EVALUATION OF THE RIBEYE DEFLECTION MEASUREMENT SYSTEM

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ABSTRACT

The objective of the present study is to evaluate the RibEye system used to obtain deflections in impact-related tests. A description of the system is presented based on the specifications of the manufacturer. Evaluations included chest compression tests under varying loading condition: mid-sternum, offset, and diagonal loading. Accuracy assessment tests included: sternum-mounted, and rib-mounted LEDs with and without initial chest rotation about the z-axis, and indenter-mounted LEDs. These quasi-static tests were followed by pure and oblique pendulum tests to the thorax at velocities of 4.8 and 6.6 m/s. LEDs on the sternum responded similar to the available internal chest potentiometer. The accuracy of the system depended on positioning of the LEDs on the rib, magnitude of rib deformation, and potential interference from devices such as the presence of the internal chest potentiometer. Signal drop out depended on the type of indenter, with diagonal loading producing more signal loss. The deflection response along the x-and y-directions were deemed to be reasonable in oblique loading tests. Results from dynamic tests indicated that light interference from the internal component(s) restricts the ability of the system to obtain accurate deflections including signal drop out. In oblique tests, the system captured the asymmetric motions of the chest by demonstrating greater deflections on all left side ribs than right side ribs, thus showing its potential under this loading condition. The current fundamental evaluations helps in understanding of the performance of the system as installed in the mid-size male Hybrid III dummy.

INTRODUCTION

crashworthiness assessments for frontal impact in the United States Federal Motor Vehicle Safety Standard (FMVSS) No. 208 used the Hybrid III dummy family [1]. As far as chest instrumentation is concerned, the dummy houses a triaxial accelerometer on the spine to record the chest acceleration, and an internal deflection potentiometer to measure the chest deflection. The chest force-deflection responses are applicable to blunt frontal impacts and are based on tests to the mid-sternum impacts using a 23.4 kg pendulum at velocities of 4.3 and 6.7 m/s [2-4]. The peak chest deflection is obtained from the internal potentiometer measuring the linear displacement of the sternum with respect to the thoracic spine, and the force is recorded from a load cell attached to the pendulum impactor. Data are gathered and processed according to the Society of Automotive Engineers SAE J211 specifications [5].

Chest deflection measurements at multiple points facilitate an assessment of non-uniform, asymmetric thorax loading. Occupant out-of-position effects may also contribute to asymmetrical chest deformations even in pure frontal impacts. Eppinger from the National Highway Traffic Safety Administration of the United States Department of Transportation developed a dedicated instrument, chestband, for measuring deformations [6]. It is a noninvasive device made of high carbon steel alloy strip with strain gauges bonded at 59 locations. During the early years of development, lesser gages were used. Deflections at multiple levels have been obtained using more than one chestband. This device has been used to compare chest deflections in simulated frontal impacts in a laboratory environment [7, 8].

Recognizing that deflections can be used for understanding injury mechanisms and might serve to define injury criteria, recently, an optically-based instrument, termed RibEye, has been developed by Robert A. Denton, Inc., to measure internal chest deflection of devices such as the Hybrid III dummy [9]. As a systematic evaluation have not been reported, this paper describes procedures to evaluate the RibEye system in the mid-size Hybrid III dummy with a focus on frontal impact applications.

DETAILS OF THE SYSTEM

The underlying concept is that an optically-based system, being not affixed to a specific mechanical linkage such as the internal chest potentiometer connecting the spine and sternum, can enhance the number of deflection measurements. Briefly, the

RibEye system is comprised of up to twelve light emitting diodes (LEDs) mounted to the ribs of the dummy internally, two incident light detectors (sensors) that receive light from the LEDs, a controller, and an interface box (Figures 1-7). The current version of the system is capable of obtaining deflection data along the x- and y-directions, fore-aft and side to side. The sensors are mounted laterally to each side of the thoracic spine of the dummy, and the controller is located within the spine box at its uppermost location. LEDs connect to the controller via a block mounted superior to the sensor heads. The interface box can be secured in the trunk of the test vehicle in full scale experiments.

LEDs can be mounted at various positions on the inside surface of the ribs or sternum. The default LED locations are placed one on each rib on either side. However, the RibEye allows the user to override the default condition and position multiple LEDs on the same rib or sternum as long as proper z-axis location is maintained. All LEDs are connected via a cable to the data acquisition system housed within the thoracic spine of the Hybrid III dummy. The user indicates the position of the LED in the "Location" field of the user-interface. Three LED case designs exist: with different back angles that direct light toward the RibEye sensors (Figure 4). The flat back LEDs are designed for positioning on ribs three and four, the 20-deg angled back LEDs are designed for positioning on ribs two and five, and the 35-deg angled back LEDs are designed for positioning on ribs one and six. Optionally, the 35-degree angled back LEDs may be positioned on the upper and lower sternum using the mounting plates (Figures 5-7).

Each LED is powered sequentially and sampled at 10,000 Hz during testing, while two sensors detect the angle of the LED with respect to frontal and lateral planes. The resulting digital data are stored in memory. This constitutes the "raw data" from the RibEye system. These data are then corrected for ambient light conditions and adjusted using calibration curves housed within the software of the data acquisition system. In other words, the light intensity data collected based on the incident angle is converted by an embedded microprocessor using optical triangulation techniques to compute deflection records at each LED position. These processed data are then stored in the RibEye flash memory. Data are downloaded to an external computer and saved as a text file using the RibEye interface within a web browser (Figure 7). Thus, it is possible to obtain fore-aft and side-side coordinates of deflection of the rib or sternum at the positioned LED location during loading. Using twelve sensors, deflections can be determined at twelve locations. The system allows the user to download "raw data" using the Hyperterminal software. However, processing of this "raw data" to provide LED deflections can be only be done by the manufacturer, Robert A. Denton, Inc.

The following multi-point deflection measurement system specifications were extracted from the User Manual. The measurement ranges in the x-y and x-z planes are demonstrated in Figures 8-9. For Figures 8 and 9, the x=0, y=0, z=0, i.e., origin, is the midpoint of the line segment connecting the two sensors. With respect to the dummy, this is approximately on the front surface of the spine mount box in the center of the chest. Thus, the absolute location of the midsternum is approximately x=87, y=0, z=0 mm. The system does not account for out-of-plane movements. Thus, any z-axis movement of an LED will produce measurement inaccuracies. Tables 1 and 2 list the system accuracy associated with z-direction deflection ranges.

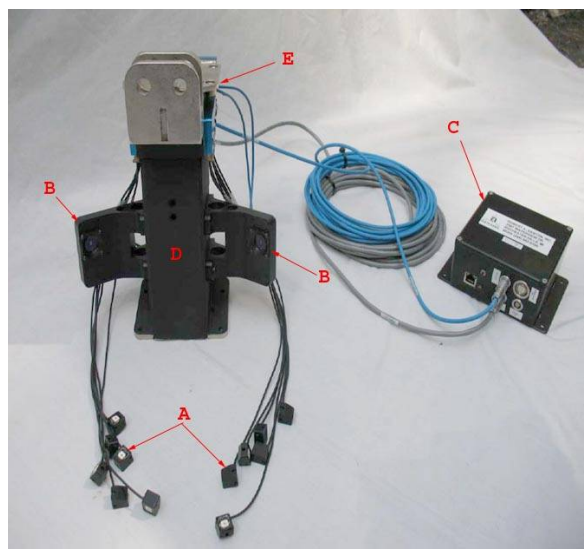

Figure 1. RibEye system: LEDs (A), two sensor heads located on both sided of the thoracic spine (B), interface box (C and E), dummy thoracic spine box (D), and LED connector block (F).

The power supply to the system should be 12 to 36 volts DC. Fuse protection is an internal self-resetting polymer fuse in the interface box. RibEye's self-contained data system has a sampling rate of 10,000

Hertz per LED and an acquisition time of 90 milliseconds pre-trigger, 910 milliseconds post-trigger (1 second total). All data are collected in RAM and stored post-test in the system memory.

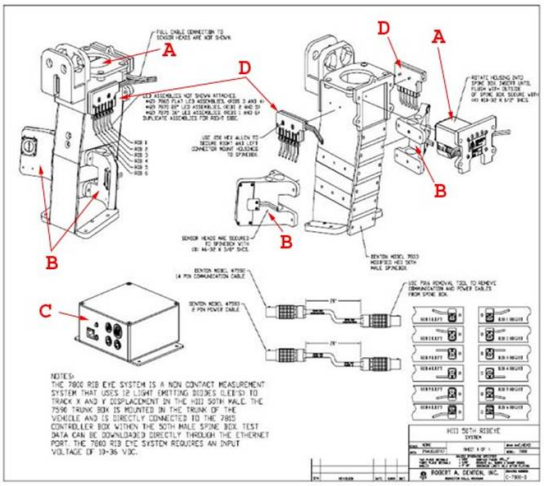

Figure 2. RibEye system components showing the controller (A), sensor heads (B), interface box (C), and LED connector block (D).

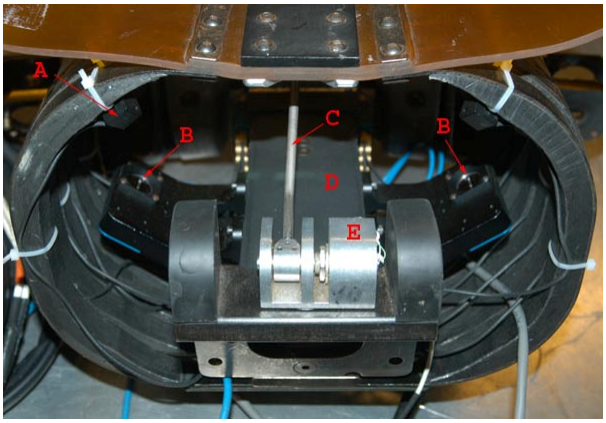

Figure 3. RibEye system shown installed in the mid-size Hybrid III dummy. The photo shows an LED fixed to right sixth rib (A), sensors (B). The standard Hybrid III sternum displacement slider arm (C), dummy thoracic spine box (D), and internal chest potentiometer assembly (E) are also shown.

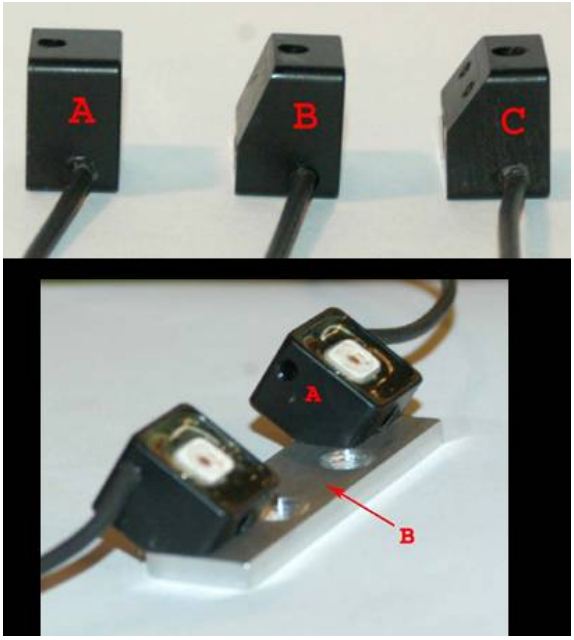

Figure 4. The top illustration shows the LED case design: flat back LED (A), 20-deg angled back LED (B), and 35-deg angled back LED (C). The bottom illustration shows the 35-deg angled back LED (A) and the sternum mounting plate (B).

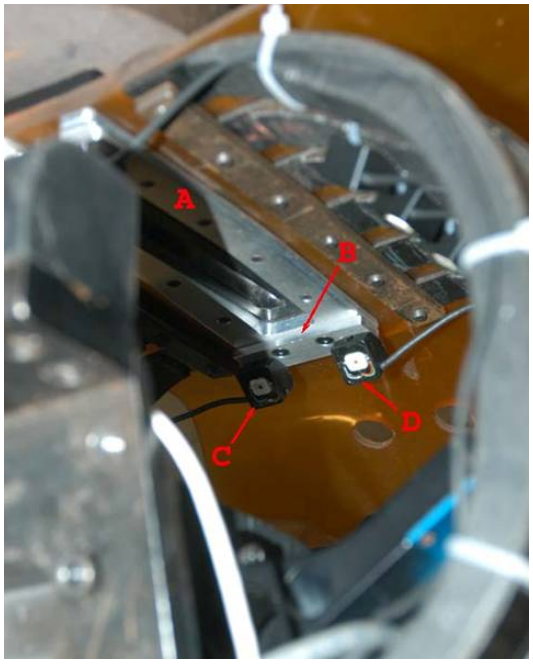

Figure 5. Mid-size Hybrid III dummy chest showing the sternum assembly (A), sternum mounting plate (B), upper right and left sternum LEDs (C and D).

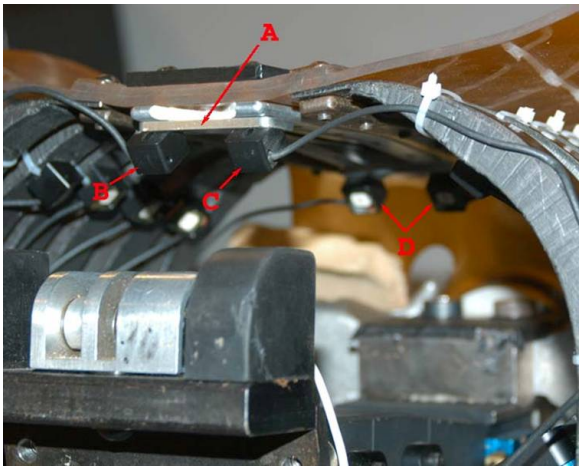

Figure 6. Inferior view of the sternum-mounted LED: sternum mounting plate (A), lower right and left sternum LEDs (B, C), and upper sternum LED (D).

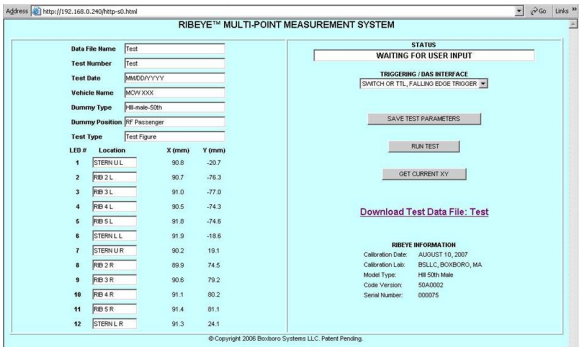

Figure 7. RibEye use interface.

Table 1.
RibEye accuracy with z-axis deviation

z-deviation mm	x-accuracy mm	y-accuracy mm
0	1.0	1.0
± 12.5	1.0	2.0
12.5 to 25.0	2.0	2.0
-12.5 to -25.0	2.0	2.0

Table 2.
Power requirements

Operating conditions	Interface box (W)	Controller and LEDs (W)	Total (W)
On or idle	3.3	2.0	5.3
Collecting data	3.3	5.0	8.3
Maximum*	3.3	9.0	12.3

*: when all LEDS are out of view of both sensors and driven to full power

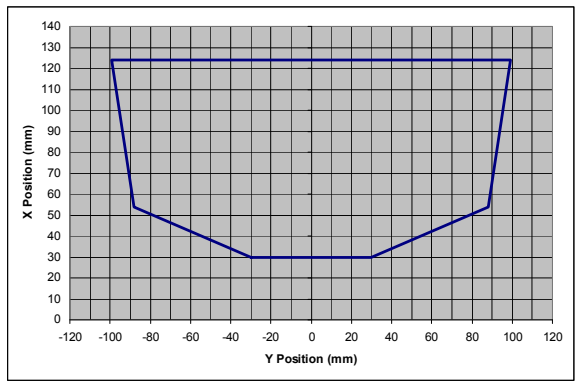

Figure 8. The specified range for LED x-y positions for the mid-size Hybrid III dummy.

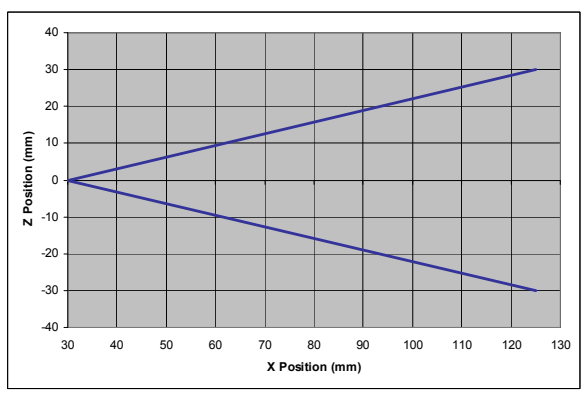

Figure 9: The specified range for LED x-z positions for the mid-size Hybrid III dummy.

QUASI-STATIC EVALUATIONS

LED Positioning

This was accomplished as follows. The thorax of the mid-size male Hybrid III dummy was mounted on a cross table and attached to a testing device. LEDs were positioned on the inside surface of the ribs and position measurements were obtained from the midline of the sternum along the outer surface of the ribs.

LED Signal Drop Out Assessment

In order for the RibEye system to optically track the position of the LEDs, there must be sufficient light projected from each LED onto the spine box-mounted sensors. If either or both sensors detect inadequate light intensity, data from that particular LED will be forced out of range and the system will not track the LED motion until the light intensity requirement is again satisfied. This light intensity requirement can also be affected by extraneous light such as those resulting from high intensity lighting systems, typically used in crashworthiness studies (example, sled tests) to obtain overall kinematics. However, the dummy chest jacket use minimizes extraneous light interference. When sensors detect inadequate light intensity, signal drop out occurs, resulting in gaps within the RibEye deflection records.

In the x-direction deflection plot, drop out appears an instantaneous negative change in the displacement of the LED followed by a horizontal interval (Figure 10). The displacement magnitude of the horizontal interval indicates the initial absolute position of the LED prior to compression, and any association with the indenter and chest potentiometer traces is coincidental. At the end of the drop out period, there is an instantaneous positive change in the displacement as normal LED tracking resumes. In the y-direction deflection plot, signal drop out pattern is similar to the x-direction, but in right-sided LEDs the deviation is negative and in left-sided LEDs it is positive (Figure 11).

The graphical appearance of signal drop out is therefore, a consequence of the RibEye system methodology in data processing under inadequate signal conditions. If inadequate light from a particular LED is provided to the left sensor, all data for that LED during the period of diminished optical signal is assigned an integer value, "1." On the other hand, if inadequate light is provided to the right sensor, all data for that particular LED is assigned an integer value, "2." However, if inadequate light is provided to both sensors, all data for that LED is assigned an integer value, "3." These values do not appear to be in the "raw data", but is most likely included in the output from the microprocessor which feeds into the flash memory.

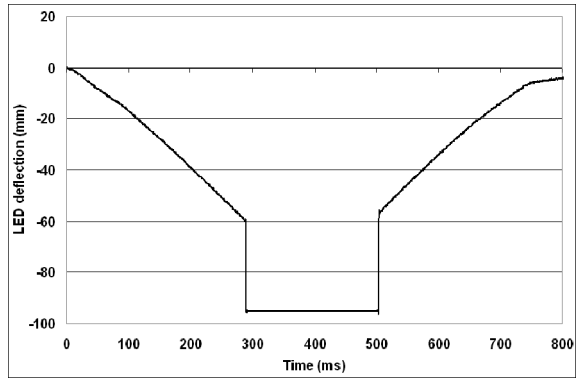

Figure 10. Deflection along the x-direction of the right fourth rib LED positioned at 6 cm. While the indenter continues to compress the chest, drop out occurs in the LED signal. The shape of the drop out pulse is similar regardless of the positioning of the LED.

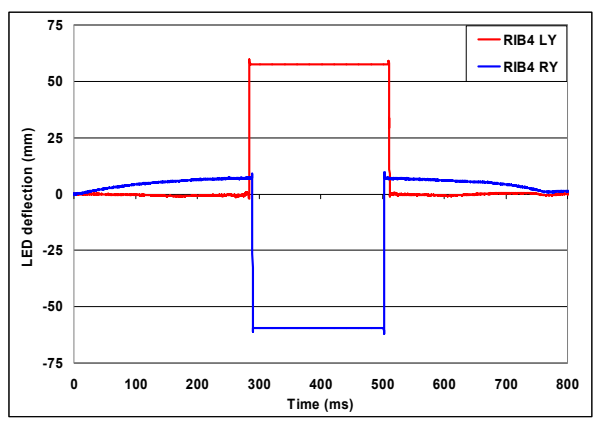

Figure 11: Deflections along the y-direction of the right and left fourth rib LEDs positioned at 6 cm. The drop out occurs in both LEDs. The polarity reversal between the left and rib LEDs are discussed in the text. The shape of the drop out pulse between the left and right LED is similar regardless of the positioning of the LED.

Appendix A contains a portion of the text output from the RibEye web interface software. The output provides absolute xy location information for each LED. Note that data demonstrating insufficient light detection by the left sensor from the LED affixed to left rib six (RIB6 LX and RIB6 LY) at 100.3 milliseconds are assigned the integer value, "1". The right sensor detected inadequate light projected from LEDs attached to right ribs one and two during the 99.3 – 100.9 millisecond interval shows the integer value, "2". In this example, at no time were the LED light signals undetectable by both sensors. In subsequent plots the absolute position data are filtered and converted to relative data such that all sensors begin at zero. In other words, the initial absolute position value is subtracted from all values to establish zero base line. This process results in converting integer values indicating drop out to relative deflection magnitudes.

LED signal drop out may occur from ribcage (rib or sternum) bending that directs the light beam away from the sensor(s), or, obstruction of the beam by another component of the mid-size III dummy such as the slider arm of the chest potentiometer. Signal drop out secondary to the bending path appears as a horizontal interval symmetric about the center of the indenter trace corresponding to maximal compression. In contrast, signal drop out due to the slider arm obstruction appears as two shorter intervals. The initial drop out interval occurs during compression while the second interval occurs symmetrically during release (Figure 12).

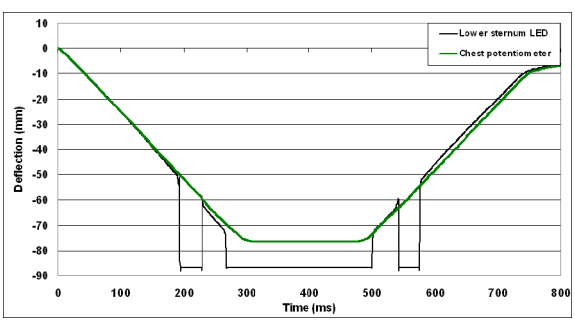

Figure 12. Plot showing drop out from the lower sternum LED on the right side (deflection shown is along the x-direction) due to light interference from the presence of the slider arm of the internal chest potentiometer. Displacement data from the potentiometer is included. Data corresponds to 3-in chest compression test.

Drop out assessment tests were conducted using a ramp waveform and indenter displacements ranged from 1-in to 3-in. It should be noted that the maximum sternum deflection specified FMVSS 208 is 2.5 inches [10]. Indenter velocities were 0.25 or 0.50 m/s. All tests, except with LEDs at the 11 cm position, were performed with and without the internal chest potentiometer slider arm. RibEye data were separated into individual channels and a CFC600 filter was used according to SAE J211-1 2003 specifications for filtration of thorax deflections.

In mid-Sternum compression loading, a wooden cylinder of diameter 15 cm attached to the actuator of the testing device was used to determine the drop out with varying LED positions and sternum compression parameters. The loading paralleled the mid-size Hybrid III dummy evaluation criterion. Quasi-static compression tests were performed with LEDs mounted to ribs one through six on each side in the following configurations: 6, 8, 9, 10, 11, or 13 cm from the sternum midline. The center of the indenter contacted the thorax at mid-sternum (Figure 13).

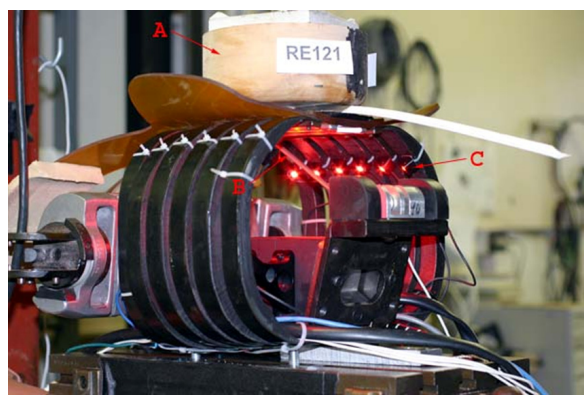

Figure 13. Photograph showing the test system with the wooden indenter (A) and LEDs positioned on the left sixth rib (C) at 11 cm. The dummy rights ribs are identified (B).

The sternum attachment option was evaluated with four LEDs mounted to the upper and lower corners of the sternum plate via screws. The remaining LEDs were mounted to ribs two through five at either 8 or 9 cm from the midline (Figure 14). The RibEye system was compressed using a 15 cm square aluminum plate indenter in these tests. A leveling

plate was used to compensate for the convexity of the sternum plate and provide level contact surface for loading the sternum.

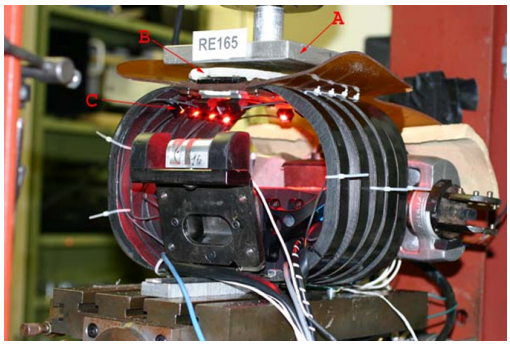

Figure 14. Photograph showing the test system with the aluminum indenter (A) and LEDs positioned at 8 cm on the right 2-5 ribs (C). The PMMA leveler is identified (B).

The presence of the linkage arm of the internal chest potentiometer in the mid-size Hybrid III dummy appeared to increase the likelihood of interference as the location of LEDs moved away (towards left or right) from the 9 cm position. As expected, increasing the magnitude of the chest compression increased the likelihood of drop out. The percentage of LED drop out was sensitive to positioning, the magnitude of sternum compression (1-in test), and the presence of the internal chest potentiometer. No drop out occurred in tests with 1-in sternum compression. This was independent of the presence or absence of the mid-size Hybrid III dummy the internal chest potentiometer. In the 2-in compression test without the presence of the potentiometer, the drop out occurred only at the 13 cm position. However, the presence of the potentiometer at this compression magnitude produced drop out at the following positions: 6 cm; 8 cm; 13 cm; and the sternum. The 3-in sternum test without the chest potentiometer produced dropout at all LED positions except the 9 cm position. Inclusion of the potentiometer in the 3-in compression test resulted in LED dropout in all configurations. These findings indicate that the mechanism of signal drop out can be influenced by obstruction within the light field (presence of internal chest potentiometer slider arm), initial position of the LED, and orientation of the LED deflection path of the ribcage.

Peak chest compressions before drop out depended on the position of the LED. The 9 cm position showed no drop out (the 3-in compression test) and increasing drop outs occurred with positions away from the 9 cm position. As shown in Figure 15, at the 6 cm LED position, the peak compression before drop out was 62 mm, followed by 70 mm at the 8 cm, 64 mm at the 10 cm, and 24 mm at the 13 cm LED positions. At the sternum, the peak chest compression occurred at 66 mm. These results suggest that 9 cm position is optimal. Because the peak sternum compression exceeded the injury assessment reference value (IARV) of 63 mm, according to FMVSS No. 208, (section S6.4, Code of Federal Regulations, 10/1/2006 edition) with LEDs positioned at 8 cm, 9 cm, and 10 cm, and on the sternum, it may be appropriate to use these positions when the symmetrical load is on the center of the sternum in the mid-size Hybrid III dummy.

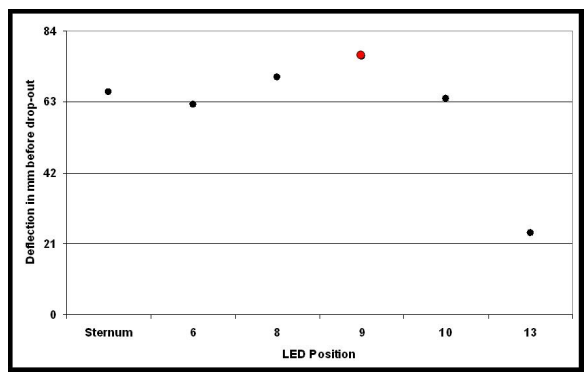

Figure 15. Peak chest compression before drop out from LEDs positioned at locations shown on the x-axis. The 9 cm positioned LED did not have any drop out and hence the maximum displacement achieved by the indenter was recorded. The sternum compression before drop out exceeded the IARV of 63 mm in LEDs positioned at 10, 9, and 8 cm and sternum. Note the decreasing peak deflections before drop out as LED positioning moves away from 9 cm position.

The purpose of offset tests was to determine the drop out characteristics with asymmetric loading to the ribcage in the mid-size Hybrid III dummy. In the left side offset tests, the longitudinal edge of the indenter, 51 mm x 102 mm, was aligned with the front end stiffener plate of the left side ribs two through five. The performance was evaluated in the 1-, 2-, and 2.5-in compression tests, with LEDs mounted at the 6

cm, 9 cm, and 13 cm positions, resulting in nine tests. The extreme case of the 3-in compression test was not considered because subjecting the mid-size Hybrid III dummy thorax to this magnitude may exceed its capacity. The purpose of the diagonal loading tests was to determine the drop out characteristics with asymmetric loading generated by a typical diagonal shoulder belt. Loading was accomplished using a 51 mm wide metal plate angled at approximately 45 deg in the frontal plane and positioned with its center at mid-sternum. LEDs were positioned at the 9 cm location, and the plate was displaced to compress the dummy chest to 1-in, 2-in, and 3-in. Two tests at each of the two lower compressions were conducted. These tests indicated that system is able to follow the offset loads. The upper- and lower-most LEDs appear to be sensitive to drop out in the diagonal loading, with no drop outs occurring in the middle ribs. Drop out only occurred in the 3-in compression test and the first LED dropped out at an indenter displacement exceeding the sternum compression IARV. Because drop outs occurred in multiple LEDs, the system may not fully capture the ribcage motion at this severe chest displacement in the mid-size Hybrid III dummy.

Accuracy Assessments

The purpose of these tests was to directly compare the deflection measuring capability of the RibEye system with the current deflection measuring standard (internal chest potentiometer) or with the indenter deflection. The potentiometer measures sternum compression via a transducer arm whose end travels in a midline track within the dummy sternum. The transducer arm induces rotation in a potentiometer during compression and the resulting electrical signal is converted to linear displacement. These tests were designed to evaluate the accuracy of deflection records along x- and y-directions (Table 3). Tests in this series consisted of four subseries. The first three subseries involved test configurations that maintained the integrity of the dummy thorax such that LEDs were mounted to the sternum, rib, or rib inter-space while the chest compression was induced by the indenter. The fourth subseries entailed mounting an LED directly to the actuator of the test device and tracking its displacement. Indenter displacement and velocity were varied with each subseries. Following each test the RibEye data was separated into individual channels and CFC60 filter was used. RibEye deflection data were compared to the displacement of the indenter and with the chest displacement potentiometer data in the sternum-mounted subseries of tests.

Table 3.
Accuracy description of tests

LED Location	Loading	Compare with	Accuracy
Sternum	central sternum	pot + Indenter	x
Right rib 4	over LED	Indenter	x (+/- z deviation)
Right rib 4 (rotated thorax)	over LED	Indenter	x and y
Indenter extension	None	Indenter	x

Sternum-mounted LED tests evaluated the accuracy of RibEye detection of four LEDs mounted on the upper and lower corners of the sternum (Figure 16). The remaining eight LEDs were considered secondary and mounted on the sternum or, onto ribs two through five at either 8 or 9 cm from the midline. It was expected that the deflections from the corner mounted LEDs will match the internal chest potentiometer deflection. However, because of bib flexibility in the mid-size Hybrid III dummy chest, mismatch can occur between the internal chest potentiometer and the indenter.

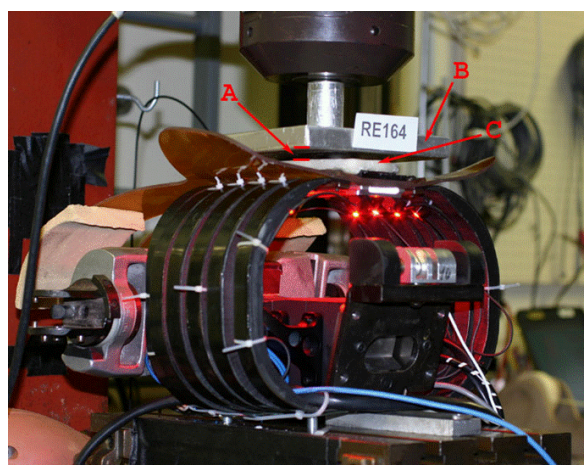

Figure 16. Test configuration for sternum-mounted loading. A: Offset for the trigger system, B: the Aluminum plate indenter, and C: PMMA leveler.

Rib-mounted LED tests were done using the standard z-location at the center of each rib and at a z-direction offset position of 1.5 cm from the center of each rib. The latter offset position corresponds to the interspace between adjacent ribs. An LED was mounted at the antero-medial rib margin of the right fourth rib (Figure 17).

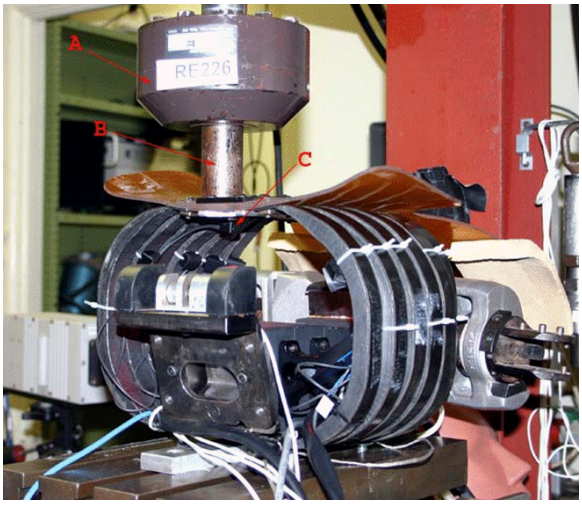

Figure 17. Test configuration for rib-mounted loading. A: indenter load cell, B: indenter, C: LED at right frontend stiffener plate at 4th rib.

Rib-mounted LED tests with rotated chest were conducted with the dummy chest rotated 13 degrees about its z-axis, as shown in Figure 18, and securely fixed to the cross table. The small circular indenter was placed directly over an LED attached to the right fourth rib at 8 cm from the sternum midline. and chest compression tests were performed.

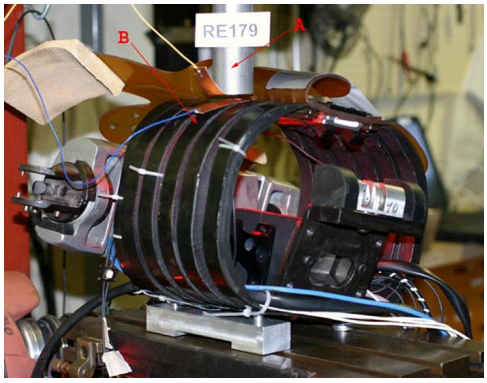

Figure 18. Photograph showing the setup for thorax rotated loading tests. A: indenter and B; right fourth rib.

Table 4 compares peak LED deflections with indenter displacements corrected for the initial rotation. In the subsequent subseries of indenter-mounted accuracy tests, an LED was mounted to an extension of the indenter that allowed for positioning of the LED directly under the rib of interest. The mid-size Hybrid III dummy sternum was modified to allow the indenter extension to pass between the ribs, but maintain the original thorax geometry (Figure 19). This configuration essentially produced an accuracy bench test that maintained integrity of both the mid-size Hybrid III dummy and RibEye system. Compression tests were performed at the left third and right sixth ribs. Velocities ranged from 0.08 m/s to 0.25 m/s with nominal deflections of 12 to 60 mm.

Table 4.
Right rib 4 LED deflections compared to indenter displacement in oblique thorax tests

Peak Indenter deflection (mm)	Peak Rib 4 deflection (mm)	Change (mm)	% Change
-15.8	-14.3	-1.5	-9.4
-21.9	-21.2	-0.7	-3.4
-28 5	-27.6	-0.9	-3.1
-40.8	-40.0	-0.8	-1.9

These tests indicated that the RibEye system is capable of capturing the ribcage deformations in the mid-size Hybrid III dummy. LEDs on the sternum respond similar to the available internal chest potentiometer. The accuracy of the system depends on where the LEDs are positioned on the rib, magnitude of rib deformation, and potential interference from devices such as the presence of the internal chest potentiometer. Optimum locations appear to be at a distance of 9 cm measured along the outer curvilinear path of the rib from mid-sternum on either side. At this positioning, the system showed no signal drop out at deflections representative of current frontal impact standards. However, it should be noted that eccentric z-axis placement of LEDs may result in loss of accuracy of deflection of measurements. The signal drop out depended on the type of indenter, with the diagonal indenter producing more signal loss and affecting accuracy. The deflections response along the x-and y-directions were deemed reasonable in oblique loading tests in these tests.

DYNAMIC EVALUATIONS

The RibEye system was also subjected to pendulum tests. Seven tests were conducted with the mid-size Hybrid III dummy in the neutral and two tests were conducted with the dummy in the 25-degree oblique position about the vertical (z) axis so that the pendulum impacted the right side of the thorax. The neutral positioning used in these tests followed specifications according to 49 CFR 572.34 [3].

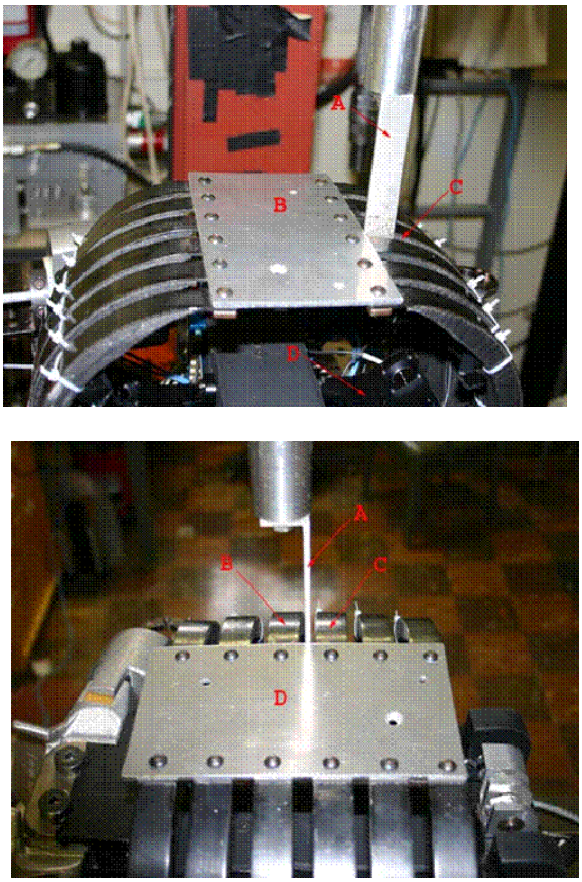

Figure 19. Setup used in indenter-mounted LED tests. Top: A: indenter extension, B: sternum modification, C: left 3-4 interspace, and D: RIbEye sensor head. Bottom: A: indenter extension, B and C: left third and fourth ribs, and D: sternum

Impact velocity measured with an optical system for Hybrid III thorax qualification tests ranged from 3.0 m/s to 6.6 m/s. The internal chest potentiometer was used in four of the neutral tests. It was not used in any oblique test. The initial test in this series (Test 1, probe velocity = 6.6 m/s) served as a thoracic impact calibration test. The maximum sternum deflection measured by the internal chest potentiometer, 67 mm, was within the qualification corridor in 49 CFR 572.34. Drop out did not occur in tests conducted at velocities ranging from 3.0 to 4.8 m/s, regardless of the presence or absence of the dummy internal chest potentiometer (Table 5). However, drop out occurred in three of twelve (25%) LEDs in the 6.6 m/s test in the neutral position with inclusion of the internal chest potentiometer. The analogous test without the potentiometer produced no drop out and implicated the chest pot slider arm as the source of sensor interference.

Table 5.
Summary of pendulum test data

ID	1	2	3	4	5
Position	N	N	N	N	N
Velocity (m/s)	6.6	4.1	3.0	4.1	4.1
Chest pot use	Y	Y	Y	Y	N
Pot def (mm)	66.8	39.5	27.0	41.1	-
LED drop out	3	0	0	0	0
% drop out	25.0	0.0	0.0	0.0	0.0

ID	6	7	8	9
Position	**N**	N	O	O
Velocity (m/s)	3.0	6.6	4.1	4.8
Chest pot use	N	N	N	N
Pot def (mm)	-	-	-	-
LED drop out	0	0	0	0
% drop out	0.0	0.0	0.0	0.0

Figures 20-22 include deflections along the x-direction from the upper, middle, and lower ribs with LED drop out associated with the lower rib output. The internal chest potentiometer data are also included in all plots. Rib deflection profiles closely followed the sternum deflection measured by the chest potentiometer in both timing and shape. The morphologies of these profiles were found to be similar. As expected, rib deflections were lower than the sternum deflection secondary to positioning of LEDs on the ribs and rib motion during compression. Because of the three-dimensional nature of the ribcage and off-central locations of the LEDs,

sternum-measured displacements were greater than the displacements recorded by the LEDs positioned on the ribs.

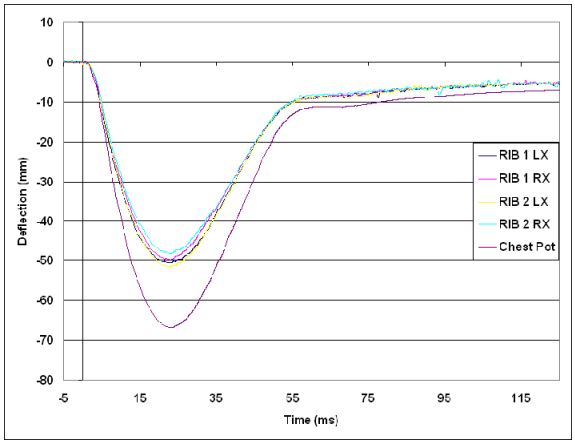

Figure 20. Comparison of deflections in the x-direction from the internal chest potentiometer and LED positioned at 9 cm on ribs one and two during 6.6 m/s pendulum test.

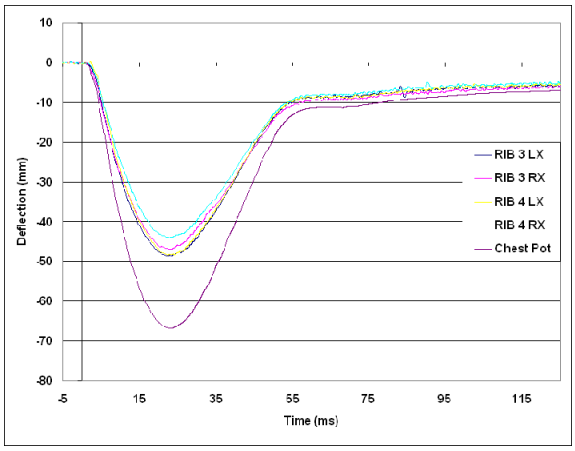

Figure 21. Comparison of deflections in the x-direction from the internal chest potentiometer and LED positioned at 9 cm on ribs three and four during 6.6 m/s pendulum test.

Figure 23 shows deflections along the y-direction. The ribs on the right side deflect along the positive y-direction while the opposite is true for the left side (hoop deformation). This expected response is reflective of central loading of the mid-size dummy chest during impact from the pendulum.

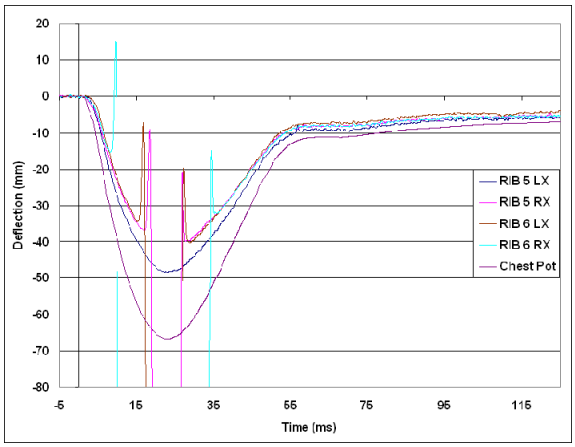

Figure 22. Comparison of deflections in the x-direction from the internal chest potentiometer and LEDs positioned at 9 cm on ribs five and six during 6.6 m/s pendulum test. Drop out occurred in three LEDs.

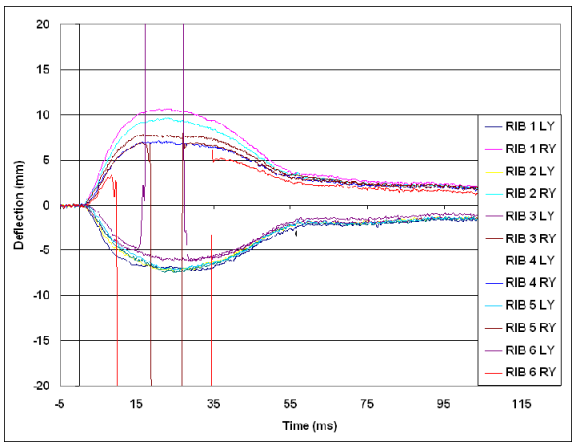

Figure 23. Deflections in the y-direction from LEDs positioned at 9 cm on all ribs during 6.6 m/s pendulum test. Drop out occurred in three LEDs.

Figures 24-26 include deflections along the x-direction from the upper, middle, and lower ribs for the test without the internal chest potentiometer. No signal drop out occurred in these evaluations. Figure 27 shows deflections along the y-direction for all LEDs demonstrating no drop out.

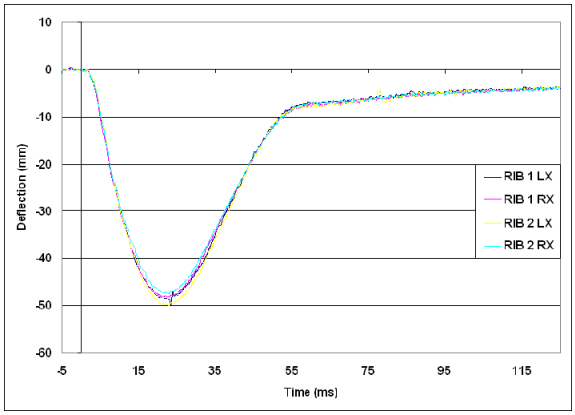

Figure 24. Deflections in the x-direction from LEDs positioned at 9 cm on ribs one and two during 6.6 m/s pendulum test.

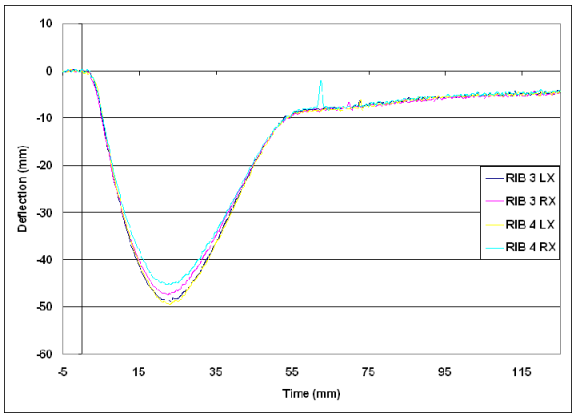

Figure 25. Deflections in the x-direction from LEDs positioned at 9 cm on ribs three and four during 6.6 m/s pendulum test.

Figures 28-30 include deflections along the x-direction from the upper, middle, and lower ribs for the oblique test. The right side ribs demonstrated greater deflection magnitudes in the x direction compared to the left side ribs. This is reflective of the right oblique chest loading imparted by the pendulum. No signal drop out occurred in these evaluations. Figure 31 shows deflections along the y-direction for all LEDs, again demonstrating no drop out. These deflections were approximately the same magnitude, which would be expected because the loading is from the right to the left side causing a deflection of all ribs toward the left side.

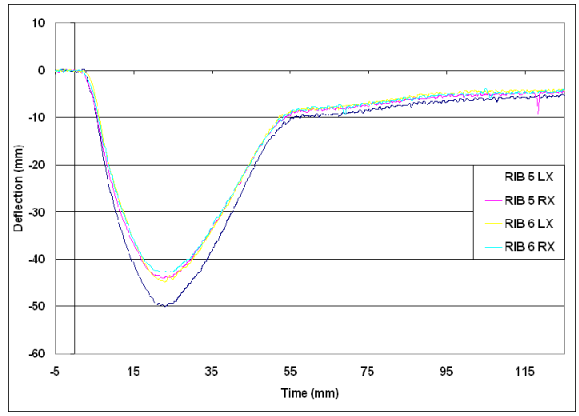

Figure 26. Deflections in the x-direction from LEDs positioned at 9 cm on ribs five and six during 6.6 m/s pendulum test.

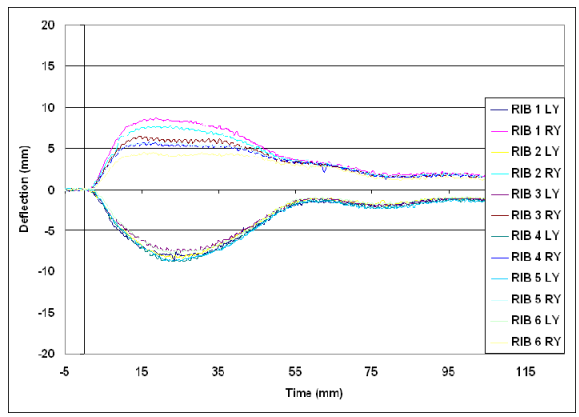

Figure 27. Deflections in the y-direction from LEDs positioned at 9 cm on all ribs during 6.6 m/s pendulum test.

The system evaluated is with specific reference to the mid-size Hybrid III dummy. As the construction of the dummies is different for different sizes even in the Hybrid III family, the same system cannot be incorporated into the other dummies. In the same vein, while a modified system has the potential to be incorporated into other types of dummies, the present evaluations should be considered only as a first step in the performance of such systems. It should be noted that the system is stand-alone and requires integration into standard data acquisition systems that are used in routine crashworthiness tests, and the sample frequency and recording time are fixed for the current version. In tests conducted in the present

evaluation study, occasional data download issues included browser and system re-boots in addition to data delimiters were missing in six tests. Thus additional studies may be needed to resolve such issues.

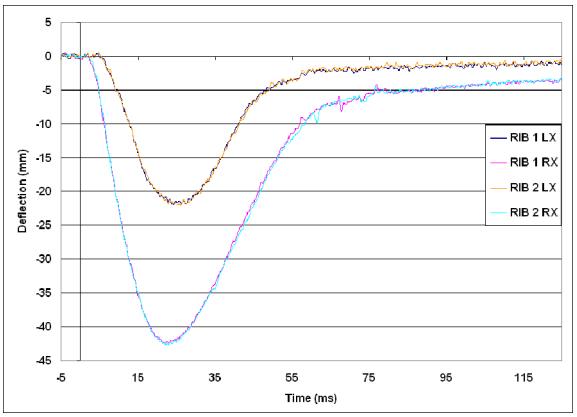

Figure 28. Deflections in the x-direction from LEDs positioned at 9 cm on ribs one and two during 4.8 m/s oblique pendulum test.

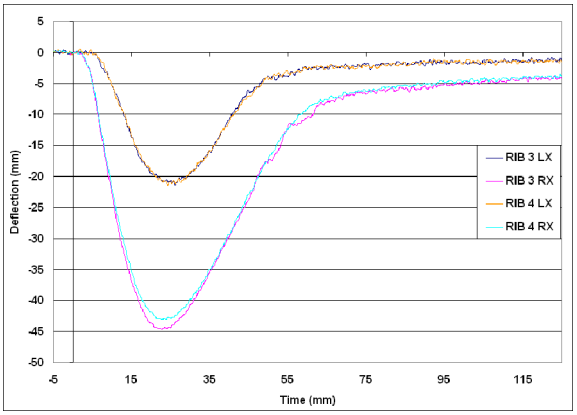

Figure 29. Deflections in the x-direction from LEDs positioned at 9 cm on ribs three and four during 4.8 m/s oblique pendulum test.

To summarize, the objective of the present study was to evaluate the RibEye system intended for obtaining deflections in impact-related tests. To achieve the objectives, signal drop out and accuracy assessment tests were conducted using quasi-static and dynamic loading conditions. The former series of experiments were conducted using a custom-designed testing device. In contrast, the latter dynamic tests were conducted using a pendulum impactor at velocities ranging from 3.0 to 6.6 m/s. Mid-size Hybrid III dummy internal chest potentiometer was used along with the testing device indenter records in the assessment processes.

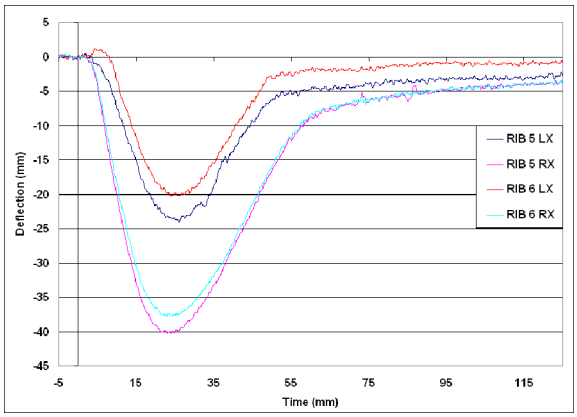

Figure 30. Deflections in the x-direction from LEDs positioned at 9 cm on ribs five and six during 4.8 m/s oblique pendulum test.

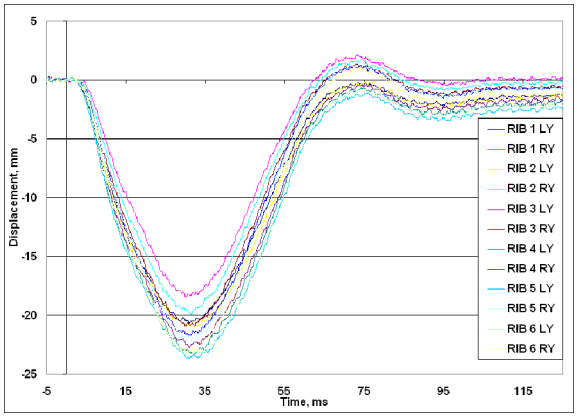

Figure 31. Deflections in the y-direction from LEDs positioned at 9 cm in all ribs during 4.8 m/s oblique pendulum test.

Signal drop out depended on the type of indenter, with the belt-type indenter producing more signal loss. The deflections response along the x-and y-directions were deemed reasonable in oblique loading tests. Results from dynamic tests indicated that light interference from internal components restricts the ability of the system to obtain deflections including signal drop out. In oblique tests, the

system captured the asymmetric motions of the chest by demonstrating greater deflections on all left side ribs than right side ribs, demonstrating its potential under this loading condition. These evaluations assist in understanding of the performance of the system as installed in the mid-size Hybrid III dummy.

ACKNOWLEDGMENTS

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Appendix A: RibEye data demonstrating drop out

Time (ms)	RIB5 LX	RIB5 LY	RIB6 LX	RIB6 LY	RIB1 RX	RIB1 RY	RIB2 RX	RIB2 RY
99.3	47.5	-118.6	46.3	-103.8	2	2	2	2
99.4	47.2	-118.5	47.1	-103.2	2	2	2	2
99.5	47.4	-119.0	46.7	-103.0	2	2	2	2
99.6	47.8	-119.2	46.6	-102.6	2	2	2	2
99.7	47.6	-119.2	46.1	-102.4	2	2	2	2
99.8	47.4	-119.3	45.8	-102.6	2	2	2	2
99.9	46.9	-119.4	45.5	-102.0	2	2	2	2
100	47.4	-118.8	46.2	-101.7	2	2	2	2
100.1	47.7	-118.9	45.9	-101.3	2	2	2	2
100.2	47.5	-119.4	46.0	-100.7	2	2	2	2
100.3	47.8	-119.4	1	1	2	2	2	2
100.4	47.0	-120.0	1	1	2	2	2	2
100.5	47.7	-119.0	1	1	2	2	2	2
100.6	47.8	-118.9	1	1	2	2	2	2
100.7	47.1	-119.7	1	1	2	2	2	2
100.8	47.0	-120.1	1	1	2	2	2	2
100.9	46.9	-120.4	1	1	2	2	2	2

Note: “1”: left sensor drop out; “2”: right sensor drop out; and “3”: would indicate drop out from both sensors.