged one of the shoulder bolts, preventing it from releasing until the bolt ruptured at a load of 2,819 lbs. Pre-test and post-test photographs are presented in Figure 97. Sequential photographs for test no. SBB-14 are presented in Figure 98, and force-time data is presented in Figure 98.

Pre-Test **Post-Test**

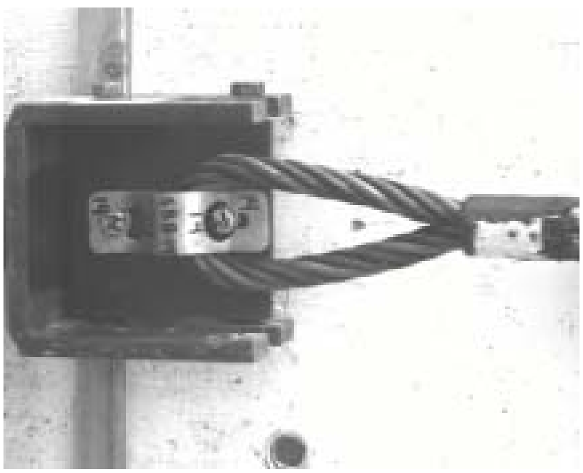
Figure 97. Pre-Test and Post-Test Photographs for Test No. SBB-14



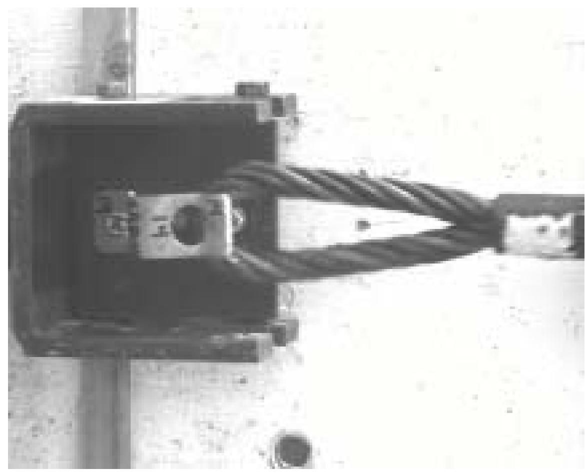
Time = 0ms



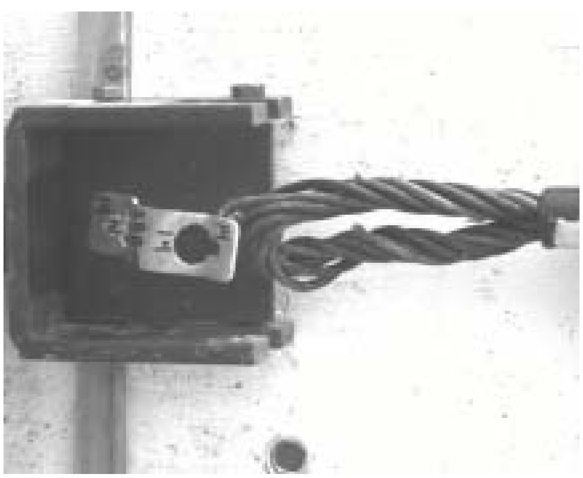
Time = 68ms



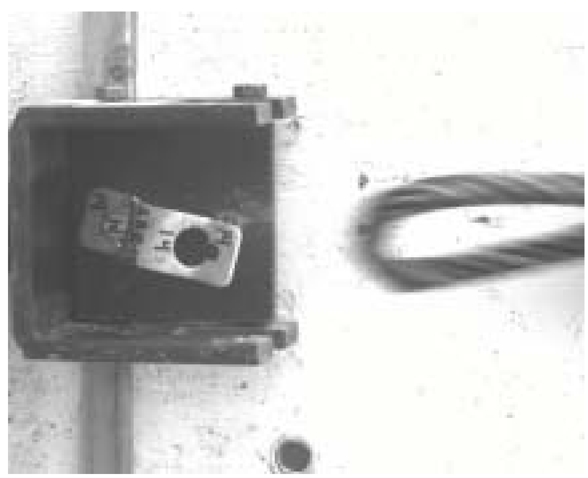
Time = 88ms



Time = 94ms



Time = 136ms



Time = 146ms

Figure 98. Sequential Photographs, Test No. SBB-14

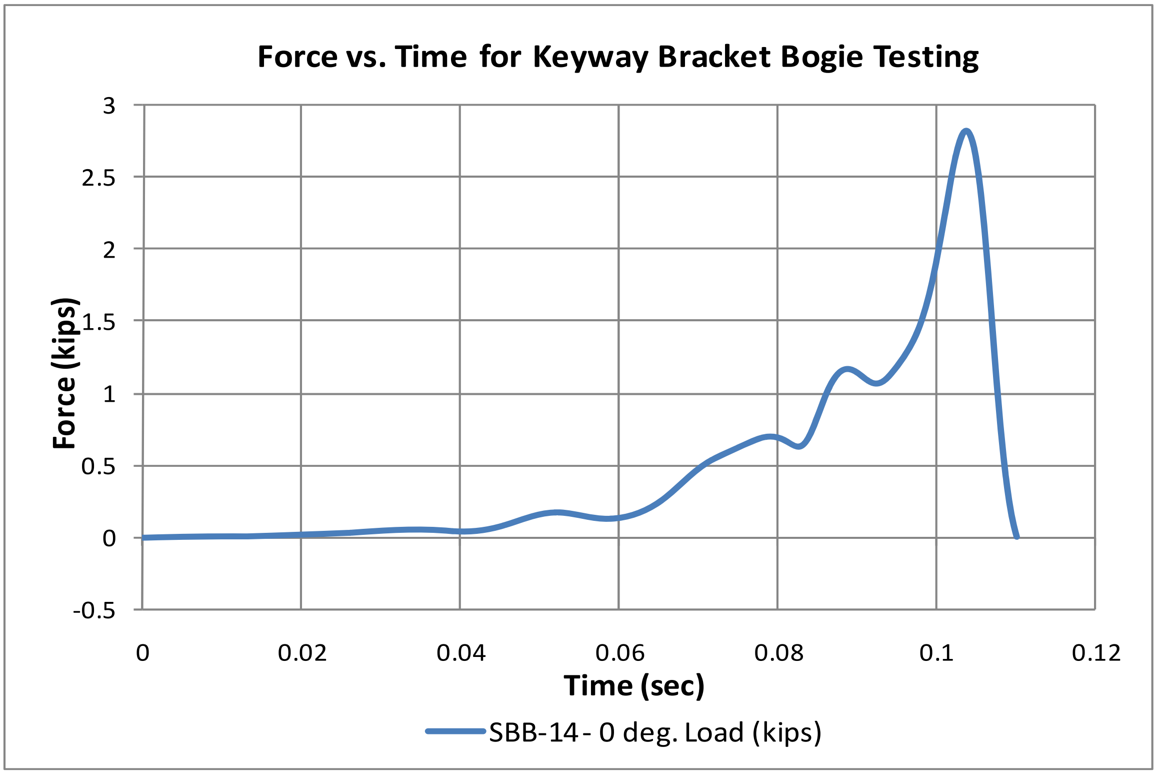


Figure 99. Force-Time Data for Test No. SBB-14

7.2 Discussion of Results

The results of the dynamic testing confirmed that the curved keyway bracket satisfied the initial design criteria. With the addition of shoulder bolts to attach the bracket to the post, the system proved that it could develop the desired load ratios reliably under dynamic loads. Laterally, the bracket test with shoulder bolts failed at 5,723 lbs. While this is slightly less than the original design specifications, the design of the cable posts had changed to compensate for this effect. The brackets were moved 8.5 in. higher on the posts, which reduced the required bracket strength for developing the full post capacity. Vertically, the bracket test with shoulder bolts allowed the brackets to release the cable near the target load of 1,000 lbs.

Tests which subjected the bracket to loads at other angles also had positive results. Test no. SBB-13, which inclined the cable 30 degrees from the bracket's vertical orientation, resulted in the bracket releasing the cable at a load of 1,167 lbs. This value was considered to be in the ideal range for optimal system performance.

8 SPLICE AND END-FITTING DYNAMIC TESTING

8.1 Purpose

Dynamic tests were performed on a variety of existing cable end-fittings and splices to evaluate their potential performance in the cable median barrier. It was desired to identify an end-fitting and a splice that could develop the full capacity of the cable, or a load of 39,000 lbs. End-fitting designs from Bennett Bolt and Brifen were tested along with cable splice designs from Bennett Bolt and Armor Flex.

8.2 Scope

Dynamic cable pull-tests were performed on several different cable release terminals through use of a bogie. These tests were performed by attaching one end of a cable to the bogie and anchoring the other end to a cable terminal. The cable was passed over a concrete barrier near the end-fitting to align the cable with an axis normal to the terminal. The cable was initially slack as the bogie was set in motion away from the terminal. As the bogie moved, the cable was pulled taut and a dynamic tensile load was placed on the cable and its connections. Six different dynamic tests were performed on the cable end-fittings and splices. A layout of the test setup is presented in Figure 100, and a summary of the tests performed is presented in Table 30. Photographs of the test setup are presented in Figure 101.

Table 30. Cable End-Fitting and Splice Test Data

Test No.	End-Fitting	Rod Diameter	Rod Grade	Splice
4CTB-1	Bennett Bolt low-tension	0.75 in.	ASTM A449	Bennett low-tension
4CTB-2	Bennett Bolt low-tension	0.75 in.	ASTM A449	Bennett low-tension
4CTB-3	Bennett Bolt high-tension	0.875 in.	ASTM A449	Bennett low-tension
4CTB-4	Bennett Bolt high-tension	0.875 in.	ASTM A449	Bennett low-tension
4CTB-5	Bennett Bolt high-tension	0.875 in.	ASTM A449	None
4CTB-6	Armor Flex self-swaging	0.945 in.	Grade K 1040	Armor Flex

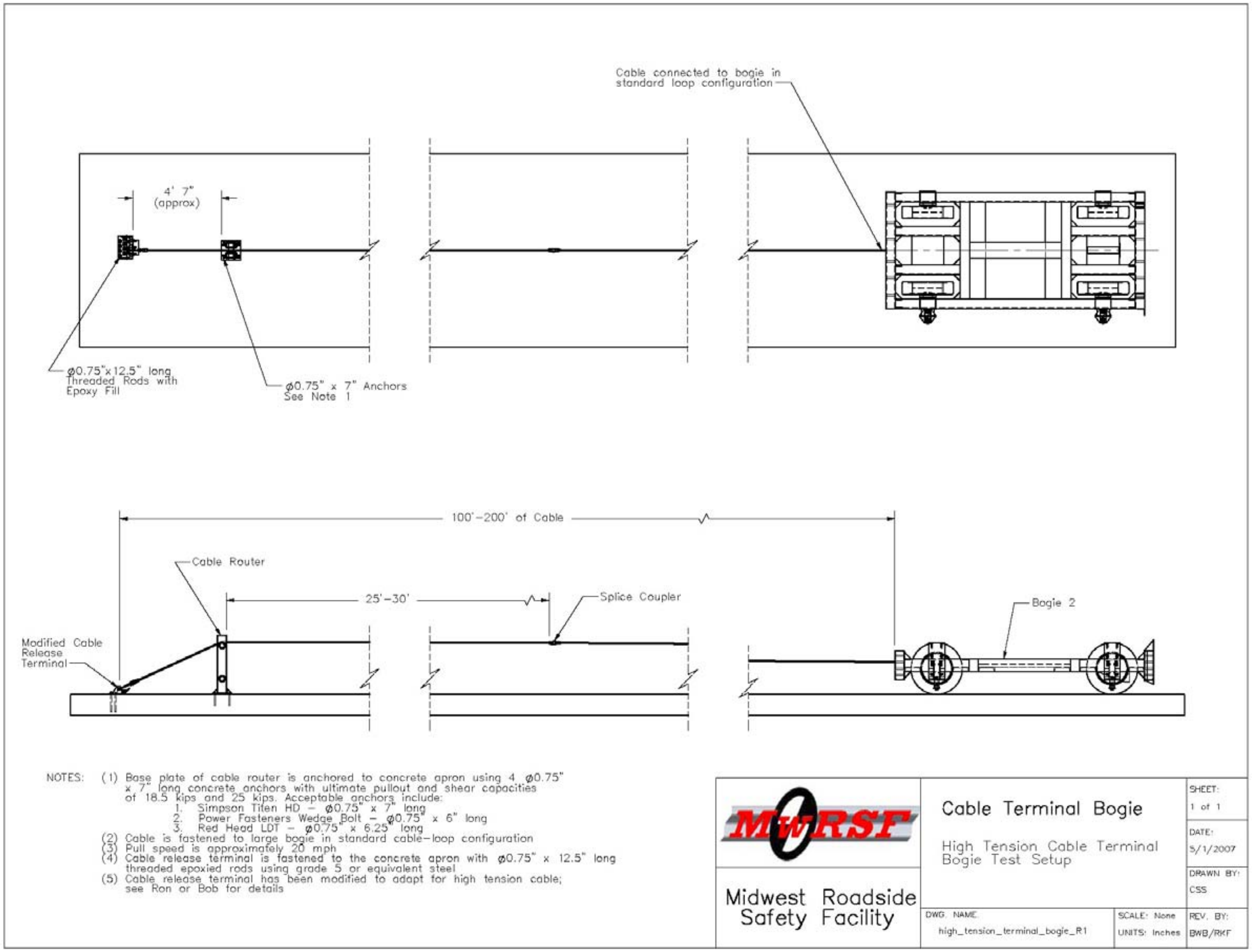


Figure 100. Test Setup for Test Nos. 4CTB-1, 2, 3, 4, 5, and 6

Figure 101. Bogie and Test Setup

8.3 Testing Facility

High-tension cable terminal bogie testing was performed at the MwRSF's outdoor testing facility at Lincoln Airpark, on the northwest side of the Lincoln Municipal Airport.

8.4 Equipment and Instrumentation

A variety of equipment and instrumentation was used to record and collect data. It was important to gather correct data using accurate instrumentation in order to understand and derive meaningful conclusions from the dynamic tests. The main equipment and instruments used for the tests were:

- Bogie
- Accelerometer
- Photography Cameras

8.4.1 Bogie Vehicle

A rigid-frame bogie was used to apply a dynamic load for the cable pull tests. The weight of the bogie was 4,622 lbs.

A pickup truck with a reverse cable tow system was used to propel the bogie. When the bogie reached the end of the guidance system, it was released from the tow cable, allowing it to be free rolling as the cable was pulled taut. A remote braking system was installed on the bogie, thus allowing it to be safely brought to rest after the test.

A picture of the bogie used in dynamic testing is presented in Figure 102.

Figure 102. Bogie Used in Dynamic Testing

8.4.2 Accelerometer

A tri-axial piezo-resistive accelerometer system with a range of ± 200 g's was mounted on the frame of the bogie at approximately the center of gravity. It measured the accelerations in the longitudinal, lateral, and vertical directions. The accelerometer system, known as the Model EDR-3, was used previously for the cable attachment dynamic testing. Details for the EDR-3 are presented in Section 6.5.1.

A laptop computer downloaded the raw acceleration data immediately following each test. Computer software "DynaMax 1 (DM-1)" and "DADiSP," was used to analyze and plot the accelerometer data. The data was processed as per the SAE J211/1 specifications.

8.4.3 High-Speed Digital Photography

Four high-speed AOS VITcam video cameras, designated AOS-1, AOS-2, AOS-3, and AOS-4, were used over the course of dynamic testing to record video imagery of the system.

These cameras, which operated at 500 frames/sec, were focused on the cable end-fittings, splices, and other portions of the system.

8.4.4 Digital Photography

Three JVC digital video cameras, designated JVC-3, JVC-4, and JVC-5, were also used to film the dynamic tests. These cameras, which operated at a speed of 29.97 frames/sec, were focused on the cable end-fittings, splices, and other portions of the system.

A digital camera was used to record still images of the dynamic tests. This camera was a Nikon D50.

9 SPLICE AND END-FITTING DYNAMIC TESTING RESULTS AND DISCUSSION

9.1 Results

A series of six dynamic tests were performed on cable end-fittings and splices. The results of those tests are presented in the following sections. A summary of the tests and their results is presented in Table 31. Summary sheets for the dynamic tests are presented in Appendix C.

Table 31. Dynamic Testing of Splices and End-Fittings Results

Test No.	End-Fitting Type	End-Fitting Rod	Splice Type	Initial Speed (mph)	Peak Force (kips)	Comments
4CTB-1	Bennett low-tension	0.75-in. dia. Grade A449	Bennett low-tension	20.00	N/A	End fitting released from terminal, invalid results
4CTB-2	Bennett low-tension	0.75-in. dia. Grade A449	Bennett low-tension	20.14	24.38	End-fitting cracked, released cable
4CTB-3	Bennett high-tension	0.875-in. dia. Grade A449	Bennett low-tension	19.33	16.30	Cable clamps on bogie released, invalid results
4CTB-4	Bennett high-tension	0.875-in. dia. Grade A449	Bennett low-tension	19.87	33.63	Splice cracked, released cable
4CTB-5	Bennett high-tension	0.875-in. dia. Grade A449	none	22.26	41.25	End-fitting sustained desired load before failure
4CTB-6	Armor Flex self-swaging	0.945-in. dia. Grade K 1040	Armor Flex self-swaging	21.10	39.07	End-fitting and splice sustained desired load

9.1.1 Test No. 4CTB-1.

Test no. 4CTB-1 featured a Bennett Bolt low-tension cable end-fitting with a 0.75-in. diameter, Grade A449 rod and a Bennett Bolt low-tension cable splice. During the test, the end-fitting bent the keeper rod and was released from the terminal, invalidating the results. As such, the test was repeated in test no. 4CTB-2 with a modified keeper rod. Photographs of the end-fitting and splice used in test no. 4CTB-1 are presented in Figure 103**.** Sequential photographs are shown in Figure 104.

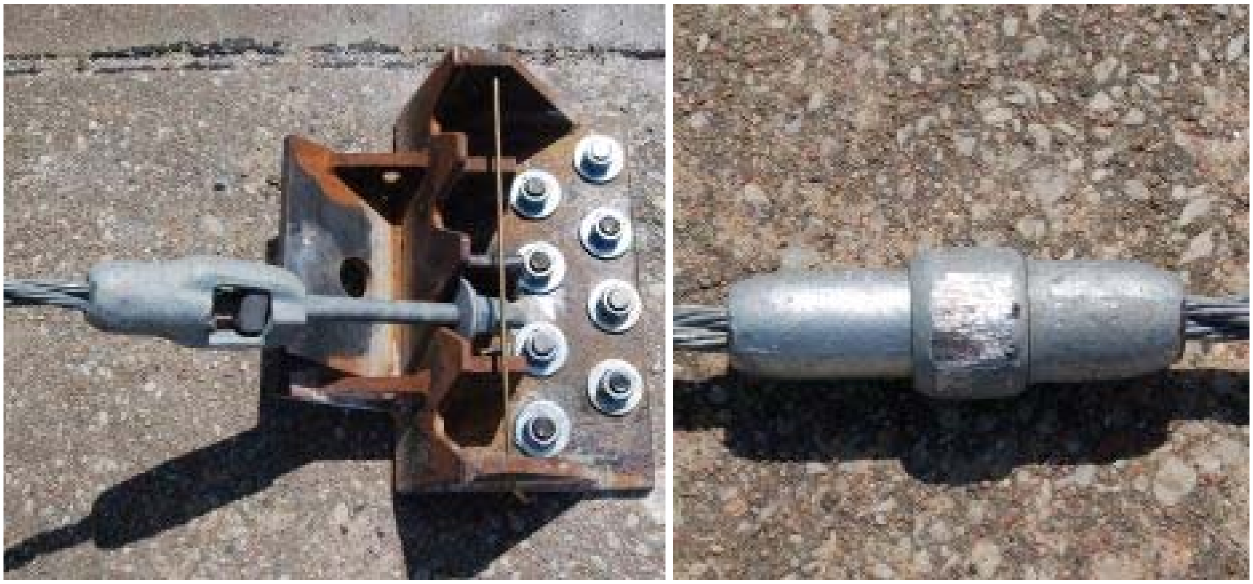
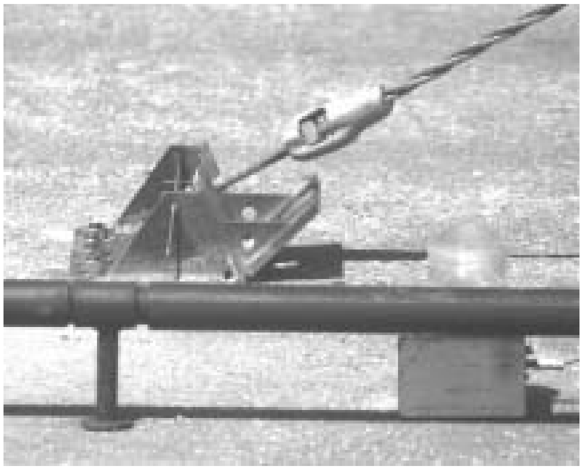
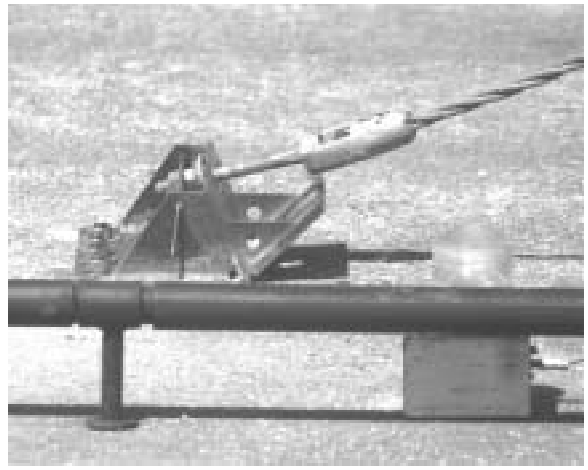
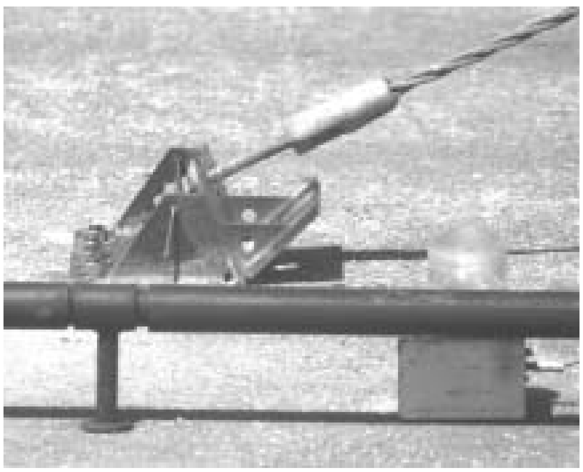


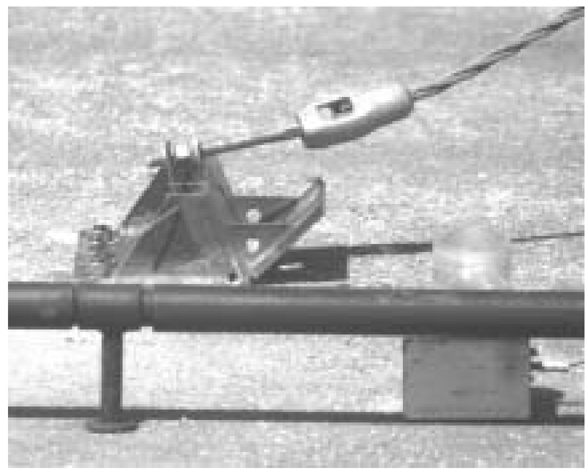
Figure 103. End-Fitting and Splice, Test No. 4CTB-1



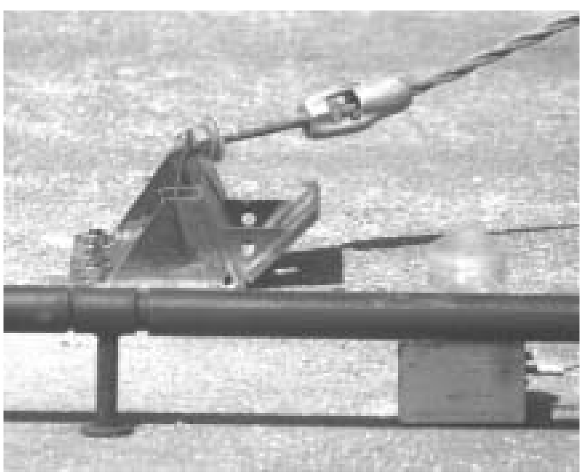


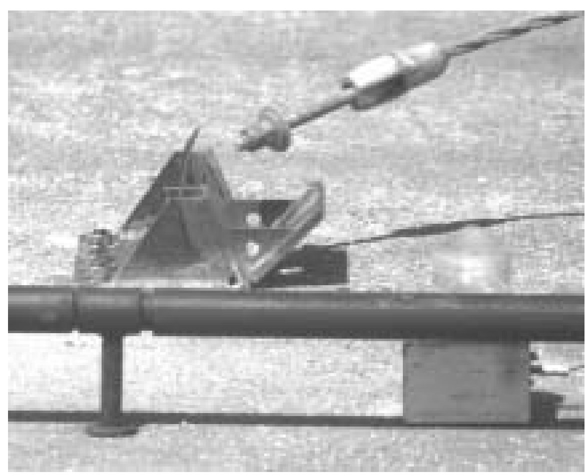
Time = 0ms **Time = 74ms**





Time = 148ms **Time = 156ms**





Time = 162 ms **Time = 170ms**

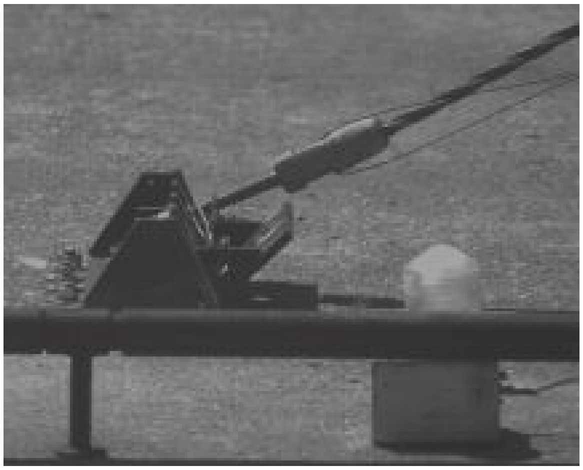
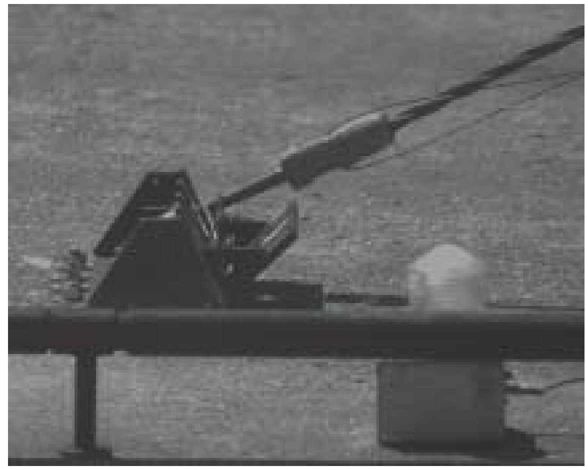
Figure 104. Sequential Photographs, Test No. 4CTB-1

9.1.2 Test No. 4CTB-2

Test no. 4CTB-2 utilized the same components as test no. 4CTB-1, including a Bennett Bolt low-tension cable end-fitting with a 0.75-in. diameter, Grade A449 rod and a Bennett Bolt low-tension cable splice. The end-fitting cracked and released the cable when the load reached 24.38 kips. As the end-fitting failed before reaching the target load of 39 kips, additional testing was deemed necessary. Pre-test and post-test photographs of the end-fitting used in test no. 4CTB-2 are presented in Figure 105, and sequential photographs are shown in Figure 106.

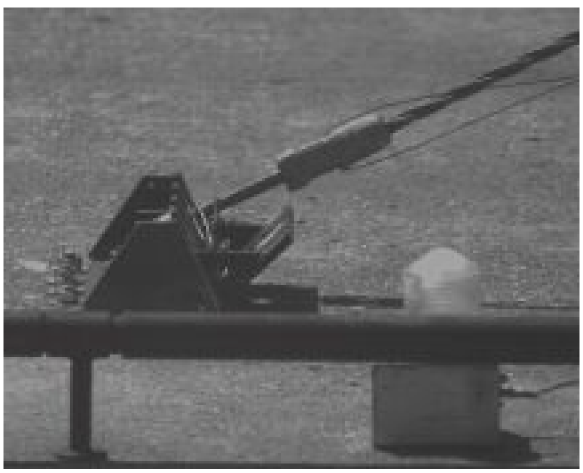
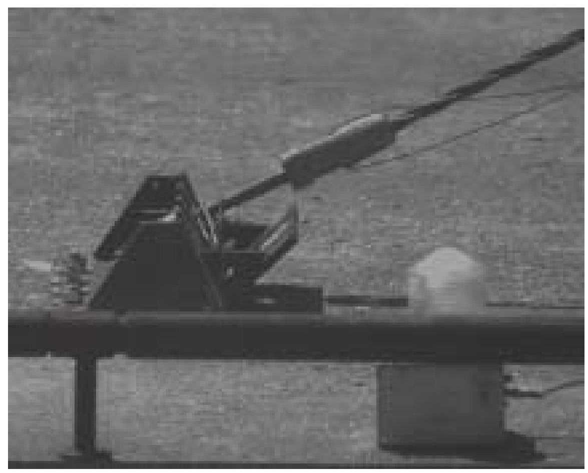
Pre-Test **Post-Test**

Figure 105. Pre-Test and Post-Test Photographs of End-Fitting, Test No. 4CTB-2

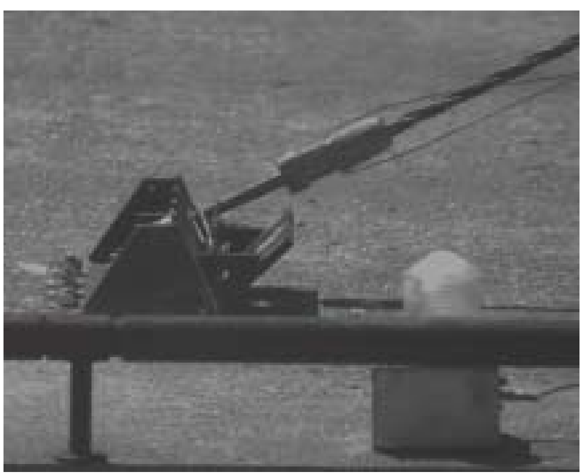
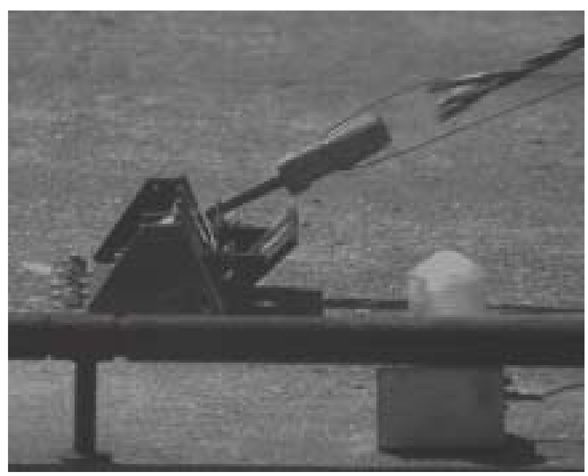
Time = 0ms

Time = 50ms

Time = 100ms

Time = 110ms

Time = 120ms

Time = 130ms

Figure 106. Sequential Photographs, Test No. 4CTB-2

9.1.3 Test No. 4CTB-3

Test no. 4CTB-3 was performed using a Bennett Bolt high-tension end-fitting. The new end-fitting used a stronger body casting and the size of the threaded rod was increased to 0.875 in. Another Bennett Bolt low-tension cable splice was also included in the test. During the test, the connection between the bogie and the cable failed at a load of 16.30 kips, invalidating the results. As such, the test was repeated in test no. 4CTB-4. Photographs of the end-fitting and splice used in test no. 4CTB-3 are presented in Figure 107, and a photograph of the cable-to-bogie connection is presented in Figure 108.

Figure 107. End-Fitting and Splice, Test No. 4CTB-3

Figure 108. Cable-to-Bogie Connection, Test No. 4CTB-3

9.1.4 Test No. 4CTB-4

Test no. 4CTB-4 utilized the same components as test no. 4CTB-3, including a Bennett Bolt high-tension cable end-fitting with a 0.875-in. diameter, Grade A449 rod and a Bennett Bolt low-tension cable splice. The cable splice cracked and released one of the cables when the load reached 33.63 kips. As the splice failed before sustaining the target load of 39 kips, additional testing was deemed necessary. Pre-test and post-test photographs of the cable splice used in test no. 4CTB-4 are presented in Figure 109, and sequential photographs are shown in Figure 110.

Pre-Test

Post-Test

Figure 109. Pre-Test and Post-Test Photographs of Cable Splice, Test No. 4CTB-4

Time = 0ms

Time = 110ms

Time = 112ms

Time = 114ms

Time = 116ms

Time = 118ms

Figure 110. Sequential Photographs, Test No. 4CTB-4

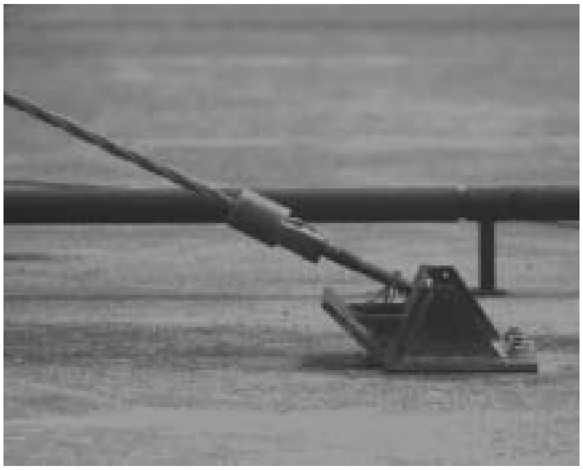
9.1.5 Test No. 4CTB-5

Test no. 4CTB-5 was performed using a Bennett Bolt high-tension end-fitting without a cable splice. This was done to explicitly determine the capacity of the end-fitting. During the test, the cable slipped out of the end-fitting at a load of 41.25 kips, which surpassed the target load of 39 kips. Pre-test and post-test photographs of the end-fitting used in test no. 4CTB-5 are presented in Figure 111, and sequential photographs of test no. 4CTB-5 are presented in Figure 112.

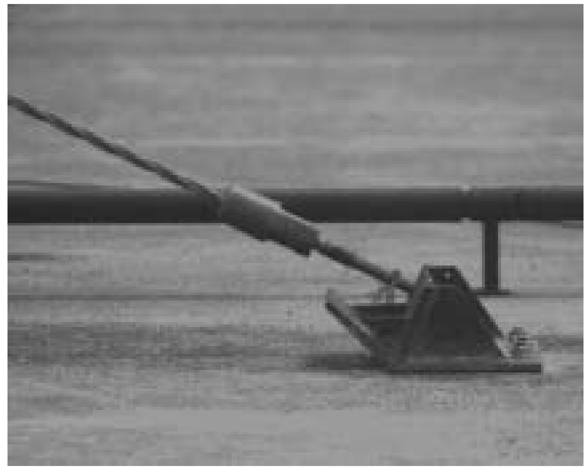
Pre-Test

Post-Test

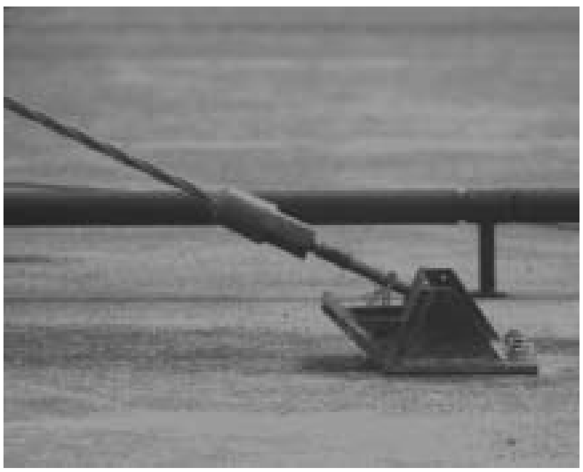
Figure 111. Pre-Test and Post-Test Photographs of End-Fitting, Test No. 4CTB-5



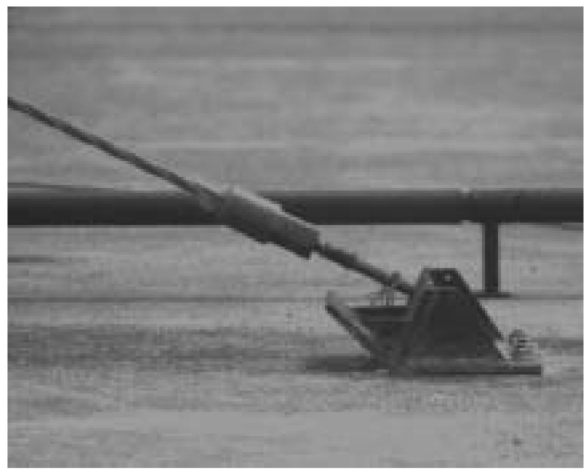
Time = 0ms



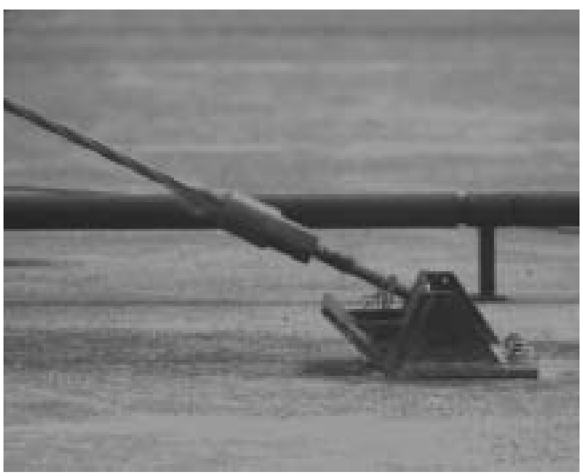
Time = 98ms



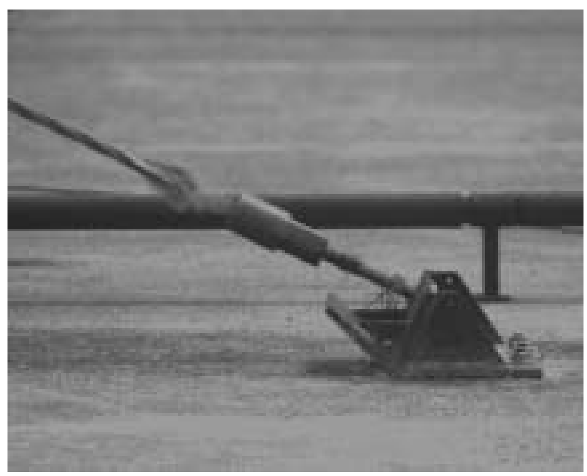
Time = 100ms



Time = 102ms



Time = 104ms



Time = 106ms

Figure 112. Sequential Photographs, Test No. 4CTB-5

9.1.6 Test No. 4CTB-6

Test no. 4CTB-6 was performed using an Armor Flex self-swaging end-fitting with a 0.945-in. diameter, Grade K 1045 rod and an Armor Flex cable splice. During the test, the cable slipped out of the end-fitting at a load of 39.07 kips, which satisfied the target load of 39 kips. Therefore, the performances of both the end-fitting and cable splice were considered adequate. Pre-test and post-test photographs of the end-fitting used in test no. 4CTB-6 are presented in Figure 113, and a photograph of the cable splice is presented in Figure 14. A drawing of the end-fitting is presented in Figure 115, and sequential photographs of test no. 4CTB-6 are presented in Figure 116.

Pre-Test **Post-Test**

Figure 113. Pre-Test and Post-Test Photographs of End-Fitting, Test No. 4CTB-6

Figure 114. Cable Splice, Test No. 4CTB-6

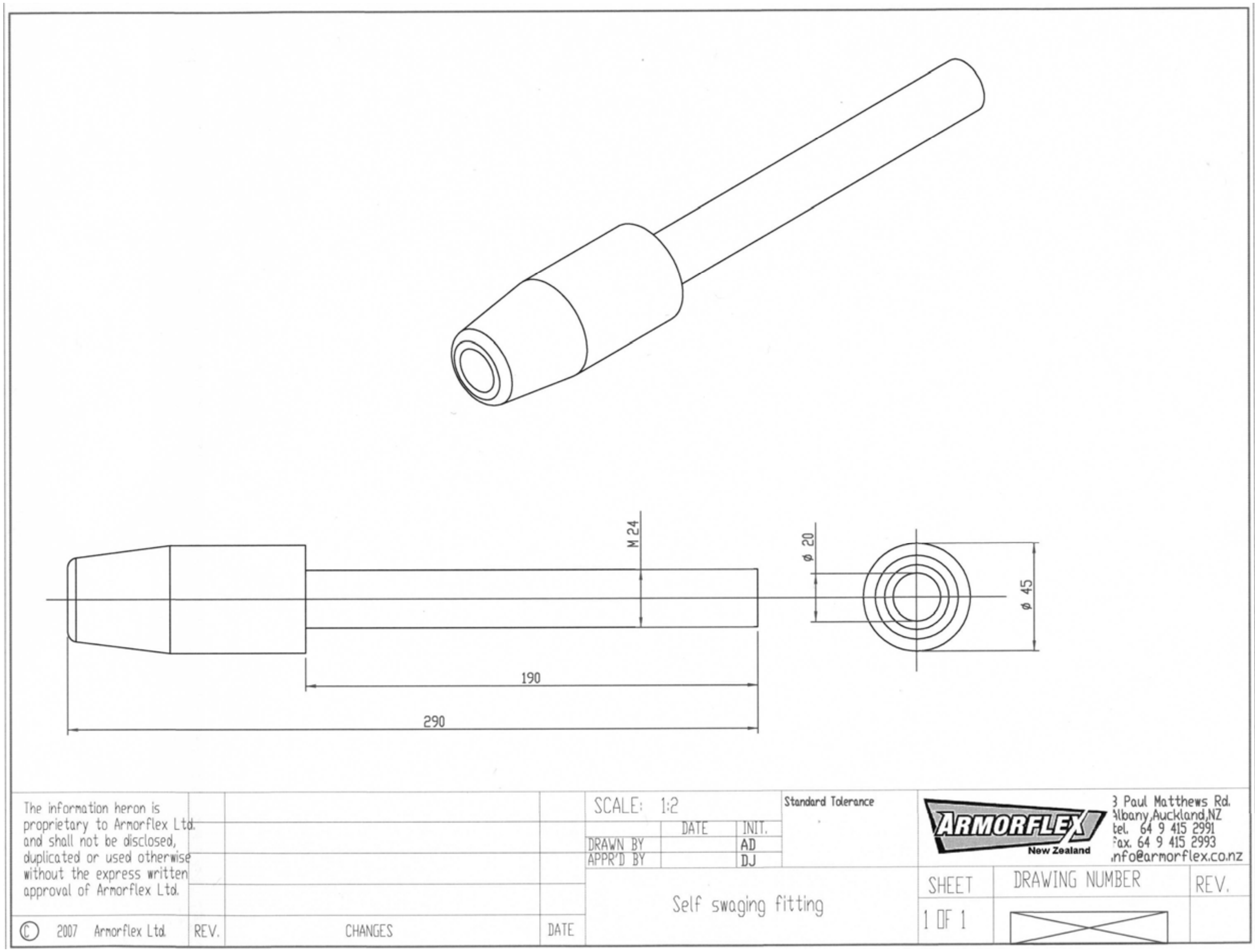
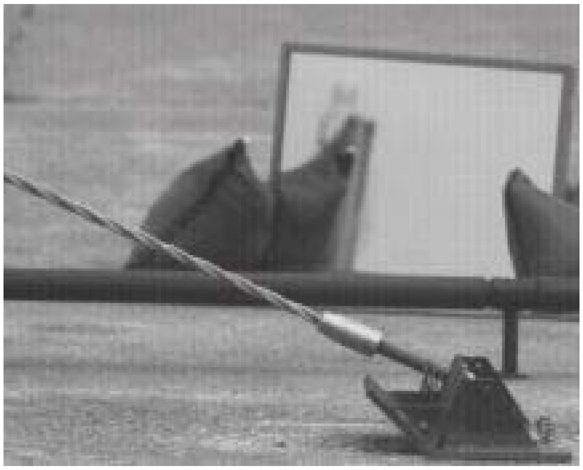
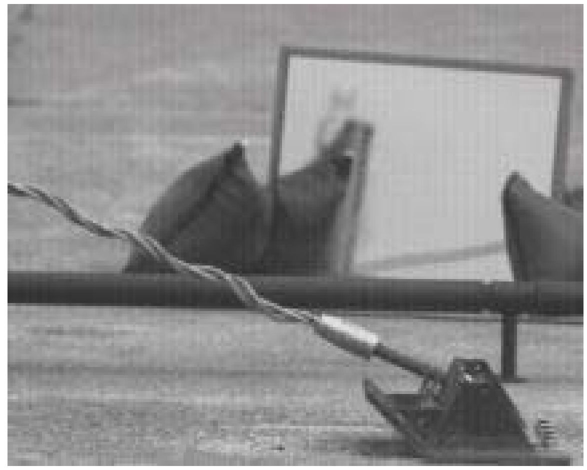


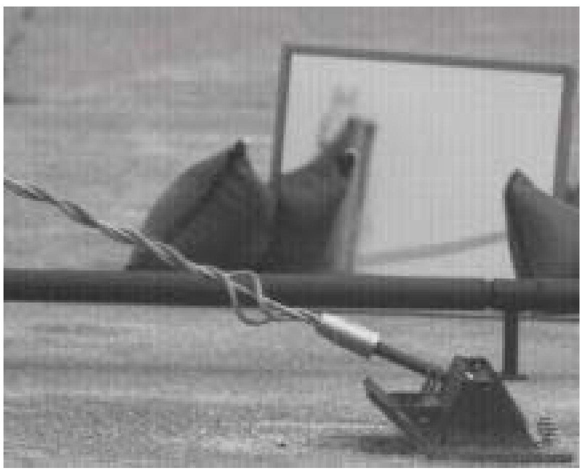
Figure 115. Armor Flex Self-Swaging End-Fitting



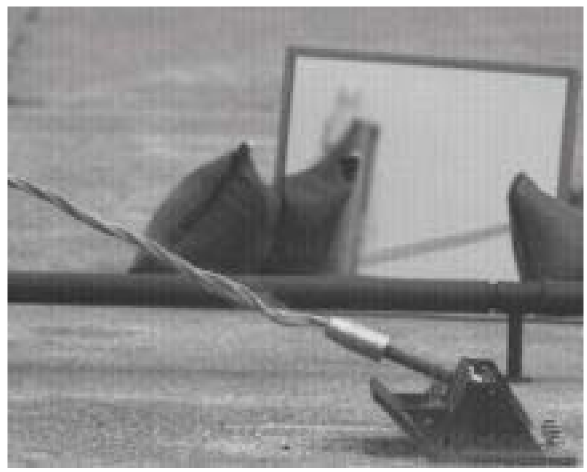
Time = 0ms



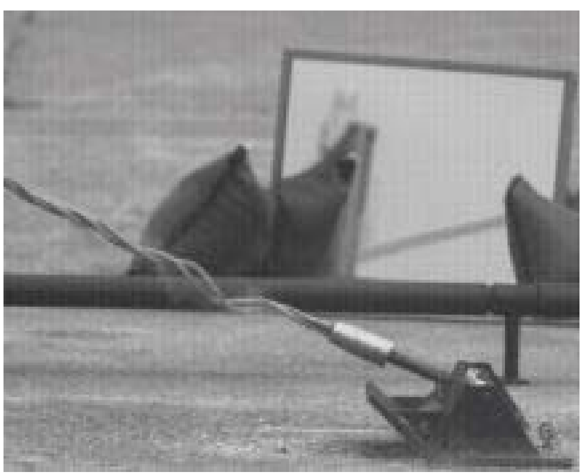
Time = 100ms



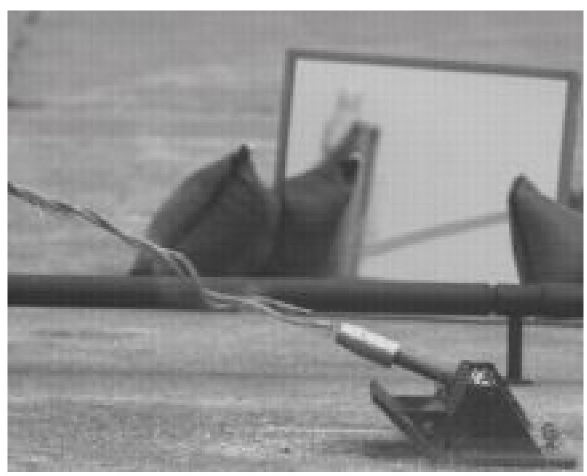
Time = 104ms



Time = 108ms



Time = 112ms



Time = 114ms

Figure 116. Sequential Photographs, Test No. 4CTB-6

9.2 Discussion

The results of the dynamic testing indicated that certain components were suitable for use in the high-tension cable median barrier while others were not.

The Bennett Bolt low-tension end-fitting with a 0.75-in. diameter, Grade A449 threaded rod was not capable of developing the target load of 39 kips. However, both the Bennett Bolt high-tension end-fitting with a 0.875-in. diameter, Grade A449 threaded rod and the Armor Flex self-swaging end-fitting with a 0.945-in. diameter, Grade K 1045 rod did develop loads greater than the target prior to failure. Based on anecdotal evidence that the Armor Flex end-fitting could release from the terminal early under conditions of cable whip, it was decided to select the Bennett high-tension end-fitting as the end-fitting for the high-tension cable median barrier.

Testing of the two cable splice options revealed that only one was suitable for use in the high-tension cable median barrier. While the Bennett Bolt low-tension slice was not capable of developing the target load of 39 kips, the Armor Flex splice was found capable. As such, the Armor Flex splice was selected for use in the high-tension, cable median barrier.

10 SUMMARY AND CONCLUSIONS

Components for the high-tension, cable median barrier were selected through the process of static and dynamic testing of various alternatives. End-fittings, splices, and cable-to-post attachments were all selected based on the results of the research.

Through development and testing of many slotted-bracket and U-bolt cable-to-post attachment concepts, the curved keyway bracket with shoulder bolts was determined to be the best option for use in the cable median barrier. The bracket was required to develop lateral loads of 6,000 lbs prior to failure while releasing the cable at loads of approximately 1,000 lbs when loaded vertically. Preliminary static testing indicated that the curved keyway bracket was capable of meeting these criteria, and dynamic testing confirmed that, with the use of shoulder bolts to fasten the bracket to the post, it was capable of performing as desired. Therefore, it was selected as the cable-to-post attachment for the barrier.

Dynamic testing was performed on various existing end-fittings and cable splices to identify optimal components for use in the high-tension, cable median barrier. These components were required to develop the full strength of 0.75-in. diameter, 3x7 wire rope used in the barrier, or a load of approximately 39 kips. End-fittings manufactured by Bennett Bolt Works, Inc. and Armor Flex were found capable of sustaining this load, and based on anecdotal evidence, the Bennett high-tension end-fitting with a 0.875-in. diameter, Grade A449 threaded rod was selected for use in the barrier. Of the two cable splices tested, only the Armor Flex splice was able to sustain the target load. Therefore, it was selected for use in the barrier.

11 REFERENCES

1. Bergendahl, Peter. “Cable Safety System.” U.S. Patent No. 6,962,328 B2. 8 November 2005.

2. Bergendahl, Peter. “Cable Safety System.” U.S. Patent Application No. 2005/0284695 A1. 29 December 2005.

3. Alberson, Dean C., et al. “Locking Hook Bolt and Method for Using Same.” U.S. Patent No. 6,948,703 B2. 27 September 2005.

4. Neusch, William H. “Cable Barrier System.” U.S. Patent Application 2007/0007501 A1. 11 January 2007.

5. Nilsson, Hakan. “Side Guard Fence.” Patent Application No. 2002/0014620 A1. 7 February 2002.

6. Nilsson, Hakan. “Wire Rope Safety Barrier.” U.S. Patent No. 6,902,151 B1. 7 June 2005.

7. Stacey, Andrew G. “Safety Fences.” U.S. Patent No. 5,039,066. 13 August 1991.

12 APPENDICES

APPENDIX A – Material Information

Ronald K. Faller

From: <BennettBolt@aol.com>
To: <rfaller1@unl.edu>
Sent: Thursday, November 06, 2003 3:48 PM
Attach: HOOKBOLT.pdf
Subject: QUOTATION

Pricing on hook bolts and nuts follows. Please see attached drawing in pdf file.

700 pcs
3/8-16 x 1 3/4 J Hook Bolt C1038 Heat Treated Galvanized B695 CL55 100 ea.
$2.65 each

700 pcs
3/8-16 x 1 3/4 J Hook Bolt C1018 Galvanized B695 CL55 100 ea.
$2.40 each

2800 pcs
3/8-16 Hex Nut A563 Grade A Galvanized B695 CL55
$.08 each

1 Freight Charge: $85.00

FOB: Jordan, New York 13080
Ship Via: FedEx Freightways
Delivery: 3 weeks

Sincerely,
Don

Bennett Bolt Works, Inc.
12 Elbridge Street
PO Box 922
Jordan, NY 13080
315-689-3981 Phone
315-689-3999 Fax
bennettbolt@aol.com Email
www.bennettbolt.com Website

11/6/2003

Figure A-1. J-Bolt Material Specifications

Service in Metals Since 1953

Murphy and Nolan, Inc.

BAR and TUBING SPECIALISTS

www.murphynolan.com

P.O. BOX 6689, 340 PEAT ST.
SYRACUSE, N.Y. 13217-6689
(315) 474-8203
1-800-836-6385
FAX (315) 474-8208

55 INDUSTRIAL PARK CIRCLE
ROCHESTER, N.Y. 14624-2493
(585) 426-1420
1-800-333-0827
FAX (585) 247-1962

07/26/05

BENNETT BOLT WORKS

P.O. BOX 922
JORDAN, NY 13080

Order Number: 325647
Your PO: 75210
Ship Date:
Fax Number: 315-689-3999

Ln. Description
Heat Number Certificate of Mill Test Reports

CARBON STEEL ROUND BAR 1018 C F ASTM A108 (RED)
8 PC(S) (16#) 1/4" RD x 10/12' R/L
Heat Number: A78762

Chemical Composition

C	SI	MN	P	S
0.1700	0.1700	0.6700	0.0080	0.0110

AL
0.0050

Mechanical Properties

Yield Strng	Tensile Strng	% Elong	Brinell Hardness Hardness
54,000	64,000	15	126

Figure A-2. U-Bolt Material Specifications, Continued

INFASCO

BOLTS, NUTS AND FASTENER PRODUCTS

¼-20 x 1 x 2½ Round Bend U Bolt
SAE J429 grade 5

LOT NO.: 0107–56427

FASTENER TEST REPORT

(THIS DOCUMENT MAY BE REPRODUCED, BUT ONLY IN ITS ENTIRETY)

36000

11001
BENNETT BOLT WORKS INC
12 ELBRIDGE ST - PO BOX 922
JORDAN, NY
13080-

PART NO.	DATE
	2002-09-19
CUSTOMER P.O. NO. 011771	REFERENCE NO. 502870
INVOICE DATE 2002-09-19	INVOICE NO. I.F.C. 331761

DESCRIPTION AND MARKING: HEX HD CAP SCREW GR5 UNC
HOLLOW TRIANGLE & 3 RADIAL LINES

SIZE	GRADE	QUANTITY
1/4-20 X 6 1/2	SAE 1036M	32,700

HEAT CHEMICAL ANALYSIS

HEAT NO.	C %	Mn %	P %	S %	Si %				
A54613	0.36	1.04	0.010	0.012	0.22				

METHOD	ASTM F606	ASTM F606	ASTM F606	ASTM F606	ASTM F606	ASTM E384
SAMPLES SELECTED BY: 0011	PROOF LOAD (psi)	WEDGE TENSILE STRENGTH (psi)	SHEAR STRENGTH	SURFACE HARDNESS (R 30N)	CORE HARDNESS (ROCKWELL)	MICRO HARDNESS
SPEC. MIN.	85,000	120,000			C 25.0	
SPEC. MAX:				54.0	C 34.0	
SAMPLE NO.1	85,000	135,000		50.7	C 27.6	
NO.2		134,000		51.2	28.0	
NO.3		137,000		50.8	27.8	
NO.4		136,000		50.2	28.3	
NO.5				51.3	28.1	
NO.6				51.7	28.2	
NO.7				50.5	28.4	
NO.8				51.6	27.9	

THE ABOVE TESTED SAMPLES HAVE BEEN INSPECTED FOR VISUAL DISCONTINUITIES AND FOUND ACCEPTABLE.
THEY COMPLY IN ALL RESPECTS WITH THE FOLLOWING SPECS:
SAE J-429, ASME B18.2.1,THREADS PER ASME B1.1 CLASS 2A,UNLESS OTHERWISE SPECIFIED.

Raw material used to manufacture fasteners is mercury and asbestos-free.
Fasteners were tested in the bare metal condition.

MANUFACTURED BY: INFASCO

700 Ouellette, Marieville (Quebec) J3M 1P6
Tel.: (450) 658-8741 Fax: (450) 460-5496

Division of IFASTGROUPE and Company, Limited Partnership (Ifastgroupe Inc., General partner)

Abdelhaq El Ouardi, eng.
ISO Coordinator

Page 1 of 1

Figure A-3. U-Bolt Material Specifications, Continued

Service in Metals Since 1953

Murphy and Nolan, Inc.

BAR and TUBING SPECIALISTS

www.murphynolan.com

P.O. BOX 6689, 340 PEAT ST.
SYRACUSE, N.Y. 13217-6689
(315) 474-8203
1-800-836-6385
FAX (315) 474-8208

55 INDUSTRIAL PARK CIRCLE
ROCHESTER, N.Y. 14624-2493
(585) 426-1420
1-800-333-0827
FAX (585) 247-1962

07/26/05

BENNETT BOLT WORKS

P.O. BOX 922
JORDAN, NY 13080

Order Number: 325647
Your PO: 75210
Ship Date:
Fax Number: 315-689-3999

Ln. Description
Heat Number   Certificate of Mill Test Reports

CARBON STEEL ROUND BAR 1018 C F ASTM A108 (RED)
8 PC(S) (25#) 5/16" RD x 10/12' R/L
Heat Number: C53405
Chemical Composition

C	MN	P	S	SI
0.1900	0.9000	0.0100	0.0090	0.2000
SN	CU	NI	CR	MO
0.0050	0.0900	0.0100	0.0300	0.0060
N	V			
0.0032	0.0010			

Mechanical Properties

Yield Strng	Tensile Strng	% Elong	Brinell Hard-ness Hardness
54.000	64.000	15	126

Figure A-4. U-Bolt Material Specifications, Continued

2-05 14:13 FROM- T-094 P.02/03 F-176

LAKE ERIE SCREW CORPORATION

311-777-34

LAKEWOOD OPERATIONS

FRANKFORT OPERATIONS

13001 ATHENS AVENUE
CLEVELAND, OHIO 44107
T 216 521 1800
F 216 228 4520

3281 WEST COUNTY ROAD O NS
FRANKFORT, INDIANA 46041-0960
T 765 654 0477
F 765 654 0857

TEST REPORT

5/16-13 X 1" X 2 1/4 Round Bend U Bolt

SAE J429 grade 5

ORDER INFORMATION

Date: 03/15/01

Certification#: LE23743300300500233137

Cust PO: 194802

Lot Nbr: 00233137

Quantity: 534 Pieces

KANEBRIDGE CORPORATION
153 BAUER DRIVE
OAKLAND NJ 07436-3150

PART INFORMATION

Part Number: 31112CH5L
Description: NC5 5/16-18 X 7 HEX CAP SCREW
Finish: ZINC 0.00015" MIN.
Headmarking: LE 3 RADIALS

RAW MATERIAL ANALYSIS

Steel Heat Nbr: CR137370
Steel Supplier: CHARTER STEEL
Steel Grade: LESC 4037M (1), LE 1.1

C	Mn	P	S	Si	Cr	Mo	Cu	Ni	Al
0.37	0.80	0.01	0.012	0.29	0.32	0.18	0.07	0.06	0.041

MECHANICAL PROPERTIES

	10° Wedge Tensile Strength Psi	Proof Load Test Lbs	Elong	Superficial R30N	Core Rc
High	139000			51.0	30.0
Low	136000			48.0	25.0
Avg	137600			49.6	28.0

CERTIFICATION TEST RESULTS INCLUDE THOSE REPORTED BY THE FOLLOWING ACCREDITED LABORATORIES:
LAKE ERIE SCREW- LAKEWOOD LAB
CHARTER STEEL

Applicable Standards, Specifications, and Sampling Schemes:
ANSI B18.2.1
SAE J429 Grade 5, ASTM F606, E8, E18, F1470, ASME B18.18.7M

The listed standards, specifications, and sampling schemes are of the revision in effect on the date of manufacture unless noted otherwise.

DEVIATIONS FROM TEST METHODS

None

This lot has been found to conform to the requirements of the above standards and specifications.

Certification Mailed to Bill-to address

We certify The product [illegible] Lake Erie Screw Corporation was manufactured, sampled, tested, and inspected in accordance with the standards and specifications [illegible] Lake Erie Screw Corporation's Quality Manual [illegible] The above data accurately represents values provided by Lake Erie [illegible] Lake Erie Screw Corporation's A2LA accredited laboratories. Statistical process control data is on file [illegible] This document may only be reproduced [illegible] and may not be used for any purpose other than the purpose of [illegible] Lake Erie Screw Corporation makes no [illegible] representations, warranties and guarantees whatsoever, whether express, implied or [illegible] warranty of merchantability or fitness for a particular purpose

Lake Erie Screw Corporation
Jerry Hine
Quality Manager

Figure A-5. U-Bolt Material Specifications, Continued

09/27/2007 10:02 3156893999 BENNETT BOLT WORKS PAGE 01

BENNETT BOLT WORKS, INC.

12 Elbridge Street
P.O. Box 922
Jordan, New York 13080

PHONE 315-689-3981
FAX 315-689-3999

FACSIMILE

TO: Bob Bielenberg **DATE:** 9.27.07
COMPANY: Midwest Roadside Safety Facility
FAX NUMBER: 402 472 2022 **NUMBER OF PAGES:** 6

From: Jim Sincerbeaux

Material Test Reports for test assemblies

Jim

Figure A-6. Bennett Bolt End-Fitting Material Specifications

BENNETT BOLT WORKS, INC.

12 Elbridge Street
P.O. Box 922
Jordan, New York 13080

PH 315-689-3981
FX 315-689-3999

MIDWEST ROADSIDE SAFETY FACILITY
UNIV. OF NEBRASKA
1901 Y STREET BLDG C
LINCOLN, NE 68588-0601
(402) 472-9064
ATTN: BOB BIELENBERG

SEPT 21,2007

CABLE FITTINGS FOR TL3-TL4 GUARDRAIL CABLE CRASH TEST

4 EA CG 198N-H 87M
TURNBUCKLE CABLE ASSEMBLY W/ 2 WEDGES
7/8-9 X 11" FLATTENED RODS A449

16 EA CG 184N-H 87M
CABLE END ASSEMBLY W/ WEDGE
7/8-9 X 11" FLATTENED ROD A449

James Limeubeaux
MANAGER QUALITY ASSURANCE

HT NO 734281	7/8-9 x 11" Flattened Rods A449 Mfg. - Southeastern Bolt & Screw, Birmingham, AL
Order NO 75410-75590	Malleable Iron Casting ASTM - A47 Grade 32510 Mfg. - Buck Co., Inc., Quarryville, PA
Order NO 6002236	Malleable Iron Casting Wedge ASTM - A47 Grade 32510 Mfg. - Buck Co., Inc., Quarryville, PA

Figure A-7. Bennett Bolt End-Fitting Material Specifications, Continued

. 09/27/2007 10:02 3156893999 BENNETT BOLT WORKS PAGE 03

39622

Southeastern Bolt & Screw, Inc
1037 16th Avenue West
Birmingham, AL 35204
(205) 328-4551

MATERIAL TEST REPORT

DATE: July 7, 2004

CUSTOMER P.O.: 013218

LAB REPORT NO.: 11065

SIZE: 7/8-9 X 48 Double End Rod

LOT NO.: L15532 (296489-01)

CUSTOMER: Bennett Bolt Works, Inc.

QUANITY: 57

SPECIFICATION: A449 Type 1

SURFACE COATING: A153 Class C

MARKINGS: SBS, Three Radial Lines

CHEMISTRY

C	MN	P	S	SI	V	Cb	CR	MO
.47	.75	.010	.030	.20	.013			

MATERIAL GRADE: 1045

HEAT NO.: 734281

MECHANICAL PROPERTIES

PROOF LOAD

Applied Tensile Force, lbf	39,250
Length Measurement Differential, in	-0.0005

AXIAL TENSILE

Axial Tensile Load, lbf	60,600
Failure Location	Threads

WEDGE TENSILE

10 Degree Wedge Tensile Load, lbf	
Failure Location	

HARDNESS MEASUREMENTS

Rockwell C Scale	28

TEST METHODS: ASTM F606

We certify that the above test results do conform to the requirements of the specifications as shown. These test results relate only to the item tested. This document may be reproduced, but only in its entirety. All material was melted and manufactured in the USA.

Jim Waddell, Quality Assurance Manager

Figure A-8. Bennett Bolt End-Fitting Material Specifications, Continued

09/27/2007 10:02 3156893999 BENNETT BOLT WORKS PAGE 04

SEP-26-2007 10:13AM FROM-Buck Co. HR 717-284-4321 T-131 P.004/004 F-840

BUCK COMPANY, INC.

897 Lancaster Pike, Quarryville, PA 17566-9738

Phone (717) 284-4114 Fax (717) 284-4321

www.buckcompany.com greatcastings@buckcompany.com

MATERIAL CERTIFICATION

Date 8-30-07 Form# CERT-7A Rev C 4-21-06

CUSTOMER Bennett Bolt, Inc

ORDER NUMBER 75590

PATTERN NUMBER CGBBWTH REV. —

This is to certify that the castings listed conform to the following specifications and comply in all respects with the drawing or ordered requirements. All Quality Assurance provisions and / or Quality Assurance requirements and / or supplementary Quality Assurance provisions have been completed and accepted. SPC data is on file and available upon request.

Type Material: Malleable Iron

Specifications: ASTM-A47

Grade or Class: 32510

Heat Number: 904

MECHANICAL PROPERTIES

Tensile Str. PSI 24,562

Yield Str. PSI 45,032

Elongation 22

PHYSICAL PROPERTIES

Brinell Hardness 163

PCS SHIPPED 20

1 of 1

CHEMICAL ANALYSIS

Total Carbon 3.70

Silicon 2.86

Manganese .34

Sulfur .016

Phosphorus .020

Chrome .045

Magnesium .049

Copper .052

DATE SHIPPED 8-30-07

[signature]

Quality Assurance Representative

Quality Castings

ISO 9001: 2000 CERTIFIED

Ferritic and Pearlitic Malleable Iron, Gray and Ductile Iron, Brass, Aluminum

Figure A-9. Bennett Bolt End-Fitting Material Specifications, Continued

. 09/27/2007 10:02 3156893999 BENNETT BOLT WORKS PAGE 05
SEP-26-2007 10:13AM FROM-Buck Co. HR 717-284-4321 T-131 P.003/004 F-840

BUCK COMPANY, INC.

897 Lancaster Pike, Quarryville, PA 17566-9738
Phone (717) 284-4114 Fax (717) 284-4321
www.buckcompany.com greatcastings@buckcompany.com

MATERIAL CERTIFICATION

Date 11/14/06 Form Number CERT-7C REV. A

CUSTOMER: Bennett Bolt Works

ORDER NUMBER 75410

PATTERN NUMBER CGBBHT REV. —

This is to certify that the castings listed conform to the following specifications and comply in all respects with the drawing or ordered requirements. All Quality Assurance provisions and / or Quality Assurance requirements and / or supplementary Quality Assurance provisions have been completed and accepted. SPC data is on file and available upon request. Melted & Manufactured in the USA.

Type Material: Malleable Iron

Specifications: ASTM-A47

Grade or Class: 32510

Heat Number: OP5

MECHANICAL PROPERTIES

Tensile Str. PSI 57,112

Yield Str. PSI 35,584

Elongation 15

PHYSICAL PROPERTIES

Brinell Hardness 121

PCS SHIPPED 105

1 of 1

CHEMICAL ANALYSIS

Total Carbon 2.53

Silicon 1.57

Manganese .33

Sulfur .130

Phosphorus .015

Chrome .036

Magnesium .001

Copper .115

DATE SHIPPED 11/14/06

Quality Assurance Representative

Quality Castings

ISO 9002 CERTIFIED

Ferritic and Pearlitic Malleable Iron, Gray and Ductile Iron • Brass • Aluminum

Figure A-10. Bennett Bolt End-Fitting Material Specifications, Continued

09/27/2007 10:02 3156893999 BENNETT BOLT WORKS PAGE 06

BUCK COMPANY, INC.

897 Lancaster Pike, Quarryville, PA 17566-9738

Phone (717) 284-4114 Fax (717) 284-4321

www.buckcompany.com greatcastings@buckcompany.com

MATERIAL CERTIFICATION

Date 6-8-07

Form# CERT-7A Rev C 4-21-06

CUSTOMER Bennett Bolt Works Inc.

ORDER NUMBER 6002236

PATTERN NUMBER W/wedge

REV. Orig

This is to certify that the castings listed conform to the following specifications and comply in all respects with the drawing or ordered requirements. All Quality Assurance provisions and / or Quality Assurance requirements and / or supplementary Quality Assurance provisions have been completed and accepted. SPC data is on file and available upon request.

Type Material: Malleable Iron

Specifications: ASTM-A47

Grade or Class: 32510

Heat Number: 109

MECHANICAL PROPERTIES

Tensile Str. PSI 58,592

Yield Str. PSI 39,273

Elongation 16

PHYSICAL PROPERTIES

Brinell Hardness 121

PCS SHIPPED 10,951

1 of 1

CHEMICAL ANALYSIS

Total Carbon	2.64
Silicon	1.59
Manganese	.30
Sulfur	.111
Phosphorus	.030
Chrome	.035
Magnesium	.001
Copper	.132

DATE SHIPPED 6-8-07

Quality Assurance Representative

Quality Castings

ISO 9001: 2000 CERTIFIED

Ferritic and Pearlitic Malleable Iron, Gray and Ductile Iron, Brass, Aluminum

Figure A-11. Bennett Bolt End-Fitting Material Specifications, Continued

Ronald K. Faller

From: Dallas [djames@armorflex.co.nz]
Sent: Monday, August 20, 2007 10:22 PM
To: Ronald K. Faller
Subject: Re: self swaging fitting

Ron.

Hope this makes sense.

Cone - grade 4140
Spring - stainless steel 316
Threaded rod and Hub - Grade K 1040
Jaws - grade XS 1112 then case hardened 0.4 -0.6 mm deep to 63 RC.

corrosion protection - threaded rod and hub - HDG
- cone - Dacromet

We ran a test down here last week using those fittings and strongbacks in the contact area. All funtioned very well. We did note a little more sheet metal damage to the side of the car but not much.

Cheers
DALLAS

----- Original Message -----
From: Ronald K. Faller
To: 'Dallas'
Sent: Tuesday, August 21, 2007 5:23 AM
Subject: RE: self swaging fitting

Dallas:

I have been asked to add the material specification to our CAD detail for the stud anchors and strongbacks. Can you tell which steel specifications were used for the various materials? We have drawn your parts into our system and will be using them. Thus, we need to know what they conform to. Thanks!

Ron

Ronald K. Faller, Ph.D., P.E.
Research Assistant Professor

Midwest Roadside Safety Facility (MwRSF)
University of Nebraska-Lincoln
527 Nebraska Hall
Lincoln, Nebraska 68588-0529

(402) 472-6864 (phone)
(402) 472-2022 (fax)
rfaller1@unl.edu

From: Dallas [mailto:djames@armorflex.co.nz]
Sent: Monday, July 30, 2007 10:57 PM

1/4/2008

Figure A-12. Armor Flex End-Fitting Rod Materials Specifications

Page 2 of 2

To: Ronald K. Faller
Subject: Fw: self swaging fitting

Ron,
Assume you use dxf files. If not let me know, we can export to pretty much any format.
Cheers
DALLAS

1/4/2008

Figure A-13. Armor Flex End-Fitting Rod Materials Specifications, Continued

APPENDIX B – Static Tests: Post-Failure Photographs

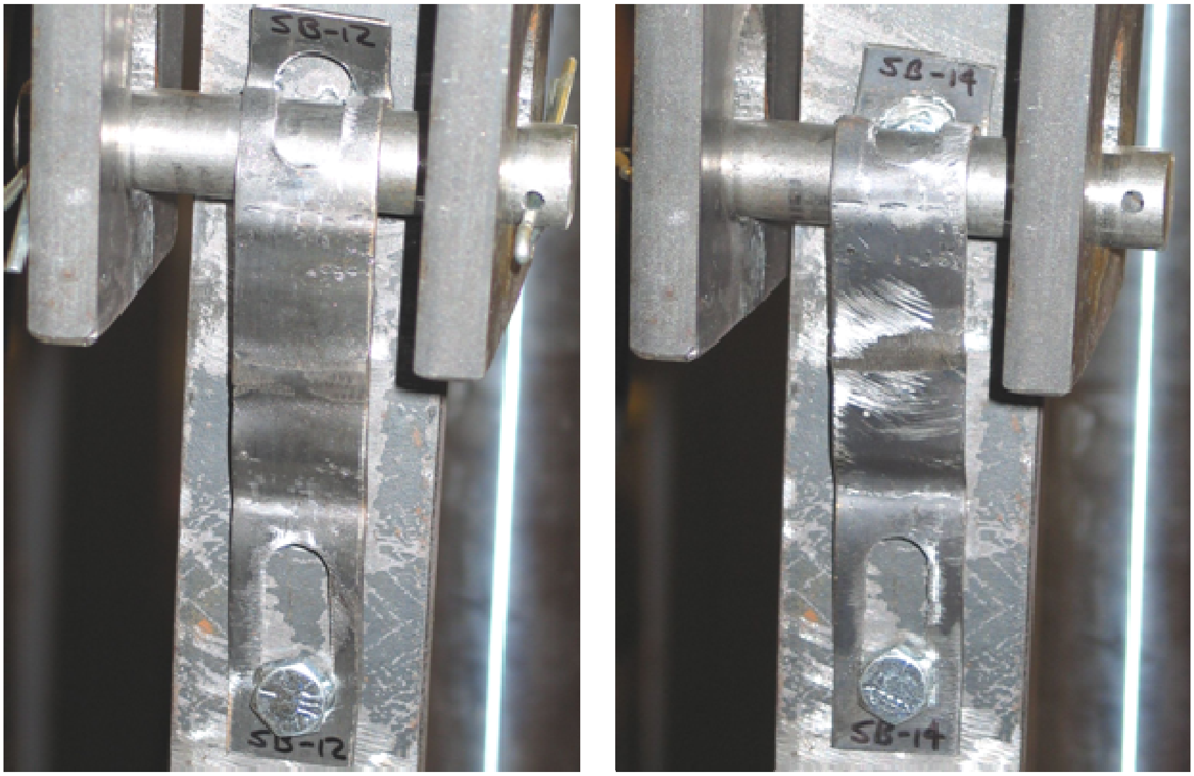


Figure B-1. Uniform Slot Brackets – Test Nos. SB-12, SB-14: Vertical Loading

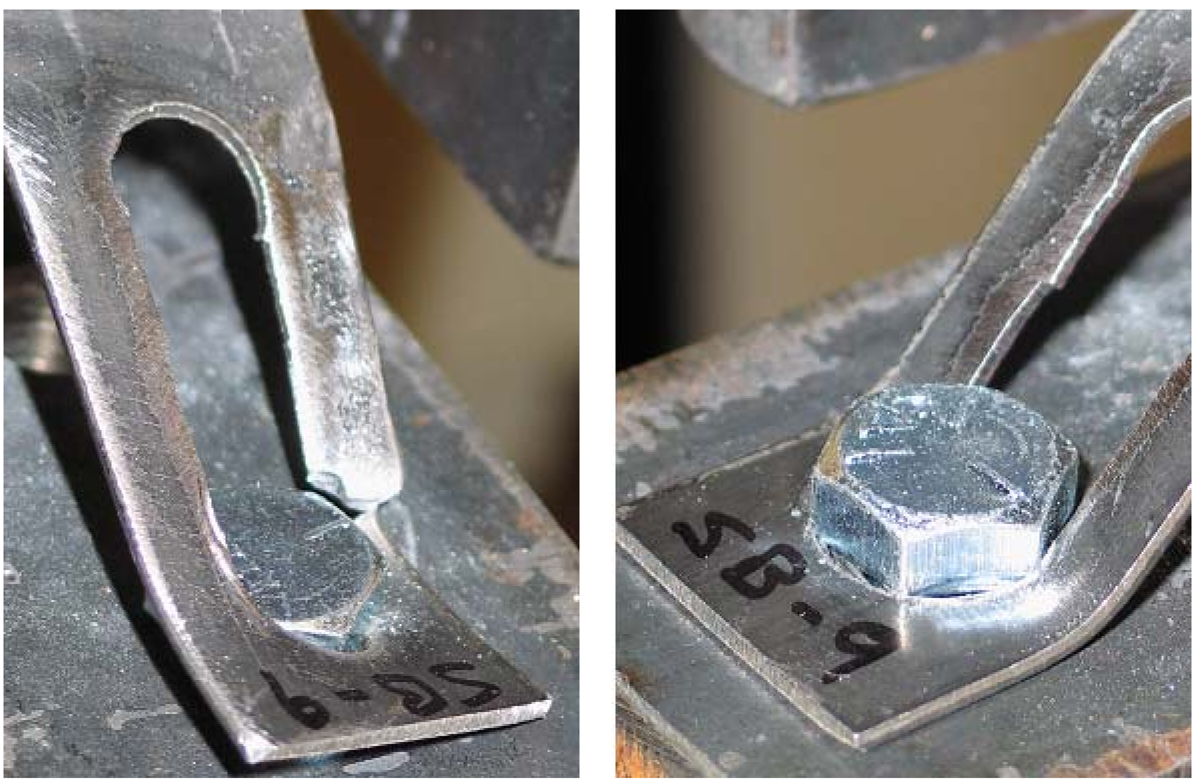


Figure B-2. Uniform Slot Brackets – Test No. SB-9: Lateral Loading

Figure B-3. Flat Keyway Brackets – Test No. SB-19: Vertical Loading

Figure B-4. Flat Keyway Brackets – Test No. SB-21: Lateral Loading

Figure B-5. Angled Slot Brackets – Test No. SB-24: Vertical Loading

Figure B-6. Angled Slot Brackets – Test Nos. SB-25, SB-26: Lateral Loading

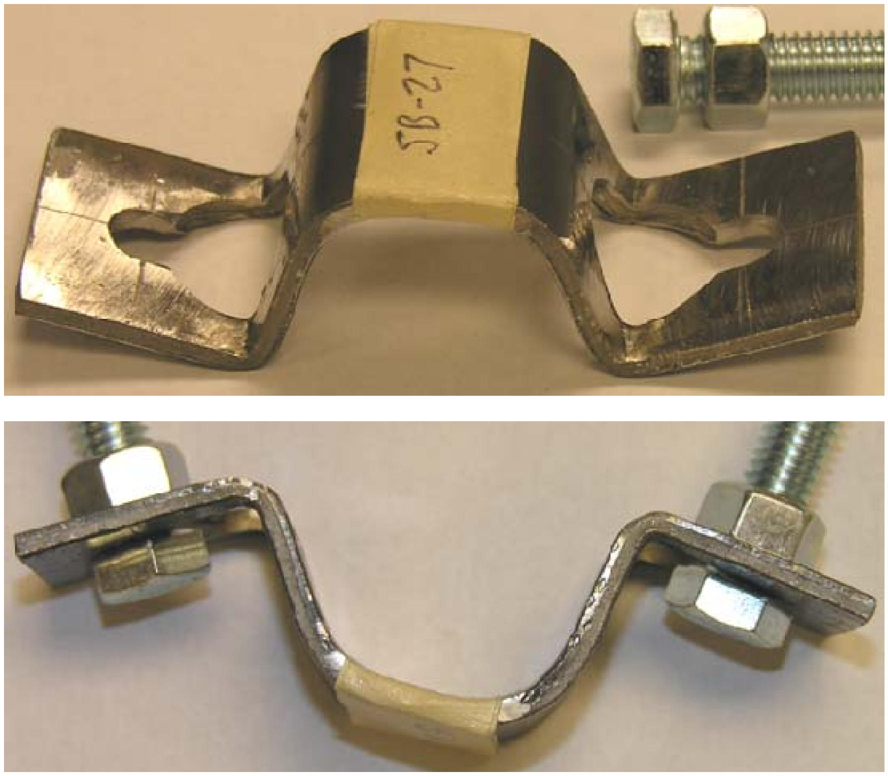


Figure B-7. Bent Keyway Brackets – Test Nos. SB-27, SB-30: Vertical Loading

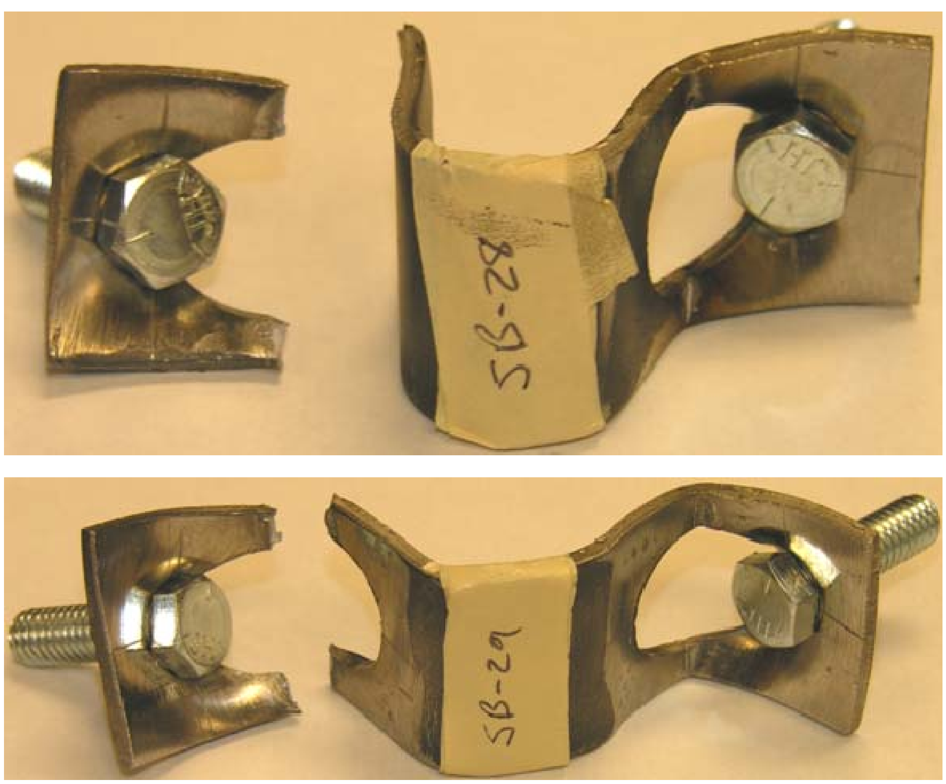


Figure B-8. Bent Keyway Brackets – Test Nos. SB-28, SB-29: Lateral Loading

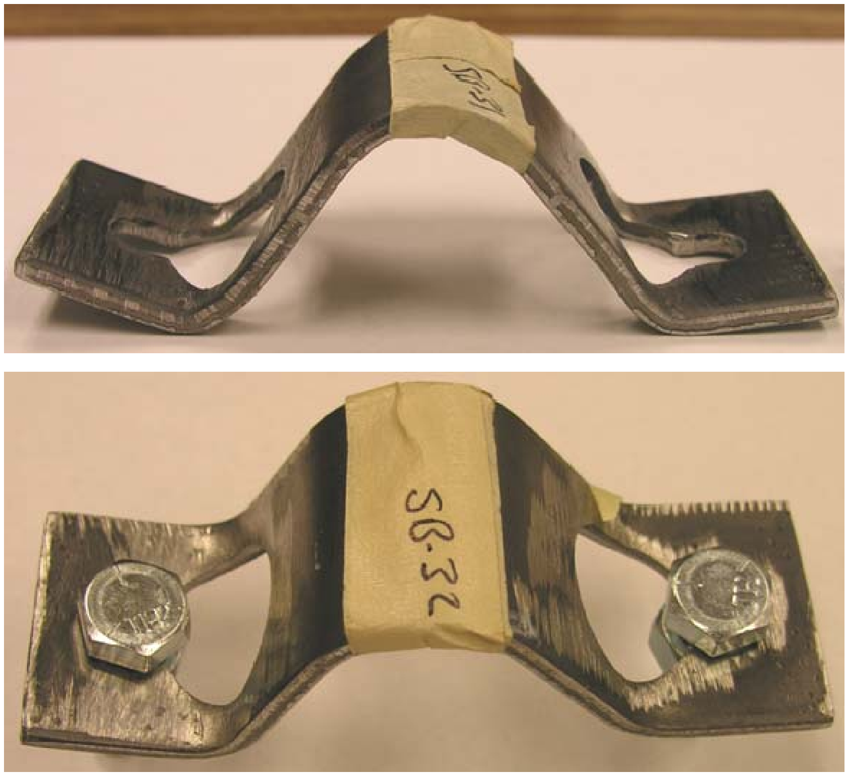


Figure B-9. Curved Keyway Brackets – Test Nos. SB-31, SB-32: Vertical Loading

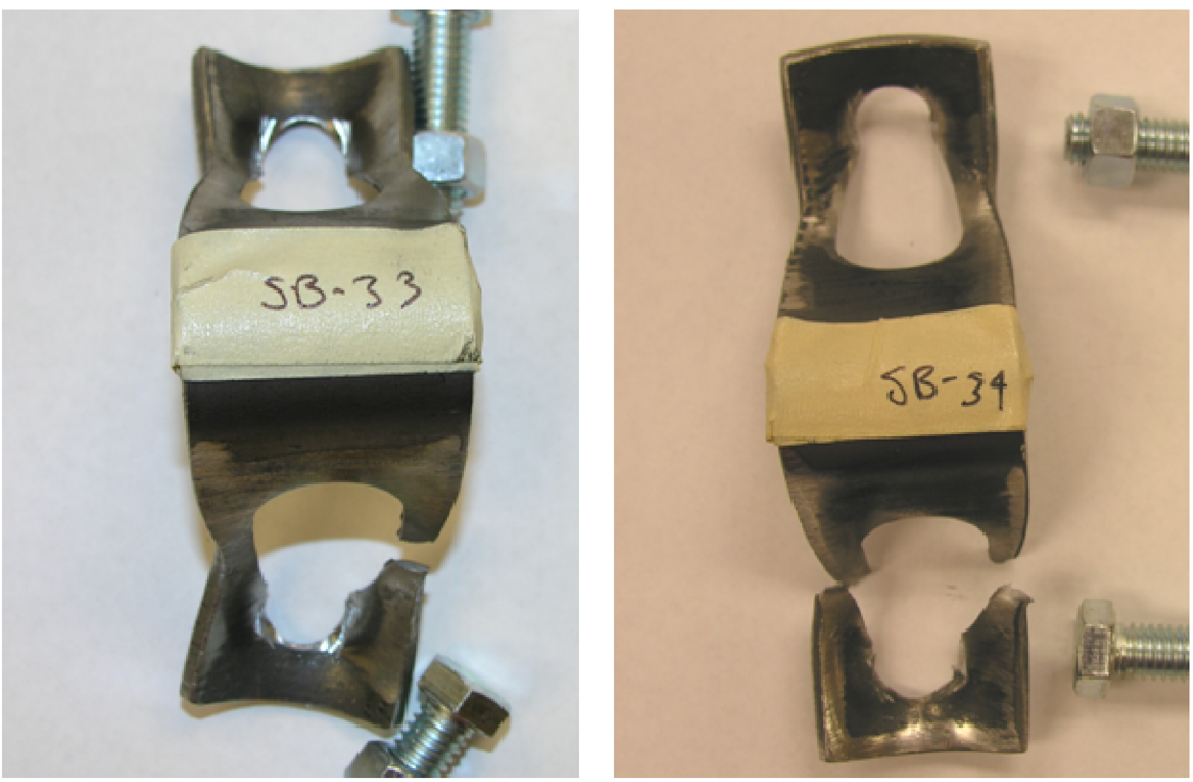


Figure B-10. Curved Keyway Brackets – Test Nos. SB-33, SB-34: Lateral Loading

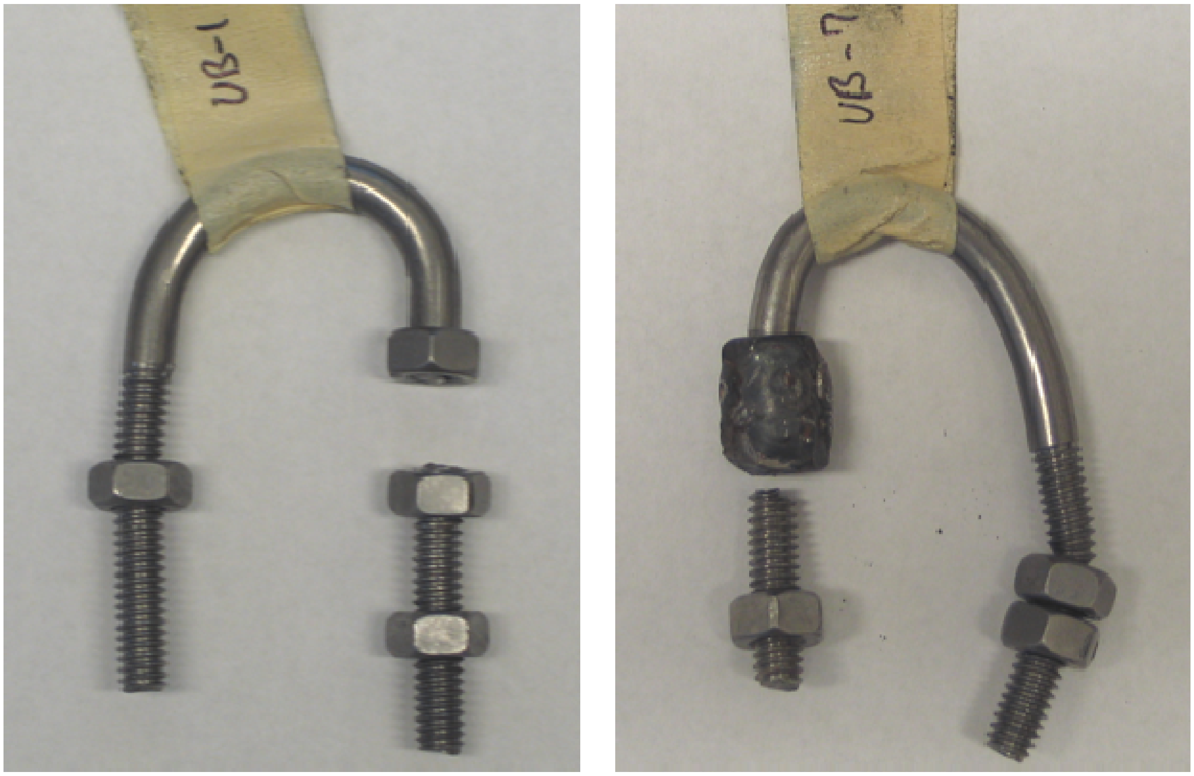


Figure B-11. U-Bolts with Nuts – Test Nos. UB-1, UB-7: Vertical Loading

Figure B-12. U-Bolts with Nuts – Test Nos. UB-8, UB-9: Lateral Loading

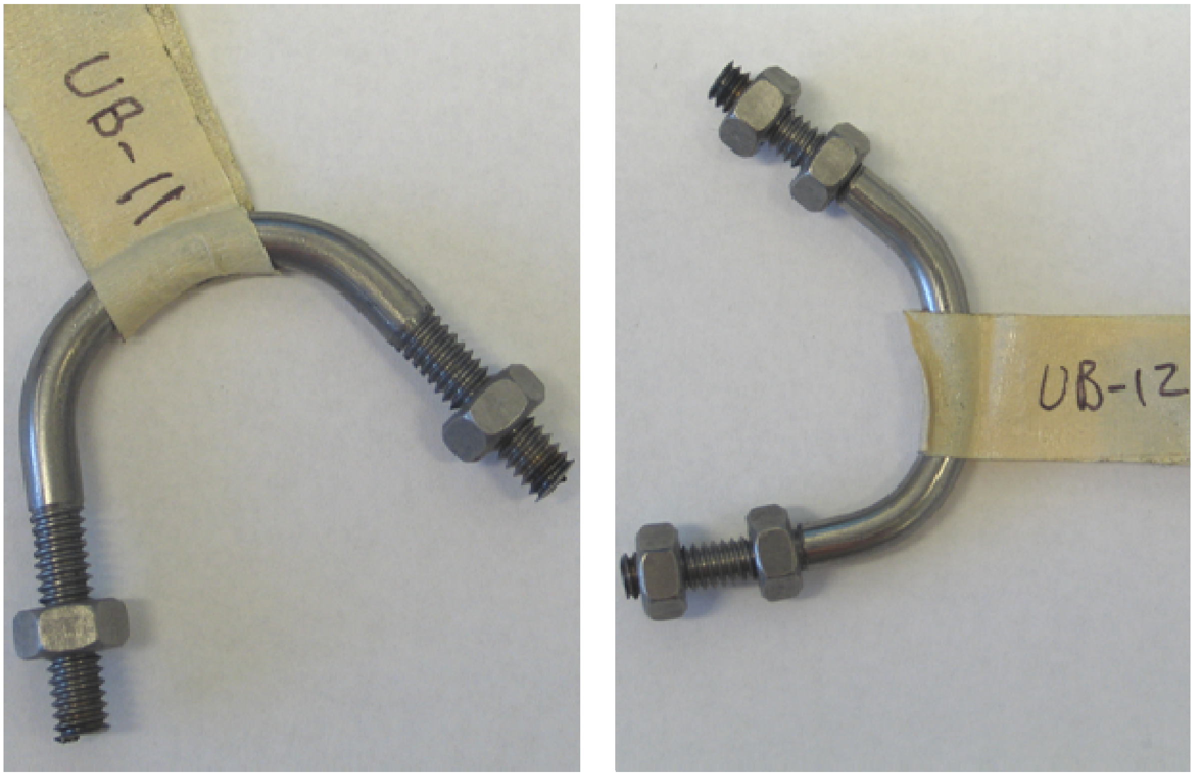


Figure B-13. U-Bolts with Keyways – Test Nos. UB-11, UB-12: Vertical Loading

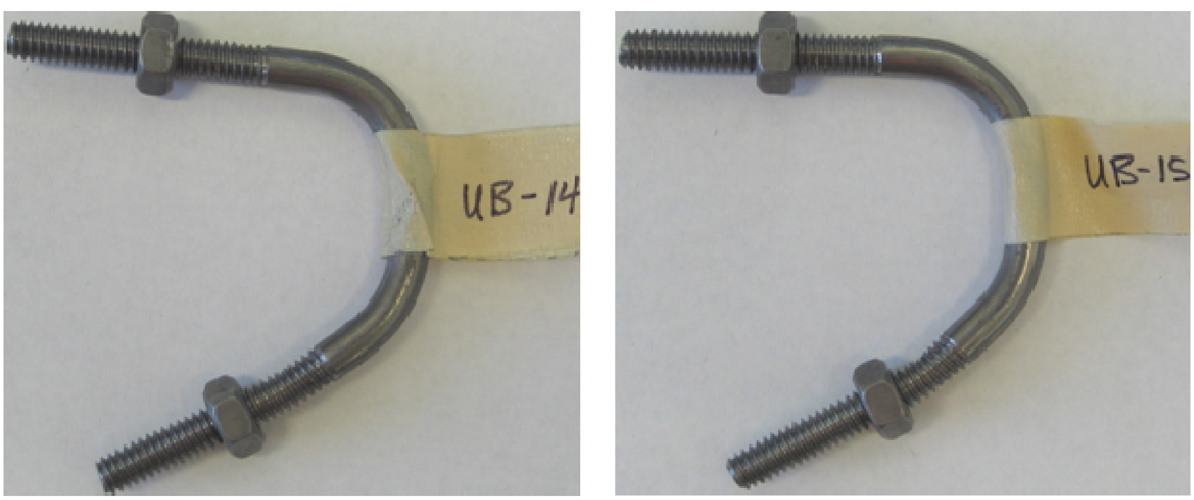


Figure B-14. U-Bolts with Slots – Test Nos. UB-14, UB-15: Vertical Loading

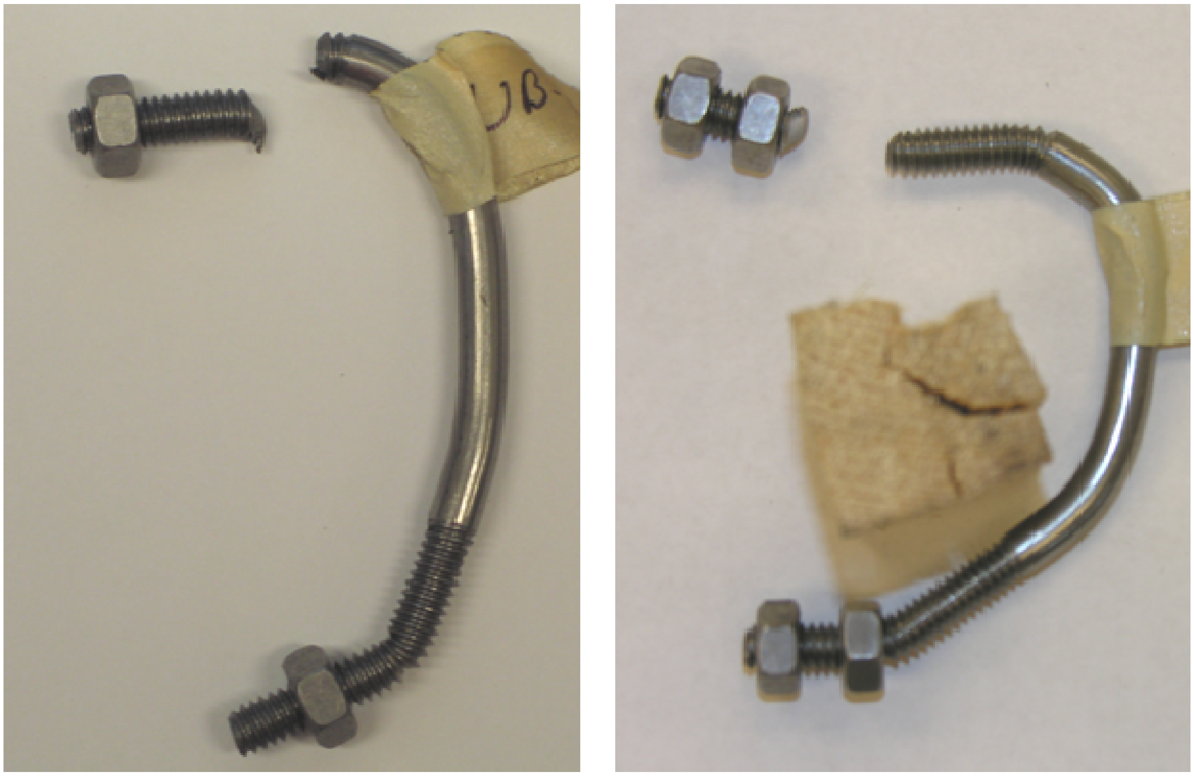


Figure B-15. U-Bolts with Spacers – Test Nos. UB-17, UB-26: Vertical Loading

Figure B-16. U-Bolts with OVS Holes – Test No. UB-30: Vertical Loading

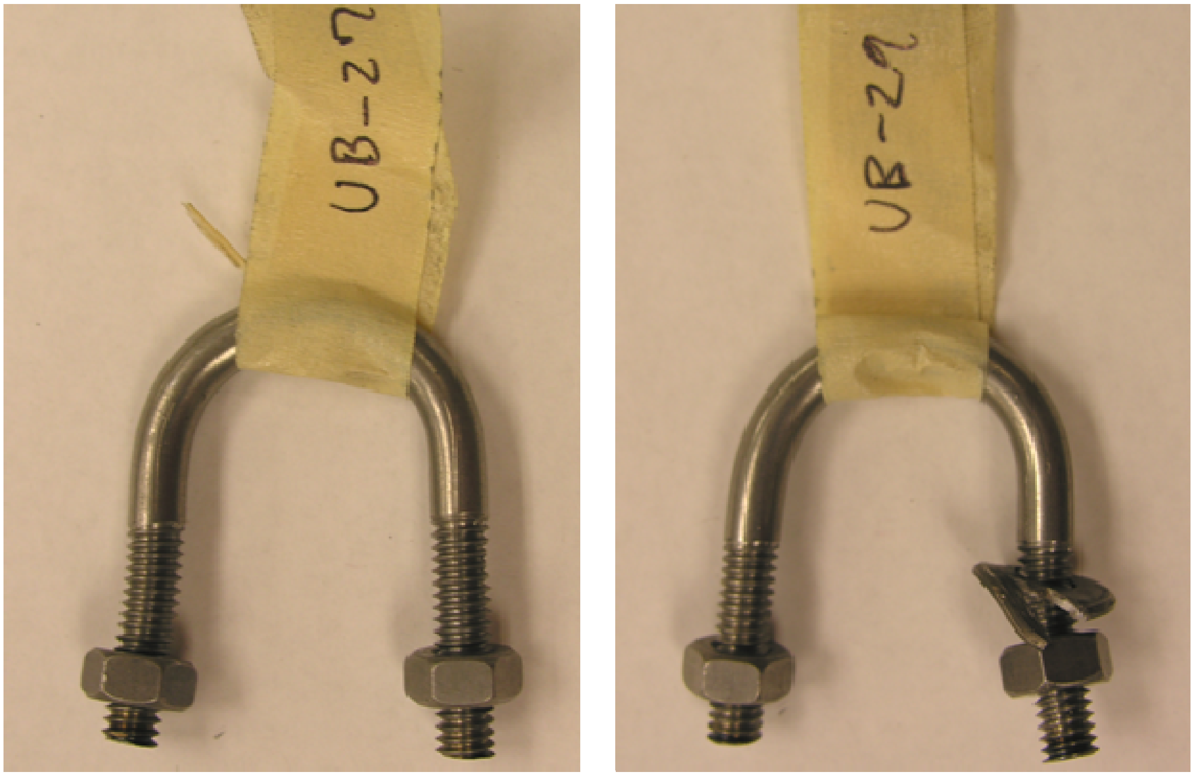


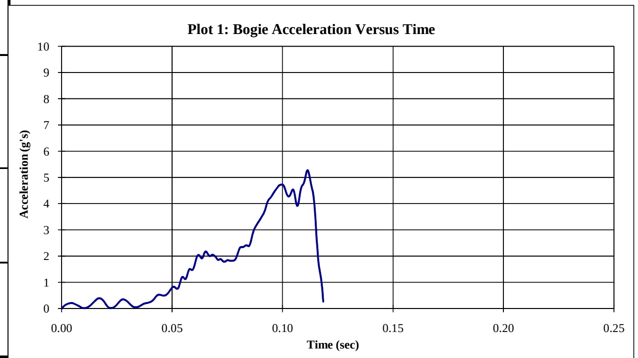
Figure B-17. U-Bolts with OVS Holes – Test Nos. UB-27, UB-29: Lateral Loading

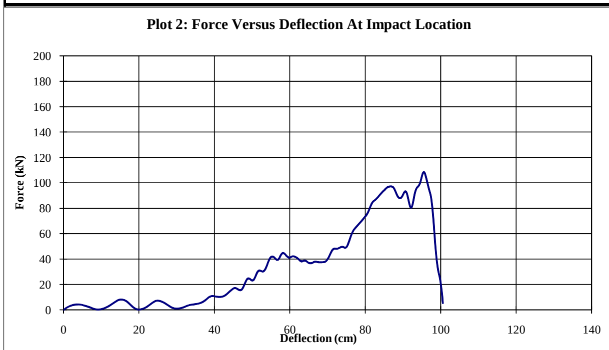
APPENDIX C – Dynamic Cable Pull Testing Summary Sheets

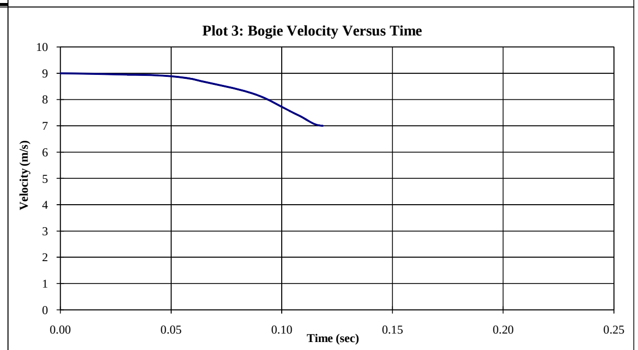
Midwest Roadside Safety Facility

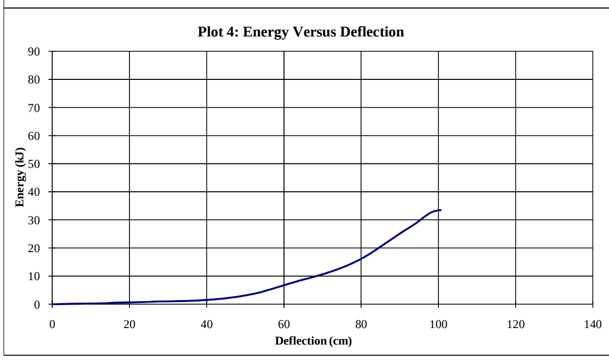
Bogie Test Summary

Test Information	Cable Pull @ 0 degrees			
Test Number:	4CTB-2			
Test Date:	17-May-2007			
Failure Type:	0			
Post Properties				
Post Type:		0		
Post Size:		0 metric		0
Post Length:		0.0 cm	(0.0 cm)	
Embedment Depth:		0.0 cm	(0.0 cm)	
Soil Properties				
Gradation:		NA		
Moisture Content:		NA		
Compaction Method:		NA		
Soil Density, γ_d:		NA kg/m³	NA	
Bogie Properties				
Impact Velocity:		8.9 m/s	(19.9 mph) (29.2 fps)	
Impact Location:	#VALUE!	NA	above groundline	
Bogie Mass:		2097 kg	(4622 lbf)	
Data Acquired				
Accelerometer Data:		EDR-3		
Camera Data:		Side View-DV and Photron		









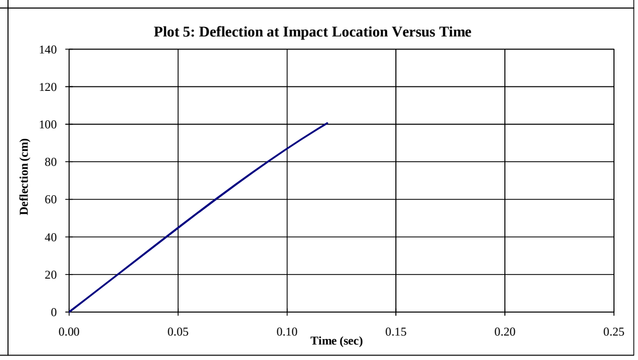
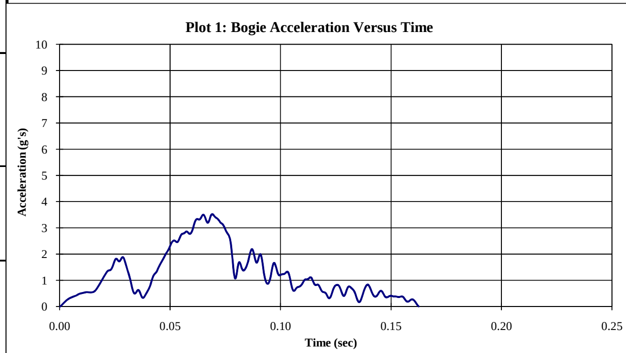
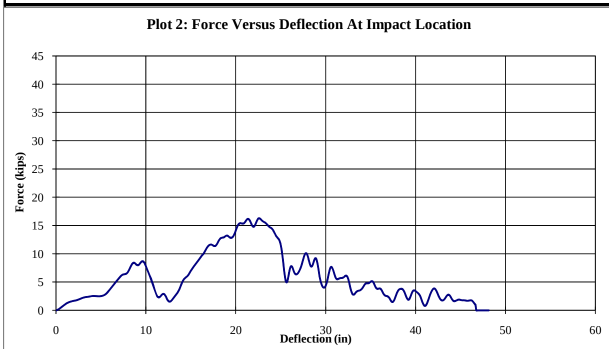


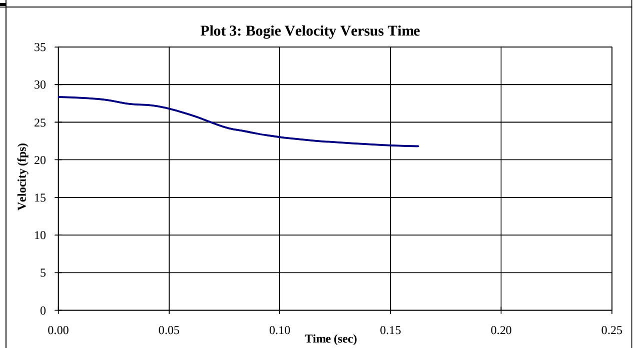
Figure C-1. Test No. 4CTB-2 Results

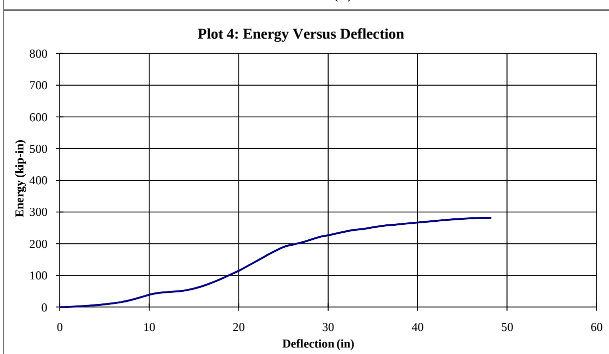
Bogie Test Summary

Test Information	Cable Pull @ 0 degrees			
Test Number:	4CTB-3			
Test Date:	29-May-2007			
Failure Type:	0			
Post Properties				
Post Type:		0		
Post Size:		0		0
Post Length:		0.0 in	(0.0 cm)	
Embedment Depth:		0.0 in	(0.0 cm)	
Soil Properties				
Gradation:		NA		
Moisture Content:		NA		
Compaction Method:		NA		
Soil Density, γ_d:		NA pcf	NA	
Bogie Properties				
Impact Velocity:		28.4 fps	(8.6 m/s)	(19.3 mph)
Impact Location:	NA	#VALUE!	above groundline	
Bogie Mass:		4622 lbf	(2097 kg)	
Data Acquired				
Accelerometer Data:		EDR-3		
Camera Data:		Side View-DV and Photron		









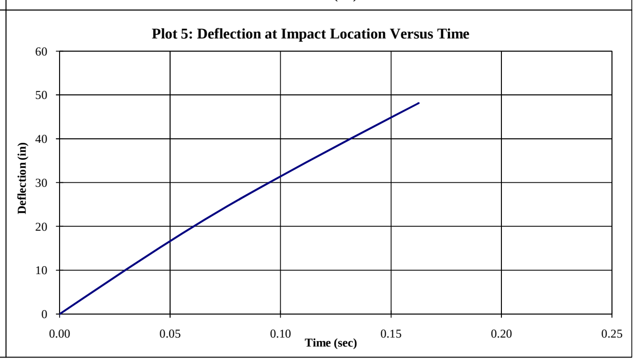
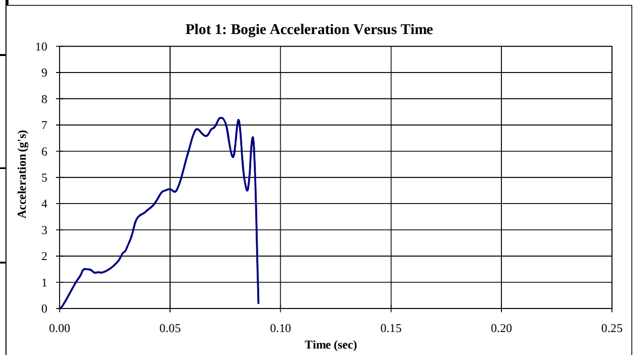
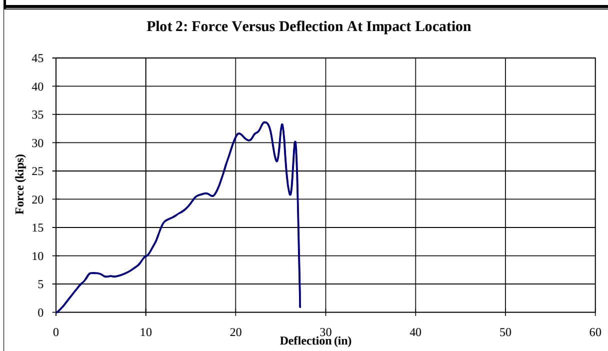


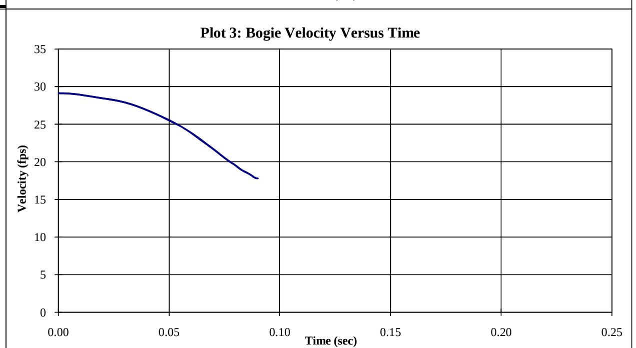
Figure C-2. Test No. 4CTB-3 Results

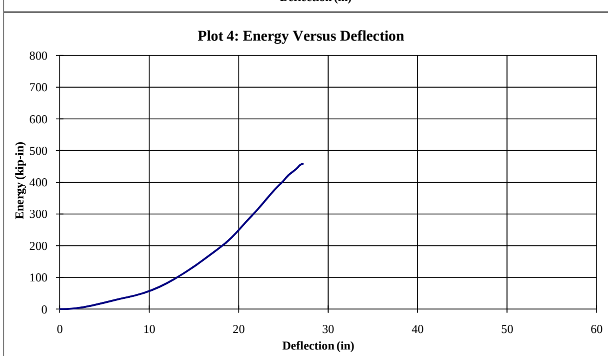
Midwest Roadside Safety Facility

Bogie Test Summary			
Test Information	Cable Pull @ 0 degrees		
Test Number:	4CTB-4		
Test Date:	29-May-2007		
Failure Type:	0		
Post Properties			
Post Type:		0	
Post Size:	0		0
Post Length:	0.0 in	(0.0 cm)	
Embedment Depth:	0.0 in	(0.0 cm)	
Soil Properties			
Gradation:		NA	
Moisture Content:		NA	
Compaction Method:		NA	
Soil Density, γ_d:	NA pcf	NA	
Bogie Properties			
Impact Velocity:	29.1 fps	(8.9 m/s)	(19.9 mph)
Impact Location:	21.7 in	(55.0 cm)	above groundline
Bogie Mass:	4622 lbf	(2097 kg)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:	Side View-DV and Photron		









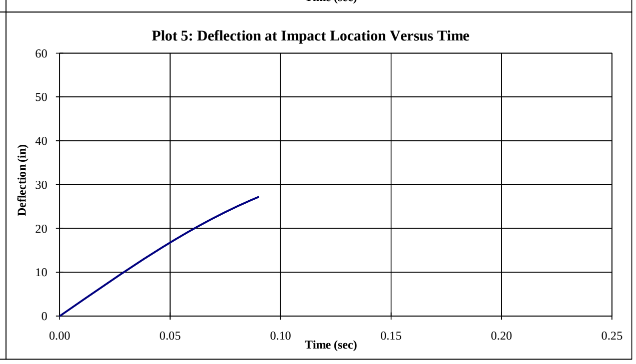
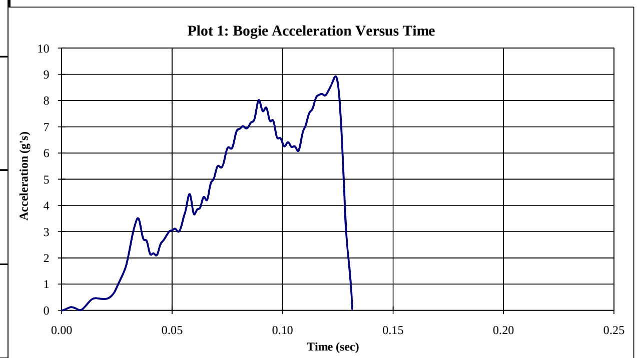


Figure C-3. Test No. 4CTB-4 Results

Midwest Roadside Safety Facility

Bogie Test Summary			
Test Information	Cable Pull @ 0 degrees		
Test Number:	4CTB-5		
Test Date:	30-May-2007		
Failure Type:	0		
Post Properties			
Post Type:		0	
Post Size:	0		0
Post Length:	0.0 in	(0.0 cm)	
Embedment Depth:	0.0 in	(0.0 cm)	
Soil Properties			
Gradation:		NA	
Moisture Content:		NA	
Compaction Method:		NA	
Soil Density, γ_d:	NA pcf	NA	
Bogie Properties			
Impact Velocity:	32.6 fps	(10.0 m/s) (22.3 mph)	
Impact Location:	21.7 in	(55.0 cm) above groundline	
Bogie Mass:	4622 lbf	(2097 kg)	
Data Acquired			
Accelerometer Data:		EDR-3	
Camera Data:		Side View-DV and Photron	



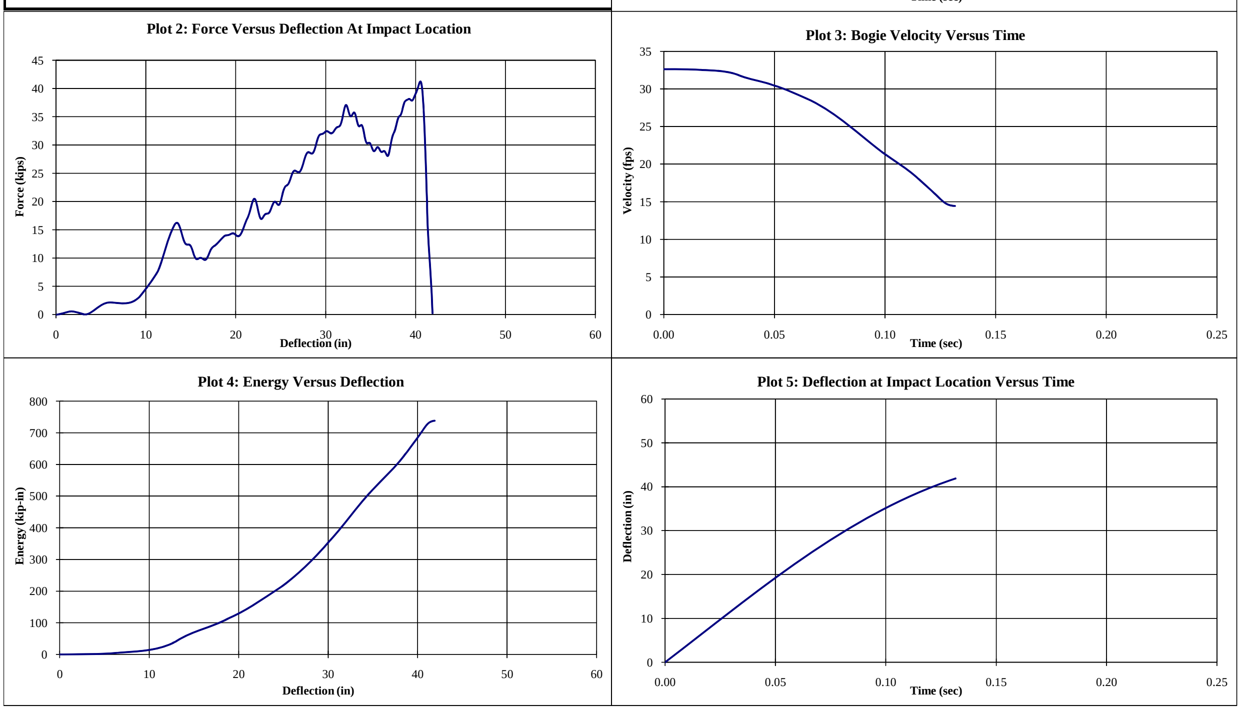
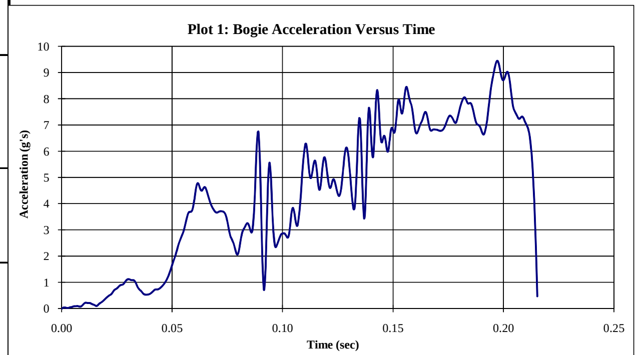
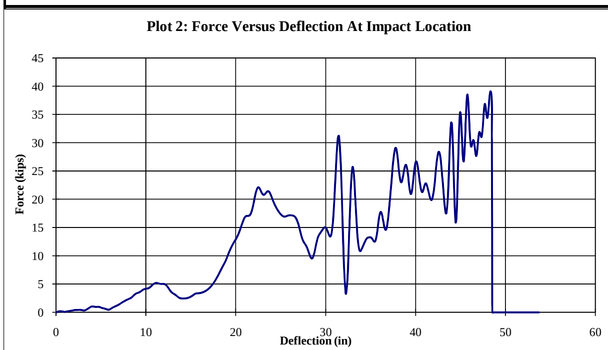


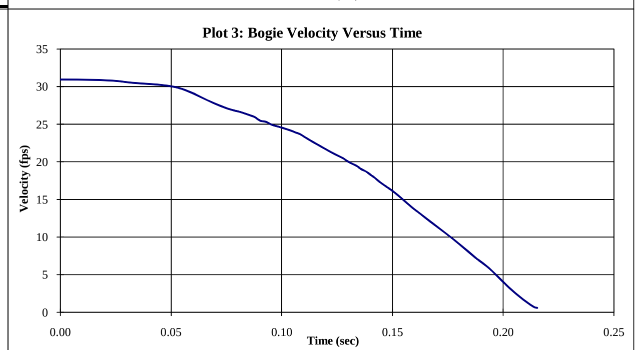
Figure C-4. Test No. 4CTB-5 Results

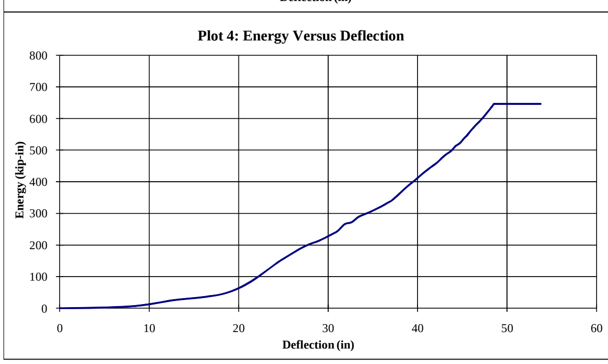
Midwest Roadside Safety Facility

Bogie Test Summary				
Test Information	Cable Pull @ 0 degrees			
Test Number:	4CTB-6			
Test Date:	23-Jul-2007			
Failure Type:	0			
Post Properties				
Post Type:			0	
Post Size:		0		0
Post Length:		0.0 in		(0.0 cm)
Embedment Depth:		0.0 in		(0.0 cm)
Soil Properties				
Gradation:			NA	
Moisture Content:			NA	
Compaction Method:			NA	
Soil Density, γ_d:		NA pcf		NA
Bogie Properties				
Impact Velocity:		30.9 fps	(9.4 m/s)	(21.1 mph)
Impact Location:	NA		#VALUE!	above groundline
Bogie Mass:		4622 lbf	(2097 kg)	
Data Acquired				
Accelerometer Data:			EDR-3	
Camera Data:		Side View-DV and Photron		









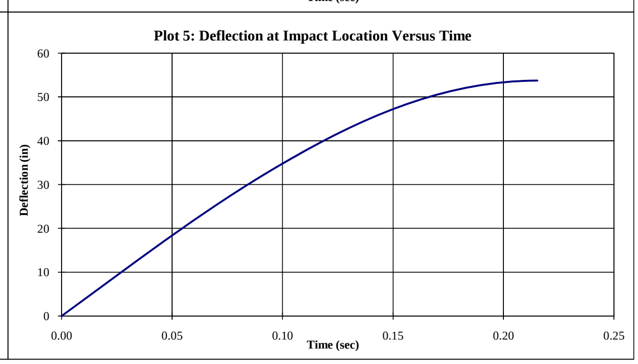


Figure C-5. Test No. 4CTB-6 Results

APPENDIX D – Supplementary Drawings

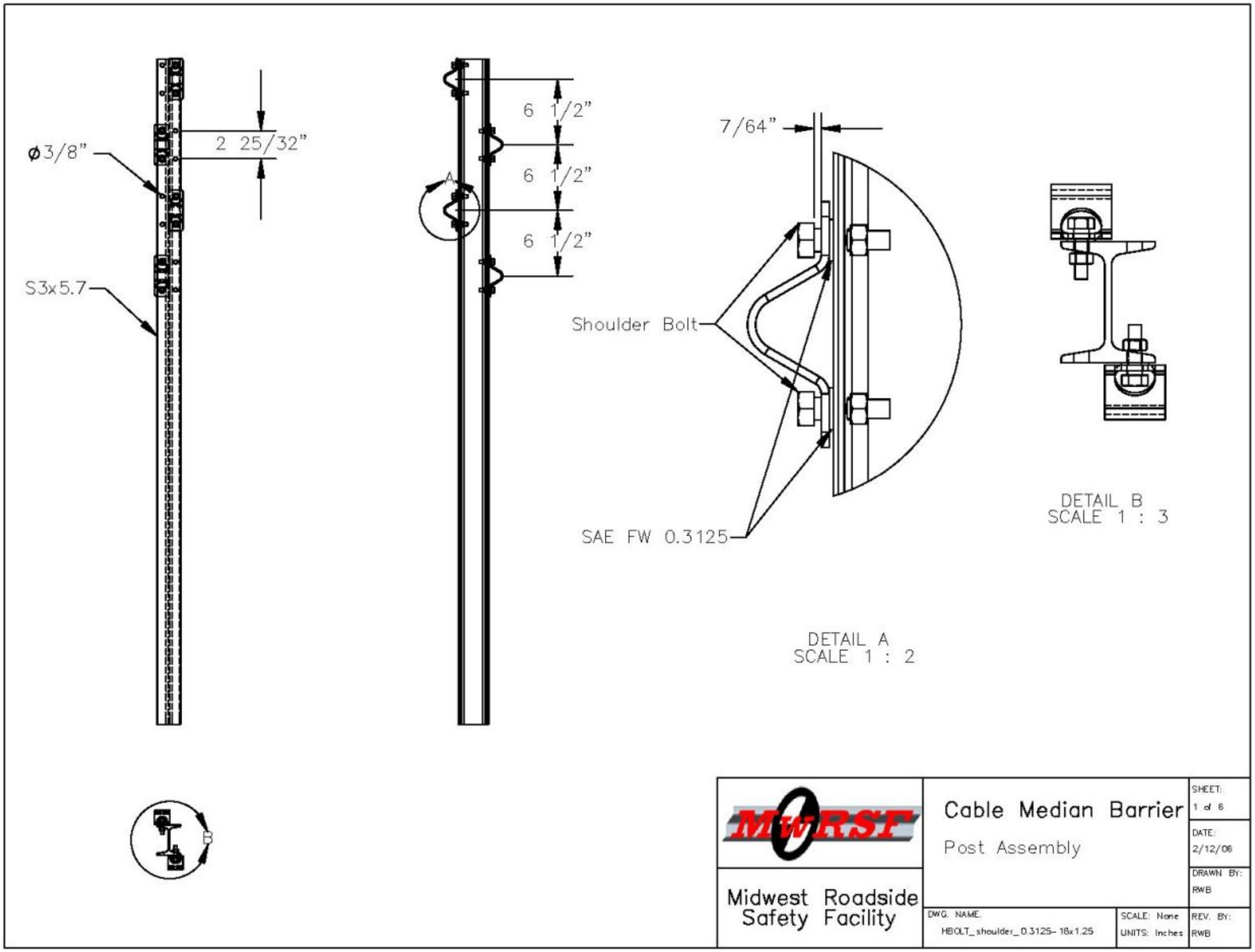


Figure D-1. Cable Median Barrier Post-to-Attachment Connection

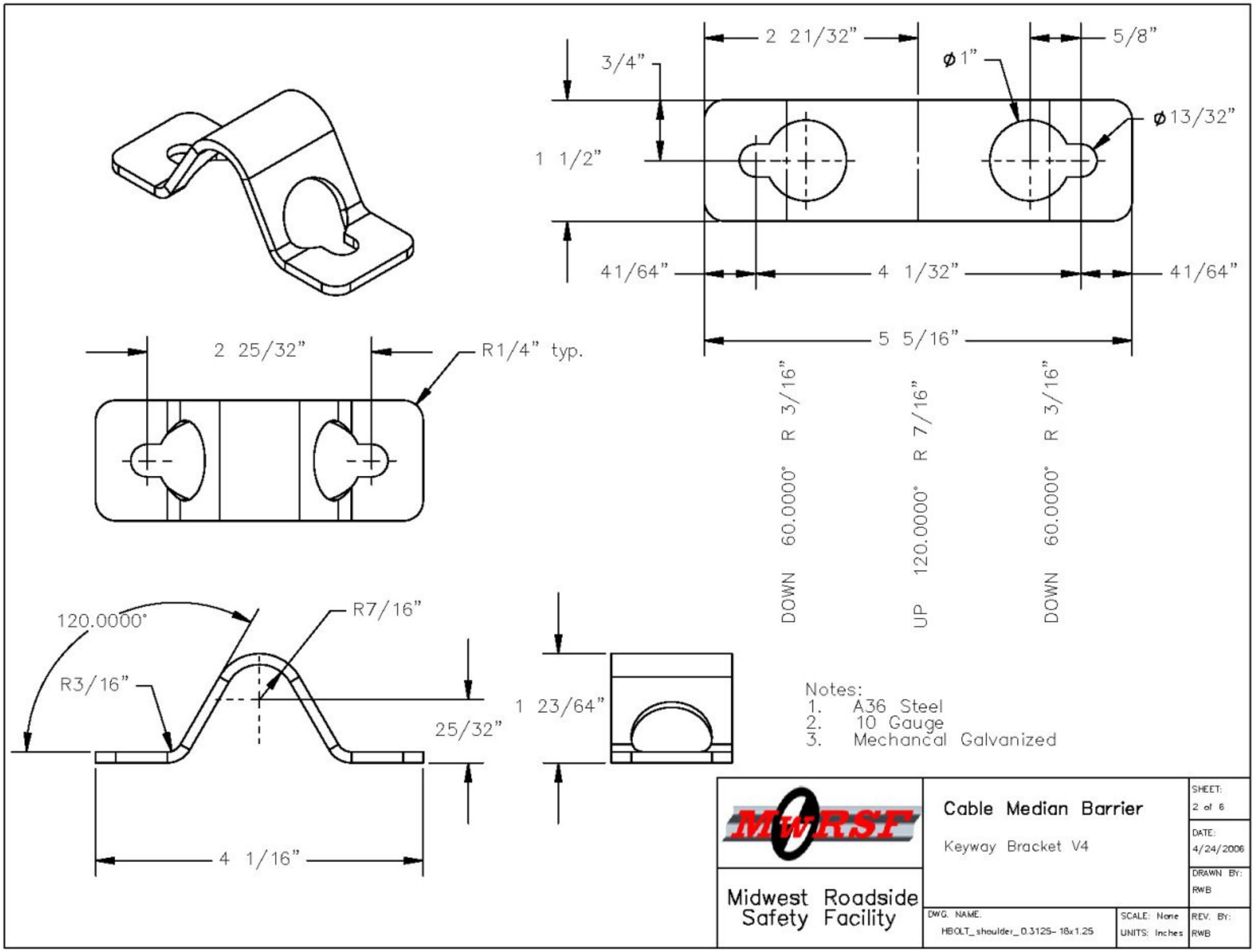


Figure D-2. Curved Keyway Bracket, Final Design (V4)

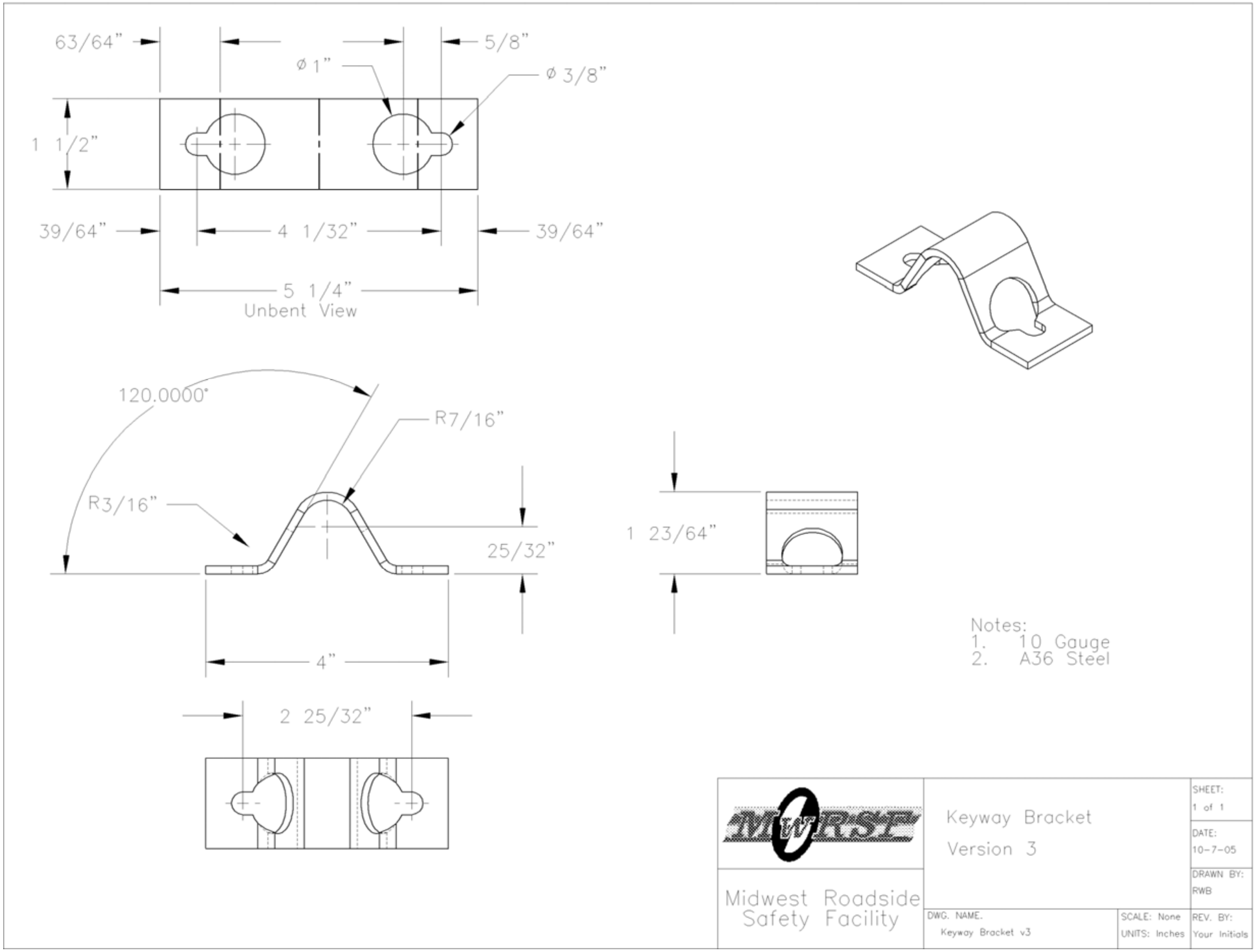


Figure D-3. Curved Keyway Bracket (V3)

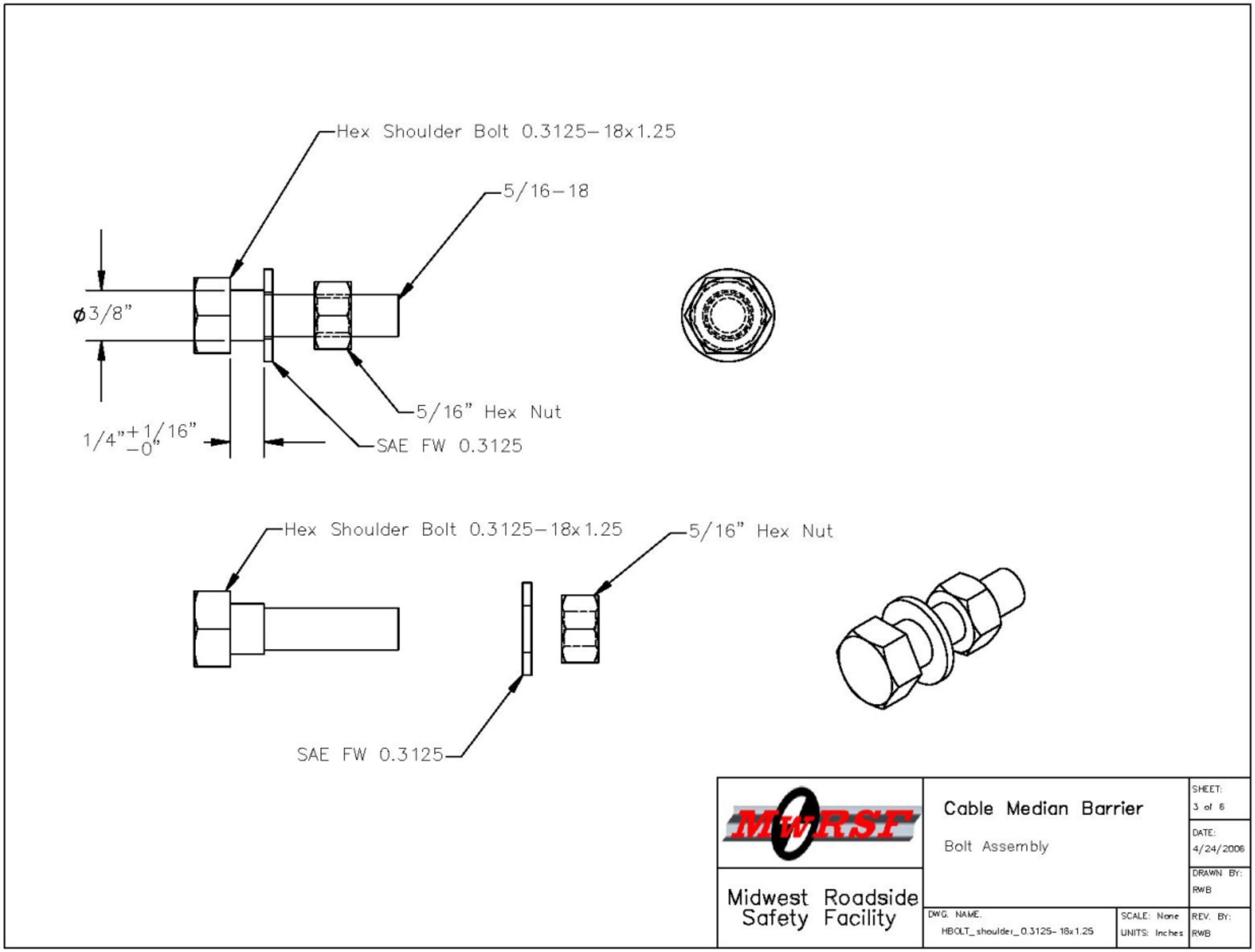


Figure D-4. Shoulder Bolt Assembly

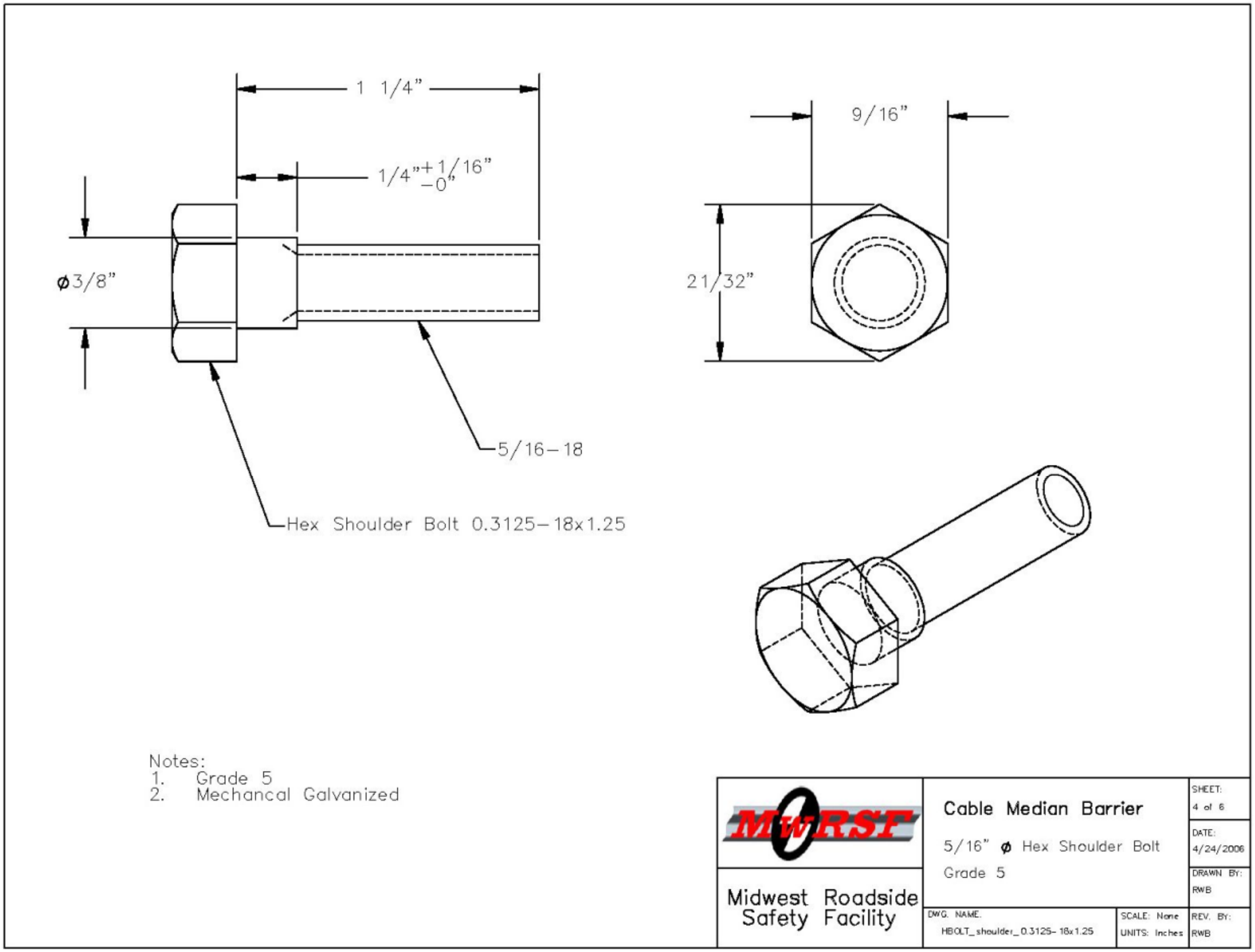


Figure D-5. Hex Shoulder Bolt

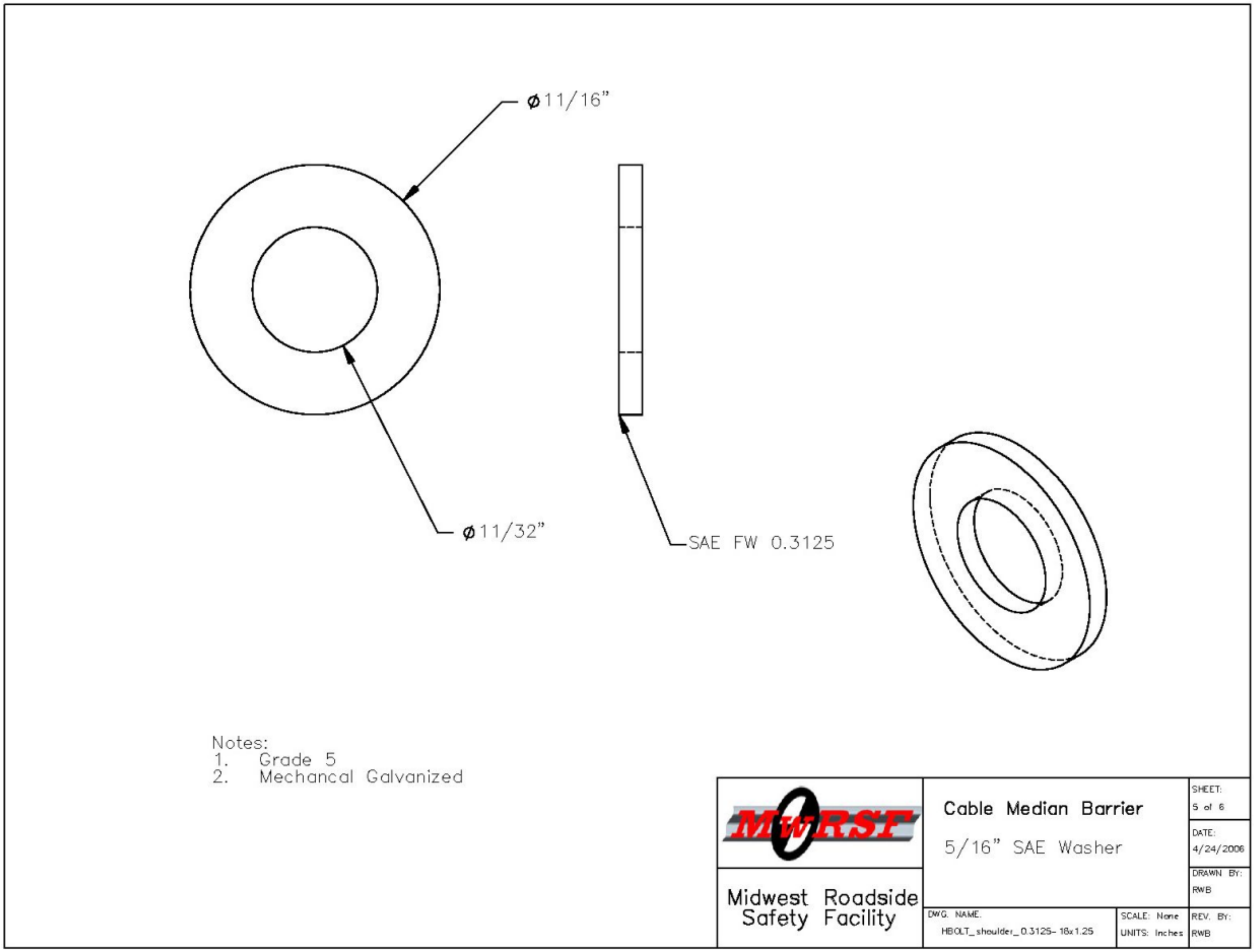


Figure D-6. Washer for Use with Shoulder Bolts

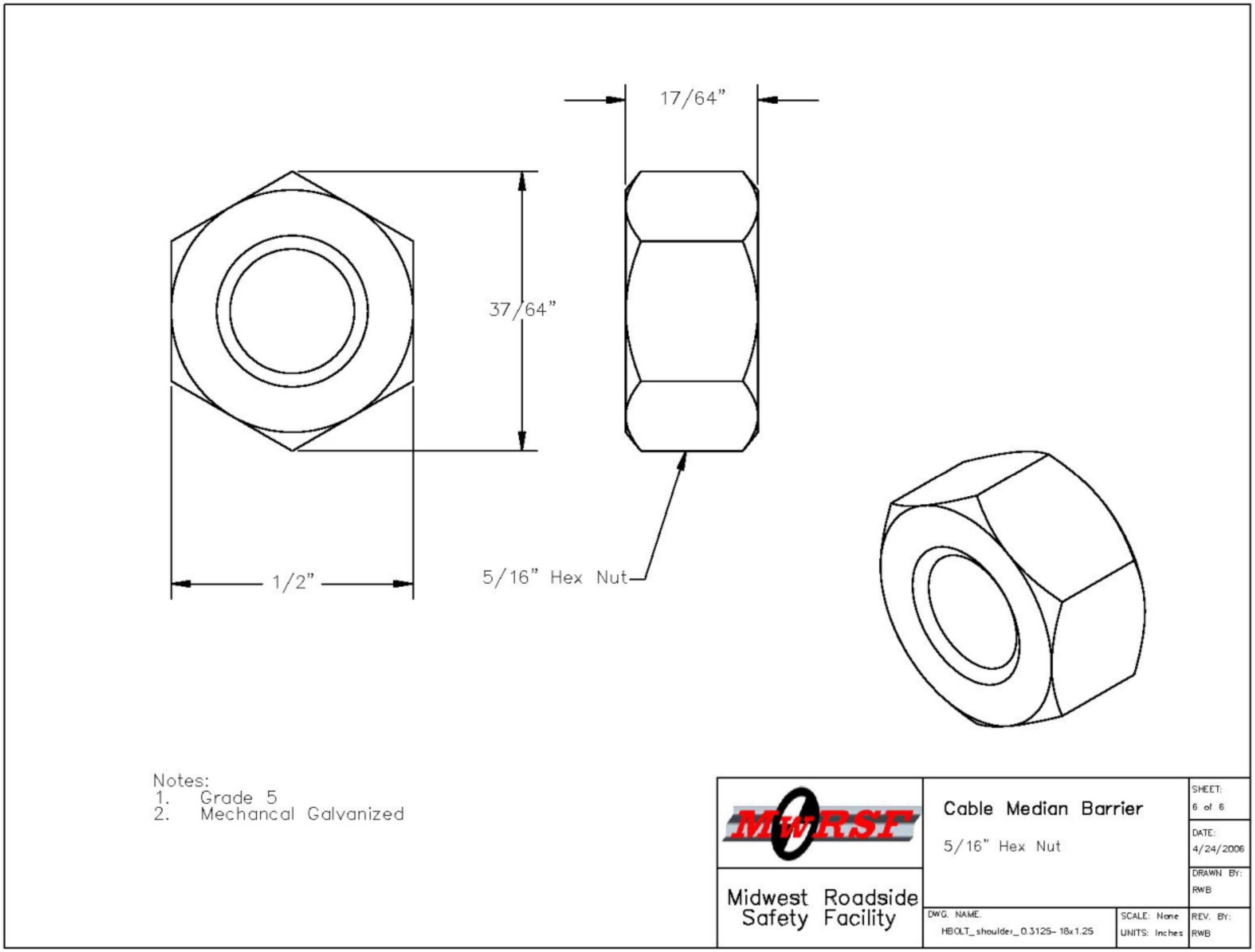


Figure D-7. Hex Nut for Use with Shoulder Bolts

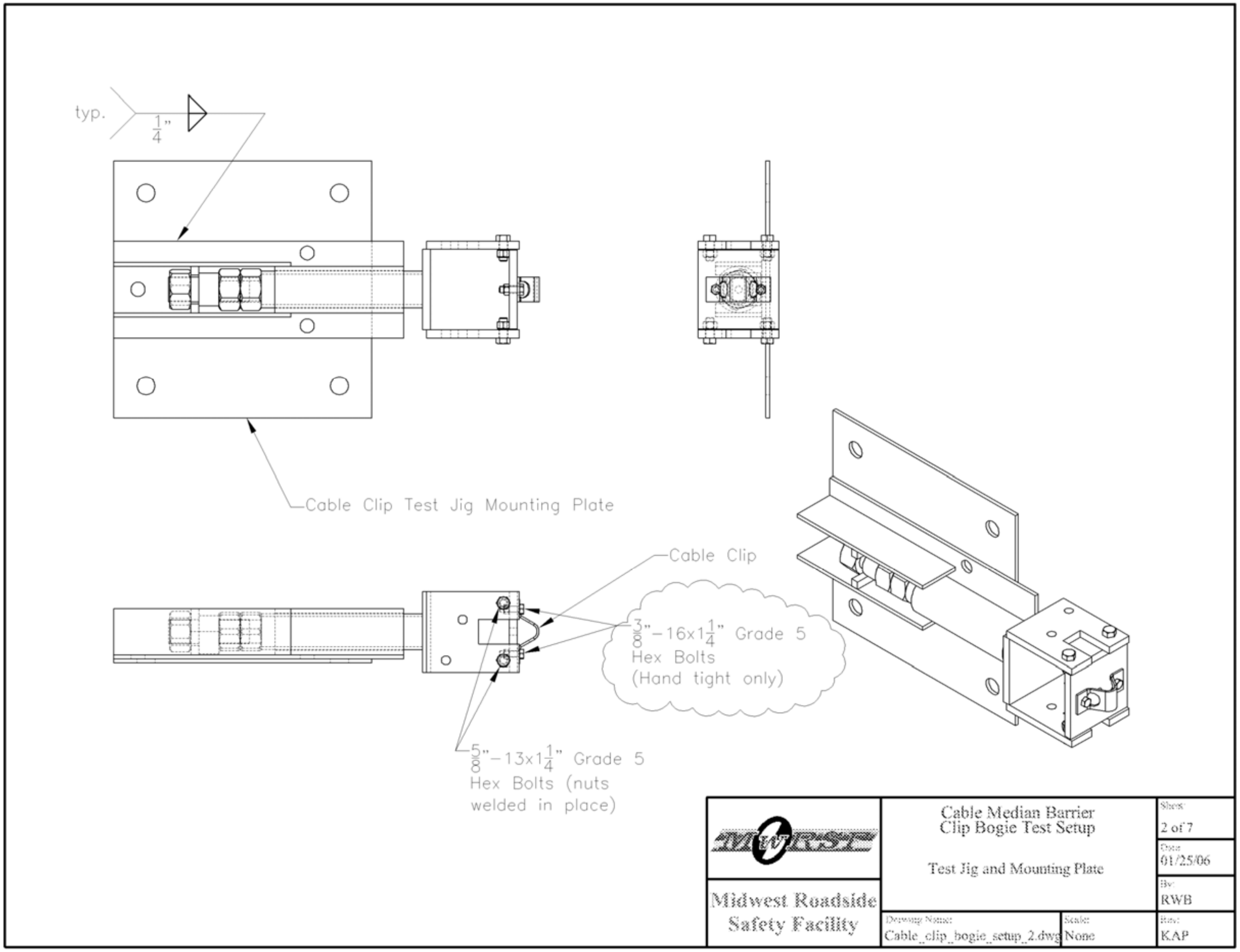


Figure D-8. SBB Test Jig and Mounting Plate

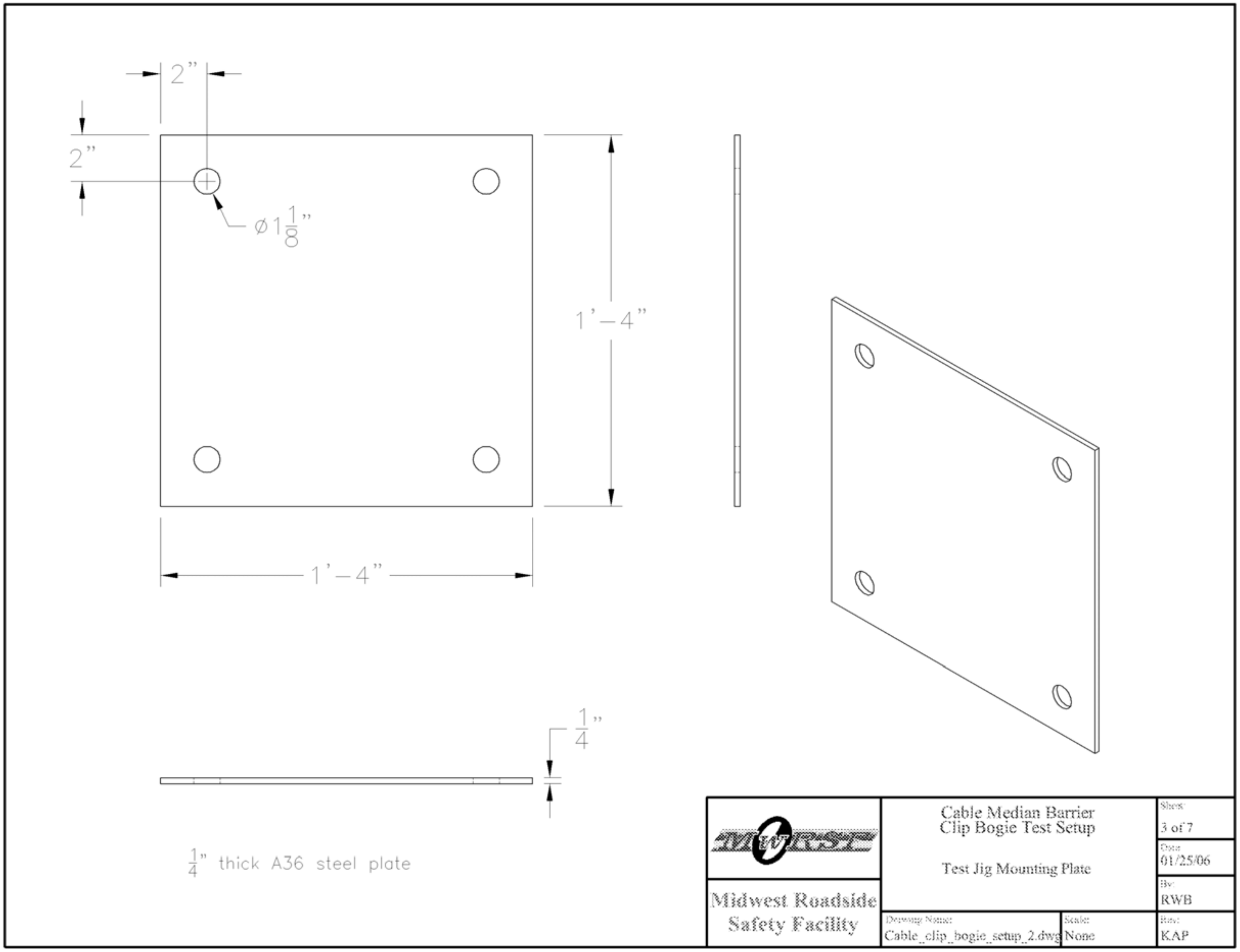


Figure D-9. SBB Test Jig Mounting Plate

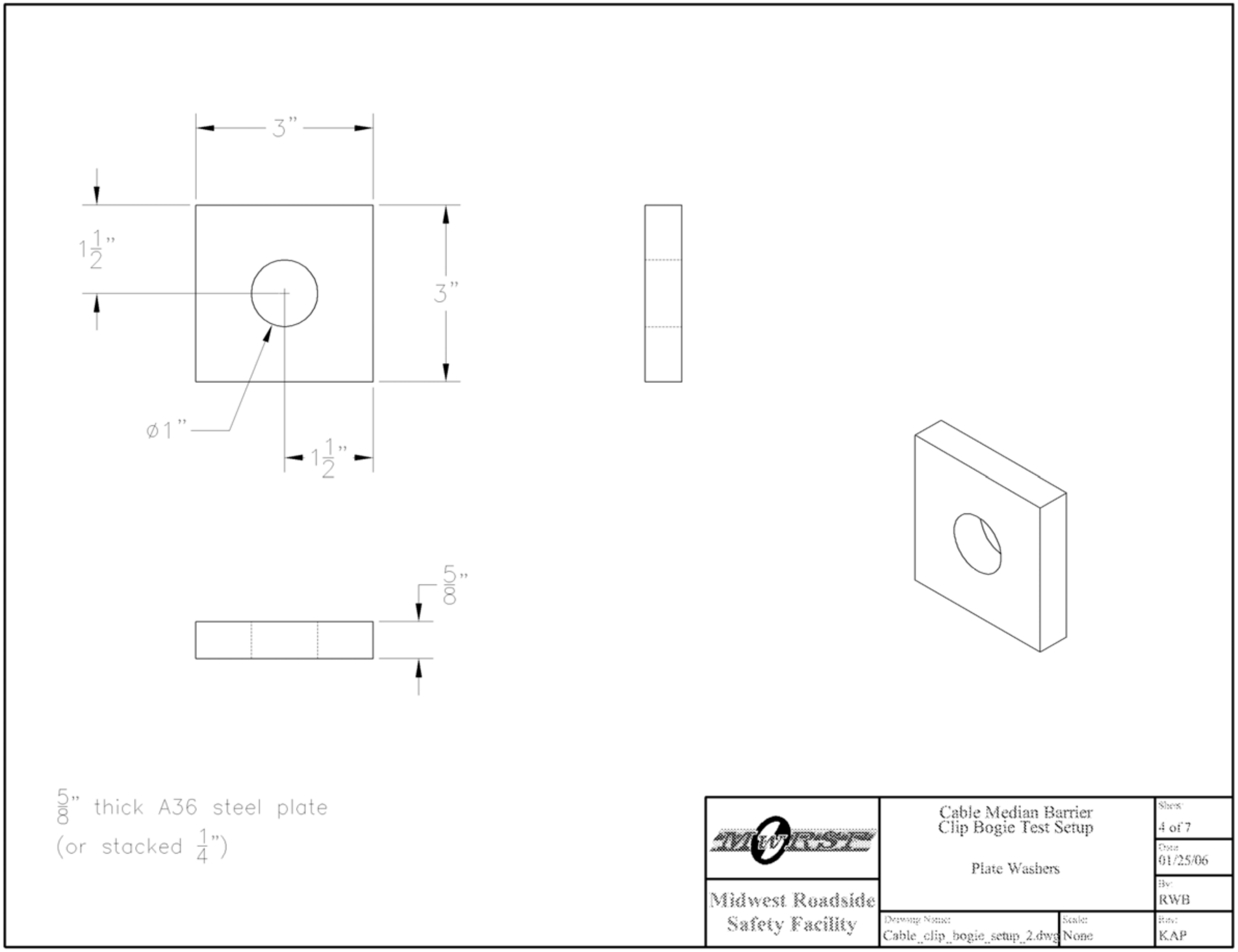


Figure D-10. SBB Test Plate Washers

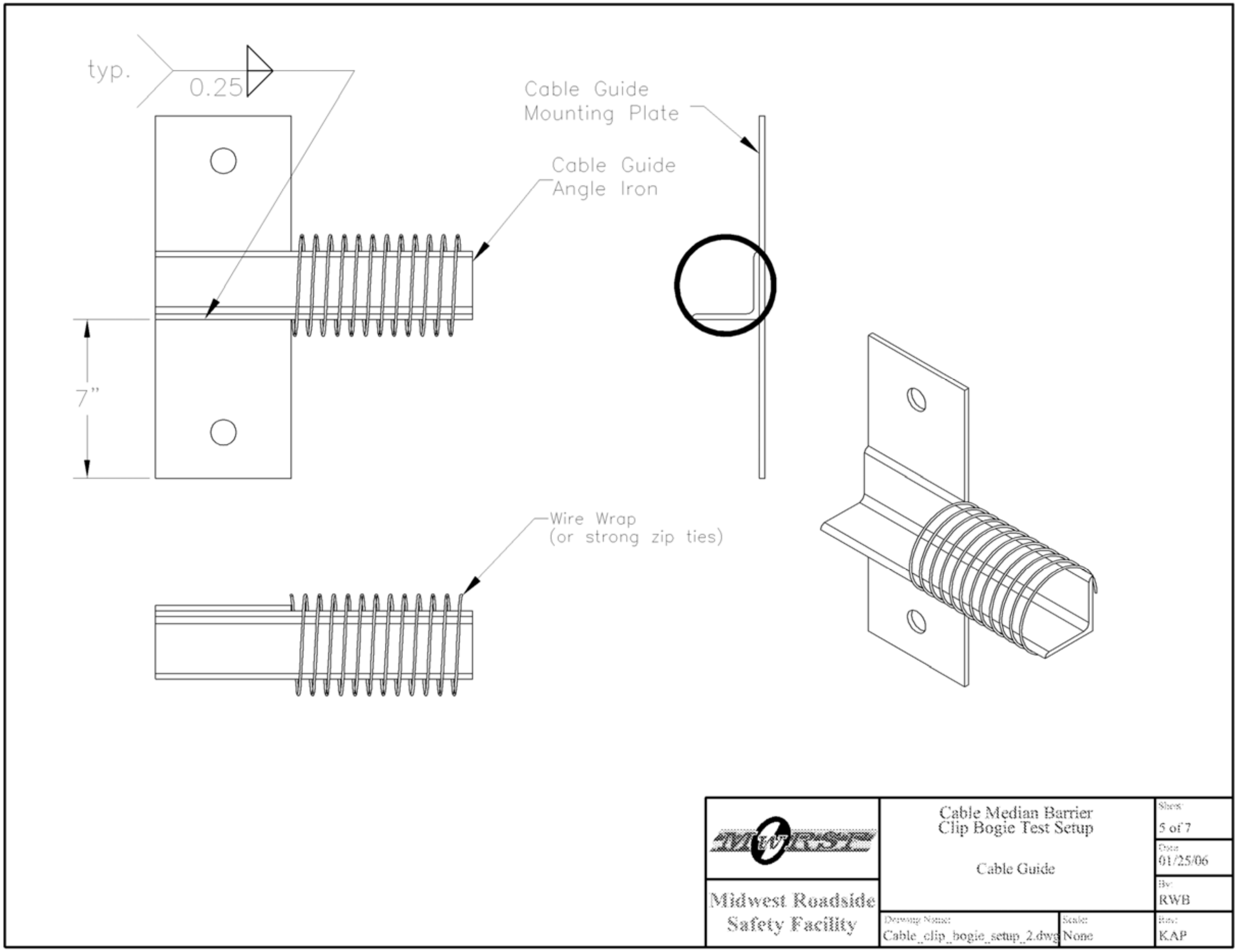


Figure D-11. SBB Test Cable Guide

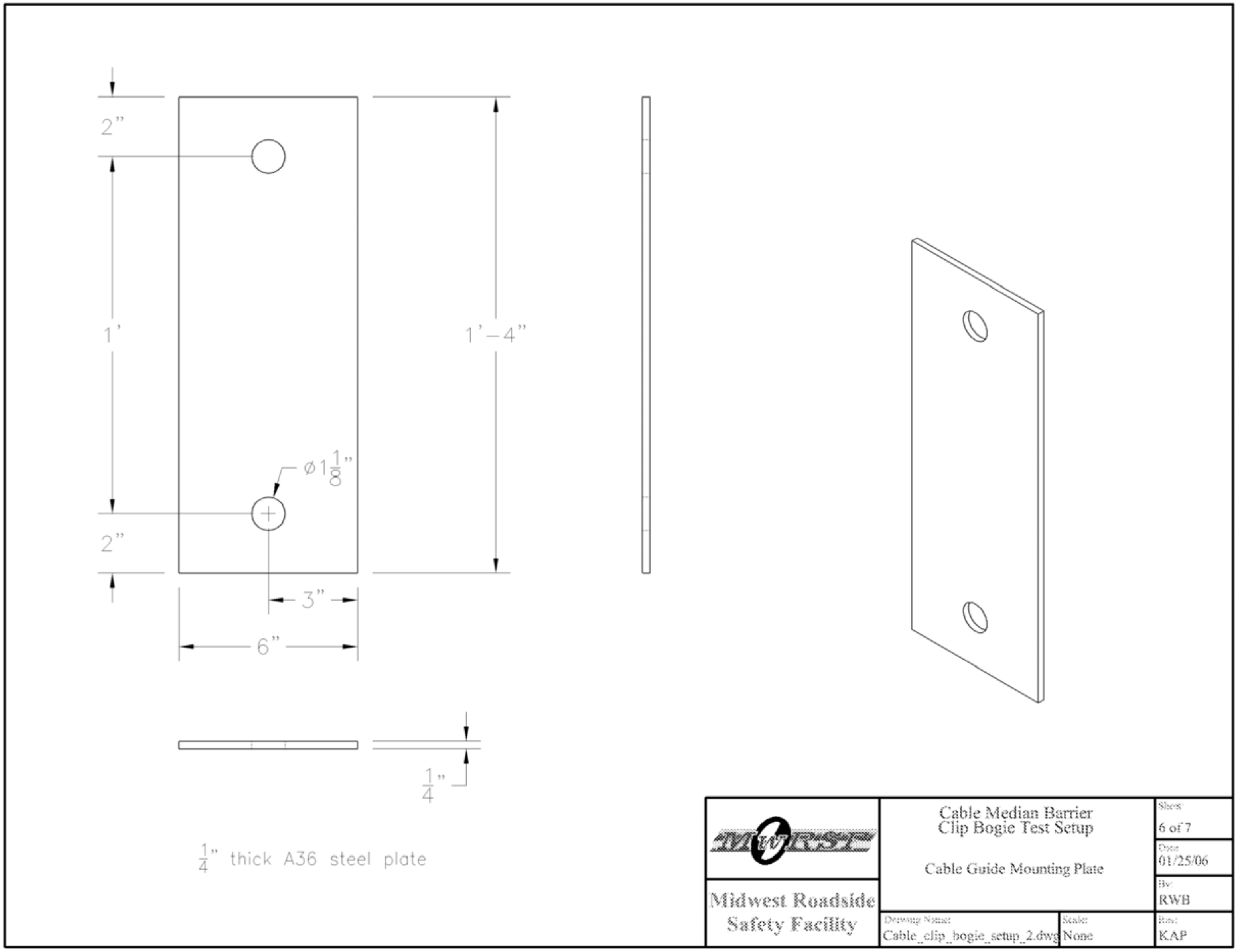


Figure D-12. SBB Test Cable Guide Mounting Plate

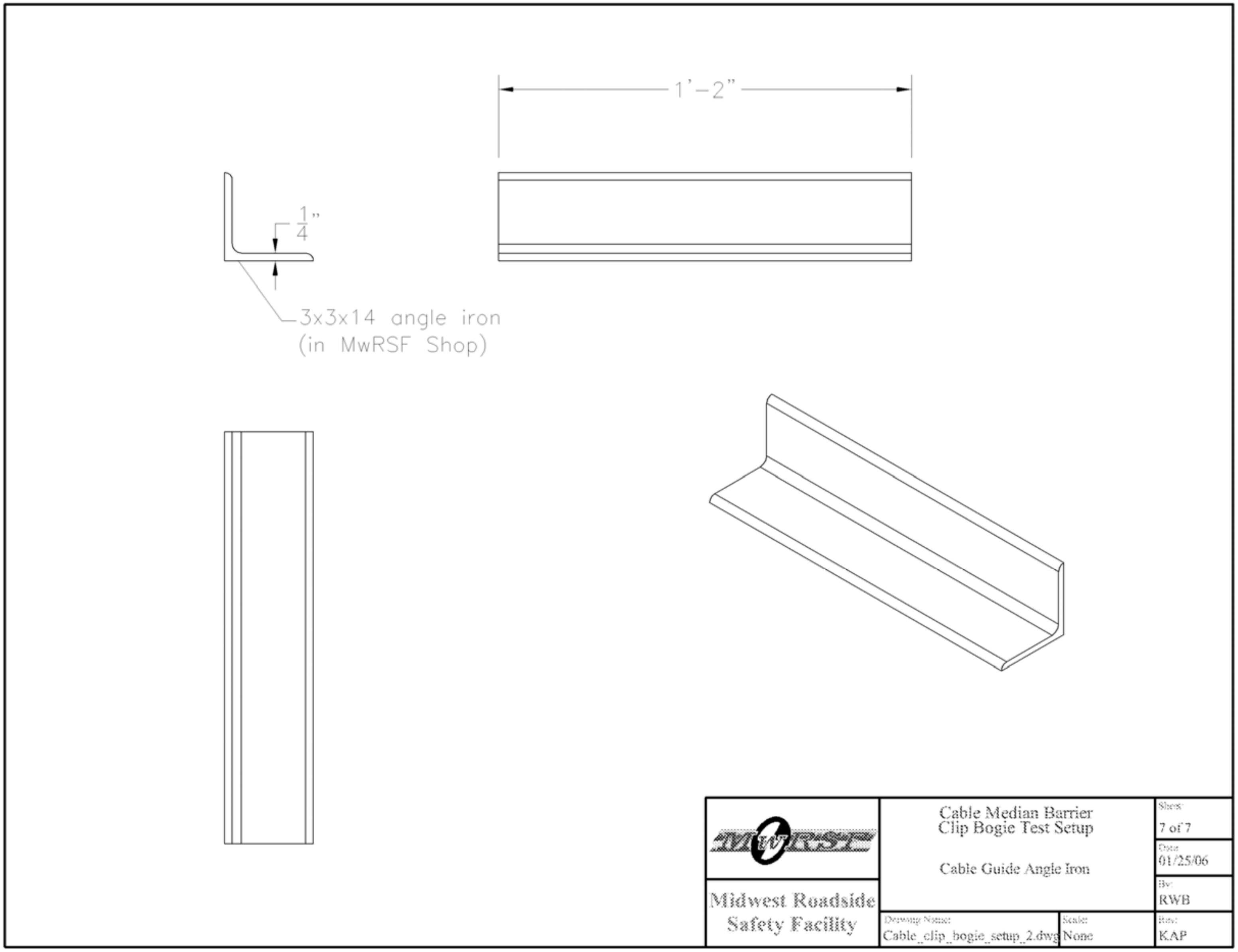


Figure D-13. SBB Test Cable Guide Angle Iron