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Recommended Citation

Gabauer, Doug; Kusano, Kristofer D.; Marzougui, Dhafer; Opiela, Kenneth; Hargrave, Martin; and Gabler, Hampton C.. "Pendulum Testing as a Means of Assessing the Crash Performance of Longitudinal Barrier with Minor Damage." *International Journal of Impact Engineering* (2010) : 1121-1137.

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Title

Pendulum Testing as a Means of Assessing the Crash Performance of Longitudinal Barrier with Minor Damage

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Abstract

Longitudinal barriers such as w-beam guardrails are subjected to a series of full-scale crash tests to determine their impact performance before being considered acceptable for use on the nation's highways. Once longitudinal barriers are installed along a roadway, however, they often sustain minor damage in various ways. Since barriers are exclusively tested in an undamaged condition, there is very little known regarding the crash performance of barriers that have sustained minor damage. Transportation agencies responsible for deploying and maintaining these barrier systems need a better understanding of damaged barrier performance to make timely and cost-effective barrier maintenance decisions under the constraints of limited resources. This study is believed to be the first evaluation of the crash performance of strong post w-beam barrier that has sustained minor damage. A pendulum impact testing methodology was developed for the evaluation of two-post sections of strong post w-beam barrier. Pendulum tests were then conducted on barrier sections with five types of damage: (1) vertical tear, (2) horizontal tear, (3) splice damage, (4) twisted blockout, and (5) missing blockout. Based on these tests, vertical tears were found to be a significant threat to the structural adequacy of the barrier section with a high likelihood for rail rupture. A missing blockout at the splice location was found to result in marginal performance with one test resulting in a large rail tear at the splice. Mid-span horizontal tears and splice damage, with one of eight bolts lacking bearing capacity, were found to have a less significant threat on the structural adequacy of the barrier. Twisted blockout damage was found to have no effect on the structural crash performance of the strong post w-beam barrier.

Keywords

Longitudinal Barrier, Impact Performance, Minor Damage, Pendulum Test

1. Introduction

Prior to being considered acceptable for use on the nation's highway system, longitudinal barriers such as w-beam guardrails must demonstrate satisfactory crashworthiness in a series of full-scale crash tests. Procedures for determining the crashworthiness of longitudinal barriers in the US are set forth in NCHRP Report 350 [1] with analogous European crash test procedures prescribed in EN-1317 [2]. The intent of these test procedures is to evaluate the crash performance of a particular barrier under practical worst-case impact scenarios. The longitudinal barrier tests involve high speed oblique angle impacts with a small passenger car and a large pickup truck. The results of the tests are evaluated against specific criteria for the structural adequacy of the barrier, the vehicle trajectory as a result of the impact, and the potential for injury to vehicle occupants.

Once longitudinal barriers are installed along a roadway, however, they often sustain minor damage. This includes small barrier deflections which may result from a low speed collision (Fig. 1) or damage resulting from routine highway maintenance operations, including snowplowing, mowing or paving. Since highway agencies operate with constrained resources, they must focus on repairing only damage that has a detrimental effect on the safety performance of the barrier. There is a critical need to know when damage to a longitudinal barrier constitutes the need for appropriate maintenance action to adequately protect occupants of a vehicle which departs the highway. Postponing repair of damage incorrectly believed to be minor may open the agency to tort liability claims. Unfortunately, the distinction between minor damage and more severe performance-altering damage is not always clear. Furthermore, crash testing experience of undamaged barriers has often demonstrated that seemingly insignificant alterations

to a barrier, such as using a rectangular washer on the post-rail connection, may result in catastrophic consequences for an impacting vehicle.



Fig. 1. Minor damage to a strong post w-beam barrier on a major state route.

There is a significant amount previous research on the crash performance of undamaged barrier. This includes numerous full-scale crash testing efforts (see Ray and McGinnis [3] for a broad summary of crash testing for various barrier types) as well as many studies using finite element simulation (see Reid [4] and Atahan [5] for more detailed reviews). There is very little known, however, regarding the crash performance of longitudinal barriers that have previously sustained minor damage of any type. The primary guidance for highway agencies regarding barrier repair is a 1990 Federal Highway Administration (FHWA) publication entitled “W-Beam Guardrail Repair and Maintenance” [6]. Although this document provides a quantitative description of what damage constitutes the need to repair damaged barrier, there is no documentation of an analytical or experimental basis for the recommended repair thresholds. Our understanding is that the guidelines were developed based on previous state experience with w-beam barrier and engineering judgment. National Cooperative Highway Research Program (NCHRP) Project 22-23 [7] was tasked with developing repair guidelines, based on an analytic and experimental foundation, to better assist highway personnel tasked with maintaining these barrier systems.

A better understanding of the influence of minor damage on the crash performance of longitudinal barriers is needed. While full-scale crash testing is the traditional mechanism of investigating barrier crash performance, this type of test is a costly undertaking requiring both the purchase of a vehicle and installation of a full-length longitudinal barrier. As part of the NCHRP Project 22-23 research effort, this paper examined pendulum testing as a surrogate method of evaluating the effects of minor damage on the crash performance of longitudinal barrier.

2. Objective

The purpose of this study was twofold: (1) to develop a pendulum test methodology to evaluate the effect of minor damage on the performance of w-beam barrier, and (2) use this test methodology to assess the effect of several different damage modes on the crash performance of strong post w-beam barrier.

3. Experimental Design Development and Test Methodology

3.1 Pendulum Apparatus and Impactor Face

The pendulum tests used the pendulum device currently located at the FHWA Federal Outdoor Impact Laboratory (FOIL) in McLean, Virginia. The FOIL pendulum consisted of a support structure, a 2000-kg (4500 lb) pendulum mass (center image in Fig. 2), and two rigid posts (left image in Fig. 2) located on either side of the suspended pendulum mass. A rounded triangular pendulum impactor face was fabricated for the tests (right image in Fig. 2). The radius of chamfer at the impactor face center was 152 mm (6 inches), which was based on measurements of a 2006 Chevrolet 1500 pickup truck. The impactor face was 420 mm (16.5 inches) tall and was capable of engaging the full w-beam cross section. The combined mass of

pendulum and the impactor face was 2061.5 kg (4,545 lbs) to represent the mass of the NCHRP Report 350 2000-kg pickup truck (2000P) test vehicle. Note that the pendulum mass was slightly higher than the 2045 kg (4508 lbs) recommended mass limit specified by NCHRP Report 350 for the 2000P test vehicle.



Fig. 2. Existing rigid posts (left), FOIL pendulum mass (center), and new impactor face (right).

3.2 W-Beam Test Section, Anchorage and Embedment

A two-post section of modified G4(1S) strong post w-beam barrier with wood blockouts was selected for testing. The steel w-beam sections used conformed to AASHTO M 180 Class A requirements [8]. Specific dimensions of the w-beam cross section can be found in drawing RWM02a of the Standardized Highway Barrier Hardware Guide [9]. The posts were A36 steel, conforming to AASHTO M 270 / M 270M [10], and had a W150x13.5 (W6x9) cross section, conforming to AASHTO M 160 / M 160M [11]. The blockouts were 150 mm x 200 mm x 360 mm (6 inches x 7.75 inches x 14 inches) with a stress grade of at least 8 MPa (1160 psi). Additional details on the posts and blockouts can also be found in drawings PWE01 and PDB01b of the Standardized Highway Barrier Hardware Guide [9], respectively. The strong post w-beam barrier was selected as it was found to be the most common barrier used in the United States [12].

The barrier test section length was constrained by the available span, approximately 5.5 m (18 feet), between the existing rigid posts on either side of the FOIL pendulum. Using standard 1905 mm (6.25 feet) post spacing and 3810 mm (12.5 feet) rail lengths, this allowed for one post to be located at a rail splice and the other post a non-splice location. As this section represents the smallest repeating unit for the strong post w-beam barrier, this configuration was thought to be most representative of a typical full-length installation. Note that this two post section is roughly one tenth the length of a barrier in a full-scale crash test, which typically has 29 posts. The w-beam section was oriented such that the impact was mid-span between the two posts. Fig. 3 is a schematic of the overall test setup. The overall rail length is approximately 5 meters (198 inches) and each post was 1830 mm (6 feet) in total length.

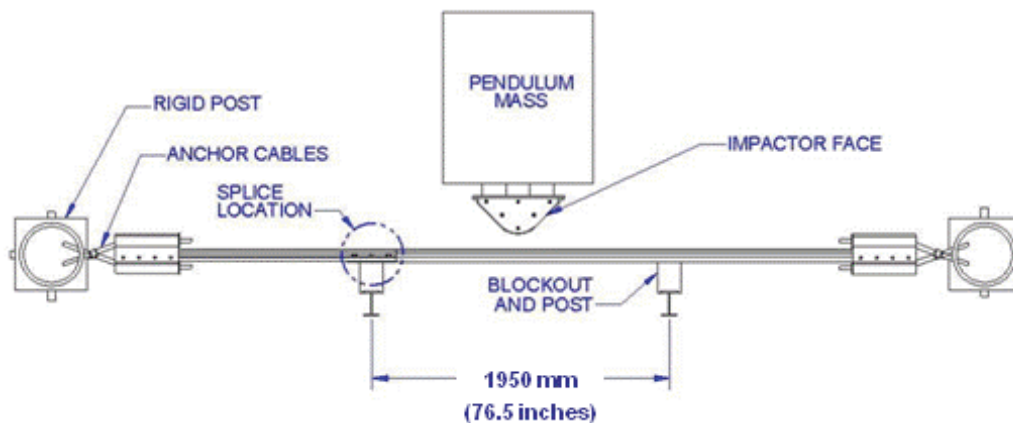


Fig. 3. Overall Pendulum Test Setup

Developing an appropriate method to anchor each end of the test section to the rigid posts proved to be most challenging portion of the test setup. The goal was to replicate a two post section as if it was within a full length barrier section, which requires each end of the test section some freedom to both translate and rotate. Due to the close proximity of the rigid posts on either side of the pendulum, the primary focus was on designing the end fixture to allow rotation of each end of the w-beam test section. Also, an effort was made to use as much standard guardrail

hardware as possible in the end fixture design. The original end fixture design selected consisted of 3 standard cable anchor brackets and a 910 mm (3 foot) version of the standard 2000 mm (6.5 foot) swaged cable typically used to anchor w-beam terminals (left image of Fig. 4). Additional details on the cable anchor brackets and swaged cable can be found in drawings FPA01 and FCA01 of the Standardized Highway Barrier Hardware Guide [9], respectively. This end anchor configuration was originally selected to ensure w-beam rail rupture would occur before failure of the anchorage.

Later, an alternative 2-cable end fixture design was developed (center image in Fig. 4). A comparison of two undamaged section pendulum tests showed no discernable difference in deflection. The 2-cable end fixture proved to be robust and was used in the remainder of the tests to simplify the test setup and reduce costs. As experience was gained in conducting these tests, several minor modifications were made to the 2-cable end fixture, primarily to prevent tearing and bending failures within the fixture. Larger 82.6 mm (3.25 inch) outside diameter washers were used inside the rigid posts to prevent pullout of the cables from the rigid posts. The length of swaged cables was increased by 102 mm (4 inches) so the cable would bend instead of the swage. To prevent tearing in the fixture, the typical washers used in conjunction with the anchor brackets were replaced by an anchor plate. Results from pendulum tests conducted using both the 2-cable and 3-cable end fixture schemes will be presented herein.



Fig. 4. Three cable (left) and two cable (center) w-beam end fixture and soil box (right)

As the anchor points on the existing rigid posts were higher than the standard w-beam rail height, a soil box (right image in Fig. 4) was used to raise the ground level around the posts by 178 mm (7 inches). The soil box was constructed of four 38 mm x 235 mm x 2.44 m (2 inches x 10 inches x 8 feet) pine boards and supported on each side by steel rebar to provide the soil restraining force such that proper compaction could be attained. As specified by NCHRP Report 350, the soil used in the test conformed to AASHTO M-147-65 [13]. A mechanical tamper was used to compact the soil surrounding each W150x13.5 (W6x9) steel post in 150 mm (6 inch) lifts. A nuclear density gauge (Troxler Model 3440) was used to determine the compaction and soil properties of each soil lift for each post. For each lift, the preferred compaction level was 95 percent.

3.3 Instrumentation and Data Analysis

Instrumentation and data collection for all tests conformed to NCHRP Report 350 [1] requirements. In each test, two accelerometers were located at the rear of the pendulum mass (Endevco model 7265A). Both accelerometers were in-line with the pendulum center of gravity and were aligned in the pendulum direction of travel. Tri-axial accelerometers, consisting of 3 Endevco model 7265A or model 7264B-2000 accelerometers, were placed on each rigid post to quantify the motion of the rigid posts during the pendulum impact. All accelerometers had a minimum range of $\pm 981 \text{ m/s}^2$ (100 G's) and all acceleration data was sampled at 10,000 Hz using a Diversified Technical Systems (DTS) TDAS Pro data acquisition system. Identification of the time of initial contact of the pendulum mass to the test section was accomplished through the use of pressure sensitive switches located on the top hump of the w-beam at the center of the test section.

Four high speed cameras, two NAC Memrecam fx K3 cameras and two NAC Memrecam fx K3R cameras, were used in all tests to capture the behavior of the w-beam section during the impact. All high speed video was recorded at 500 frames per second at a resolution of 1280 x 1024. Each test had a minimum of two common camera views: (1) a top view of the middle of the w-beam section and (2) a perpendicular rear view of the entire w-beam section. The other two high speed camera views varied between tests depending on the location of the minor damage. In addition, a real time camera was used to capture a perspective view of each test.

For all acceleration data, a pre-sample filter with channel frequency class (CFC) 3000 Hz was applied during data collection. Each channel was then bias adjusted by averaging the acceleration prior to pendulum release and subtracting that value from each data point. Before plotting acceleration data for comparison purposes, the data was filtered using a Butterworth 4-pole phaseless digital filter with CFC 60, according to SAE J-211 [14]. Prior to numerical integration, the raw acceleration data was filtered using a Butterworth 4-pole phaseless digital filter with CFC 180. After filtering, the primary and redundant acceleration data for each test was compared visually to ensure reasonable agreement, i.e. no clipping or channel failure, and then averaged to generate a single pendulum response. For each test, this single pendulum response, filtered to CFC 180, was used for the remainder of the computations described below.

Pendulum impact velocity in all tests was determined by numerically integrating the pendulum-mounted acceleration data from the time of pendulum release to the time of impact. This value was checked against the theoretical velocity of the pendulum computed using the pendulum mass and the pendulum height difference, between the release point and impact point, recorded for each test. In all cases, the computed impact velocity was lower than the theoretical velocity; the average difference was approximately 4 percent with a maximum difference of 8

percent. Note that the results of the pendulum tests as presented in [7] provided only estimated impact velocity values. Barrier deflection at the impact location was determined by numerically integrating the pendulum velocity. For cases where the pendulum penetrated the barrier test section, the time of penetration was estimated using the overhead high speed video. In these instances, the barrier deflection was only shown up to the point of penetration. The impact force on the pendulum was computed by multiplying the pendulum acceleration by the pendulum mass. This force was then plotted as a function of the computed displacement and integrated to provide an estimate of the energy imparted to the pendulum by the barrier test section.

3.4 Impact Conditions and Relevance to Full-Scale Crash Testing

The FOIL pendulum was not capable of reproducing the significant motion along the length of the barrier test section that is characteristic of an oblique impact prescribed by the NCHRP Report 350 longitudinal barrier test procedures. As such, the pendulum tests were primarily used to evaluate the performance of a damaged two-post barrier section compared to an undamaged section tested in the same impact configuration. Because of the perpendicular impact configuration, the pendulum tests were only used to evaluate the structural adequacy of barrier test section. Other relevant barrier performance factors, such as wheel snagging, vehicle rollover, and occupant risk, could not be evaluated using this pendulum test methodology. There was an effort, however, to design the pendulum impact conditions to match the lateral energy produced in a NCHRP 350 redirection test; this is illustrated below in Fig. 5.



Fig. 5. Comparison of NCHRP 350 (left) and pendulum impact (right) scenarios

Pendulum tests were conducted at two impact speeds: 32.2 km/hr (20 mph) and 28.2 km/hr (17.5 mph). A 32.2 km/hr (20 mph) impact speed was originally selected to approximate the lateral forces that would result from a 2000 kg (4500 lb) test vehicle impacting at 100 km/hr (62 mph) and 20 degrees. Assuming that all the impact energy is absorbed in a 2 post section of a full-scale test barrier, these conditions represent a lateral impact speed approximately 75 percent that of an NCHRP 350 Test 3-11 impact (100 km/hr and 25 degrees). The constraining factor was the maximum speed of the FOIL pendulum, which is 32.2 km/hr (20 mph). The speed is limited by the maximum height to which the pendulum can be raised.

The pendulum impacts, however, were more severe than a full-scale crash test for two primary reasons: (1) the pendulum test section was a more rigid system, and (2) the impact energy was distributed over a smaller area. The end fixtures attaching each end of the w-beam test section to the rigid posts allowed only minimal longitudinal translation of the rail section in contrast to the full-scale test where the posts surrounding the impact area deflect, reducing the tension in the rail and splices. Second, in a pendulum test, all the impact energy was absorbed by a single two post (1905 mm) barrier section. In several full-scale tests analyzed, however, the lateral energy was primarily distributed over two to four of these 1905 mm (6.25 foot) barrier











sections. To account for this distributed loading, the pendulum impact speed was reduced to 28.2 km/hr (17.5 mph). This impact speed conservatively assumes that the lateral impact energy in a full-scale test was absorbed by two 1905 mm (6.25 foot) barrier sections; each section absorbing half the vehicle lateral kinetic energy.

4. Test Plan and Barrier Damage Modes

A total of 3 undamaged barrier baseline tests were run: (1) a 32.2 km/hr (20 mph) baseline impact into an undamaged two-post barrier section with the 3-cable end fixture, (2) a 32.2 km/hr (20 mph) baseline impact into an undamaged two-post barrier section with the 2-cable end fixture, and (3) a 28.2 km/hr (17.5 mph) baseline impact into an undamaged two-post barrier section with the 2-cable end fixture.

Eleven tests of damaged barrier were conducted to evaluate five different barrier damage modes. These five damage modes represent a subset of ten damage modes investigated under NCHRP Project 22-23 [7]. A survey of US and Canadian transportation agencies [12], which provided anecdotal evidence of the frequency of various damage modes, served as the basis for selection of the ten evaluated damage modes. Pendulum testing was elected for those damage modes where tearing or fracture was likely, as finite element simulation is a less than ideal method of modeling this type of damage. Table 1 presents a field example of each of the five evaluated damage modes and the analogous pendulum test setup. Note that the remaining damage modes were evaluated using either finite element simulation of full-scale barrier tests or limited full-scale barrier testing; see [7] for additional details on the damage modes not contained herein.

Table 1
Tested Barrier Damage Mode

Damage Mode	Field Example	Pendulum Test Setup
Vertical Tear		
Horizontal Tear		
Splice Damage		
Twisted Blockout		
Missing Blockout		

With the exception of the splice damage, each damage mode was tested with the 3-cable and 2-cable end fixtures. All 3-cable tests were at a speed of 32.2 km/hr (20 mph) while the 2-cable tests were either at 32.2 km/hr (20 mph) or 28.2 km/hr (17.5 mph). For the purpose of the pendulum tests, the barrier damage modes were artificially induced, e.g. not through an impact typical of a field installation. This method was selected based on the damage modes to be evaluated through pendulum testing and the ability to better control the exact level of damage induced to a barrier test section. A more detailed description of how each damage mode was created is described below:

- Vertical Tear Damage: A vertical tear was simulated by cutting a slit in the w-beam using a reciprocating saw. The point at the end of the slit was intended to provide a stress concentrator similar to those observed in the field in a crash-induced vertical tear. In all vertical tear tests, the location of the tear corresponded to the pendulum mass impact location, as this was believed to have the largest risk for rail rupture. Two different length tears were tested: a 102 mm (4 inch) tear and a 13 mm (0.5 inch) tear. All tears started from the top of the w-beam section. For the 102 mm tear, the width of the tear was 13 mm (0.5 inches) at the w-beam edge and tapered to a point. For the 13 mm (0.5 inch) tear, the width of the tear was approximately 4 mm (0.15 inches).
- Splice Damage: Splice damage was simulated by removing a rectangular block of material directly in line with a single splice bolt and having width equal to the diameter of the splice bolt. The intent was to simulate complete loss of bearing capacity for a single bolt (of 8 bolts total) in the splice connection.
- Horizontal Tear Damage: A horizontal tear was simulated by cutting a longitudinal notch in the center of the upper protrusion of the w-beam using a reciprocating saw. Each end

of the notch was tapered to a point to provide a stress concentrator similar to those observed in the field in a crash-induced horizontal tear. The location of the tear corresponded to the pendulum mass impact location, as this was believed to have the largest risk for rail rupture. The horizontal tear was a total of 306 mm (12 inches) long. The middle 204 mm (8 inches) of the tear was 13 mm wide (0.5 inches) with a 51 mm (2 inch) taper on either end.

- Twisted Blockout Damage: In this case, the routed wooden blockout at the splice was installed rotated about the post-rail bolt. The blockout was rotated approximately 45° with respect to the vertical in all tests.
- Missing Blockout Damage: For this damage mode, the blockout at the splice location was not installed. The post-rail bolt remained connected to simulate a wooden blockout that had split completely and was no longer present. In both tests, there was approximately 178 mm (7 inches) of separation between the near flange of the post and the back of the w-beam rail. The splice location was thought to be the critical case as the splice is the weakest link in the rail element.

5. Results

Pendulum testing results are presented primarily for the 2-cable anchored tests as these tests included the lower speed tests that are more representative of a 2000P vehicle impacting a full-length barrier at NCHRP Report 350 TL-3 conditions. Table 2 presents a brief summary of the pendulum testing.

Table 2
Pendulum Testing Summary

Damage Mode	Test #	Anchorage	Impact Speed [km/hr]	Maximum Deflection* [mm]	Time of Max Deflection [ms]	Energy [kJ]	Crash Performance
Undamaged	01-2	3-Cable	32.0	741	135	81.36	Containment
	03-2	2-Cable	30.1	658	131	72.28	Containment
	07-1	2-Cable	25.8	594	140	53.08	Containment
Vertical Tear (102 mm)	01-3	3-Cable	29.5	564*	84	50.38	Penetration, Tear at center
	03-5	2-Cable	32.0	651*	90	61.38	Penetration, Tear at center
Vertical Tear (13 mm)	08-2	2-Cable	31.3	723	135	77.92	Containment, Tear at center
Horizontal Tear	02-1	3-Cable	32.0	738*	102	80.03	Penetration, Splice Failure
	07-3	2-Cable	26.8	618	134	57.43	Containment
Splice Damage	07-4	2-Cable	26.8	610	135	57.28	Containment
Twisted	02-2	3-Cable	29.8	628	122	70.79	Containment
Blockout	03-8	2-Cable	30.4	684	134	73.37	Containment
Missing Blockout	01-4	3-Cable	31.5	719	126	79.14	Containment, Tear at splice
	03-7	2-Cable	30.5	691*	106	65.04	Penetration, Splice Failure
	07-5	2-Cable	26.7	633	132	56.51	Containment

* If penetration, maximum deflection refers to deflection just prior to penetration

5.1 Baseline Tests

In test 03-2, the undamaged barrier contained the pendulum mass impacting at 30.1 km/hr (18.7 mph). The maximum dynamic deflection of the test section was 658 mm (25.9 inches) at 131 ms after the initial impact. The maximum static crush at the center of the w-beam was 356 mm (14.0 inches). The overall damage and individual post damage is shown in Fig. 6. The post at the splice location (center in Fig. 6) experienced more torsion than the non-splice post and had some minor cracking at the flange. The post at the splice location also remained connected to the rail while the post bolt at the non-splice location pulled through the slot in the rail. There were no failures in the anchor cables in this test and there was no visible separation of the cable from the swaged portion of the anchor cable assembly. At the splice location, there was approximately 19 mm (0.75 inches) of relative movement between the two w-beam rail

sections. No tears were evident in the guardrail and no bolt failure was observed. The left portion of Fig. 7 shows time sequential snapshots of test 03-2 obtained from the high speed camera positioned overhead. Fig. 8 (a) and Fig. 9 (a) show the measured pendulum acceleration and barrier center deflection for all three undamaged barrier baseline tests, respectively. The force on the pendulum mass as a function of barrier center deflection for these tests is shown in Fig. 10 (a).

In general, the remaining two undamaged barrier tests (no photos shown) had similar results to test 03-2. Tests 01-2 and 07-1 both had successful containment of the pendulum mass. In both tests, the post-rail connection at the splice remained intact and post-rail bolt pullout was evident at the non-splice location. The separation at the splice was also approximately 19 mm (0.75 inches) in both tests. For test 01-2, both the impact speed and maximum deflection were slightly higher compared to the analogous 2-cable test (Test 03-2, see Table 2).



Fig. 6. Test 03-2: Overall damage (right) and post damage at splice (center) and non-splice location (right)

Fig. 7. Sequential overhead photographs for undamaged section (left) and 102 mm vertical tear damage (right)

Fig. 8. Pendulum acceleration as a function of time for (a) undamaged section tests, (b) vertical tear damage tests, (c) horizontal tear damage tests, (d) splice damage test, (e) twisted blockout tests, and (f) missing blockout tests.

Fig. 9. Barrier center deflection for (a) undamaged section tests, (b) vertical tear damage tests, (c) horizontal tear damage tests, (d) splice damage test, (e) twisted blockout tests, and (f) missing blockout tests.

Fig. 10. Force on pendulum as a function of barrier deflection for (a) undamaged section tests, (b) vertical tear damage tests, (c) horizontal tear damage tests, (d) splice damage test, (e) twisted blockout tests, and (f) missing blockout tests.

5.2 Vertical Tear Damage

In test 03-5, the barrier section with a 102 mm (4 inch) vertical tear was unable to contain the pendulum mass impacting at 32.0 km/hr (19.9 mph). A vertical tear developed from the bottom tip of the induced vertical tear and continued (approximately straight downward) through the entire w-beam cross section resulting in a complete transection of the w-beam at the impact location. The deflection of the rail was 651 mm (25.6 inches) at 90 ms after initial impact, which was just prior to penetration of the w-beam section. At 118 ms after initial impact, the w-beam was completely transected.



Fig. 11. Test 03-5: Overall damage (left) and post damage at splice (center) and non-splice location (right)

The overall damage and the post damage due to impact are shown in Fig. 11. Compared to undamaged rail, the posts experienced less torsion and did not fracture. The post-rail bolt pulled out of the rail at the non-splice location. At the splice location the post-rail connection remained intact despite large deformation of the bolt. There was 6 to 13 mm (0.25 to 0.50 inches) of relative movement between the two w-beams at the splice location. Other than at the damage location, there were no other tears evident in the beam. Also, there was no relative movement between the cable and swage of any anchor cable assembly. The right portion of Fig.

7 shows time sequential snapshots of test 03-5 obtained from the high speed camera positioned overhead.

The performance of the analogous 3-cable test (no photos shown), test 01-3, was very similar with the pendulum penetrating the barrier section due to a full cross section tear at the impact location. Post damage and relative movement of the w-beam sections at the splice was similar. Again, the post-rail connection at the splice remained intact while the post-rail bolt pulled through the rail at the non-splice location.

For the 13 mm (0.5 inch) vertical tear damage in test 08-2, the barrier was able to contain the pendulum mass with a maximum deflection of 723 mm (28.5 inches). A vertical tear developed from the bottom tip of the induced vertical tear, at 13 mm (0.5 inches) from the w-beam edge, and continued (roughly straight downward) through approximately half of the w-beam cross section. The overall damage and close-up views of the tear propagation are shown in Fig. 12. Fig. 8 (b) and Fig. 9 (b) show the measured pendulum acceleration and barrier center deflection for all three vertical tear tests, respectively. The force on the pendulum mass as a function of barrier center deflection for the vertical tear tests are shown in Fig. 10 (b).



Fig. 12. Test 08-2: Overall damage (left) and detail views of the additional tearing caused by the pendulum impact (center and right)

5.3 Horizontal Tear Damage

The horizontal tear damaged barrier in test 07-3 contained the pendulum mass impacting at 26.8 km/hr (16.7 mph). The maximum dynamic deflection of the test section was 618 mm (24.3 inches) at 134 ms after the initial impact, computed from the pendulum acceleration data. The maximum static crush at the center of the w-beam was 406 mm (16.0 inches). The damage at the impact location and individual post damages are shown in Fig. 13. Both post-rail connections remained intact and there was 16 mm (0.63 inches) of relative movement between the two w-beams at the splice location. The left portion of Fig. 14 shows time sequential snapshots of test 07-3 obtained from the high speed camera positioned overhead. Fig. 8 (c) and Fig. 9 (c) show the measured pendulum acceleration and barrier center deflection, respectively, for both horizontal tear tests conducted. The force on the pendulum mass as a function of barrier center deflection for the vertical tear tests are shown in Fig. 10 (c).



Fig. 13. Test 07-3: Detail view of impact location (left) and post damage at splice (center) and non-splice location (right)

Fig. 14. Sequential overhead photographs for horizontal tear damage (left) and splice damage (right)

In test 02-1, the horizontal tear damaged barrier (overhead sequence not shown) was unable to contain the pendulum mass impacting at 32.0 km/hr (19.9 mph). The deflection of the

rail was 738 mm (29.1 inches) at 102 ms after the initial impact, which was just prior to penetration of the w-beam section. The barrier section failed at the splice due to the splice bolts pulling through holes in the rail with none of the individual splice bolts fracturing. At both the splice and non-splice location, the post bolt pulled through the rail element. The splice failure and post damage is shown in Fig. 15.



Fig. 15. Test 02-1: Detail view of splice failure (left) and post damage at splice (center) and non-splice location (right)

5.4 Splice Damage

In test 07-4, the splice damaged barrier contained the pendulum mass impacting at 26.8 km/hr (16.7 mph). The maximum dynamic deflection of the test section was 610 mm (24 inches) at 135 ms after the initial impact. Both post-rail connections remained intact and no serious splice separation was observed in the splice damage created prior to the impact. There was approximately 13 mm (0.5 inches) of relative movement between the two w-beams at the splice location. A detailed view of the splice damage and the individual post damage is shown in Fig. 16. The right portion of Fig. 14 shows time sequential snapshots of the test obtained from the overhead camera. Fig. 8 (d) and Fig. 9 (d) show the measured pendulum acceleration and barrier center deflection, respectively, for this test. The force on the pendulum mass as a function of barrier center deflection for the splice damage test is shown in Fig. 10 (d).



Fig. 16. Test 07-4: Detail view of splice bolt damage after test (left) and post damage at splice (center) and non-splice location (right)

5.5 Twisted Blockout Damage

In test 03-8, the twisted blockout damaged barrier contained the pendulum mass impacting at 30.4 km/hr (18.9 mph). The maximum dynamic deflection was 684 mm (26.9 inches) at 134 ms after the initial impact. The maximum static crush at the center of the w-beam was 356 mm (14 inches). The overall damage and the post damage due to impact are shown in Fig. 17. The left portion of Fig. 18 shows time sequential snapshots of test 03-8 obtained from the overhead high speed camera.

The posts experienced similar damage to that in previous tests that contained the pendulum. The post at the splice location experienced more torsion than the non-splice post and had some minor cracking at the flange. The post at the splice remained connected to the rail while the post-rail bolt at the non-splice location pulled out of the slot in the rail. There were no failures in the anchor cables in this test and there was no separation of the cable from the swage portion of the anchor cable assembly. Splice separation was similar to previous tests, approximately 19 mm (0.75 inches) of relative motion between the w-beam sections. No tears developed in the guardrail and no bolts failed. The analogous 3-cable test (no photos shown), test 02-2, also contained the pendulum mass with very similar impact performance. Fig. 8 (e) and Fig. 9 (e) show the measured pendulum acceleration and barrier center deflection,

respectively, for both twisted blockout tests conducted. The force on the pendulum mass as a function of barrier center deflection for both twisted blockout tests are shown in Fig. 10 (e).

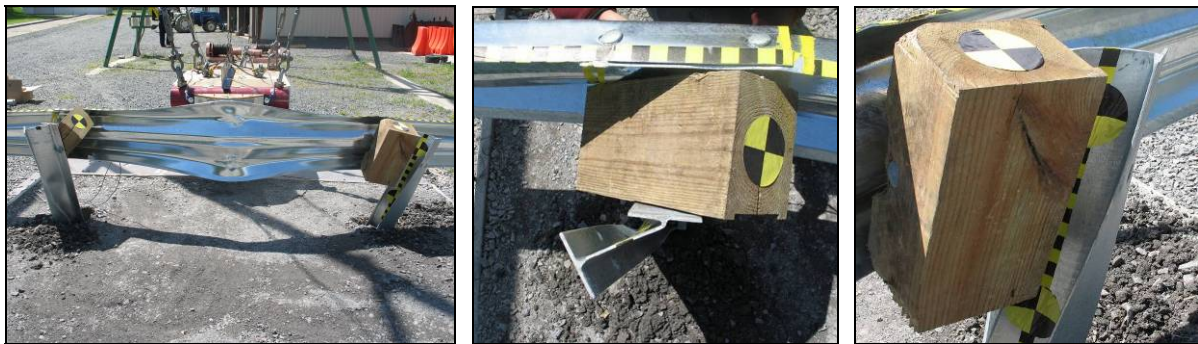


Fig. 17. Test 03-8: Overall damage (left) and post damage at splice (center) and non-splice location (right)

Fig. 18. Sequential overhead photographs for twisted blockout damage (left) and missing blockout damage (right)

5.6 Missing Blockout Damage

For the missing blockout damage, two 2-cable tests were performed. In the first test (test 03-7), the barrier was unable to contain the pendulum mass impacting at 30.5 km/hr (19.0 mph). The barrier section failed at the splice due to the splice bolts pulling through holes in the rail with none of the individual splice bolts fracturing. This failure was similar to that observed in test 02-1 with the horizontal tear damaged section. The deflection of the rail was approximately 691 mm (27.2 inches) at 106 ms after the initial impact, which was just prior to penetration of the w-beam. At 116 ms, the splice was completely separated.

The deformation of the posts was less than in the undamaged section test, as there was almost no torsion experienced by the post at the splice location. There was no visible cracking of either post. As with most previous tests, the post-rail bolt pulled through the w-beam rail at the non-splice location. The post-rail bolt at the non-splice location experienced large bending

deformation while the bolt at the splice location fractured in the threaded region. Fig. 19 shows the post damage and the splice failure. No tear developed and none of the bolts failed, but rather the bolt holes deformed enough to allow the two sections to separate. The right portion of Fig. 18 shows time sequential snapshots of the test 03-7 obtained from the overhead high speed camera.

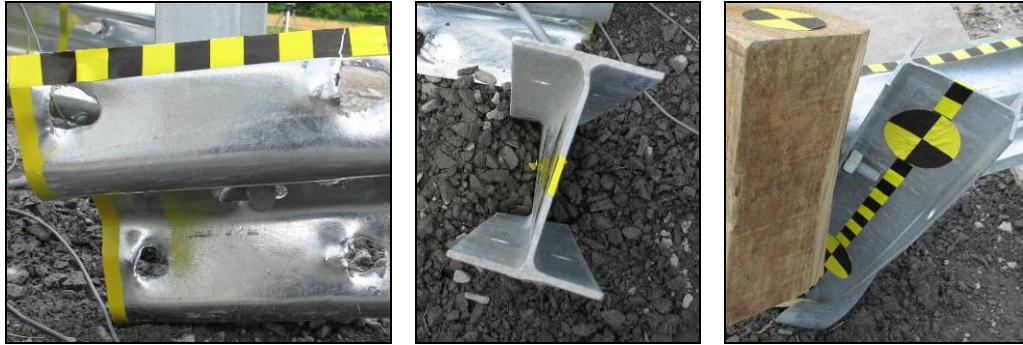


Fig. 19. Test 03-7: splice failure (left) and post damage at splice (center) and non-splice location (right)

In the second test (overhead sequence not shown), the barrier was able to contain the pendulum mass impacting at 26.7 km/hr (16.6 mph). The deflection of the rail was approximately 633 mm (24.9 inches) at 132 ms after the initial impact. Damage that the barrier section sustained in Test 07-5 is shown below in Fig. 20.



Fig. 20. Test 07-5: overall damage (left), detail view of damage at splice (center) and post damage at non-splice location (right)

In test 01-4, the barrier had a different impact performance. The barrier section contained the pendulum mass impacting at 31.5 km/hr (19.6 mph). The maximum dynamic deflection of the rail was 719 mm (28.3 inches) at 126 ms after the initial impact. The asymmetry caused by

the missing blockout resulted in a significant twisting of the pendulum (approximately 6 degrees) in the horizontal plane. The vertical tear that developed at the splice location was 229 mm (9 inches) in length, approximately two-thirds of the total w-beam cross section, and along the line of the splice bolts. A close-up of the tear is shown in the center image in Fig. 21. Fig. 8 (f) and Fig. 9 (f) show the measured pendulum acceleration and barrier center deflection, respectively, for the missing blockout tests conducted. The force on the pendulum mass as a function of barrier center deflection for the missing blockout tests are shown in Fig. 10 (f).

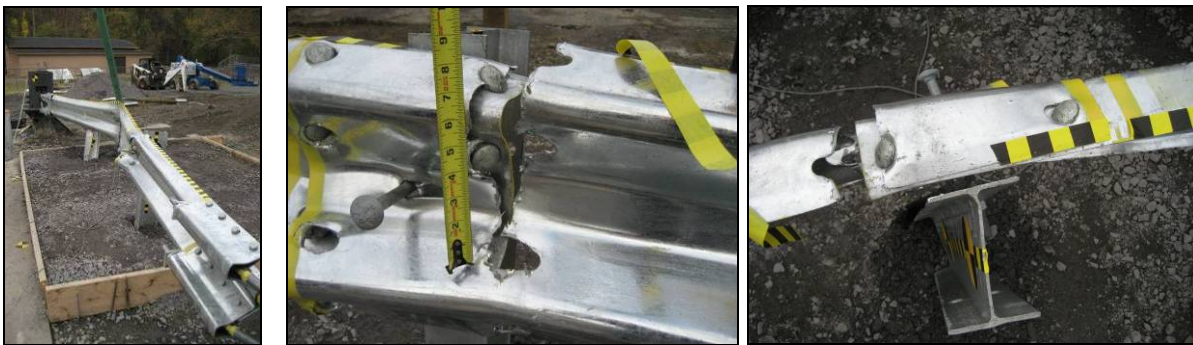


Fig. 21. Test 01-4: overall damage (left), rail tear at splice (center), and post damage at splice location (right)

6. Discussion

In all three baseline tests, the undamaged barrier section demonstrated satisfactory impact performance by containing the pendulum mass. The cable end fixture designs provided adequate connection of the w-beam section to the existing rigid posts on either side of the pendulum. With the exception of the shorter swaged cables, the end fixtures were constructed with standard barrier hardware. The cable end fixtures provide a very rigid connection of the w-beam to the essentially rigid posts on either side of the pendulum. Based on an analysis of data from the rigid post mounted accelerometers, the maximum motion of each rigid post was approximately 1 inch (data not shown) toward the pendulum mass, which would have a tendency to slightly

reduce the tension in the w-beam rail. This rigid connection coupled with the 32.2 km/hr (20 mph) pendulum impact speed, though, provides a very severe impact to the barrier section, which approaches the limit of the strong post barrier section. The ability of the w-beam barrier to withstand an impact of this severity is a testament to its structural robustness.

The pendulum tests appear to be an appropriate surrogate for determining the structural adequacy of w-beam barriers. A limitation of this test methodology is an inability to evaluate vehicle trajectory/stability as well as occupant risk. Most importantly, these tests provide insight into the crash performance of modified G4(1S) strong post w-beam barrier that has sustained minor damage. Several of these damage modes have been tested with repeated tests, albeit with slightly different impact speeds. A discussion of the effects of the different damage modes on the crash performance of the barrier is presented below.

- Vertical Tear Damage: W-beam rupture was observed in both 32.2 km/hr (20 mph) tests. While the induced tear at the impact location was roughly one third of the w-beam cross section, it is likely that any rail tear could cause a stress concentrator sufficient to cause rail rupture. In our testing, this was demonstrated by a third test; a 13 mm (0.5 inch) tear propagated to the midpoint of the w-beam cross section. In full-scale crash testing, a small tear at the bottom of the rail (caused by contact with the post during the test) was linked to rail rupture in a full-scale test conducted to develop the improved TL-3 version of the weak post w-beam barrier [16]. Based on this information, our recommendation is that vertical rail tears significantly affect the structural adequacy of the barrier and should be repaired.
- Horizontal Tear Damage: Although splice failure was observed in the 32.2 km/hr (20 mph) test, there was no evidence of rail rupture near the location of the horizontal tear.

In the 28.2 km/hr (17.5 mph) test, the damaged barrier was able to contain the impacting pendulum mass. Based on this information, our recommendation is that horizontal tears less than 306 mm (12 inches) in length and 13 mm (0.5 inches) in width do not significantly alter the performance of the barrier. Given the splice failure observed in the higher speed test, this damage should be repaired with a medium priority.

- Splice Damage: Splice damage was simulated such that one of the eight bolts in the splice connection had lost all available bearing capacity. In a 28.2 km/hr (17.5 mph) test, this barrier was able to contain the impacting pendulum mass with performance indistinguishable from the undamaged barrier section. Full-scale crash testing as well as the splice failures observed in the pendulum tests suggests the splice is a weak point in guardrail system. In light of this, our recommendation is that splice damage, where at least one bolt has compromised bearing capacity, be repaired with a medium priority.
- Twisted Blockout Damage: The performance of the barrier section with this damage was indistinguishable from that of the undamaged barrier section in two higher speed tests conducted suggesting that this damage mode has little effect on the structural adequacy of the barrier. Based on this information, our recommendation is that twisted blockout damage does not significantly alter the structural performance of the barrier and, as a result, is a low priority repair.
- Missing Blockout Damage: The crash performance of a barrier section with a missing blockout at the splice was marginal to unacceptable for the higher speed tests. One test (01-4) resulted in a rail tear at the splice through a majority of the cross section while the other test (03-7) resulted in a splice failure due to pullout of the splice bolts. This difference in impact performance was likely a result of the use of the splice bolt washers

in test 01-4. The washers would allow additional tension to develop in the rail, ultimately leading to a rail tear as opposed to the bolt pullout splice failure observed in the other test. The lower speed test resulted in performance indistinguishable from the undamaged barrier. Our recommendation is that a missing blockout, especially at the splice, should be repaired with a medium priority based on the marginal performance of the barrier at the higher impact speed.

7. Conclusions

This study presents a test methodology and a first-of-a-kind evaluation of the crash performance of strong post w-beam barrier that has sustained minor damage. Using the described test methodology, pendulum tests were conducted on a two-post section of strong post w-beam barrier sections with five types of damage: (1) vertical tear, (2) horizontal tear, (3) splice damage, (4) twisted blockout, and (5) missing blockout. Based on the results of the pendulum tests, vertical tears were found to be a significant threat to the structural adequacy of the barrier section with a high likelihood for rail rupture. A missing blockout at the splice location was found to result in marginal performance at the 32.2 km/hr (20 mph) impact speed with one test resulting in a large rail tear and another in a splice failure. Horizontal tears less than 306 mm (12 inches) long and 13 mm (0.5 inches) wide and splice damage with one bolt lacking bearing capacity were found to have a less significant threat on the structural adequacy of the barrier. Both of these damage modes had acceptable performance at the 28.2 km/hr (17.5 mph) impact speed. Twisted blockout damage was found to have no effect on the structural crash performance of the strong post w-beam barrier.

8. Acknowledgements

This research was sponsored by the National Academy of Sciences under the National Cooperative Highway Research Program (NCHRP) Project 22-23, “Criteria for Restoration of Longitudinal Barriers”. The authors wish to acknowledge the guidance of Charles W. Niessner, program manager for NCHRP Project 22-23, as well as the insight of the project panel. The FHWA supported this effort by making the FOIL facility available for the testing and allowing contract staff of the National Crash Analysis Center (NCAC) from George Washington University to assist in the setup and execution of the tests.

We would also like to thank the NCAC staff including Pradeep K. Mohan (Senior Researcher) as well as Chris Story, Scott Mosser, and Eduardo Arispe (FOIL Technicians). We would also like to thank Trinity Industries, Inc. and Gregory Industries, Inc. for providing the guardrail materials for these pendulum tests. We also acknowledge Greg Webster, Craig Thor for their help conducting the pendulum tests.

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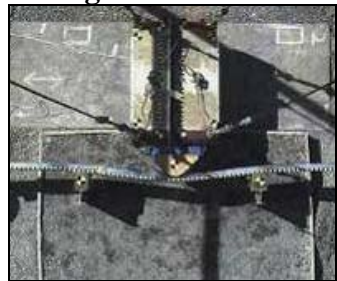
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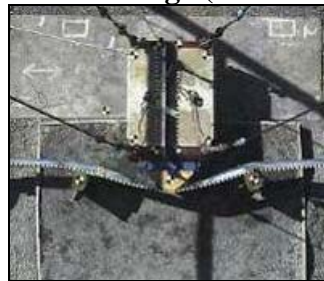
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Undamaged Two-Post Section, 2-Cable Anchorage (30.9 km/hr)



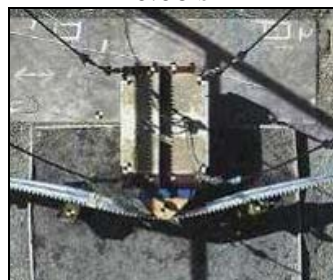
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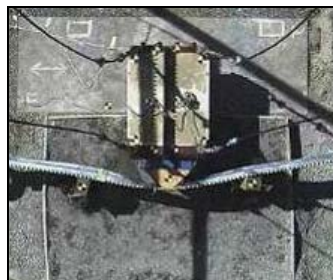
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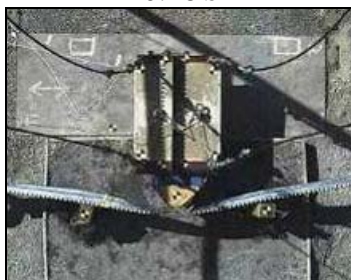
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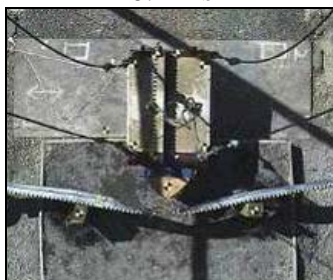
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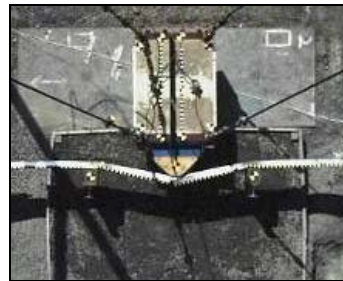


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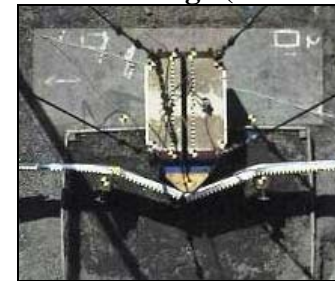


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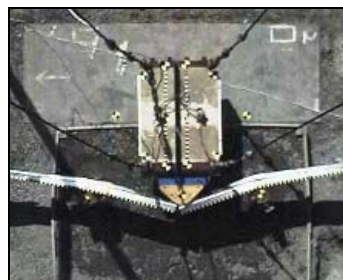
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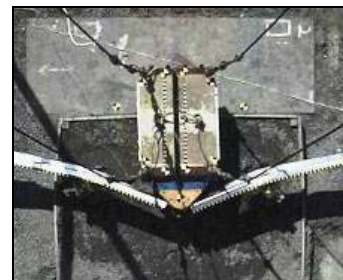
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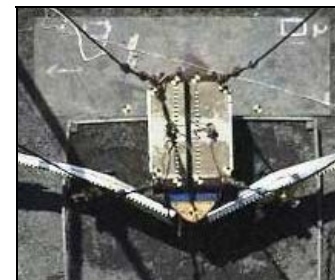
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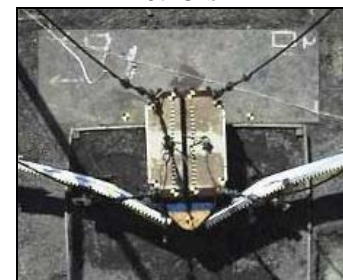
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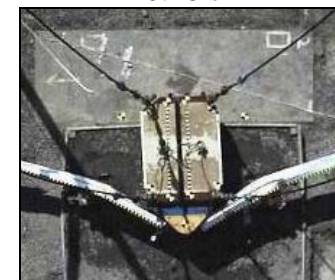
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Horizontal Tear Damage, 2-Cable Anchorage (29.3 km/hr)



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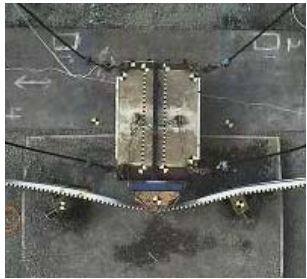
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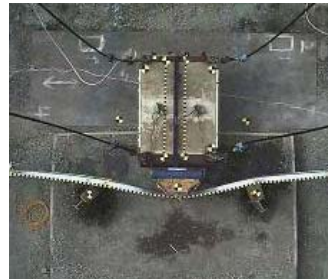
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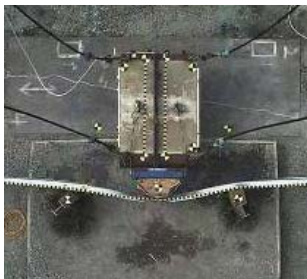
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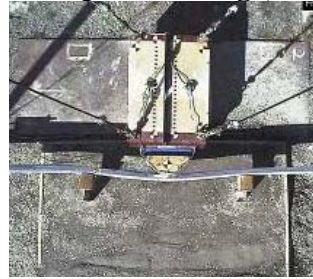


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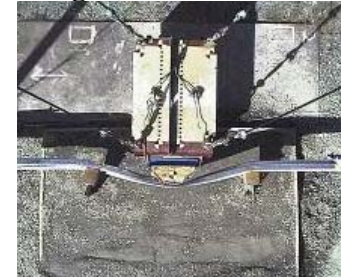


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Splice Damage, 2-Cable Anchorage (29.3 km/hr)



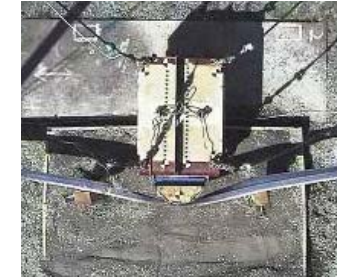
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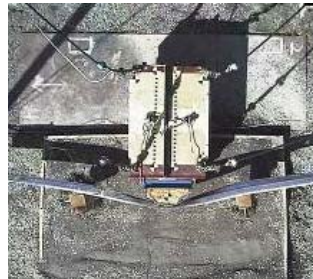
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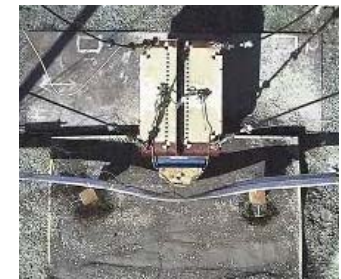
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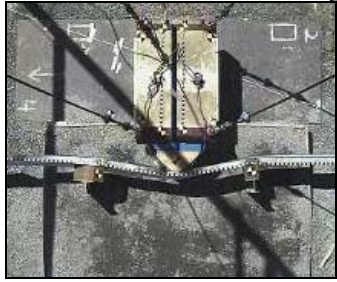


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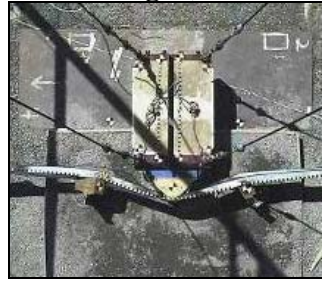


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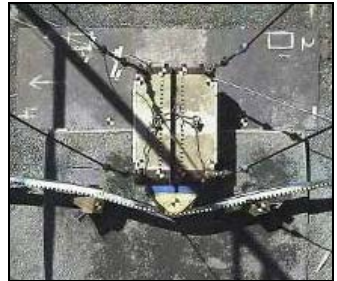
Twisted Blockout Damage, 2-Cable Anchorage (31.2 km/hr)



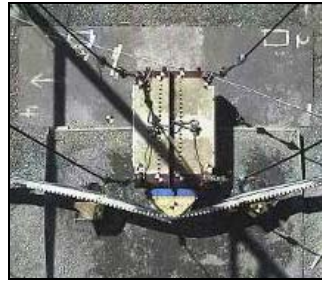
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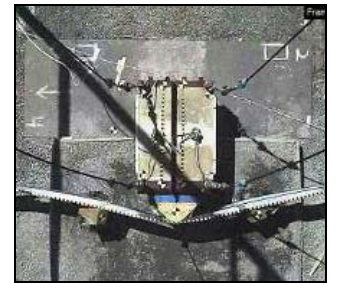
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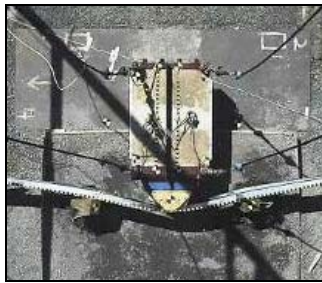
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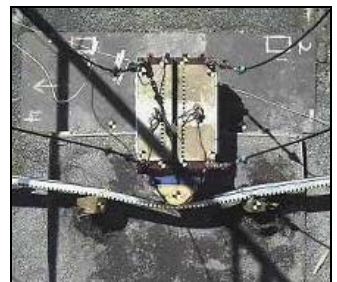
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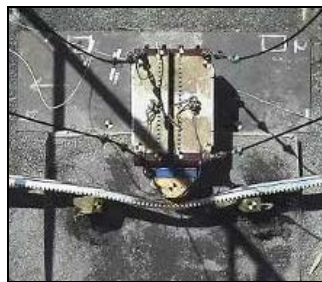
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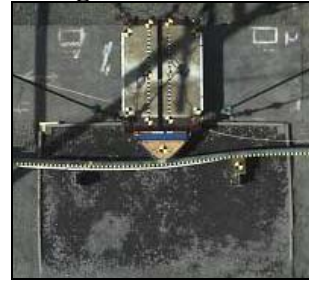


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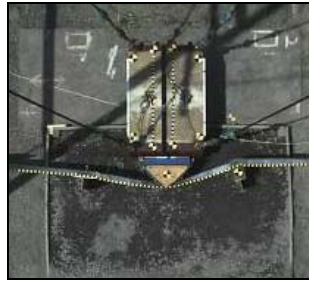
Missing Blockout Damage, 2-Cable Anchorage (30.6 km/hr)



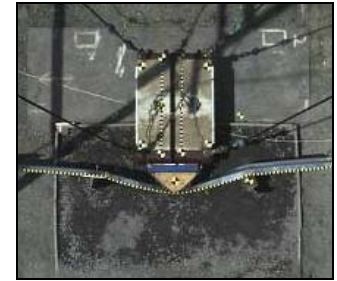
0.017 s



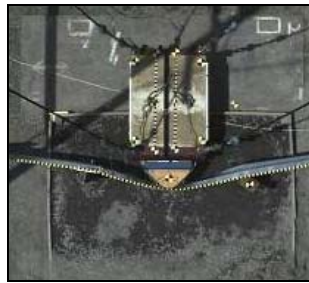
0.034 s



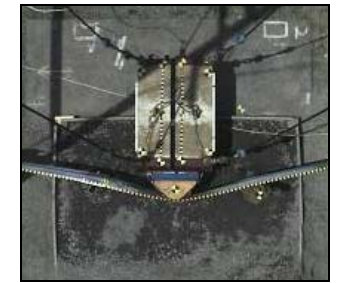
0.051 s



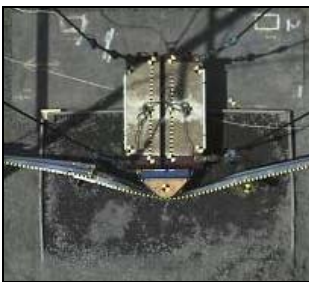
0.068 s



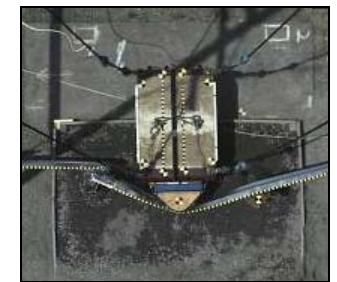
0.085 s



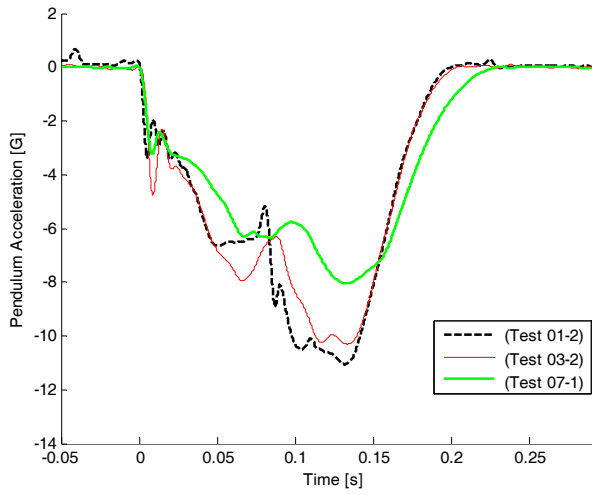
0.102 s



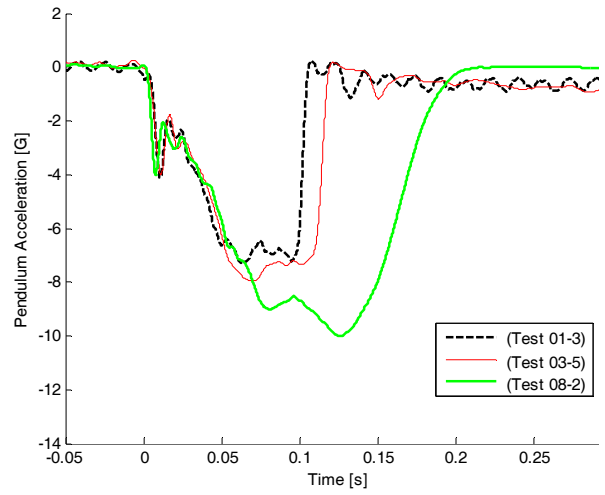
0.119 s



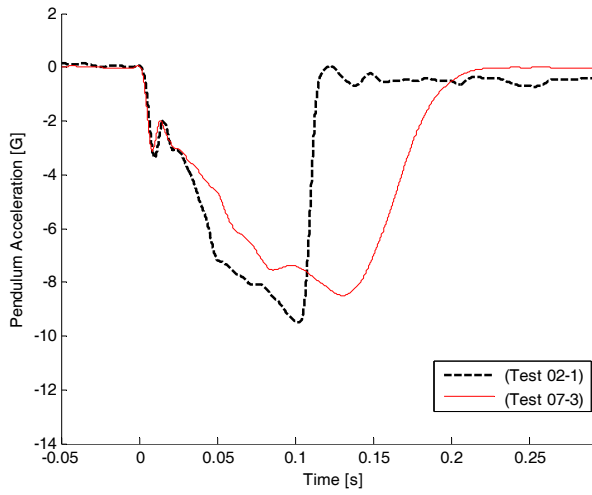
0.136 s



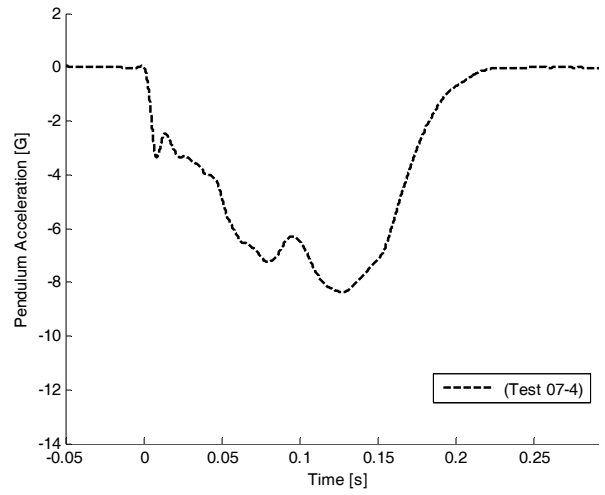
(a)



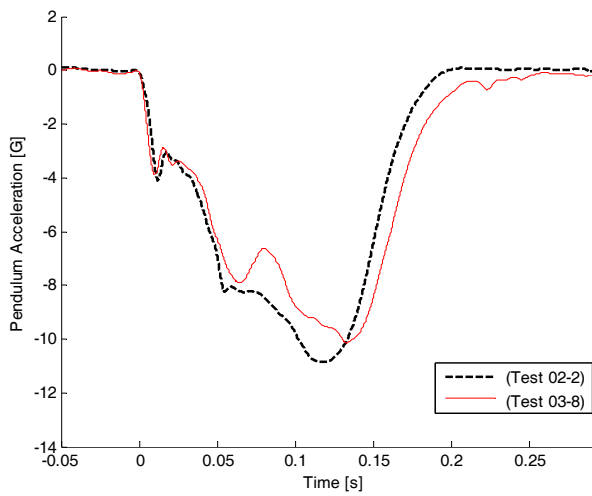
(b)



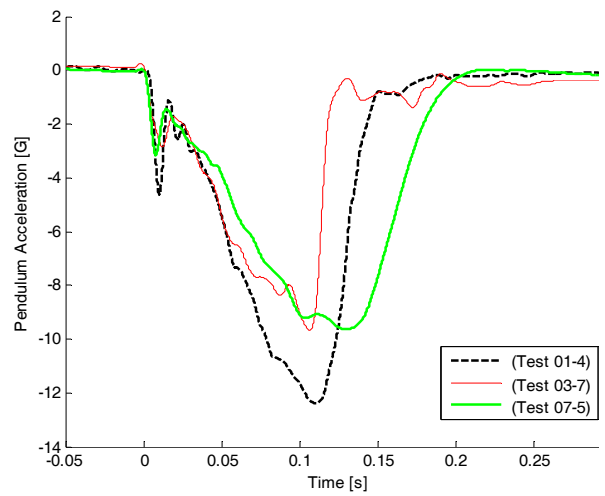
(c)



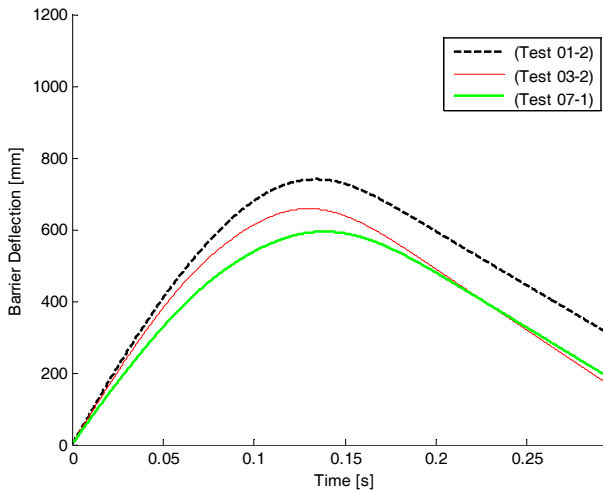
(d)



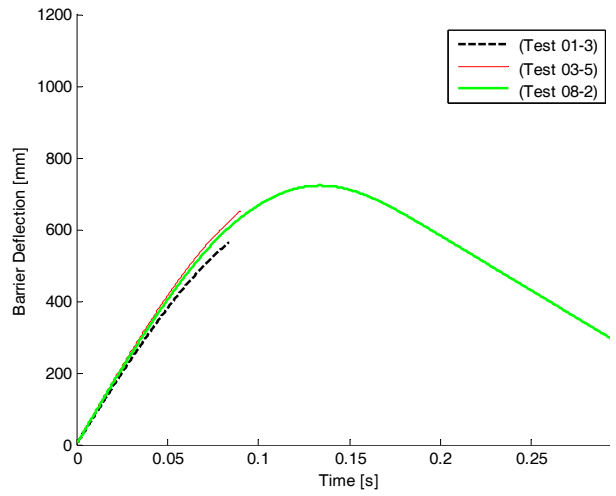
(e)



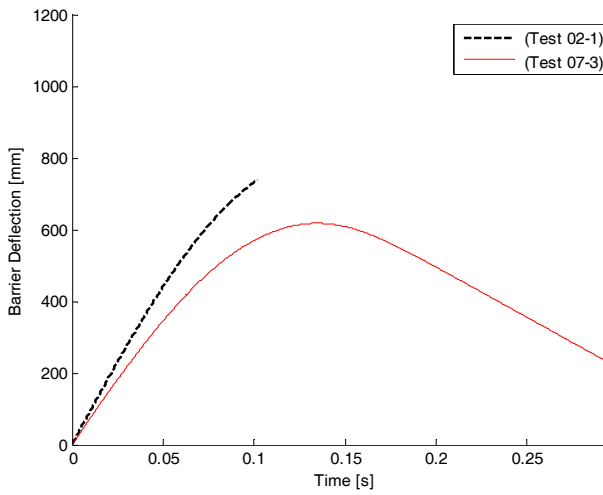
(f)



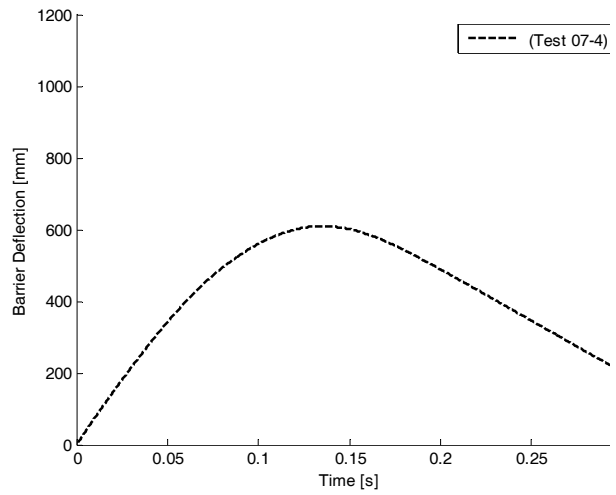
(a)



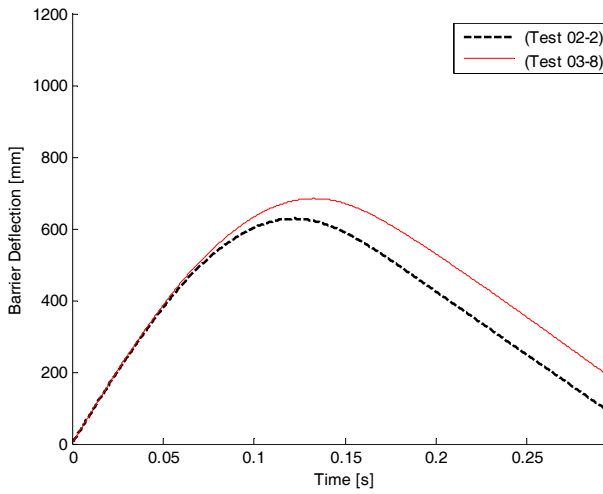
(b)



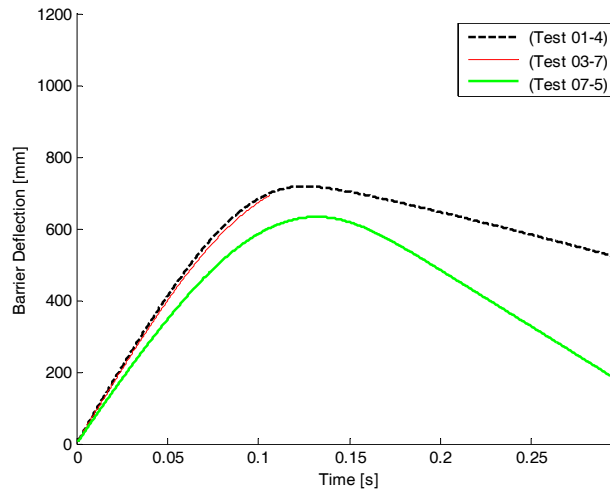
(c)



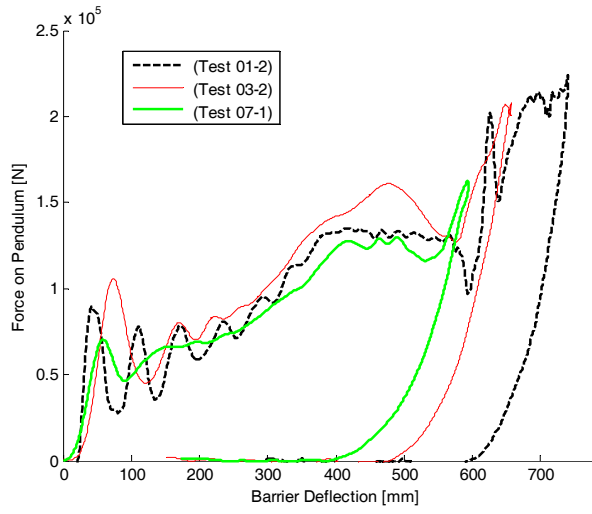
(d)



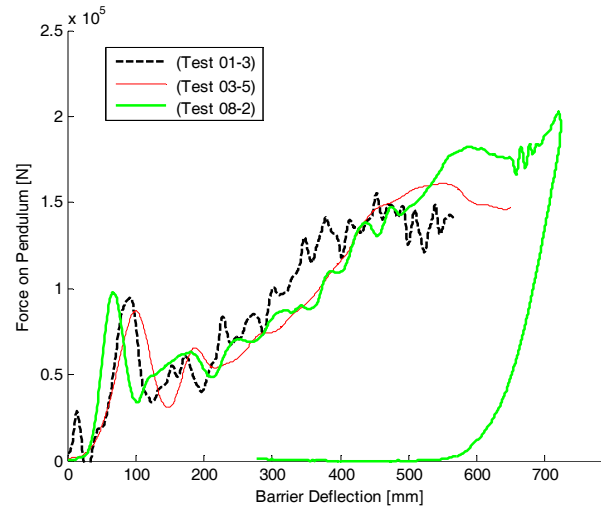
(e)



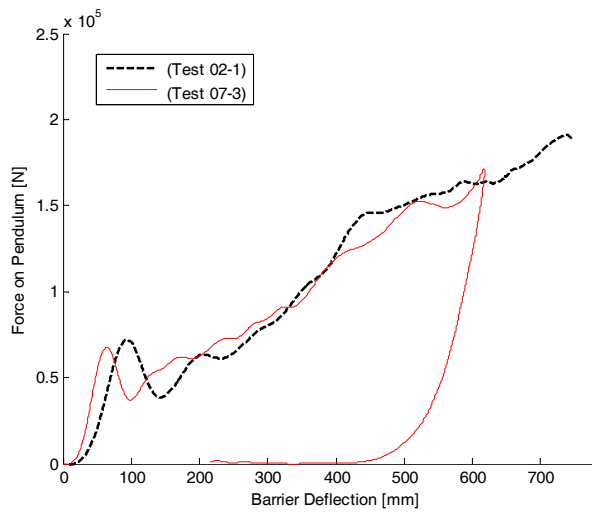
(f)



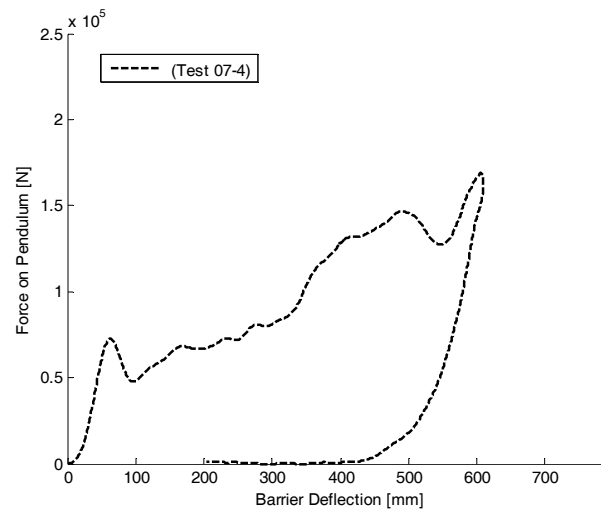
(a)



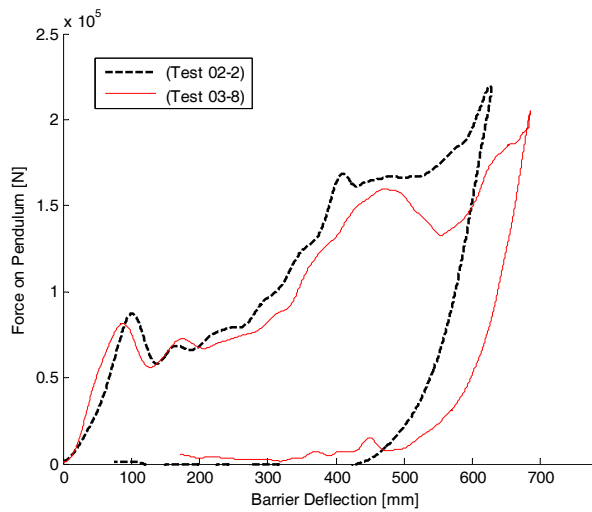
(b)



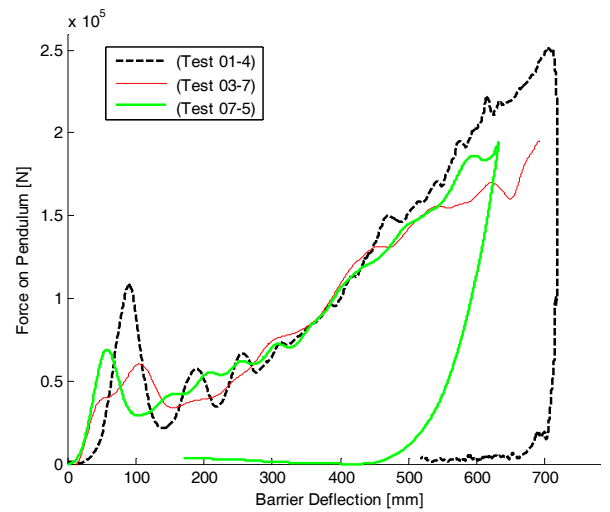
(c)



(d)



(e)



(f)