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DEVELOPMENT OF A TIE-DOWN SYSTEM FOR TEMPORARY CONCRETE BARRIERS

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16. Abstract (Limit: 200 words)

During construction of highways and bridges, it is common for temporary concrete barriers to be installed near the edge of a roadway or bridge deck during construction. Free-standing temporary barriers placed close to the bridge deck edge pose a major safety hazard to errant vehicles as there is a significant risk for the barrier segments to be propelled off of the bridge. Previous testing of temporary barriers have shown deflections of more than one meter. These large dynamic deflections, in combination with a narrow gap located behind the barriers, would prove sufficient to push the barriers as well as the impacting vehicle off of the bridge deck. In 1998, researchers at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska-Lincoln (UNL) were approached to develop a tie-down system for this type of installation. This report details the development and testing of an NCHRP 350-compliant tie-down system for use with F-shape temporary concrete barriers.

Development of the tie-down system began with the creation and evaluation of several design concepts. Following the researchers' evaluation of the design prototypes, the steel strap tie-down concept was selected for further study. This concept consisted of a steel strap that connected to the barrier joints and then bolted to the concrete bridge deck. The steel strap tie-down was analyzed and redesigned using LS-DYNA finite element computer simulation modeling. The strap tie-down is comprised of a 76-mm x 6.4-mm x 914-mm piece of ASTM A36 steel bent into a trapezoidal shape. Holes are punched in the plate to allow the connecting pin at the barrier joints to pass through the strap as well as allow the strap to be anchored to the bridge deck at each end. Anchoring of the strap to the bridge deck is done using two of 19-mm diameter drop-in anchors for each strap. The steel strap tie-down was bogie tested to evaluate its performance.

One full-scale vehicle crash test, test no. ITD-1, was conducted according to Test Level 3 (TL-3) test no. 3-11 found in the NCHRP Report No. 350. The test consisted of a 2,012-kg pickup truck impacting the temporary barrier system at a speed of 97.6 km/h and at an angle of 24.3 deg. The impact occurred 1.2 meters upstream of the barrier joint. Results from the crash test showed that the system safely redirected the impacting pickup truck, and the test was judged to be successful according to the NCHRP Report No. 350 safety performance criteria. Based on the results of the NCHRP 350 compliance test, it is recommended that this design be approved for use on Federal-aid highways. Recommendations for proper application of the new design are also given.

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1 INTRODUCTION

1.1 Problem Statement

Roadway construction or work zones are found along almost all Federal, State, and local highways in the United States. In most cases, these roadways often require the redirection of vehicular traffic around or through the construction zone. Typically, temporary concrete barriers are used to separate the flow of traffic within the construction area. In general, temporary concrete barriers are segmented, precast units which are attached end-to-end by a load-bearing connection. The segmentation of the barriers allows them to be easily installed, repositioned, and removed from the work-zone region. The barrier system is designed to protect equipment and workers in the work zone, to prevent errant vehicles from leaving the traveled way, and to safely redirect those vehicles impacting the barrier.

During bridge construction, temporary barriers are often placed adjacent to the edge of a bridge deck in order to provide adequate lane width, as shown in Figure 1. However, freestanding barrier installations placed close to the deck edge pose a major safety hazard to errant vehicles as there is a significant risk for the barrier segments to be propelled off of the bridge. Previous testing of temporary barriers have shown deflections of more than one meter (1-2). Thus, large dynamic deflections, in conjunction with a narrow gap located behind the barriers, may prove sufficient to push the barriers off of the deck along with the impacting vehicle. Therefore, a need exists to develop a system to reduce barrier deflections and to restrain the barriers from falling off of a bridge.

1.2 Objective

In 1998, researchers at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska-Lincoln (UNL) were approached to develop a tie-down system for use with free standing,

Figure 1. Temporary Barrier Positioned Near Bridge Deck Edge

F-shape temporary concrete barriers. The design had to meet the safety requirements found in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (3), as well as six additional requirements. They are as follows:

(1) to limit the deflection and rotation of the barrier segments during a vehicular impact while limiting the damage to the bridge deck,

(2) to utilize the 3.81-m long barrier segments developed in a prior Midwest States' Regional Pooled Fund study,

(3) no permanent attachments may be placed within the concrete deck, such as epoxied stud anchors,

(4) drop-in anchors used in the system could penetrate a maximum of 127 mm into the bridge deck surface,

(5) all components of the tie-down system must be placed on the backside (non-traffic side) of the barrier, and

(6) the gap between the backside of the barriers and the bridge deck edge should be minimized and be no greater than 305 mm.

The objective of the research project was to develop and evaluate a tie-down system for use with temporary F-shape concrete barrier installations where restricted deflections are desired. The tie-down temporary barrier was designed to satisfy the Test Level 3 (TL-3) criteria set forth in the NCHRP Report No. 350.

1.3 Scope

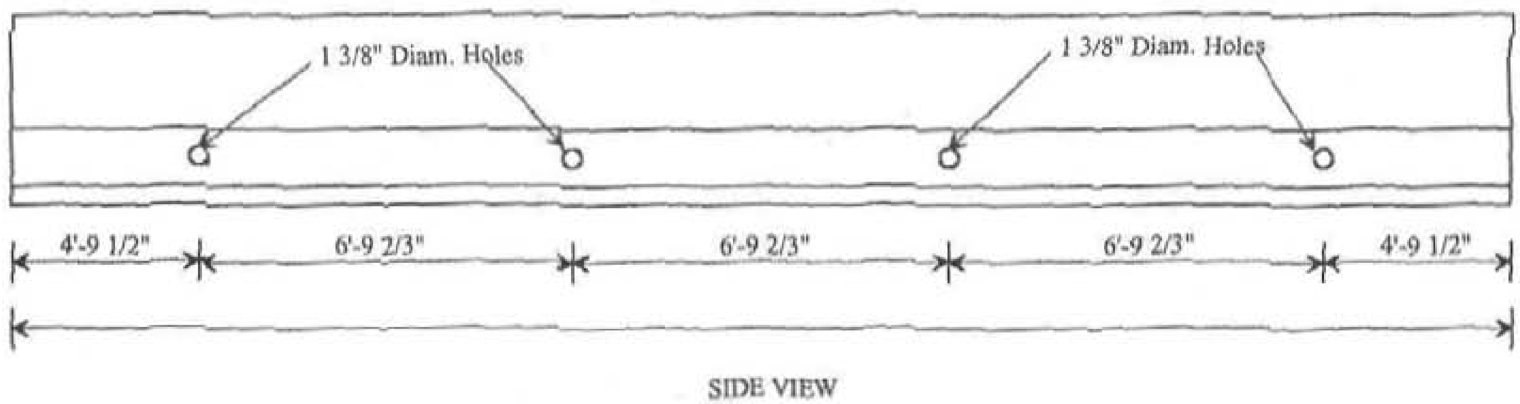
The research objective was achieved by performing several tasks. First, a literature search was performed in order to gain information about prior tie-down designs. Next, a series of design concepts were generated and evaluated. From these concepts, the best potential design was selected for further development. This design was analyzed and subjected to computer simulation modeling and then bogie tested until it was deemed ready for full-scale vehicle crash testing. The final design was crash tested according to the criteria set forth in NCHRP Report No. 350. A single crash test was conducted, consisting of an impact with a pickup truck weighing approximately 2,000-kg at a target speed of 100 km/h and a target angle of 20 degrees. The test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the tie-down system for temporary barriers.

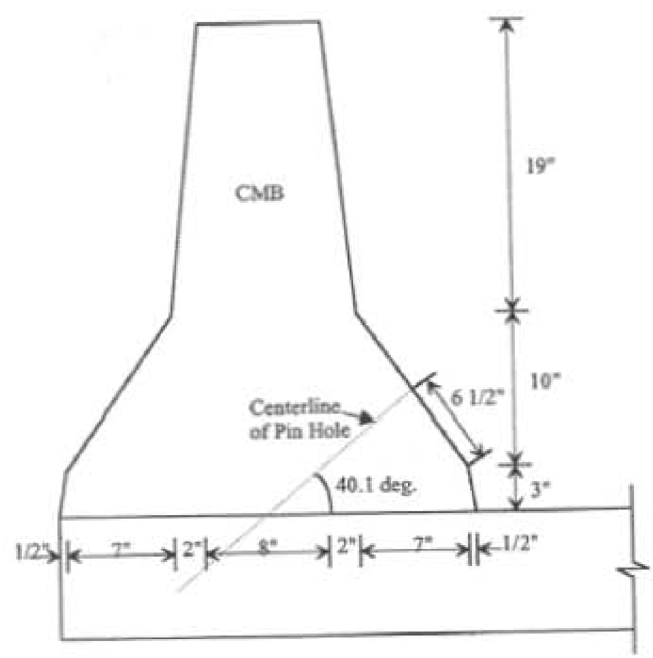
2 LITERATURE REVIEW

Temporary concrete barriers are a common safety device used in work zone and construction areas throughout the country. There are currently many temporary concrete barrier designs in use, but these designs vary widely in terms of steel reinforcement, joint connection, and segment length. The most common barriers in use are the New Jersey safety shape and the more recently developed F-shape and single-slope barriers. Currently, most of the Midwest states employ the NCHRP Report No. 350 compliant F-shape temporary concrete barrier developed by the Midwest Roadside Safety Facility (MwRSF) (1-2). As a result, this design was chosen as the base temporary concrete barrier for use in the development of the tie-down system.

As stated in the previous section, the goal of this research was to develop a tie-down temporary barrier system that could be installed in a situation where the deflection of the barriers must be constrained. The first phase of this work was to investigate previous research performed on this type of system. A literature review revealed that research on tie-down systems for temporary barriers has been previously conducted by both the Texas Transportation Institute (TTI) and the California Department of Transportation.

In 1993, TTI developed and tested a tie-down system for portable concrete barriers that was compliant with the NCHRP Report No. 350 safety criteria for longitudinal barriers (4). The TTI system consisted of 9.1-m long barrier segments that were constrained by a set of four 31.8-mm diameter by 521-mm long steel pins that passed through 35-mm diameter holes drilled into the front of the barrier and into the concrete slab, as shown in Figure 2. The holes were drilled at an angle of 40.1 degrees in order to maximize the constraint on the barrier while keeping the depth of the pins to a minimum. The vertical depth of the pins was 127 mm into the pavement. The maximum





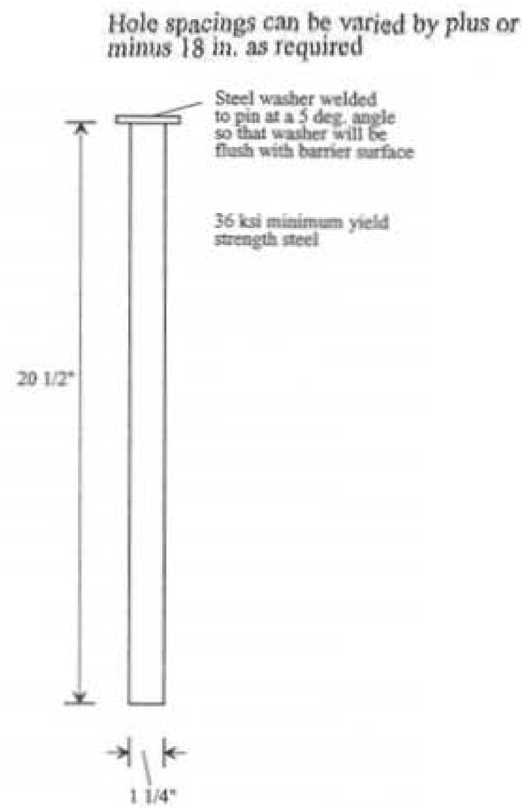


Figure 2. TTI Tie-Down Temporary Barrier System Details

permanent set and dynamic deflections measured during the testing of the system were found to be 200 mm and 400 mm, respectively.

While the TTI system demonstrated acceptable performance, there were several factors that prevented MwRSF researchers from adopting a similar design. First, the TTI system was developed for 9.1-m long portable concrete barrier segments which were significantly longer than the 3.81-m long segments identified for this project. Second, the TTI system was tested using both a channel splice and a grid slot connection. These connections are both significantly stiffer than those used with the MwRSF F-shape barrier, and therefore, helped to decrease the deflections observed in the TTI design. Finally, the researchers believed that TTI's angled pin concept could potentially cause significant damage to the bridge deck during an impact event, and it was desired that this damage be avoided.

A second tie-down temporary barrier system, a K-rail system developed by the California Department of Transportation, was also successfully tested to NCHRP Report No. 350 criteria (5). The K-rail system consisted of 6.1-m long segments of New Jersey safety shape barrier connected by a pin and loop connection. Each barrier was constrained by a set of four 25-mm diameter by 610-mm long steel stakes that were driven into the ground through cast holes near the corners of the barrier, as shown in Figure 3. These stakes penetrated to a depth of 420 mm into the road surface. The system limited the dynamic and permanent set deflections to 254 mm and 70 mm, respectively. While the system adequately constrained the barriers, the K-rail system was tested on an asphalt surface, and therefore, its performance on a concrete bridge deck was unknown. The length and depth of the anchors required were also too long to meet the 127-mm maximum embedment limit set for this study. In addition, MwRSF researchers believed that the K-rail system could potentially

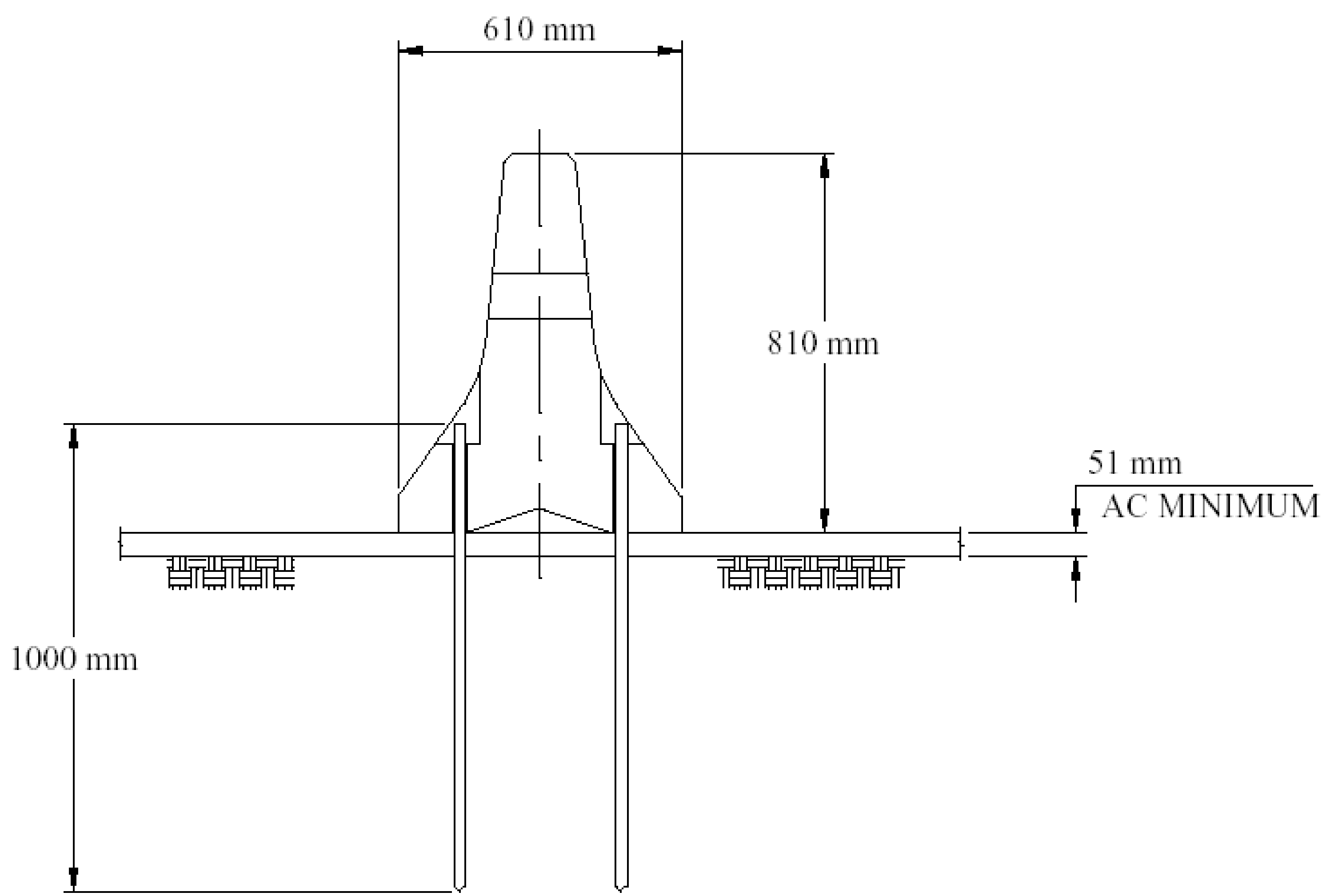


Figure 3. California Semi-Permanent K-Rail Barrier

cause significant bridge deck damage. Therefore, the K-rail system did not pose a viable solution to the problem facing the researchers.

Following the review of the previous research on tie-down systems for temporary concrete barriers, the researchers set out to develop a tie-down attachment for F-shape barriers that would meet the requirements set forth by the members of the Midwest States' Pooled Fund Program.

3 CONCEPT DEVELOPMENT

3.1 Initial Design Concepts

Initially, several tie-down concepts were developed for use with temporary concrete barriers which considered the relevant design goals and system constraints. The sponsors of the tie-down system development set forth the following design requirements.

(1) The system should constrain and limit the deflection and rotation of F-shape barriers installed on a bridge without causing significant damage to the concrete deck during an impact event.

(2) The system should utilize the 3.81-m long barrier segments developed in a prior Midwest States' Regional Pooled Fund study.

(3) The tie-down system must constrain the barriers with the use of limited anchorage to the bridge deck. No permanent attachments, such as the use of epoxied anchor studs or similar devices nor completely drilling through the bridge deck and attaching to the underside of the bridge, are allowed.

(4) Drop-in anchors could be no deeper than 127 mm into the concrete deck.

(5) All components of the tie-down system must be placed on the backside (non-traffic side) of the barrier.

(6) The gap between the barrier and the edge of the bridge deck should be minimized and be no greater than 305 mm.

A series of design concepts were created in order to meet these design requirements. Schematic diagrams of the design concepts are shown in Figures 4 through 5. The design concepts shown varied in their approach for constraining the motion of the temporary barriers. Two concepts,

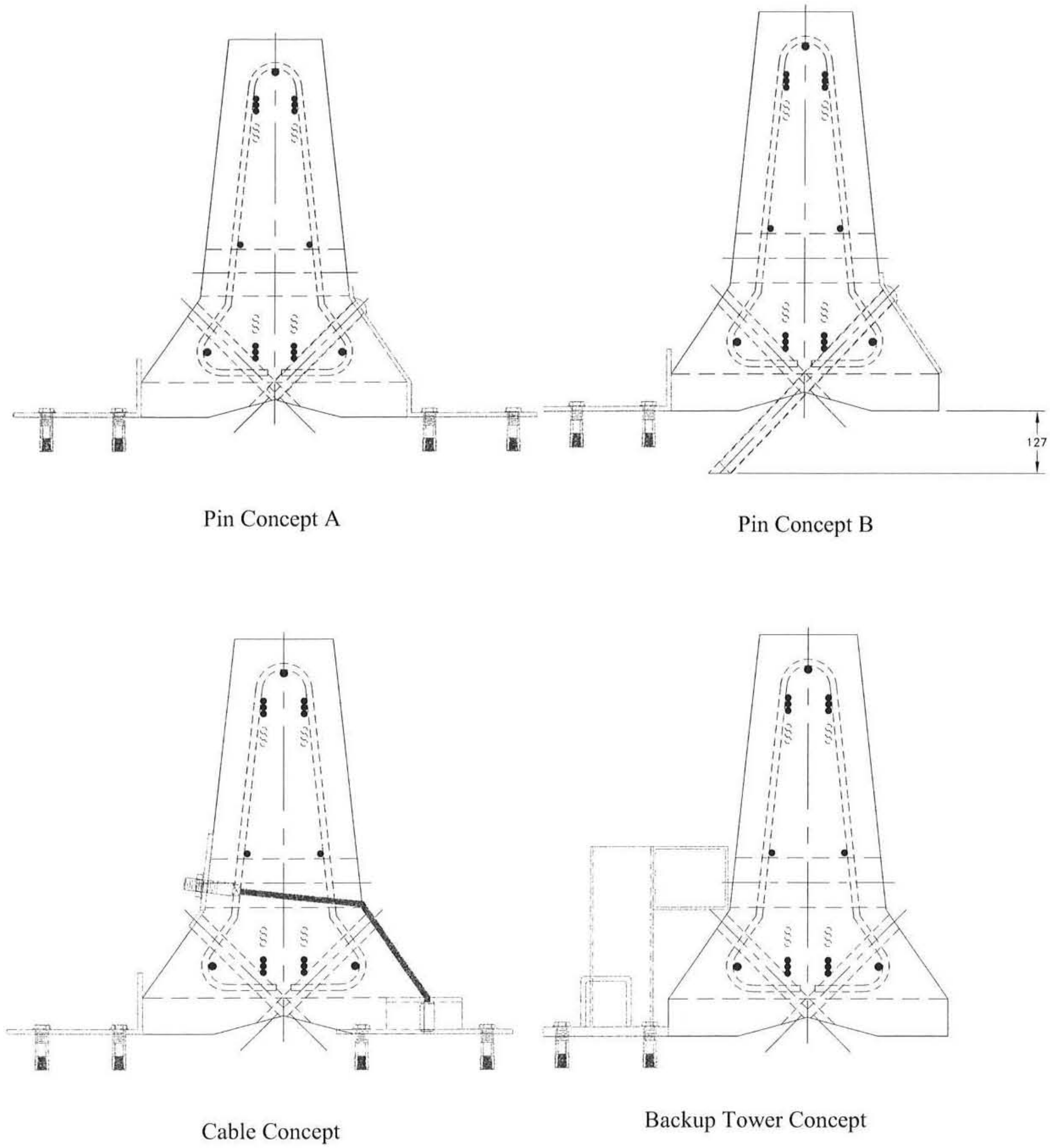
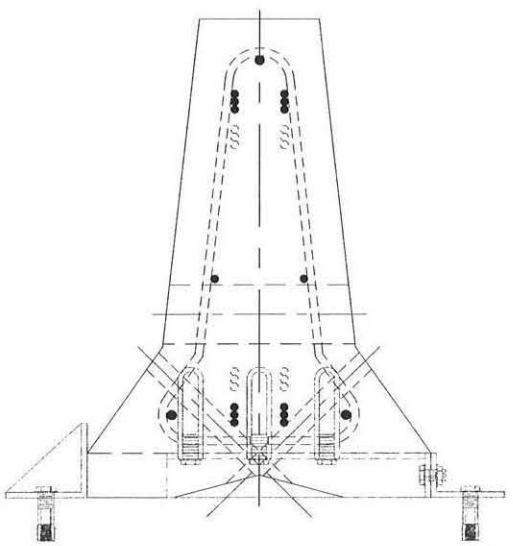
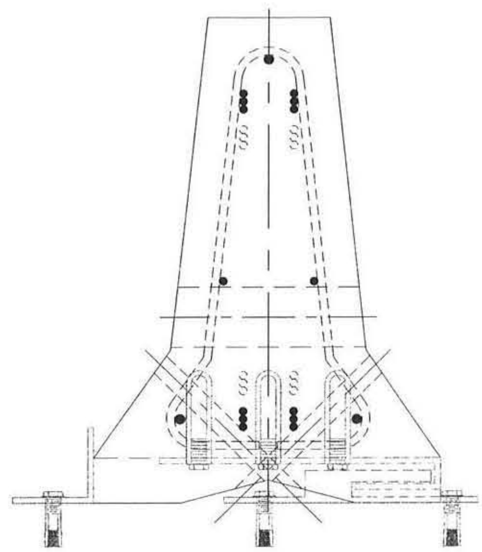


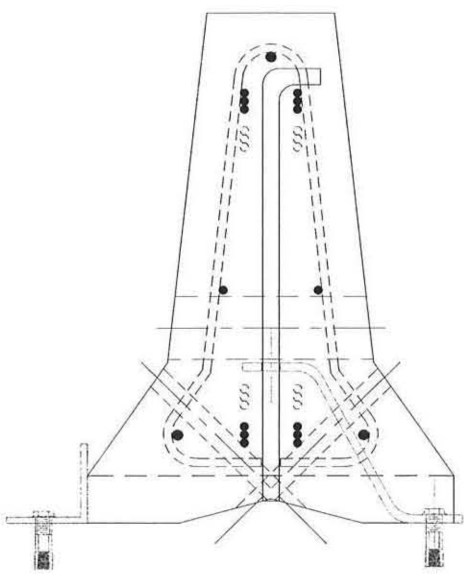
Figure 4. Tie-Down Temporary Barrier System Design Concepts



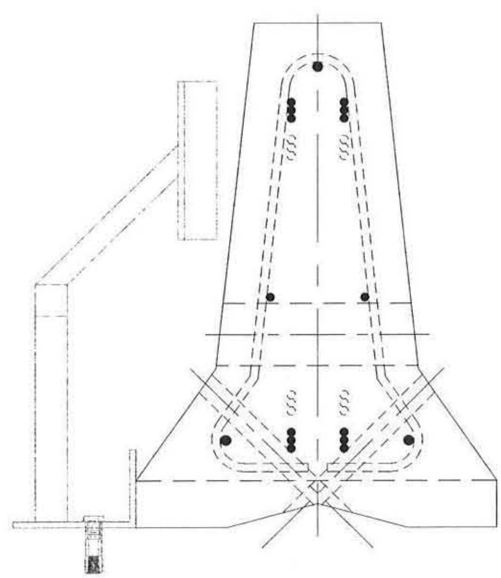
Anchored Base Plate Concept



Cleat Concept



Iowa Strap Concept



Energy Absorbing Tower Concept

Figure 5. Tie-Down Temporary Barrier System Design Concepts

pin concept A and pin concept B, were based on the use of angled steel pins, similar to the tie-down design developed at TTI, in conjunction with a kick-plate on the backside. The function of the kick-plate was to help reduce both the loads transferred to the pins and the deflection of the barrier segments. While similar systems had proven successful in the past, it was believed that the angled pin designs posed more potential for damage to the bridge deck than some of the other design concepts. Therefore, they were removed from consideration for the tie-down system.

Several of the other design concepts showed promise due to their original approach, but proved to be too complex or difficult to implement. The cable concept, consisting of a pair of cables that passed through the lifting holes in the barrier, in conjunction with a kick plate, was configured to prevent rotation and deflection of the barrier segments. However, this concept was eliminated due to the need to mount the cable and cable mounting plate hardware on the front side of the barrier segments. The anchored base plate and the cleat concepts were both based on constraining the motion of the barrier segments using a connection placed between the concrete deck surface and the underside of the barriers. However, initial analysis of the impact loads and required connections revealed that the attachment hardware would need to be installed along almost the entire barrier length. As a result, these two concepts proved to be both cost prohibitive and difficult to install. The final excluded design concept was the energy-absorbing tower concept. The energy-absorbing tower concept consisted of a large steel arm that was configured with an energy-absorbing head and used to reduce barrier deflections and rotations. However, this concept proved to be too large to be placed within the limited deck space behind the barriers.

As the majority of the design concepts for the tie-down system were ruled out, MwRSF researchers focused on the development of the two remaining concepts - the backup tower concept and the Iowa strap concept. Of the two concepts, it was initially believed that the backup tower provided the best opportunity for meeting the project objectives.

3.2 Backup Tower Concept

The backup tower consisted of a pair of steel tubes and spacer blocks welded to a base plate and attached to the bridge deck using 19-mm diameter drop-in anchors. During an impact, the backup tower located behind the temporary barriers would serve to reduce rotation and deflection of the barriers as long as sufficient anchorage was provided.

A significant research effort was put forth into the development of the backup tower concept, including finite element computer simulation modeling and bogie testing (6). A detailed discussion of this work is beyond the scope of this report; however, a copy of a paper summarizing this work is provided in Appendix A. The results from this research led to the development of the backup tower prototype, as shown in Figure 6, that was deemed ready for full-scale compliance testing.

Subsequently, the backup tower prototype was presented to the Midwest States' Pooled Fund members for review and comment. However, the returned comments on the backup tower design were not favorable. The sponsoring states believed that the backup tower design was too large and heavy to easily install, and that it required too many drop-in anchors. As a result, the states requested that a smaller system with less rigorous anchorage be developed. It was noted that reducing the size and quantity of the system's anchorage would result in a significant increase in barrier deflection. However, discussions with the states revealed that some deflection was acceptable. This was true as long as the deflections were reduced from those observed in tests on free-standing temporary barriers, and all of the barrier segments were restrained from falling off of the bridge deck. The researchers agreed with the states' comments and altered their focus toward a design concept that

Figure 6. Backup Tower Prototype

did not completely prevent barrier deflections like the backup tower, but instead allowed controlled barrier deflections while retaining the barrier segments on the bridge deck.

3.2 Strap Tie-Down Concept Development

After reviewing the design concepts previously developed for the tie-down temporary barrier design, it became apparent to the researchers that the Iowa Department of Transportation (IaDOT) steel strap concept could be developed to meet the sponsoring states' needs. The concept, as shown in Figure 7, was originally dubbed the "Iowa" strap tie-down system because it was based on the current IaDOT tie-down system for use with temporary barriers. The design consisted of a 12.7-mm thick steel strap attached to the ground with a epoxied threaded rod on one end, while the other end slips around the vertical pin located at the joint between barrier segments. The Iowa steel strap concept was intended to reduce the movement of the barrier joints, and thus reduce the deflection of the temporary barrier system.

Initial analysis of the Iowa steel strap concept showed that it had two fundamental design problems. First, the single anchor and size of the steel strap had insufficient strength to completely constrain the motion of the barrier joints during an impact, nor could the steel strap deform and absorb sufficient energy to significantly reduce barrier deflections. In addition, dynamic barrier analysis estimated that approximately three to five temporary barrier segments would be deflected off of the bridge deck edge during a vehicular impact into the design. In that event, the remaining straps in the Iowa steel strap system would have to be able to support the dead weight of the barriers deflected off of the deck. This fact lead to the second fundamental design problem with the Iowa steel strap design. Analysis of the straps showed that the steel strap and single drop-in anchor would not be capable of supporting the dead weight of three to five barrier sections, thus resulting in the

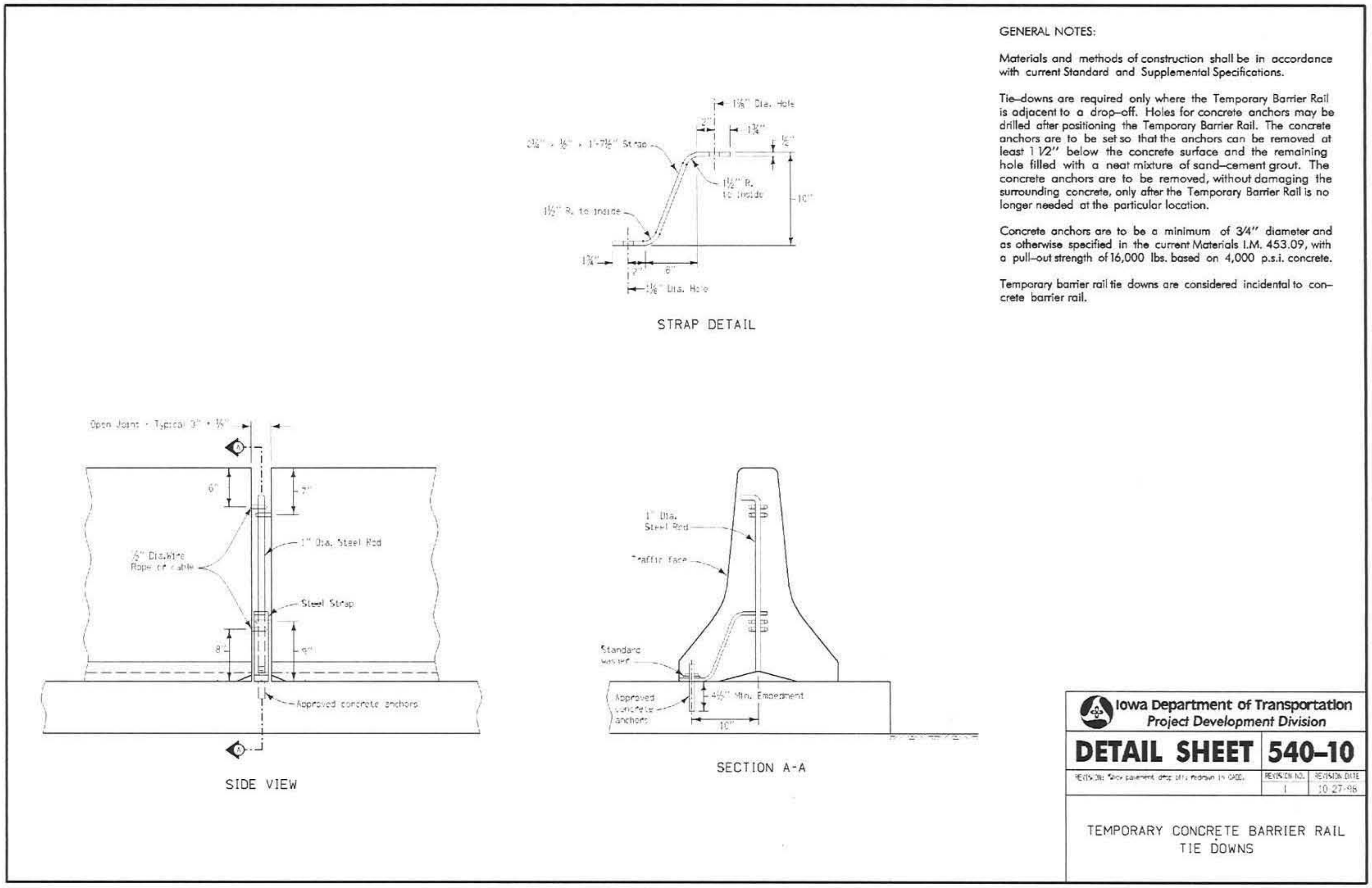


Figure 7. Iowa DOT Steel Strap Tie-Down System

temporary barrier system being incrementally pulled over the deck edge.

Based on this analysis, the researchers determined that the strap would need to be redesigned in order to absorb more energy during an impact and provide more load bearing capacity for retaining barriers already deflected off of the bridge deck edge. At this time, it was decided to apply LS-DYNA (7) finite element computer simulation modeling in order to study, redesign, and compare alternative tie-down strap designs. LS-DYNA is a nonlinear, transient finite element analysis code that has become the primary computer simulation code used in the modeling of vehicular impacts with roadside safety hardware. These computer simulations were used to analyze and evaluate incremental modifications for improving the integrity of the steel strap concept as well as to better understand their effect on the overall energy dissipation of the barrier system.

The basic simulation model used to compare the alternative strap tie-downs is shown in Figure 8. The model consisted of a steel strap, a base plate to represent the concrete, and an angled pipe to provide the loading of the strap. All three parts were modeled using shell elements. The strap was anchored to the base plate using spot welds to replicate the drop-in anchors. The spot welds were given failure criteria based on the ultimate shear and pullout loads of the 19-mm diameter drop-in anchors. The steel strap was loaded by prescribing a lateral motion of the pipe that replicated the motion of barrier joints during physical testing. Finally, the strap itself was given the proper material properties corresponding to ASTM A36 steel.

Analysis of alternative strap designs began with simulations on three plate thicknesses of the single steel strap. The plate thicknesses were 19 mm, 13 mm, and 6 mm. Typical results from these simulations are shown in Figure 9. Analysis of the results showed that the thicker straps were too stiff and allowed little deformation of the strap prior to the pullout of the drop-in anchor, while the

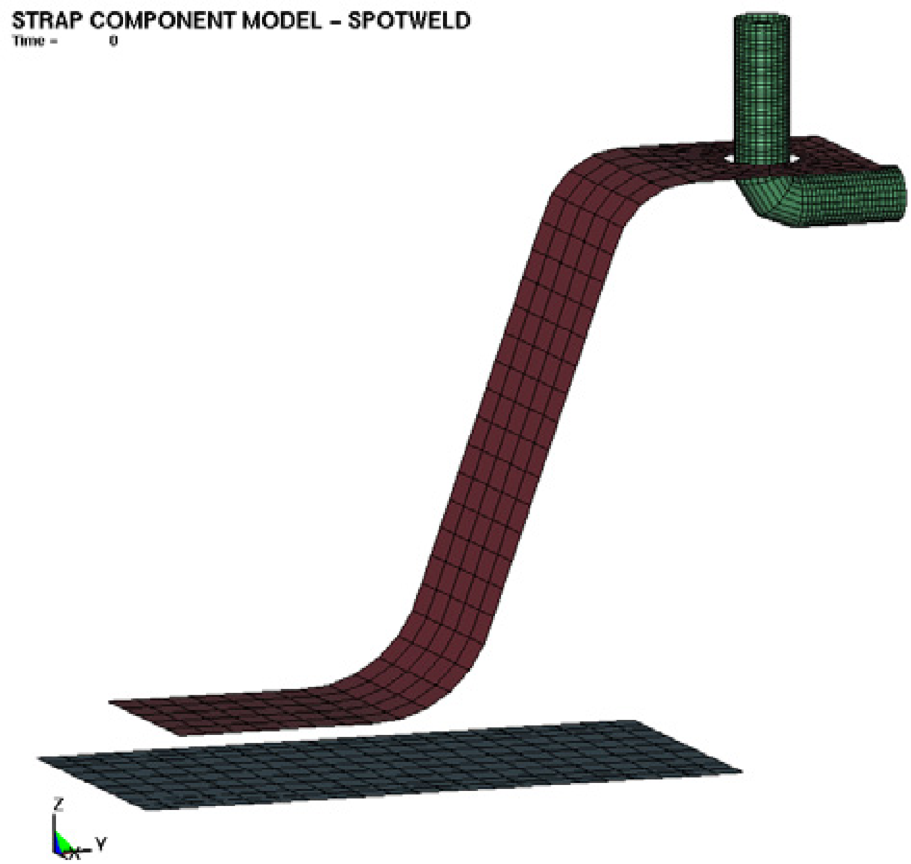


Figure 8. Strap Tie-Down Simulation Model

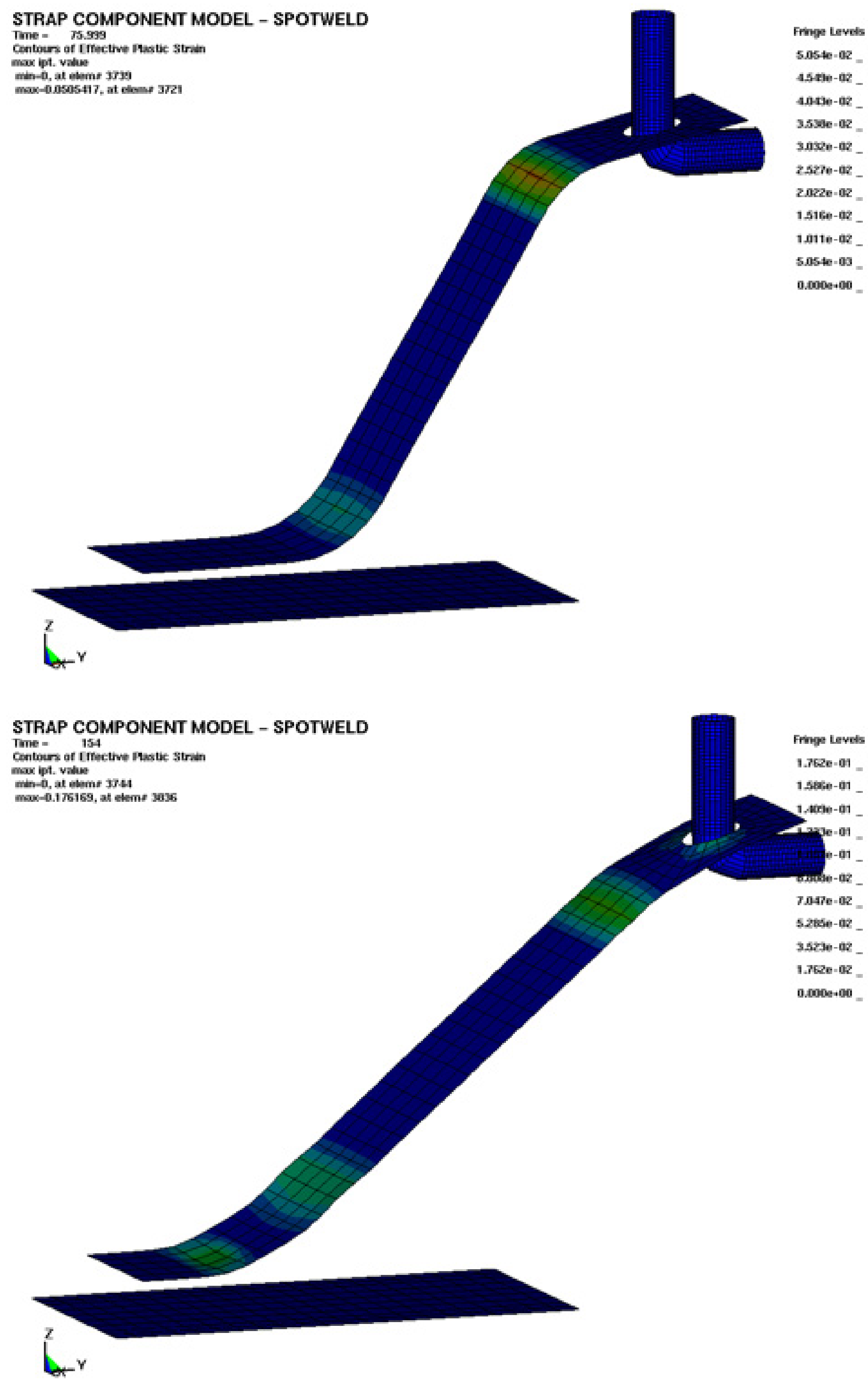


Figure 9. Strap Tie-Down Simulation

thinner straps allowed significantly more strap deformation and energy dissipation. A comparison of the energy versus deflection curves for the 19-mm and the 6-mm thick steel straps is shown in Figure 10. Based on these results, it was believed that the thinner 6-mm thick steel strap would prove the most useful because it allowed more energy to be absorbed during the loading of the strap.

Following a review of the simulation results of the 6-mm thick steel strap, further analysis was performed with regards to the tie-down strap used in combination with the full barrier system. Based on analysis of the energy absorbed by the tie-down straps, it was predicted that up to three barrier segments could be deflected off of the bridge deck. However, further calculations have shown that the tie-down straps had insufficient strength to support the dead load of three barriers deflected off of the deck with only a single drop-in anchor per strap. Therefore, an improved strap design with greater anchor capacity was needed.

A possible solution to the shortcomings of the original single steel strap design was proposed in the form of a two-sided or double strap design. The double strap design was generated by simply reflecting the single strap design about the vertical joint pin to obtain a strap with a trapezoidal shape, as shown in Figure 11. Doubling the steel strap provided two major improvements to the original single steel strap configuration. First, the double steel strap permitted the use of two drop-in anchors which ultimately allowed more load to be developed by the strap. In addition, the double steel strap design provided greater deformation of the strap prior to failure, thus resulting in increased energy dissipation.

A 6-mm thick double steel strap was simulated using LS-DYNA in the same manner as used for the single strap design. The results from this simulation, as shown Figures 12 and 13, showed very promising results. For example, the double steel strap allowed both higher loads and increased

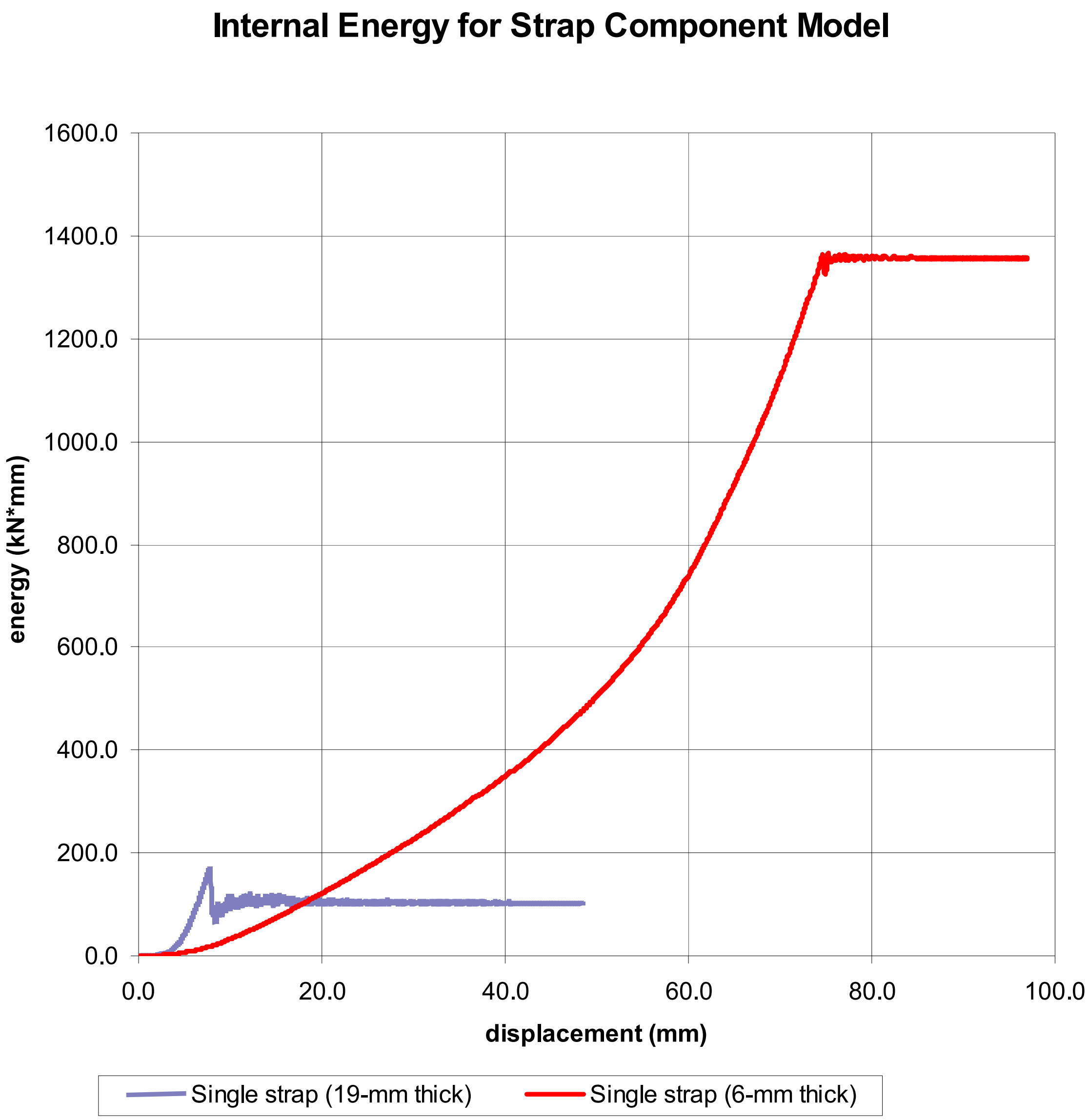


Figure 10. Single Steel Strap Tie-Down Simulation Model Energies

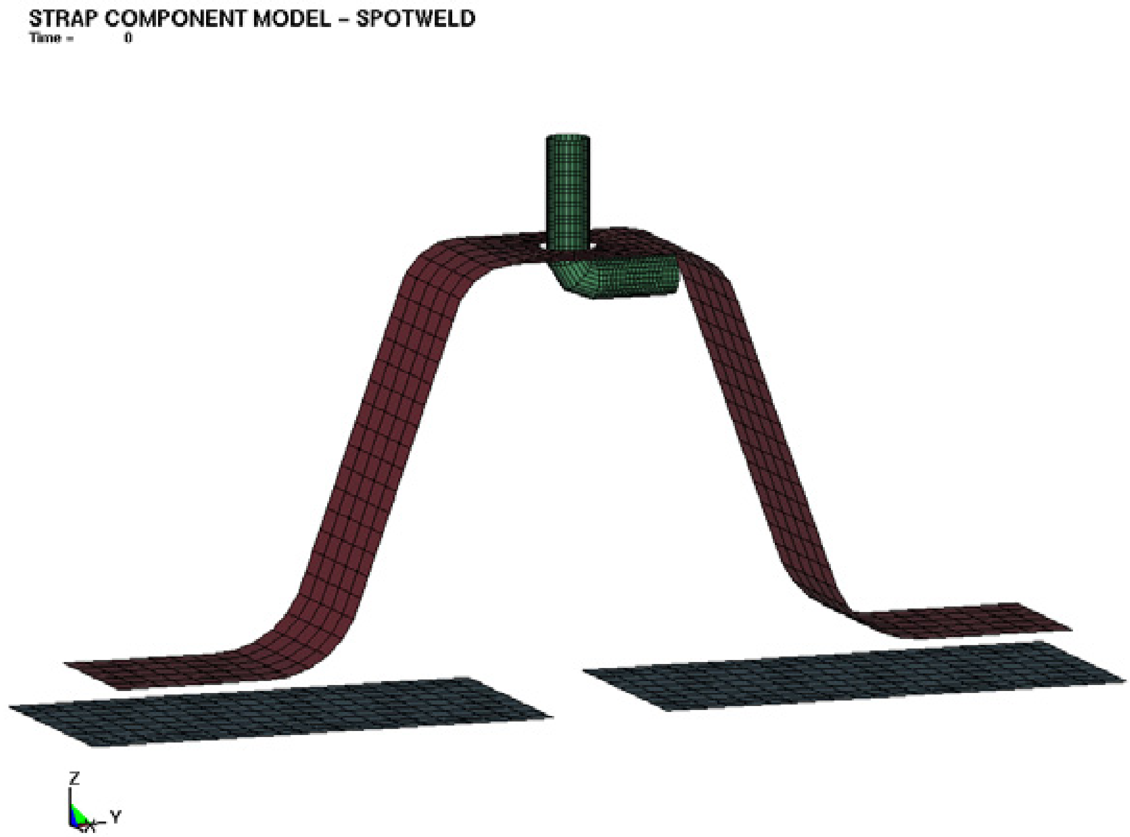


Figure 11. Double Steel Strap Tie-Down Simulation Model

Figure 12. Double Steel Strap Tie-Down Simulation

deformation, thus resulting in an increase in the energy absorbed. Figure 13 shows the energy vs. deflection curves for the 6-mm thick single and double strap designs. As shown graphically, the double steel strap absorbed approximately three times as much energy when compared to the single strap. In addition, calculations on the load capacity of the two-sided strap showed that two drop-in anchors per strap would be capable of supporting the dead weight of three barriers deflected off of the bridge deck edge.

In conclusion, the simulation results of the tie-down straps revealed that the double steel strap configuration was the best design alternative. Analysis showed that the design was capable of developing sufficient load to limit barrier deflections significantly, and that the remaining straps would provide adequate anchorage to restrain up to three barriers deflected off of the bridge deck edge. At this point, MwRSF researchers concluded that a simple component test of the double steel tie-down strap should be conducted in order to verify that the strap would develop the necessary loads and perform as desired before a full-scale test was conducted.

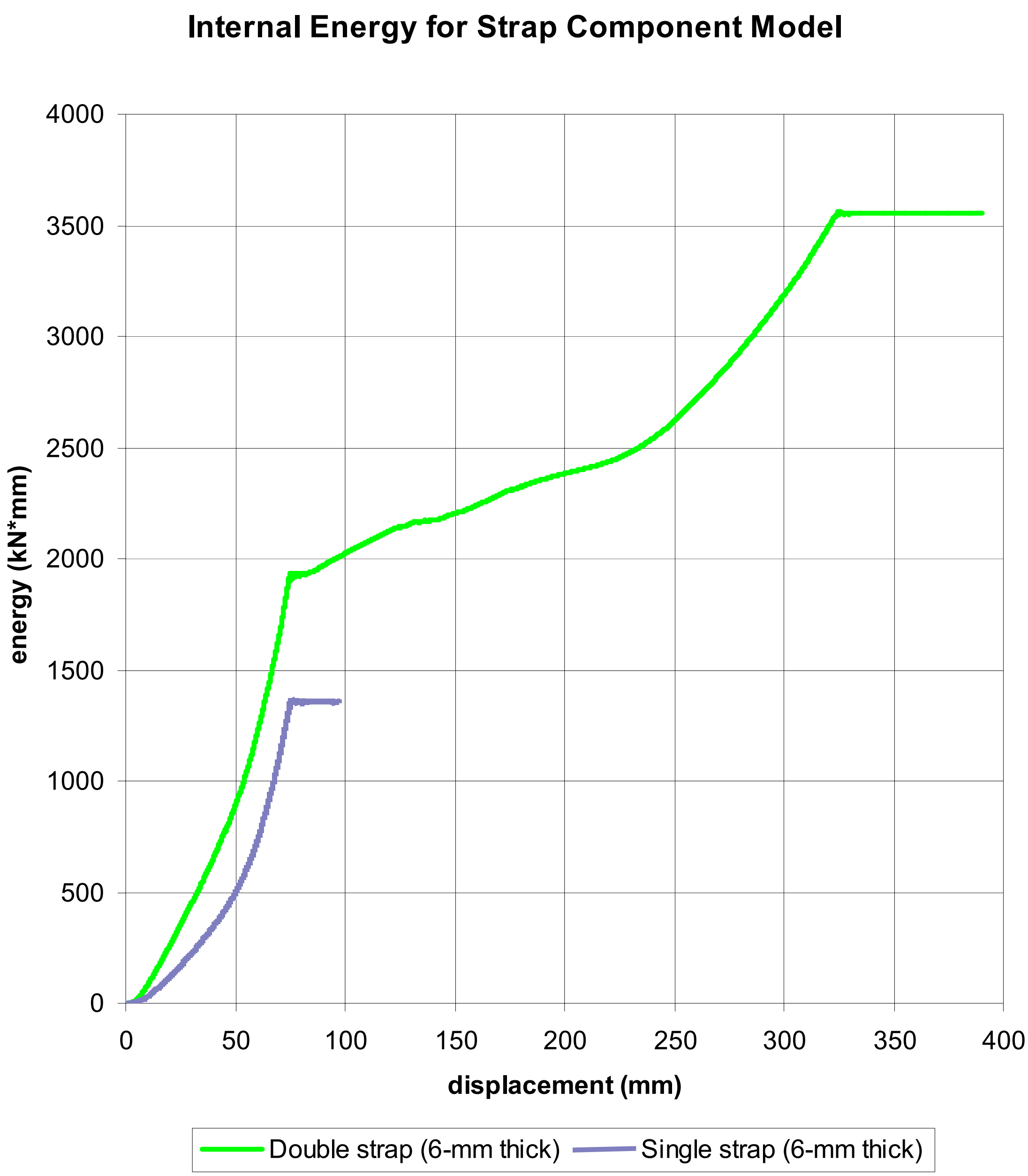


Figure 13. Comparison of Energy Absorption for the Single and Double Steel Strap Concepts

4 DEVELOPMENTAL TESTING OF TIE-DOWN STRAP

4.1 Test Matrix and Setup

Developmental testing for the tie-down system for use with F-shape temporary concrete barriers consisted of a single, dynamic bogie test of the double steel strap concept (test no. ITDB-2). As mentioned previously, this test was conducted in order to verify the performance of the tie-down strap used in conjunction with actual barriers. Specifically, the test was designed to evaluate the deflection of the strap, the failure of the drop-in anchors, and loading of the barrier joint and steel strap. The test was conducted by laterally loading a single barrier joint that contained one double tie-down strap. The barrier joint was loaded by a cable and nylon tow strap that was also attached to the back of a rolling bogie vehicle. When the cable slack was removed, the cable became taut and applied the dynamic load to the barrier joint. Details of the dynamic bogie test are given below.

4.2 Test Conditions

4.2.1 Bogie Vehicle

A rigid frame bogie was used to conduct the component testing. Photos of this bogie vehicle are shown in Figure 14. Additional details on the bogie vehicle are located in Appendix B. For the dynamic component test described herein, the rear end of the bogie was fitted with a W152 x 23.8 steel post which mounted on the two steel plates that bolted to the rear tube. The post served for mounting the tow cable used to load the system. Total weight of the bogie vehicle and its attachments was 2170 kg.

4.2.2 Bogie Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the bogie vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the bogie

Figure 14. Bogie Vehicle, Test ITDB-2

vehicle. The bogie guide track was 51.8-m long. The guide track was constructed with 57-mm diameter steel pipes, with wall thicknesses and lengths of 4.8 mm and 2,965 mm, respectively. The pipes were supported every 3,048 mm by steel stanchions. The bogie vehicle was released from the tow cable and the bogie guide track before the tow cable became loaded, allowing the bogie to become a free projectile as it came off the bogie guide track.

4.2.3 Strap Component Test Setup

For the strap component test, one of the double steel strap tie-down was installed at a single joint located between two Iowa F-shape concrete barrier segments. The steel strap was attached to the concrete by two Red Head 19-mm diameter drop-in anchors with 19-mm diameter x 57-mm long ISO Class 8.8 bolts. Two additional Iowa F-shape barrier segments were attached to the barriers comprising the joint to simulate the resistance of additional barriers in the system. These adjacent barriers were angled away from the barriers comprising the joint as much as possible in order to allow the joint with the steel strap to rotate freely. As mentioned previously, the joint containing the steel strap was loaded by passing a nylon tow strap through the joint and attaching the strap to a section of steel I-beam mounted across the backside of the joint. The tow strap was then passed out the front of the barrier joint and connected to a steel cable. Then, the cable was attached to the rear of the bogie vehicle. The bogie vehicle was pulled to a speed of 32.2 km/h. Once the desired speed was achieved, the cable was pulled tight and the barrier joint was loaded. Photographs of the test setup are shown in Figures 15 through 16.

4.2.4 Data Acquisition Systems

4.2.4.1 Accelerometer

A triaxial piezoresistive accelerometer system with a range of ±200 G's was used to measure

Figure 15. Configuration for Bogie Testing of Strap Tie-Down Concept, Test ITDB-2

Figure 16. Configuration for Bogie Testing of Strap Tie-Down Concept, Test ITDB-2

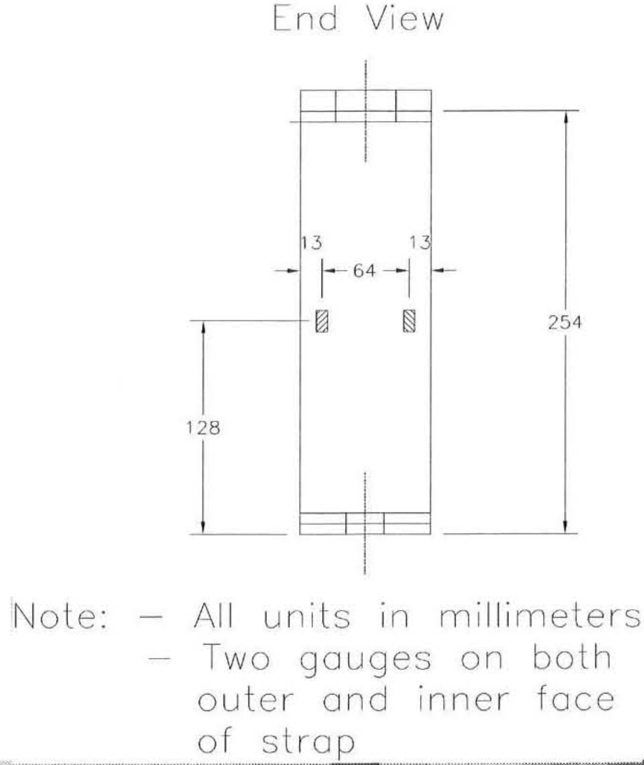
the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 3,200 Hz. The environmental shock and vibrations sensor/recorder system, Model EDR-3, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz lowpass filter. Computer software, “DynaMax 1 (DM-1)” and “DADiSP”, were used to digitize, analyze, and plot the accelerometer data.

4.2.4.2 Strain Gauges

For test no. ITDB-2, four strain gauges were installed on the tension side of the tie-down strap. Two of the gauges were mounted on the outer face of the strap while the remaining two gauges were mounted on the inner face. The strain gauges and their positioning on the steel strap are shown in Figure 17.

For the tests, weldable strain gauges were used and consisted of gauge type LWK-06-W250B-350. The nominal resistance of the gauges was 350.0 ± 1.4 ohms with a gauge factor equal to 2.02. The operating temperature limits of the gauges were -195 to +260 degrees Celsius. The strain limits of the gauges were 0.5% in tension or compression (5000 $\mu\epsilon$). The strain gauges were manufactured by the Micro-Measurements Division of Measurements Group, Inc. of Raleigh, North Carolina. The installation procedure required that the metal surface be clean and free from debris and oxidation. Once the surface was prepared, the gauges were spot welded to the test surface.

A Measurements Group Vishay Model 2310 signal conditioning amplifier was used to condition and amplify the low-level signals to high-level outputs for multichannel, simultaneous dynamic recording on "Test Point" software. After each signal was amplified, it was sent to a Keithly Metrabyte DAS-1802HC data acquisition board, and then stored permanently on the portable computer. The sample rate for all gauges was 5,000 samples per second (5,000 Hz), and



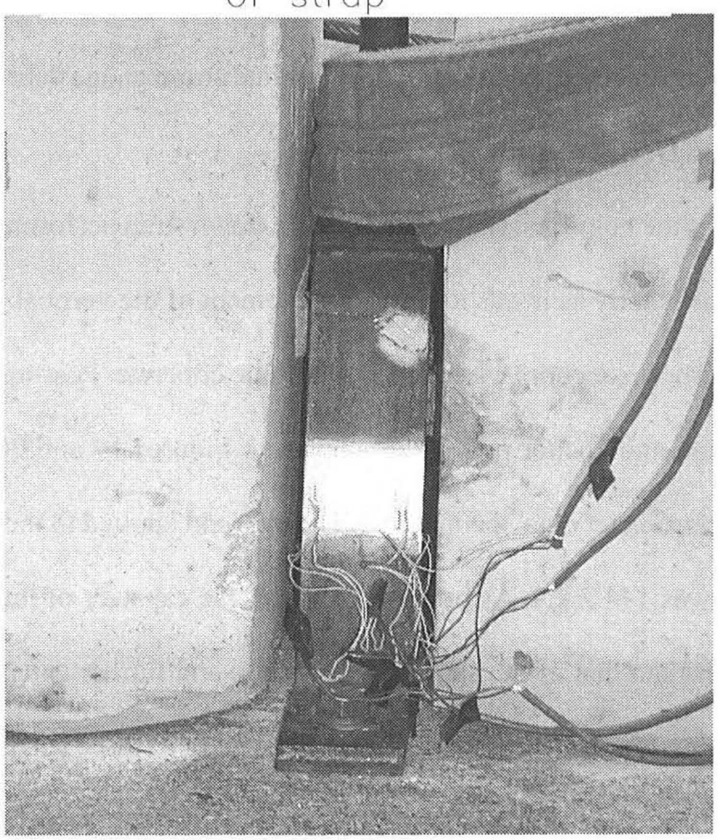


Figure 17. Strain Gauge Locations, Test ITDB-2

the duration of sampling was six seconds.

4.2.4.3 High-Speed Photography

For test no. ITDB-2, a high-speed Red Lake E/cam video camera, with an operating speed of 500 frames/sec, was mounted on a forklift platform directly above the barriers and provided an overhead view of the joint. Two Canon digital video cameras, with a standard operating speed of 29.97 frames/sec, were also used to document the test. One camera was placed upstream and to the right of the installation for an angled view, and the second was placed directly behind the barrier joint for a close of view of the strap.

4.3 Test Results

Bogie test no. ITDB-2 demonstrated the acceptable performance of the double steel strap tie-down design during joint loading of the temporary barrier system. Photographs of the test results are shown in Figures 18 through 20. Load deflection data and strain gauge data from the test are located in Appendices C and D, respectively.

The results of the bogie test showed that the tie-down strap performed as designed. The steel strap deformed significantly as it was loaded by movement of the vertical pin. With the steel strap deformation, both drop-in anchors were pulled out of the concrete. Post-test photographs detailing the strap deformation and anchor pullout are shown in Figures 19 and 20. As determined by an analysis of the accelerometer data, the maximum lateral load applied to the barrier joint containing the tie-down strap was 144.7 kN. As previously noted, the capacity of the double steel strap was significantly greater than that of the single strap design, and further calculations showed that the two-sided strap design was capable of supporting the weight of three barrier sections deflected off of the bridge deck. Based on the observed performance of the double steel strap design in the bogie

Figure 18. Bogie Test Results, Test ITDB-2

Figure 19. Bogie Test Results, Test ITDB-2

Figure 20. Bogie Test Results, Test ITDB-2

test, MwRSF researchers believed that the strap tie-down concept could be applied to safely reduce barrier deflections as well as to restrain barriers that may extend off of the bridge deck edge.

5 SYSTEM DETAILS

5.1 Strap Tie-Down Design Details

The final design of the tie-down system for use with temporary barriers consisted of two main components: (1) the Iowa F-shape temporary concrete barrier; and (2) the double tie-down strap. The Iowa F-shape temporary concrete barrier is an NCHRP Report No. 350-approved barrier system that was previously developed and tested by MwRSF (1-2). The barrier is composed of 3.81-m long concrete barrier segments, as shown in Figures 21 and 22. Barrier reinforcement consisted of eleven No. 4 vertical stirrups and five longitudinal bars - three No. 5 rebar and two No. 4 rebar. All of the steel reinforcement used in the barriers conformed to ASTM A615 Grade 60 specifications.

The Iowa F-shape temporary barriers used a constrained pin and loop type connection comprised of two sets of rebar loops on each barrier. Each loop was comprised of a triple loop of ASTM A615 Grade 60 MPa No. 4 rebar. The vertical pin used in the connection consisted of a 32-mm diameter x 692-mm long round bar composed of ASTM A36 steel, as shown in Figure 23. The pin was constrained using two 106-mm x 64-mm x 13-mm ASTM A36 steel plates with a 35-mm diameter hole centered on them. The upper plate was welded 25 mm below the top of the pin, while the second plate slid over the bottom end of the pin and was held in place by a 13-mm diameter x 254-mm long ISO Class 10.9 keeper bolt. This bolt passed through a 16-mm hole near the bottom of the pin.

The second main component of the tie-down temporary barrier system was the double tie-down straps used to constrain the motion of the barrier joints. The details for the tie-down strap and its connection to the barrier system are shown in Figures 24 through 26. The steel strap consisted

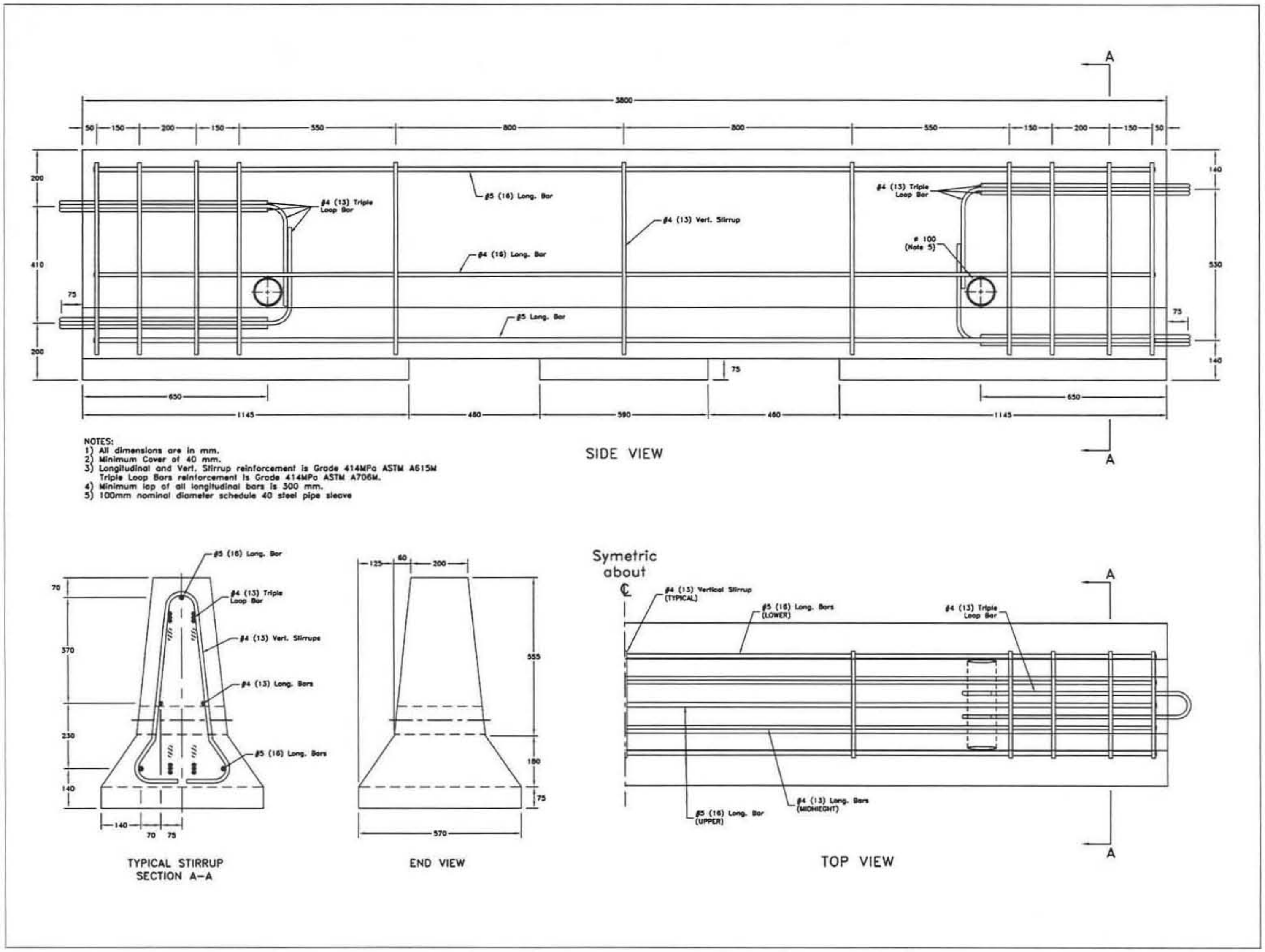


Figure 21. Iowa Temporary Barrier Details

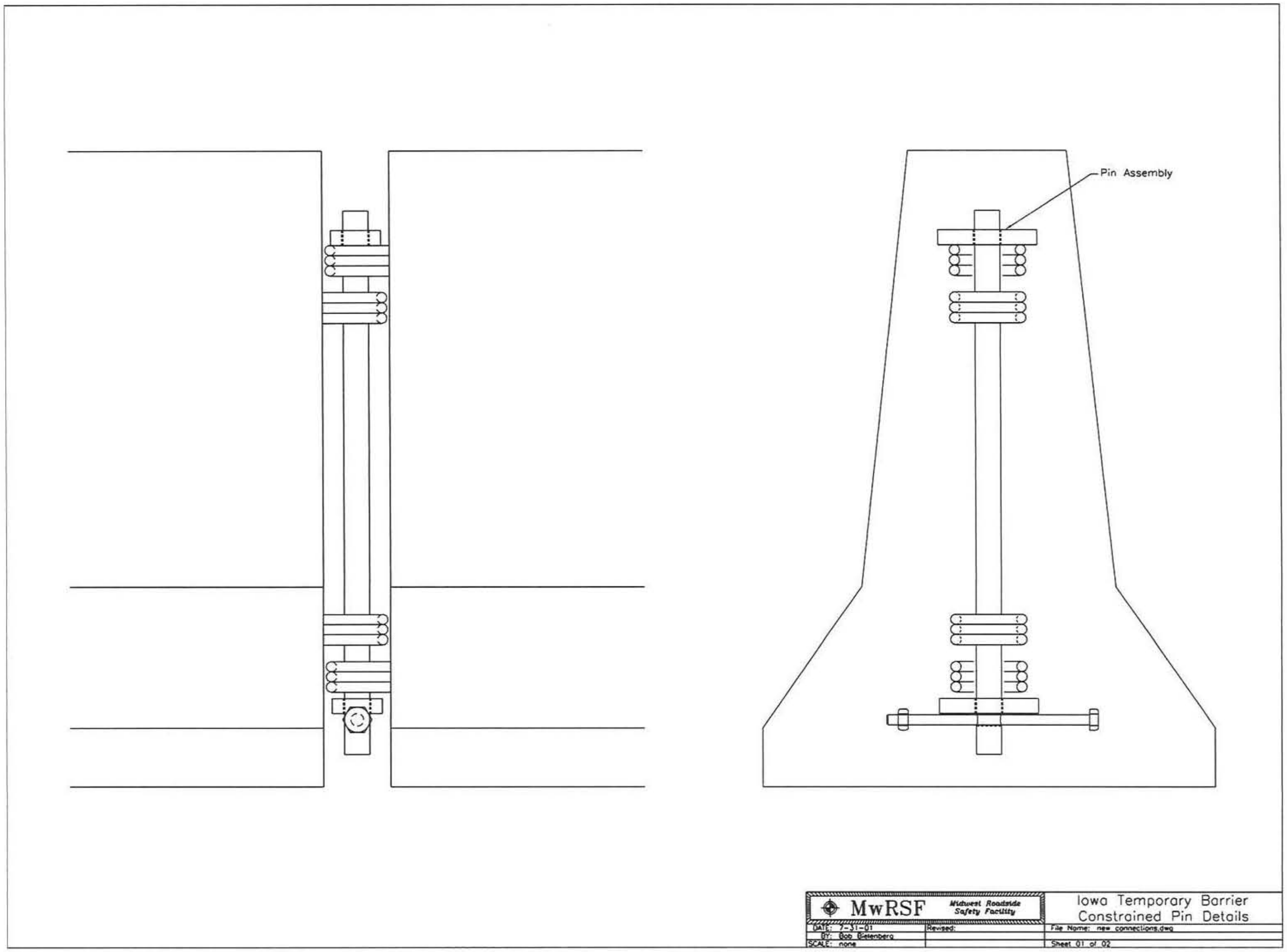


Figure 22. Iowa Temporary Barrier Details

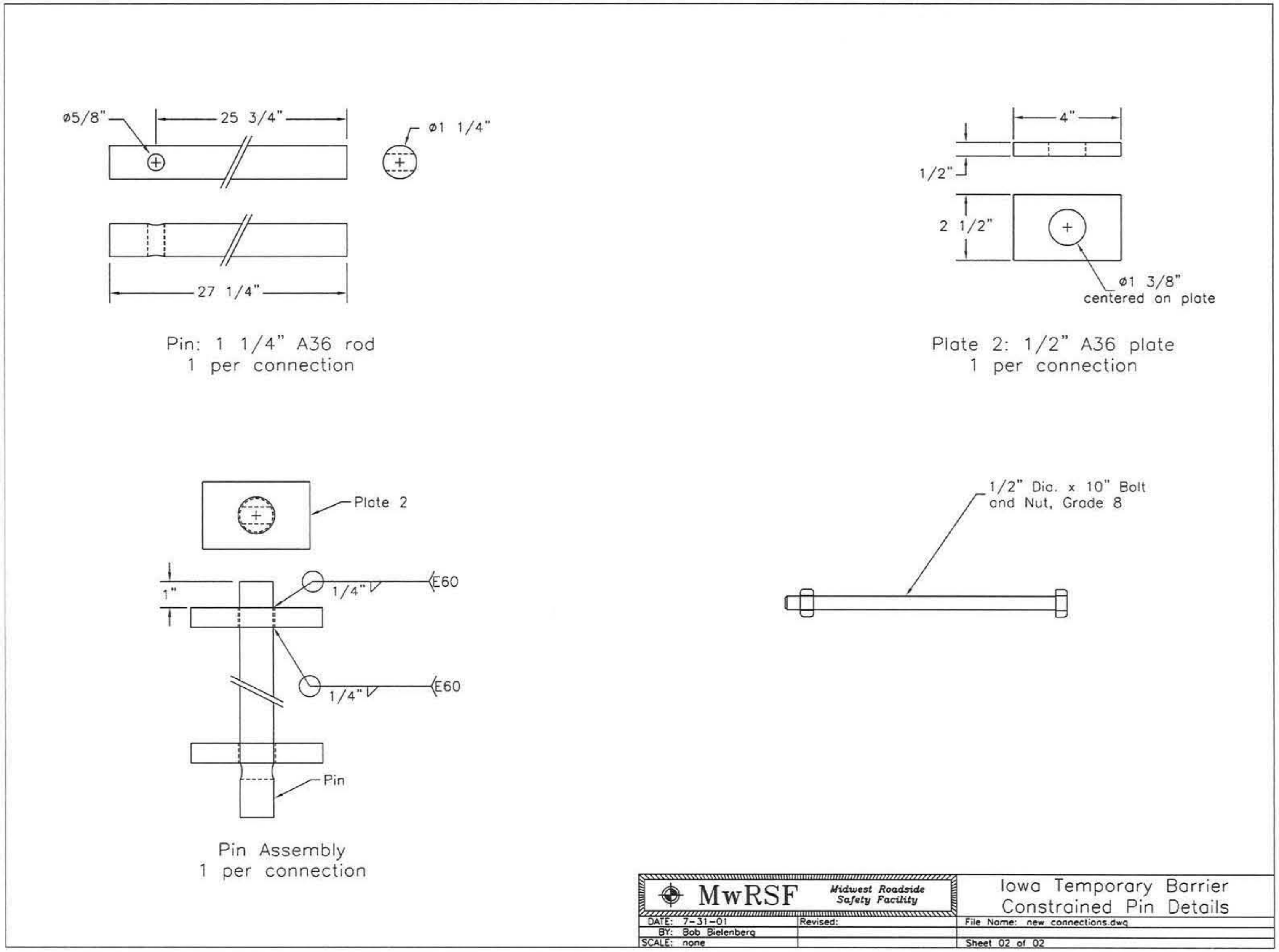


Figure 23. Iowa Temporary Barrier Details

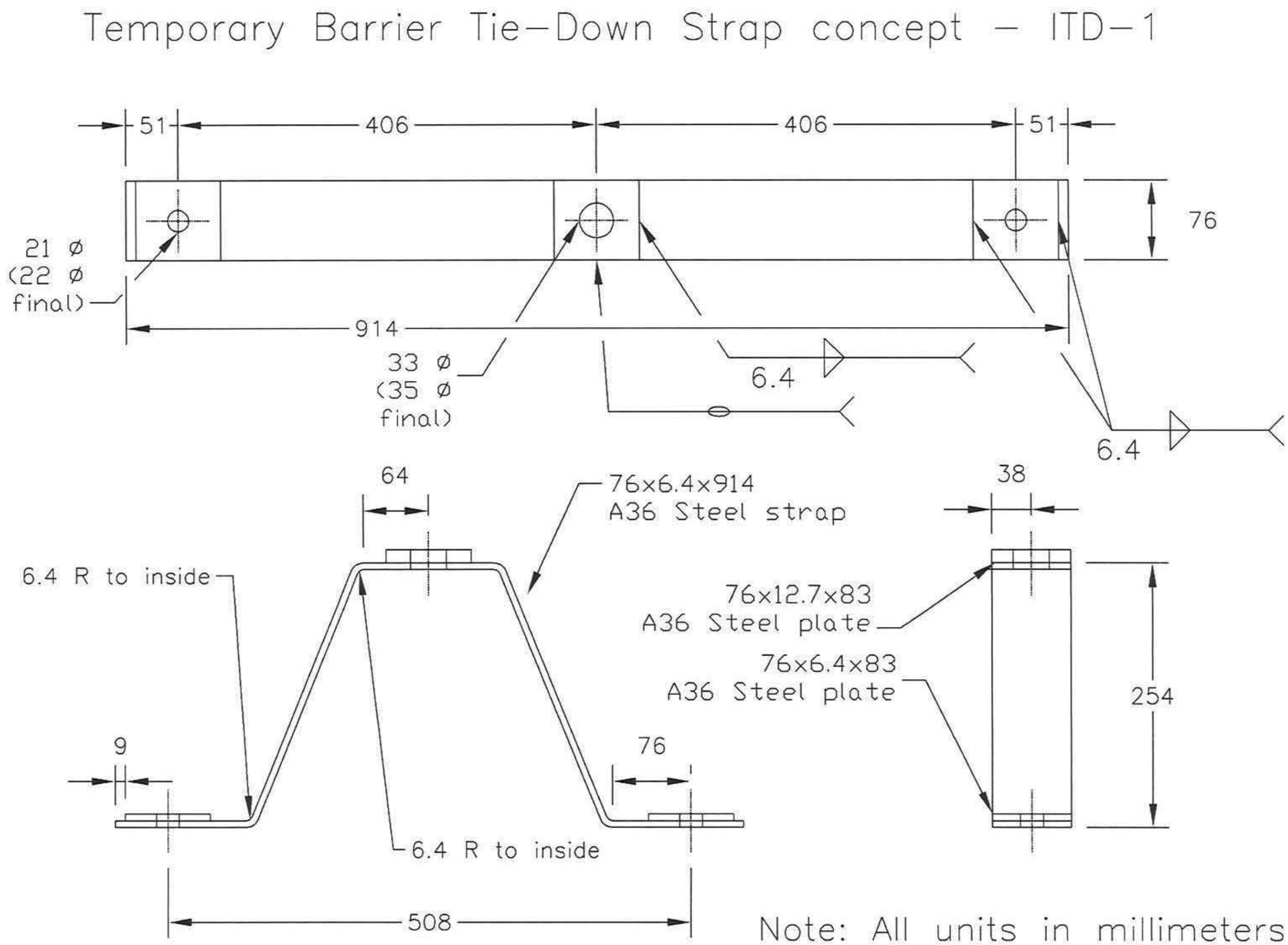


Figure 24. Double Steel Strap Details

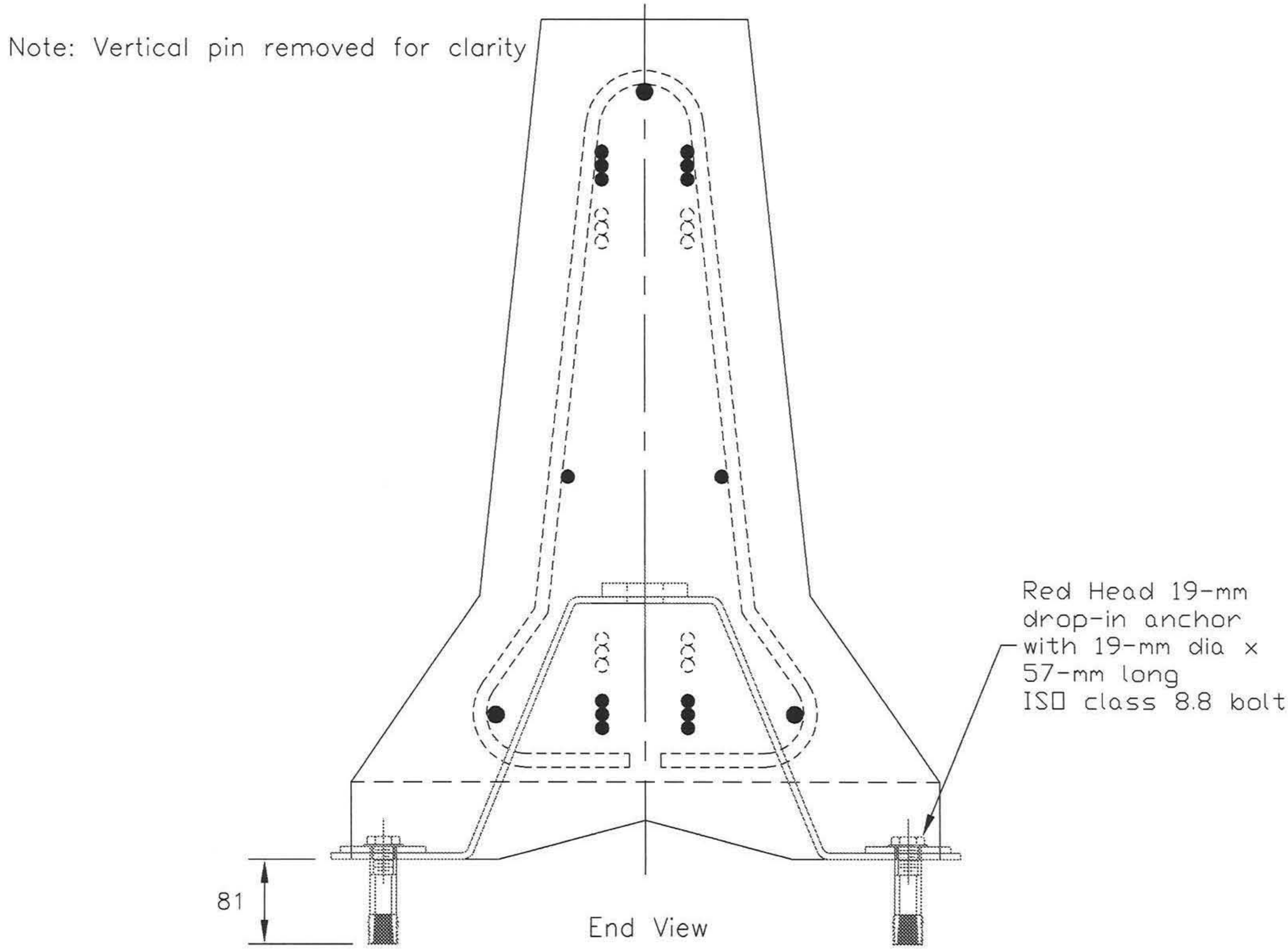
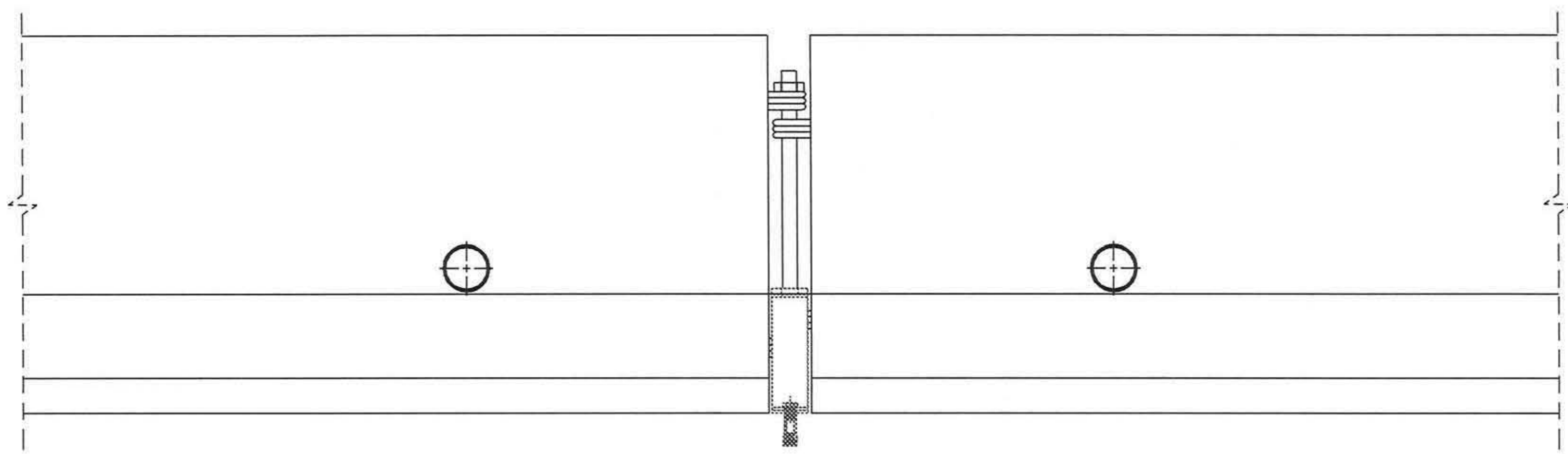


Figure 25. Tie-Down Temporary Barrier System Details

Note: Barriers must be pulled tight during installation to remove slack and provide longitudinal tension during impact



Side View

Figure 26. Tie-Down Temporary Barrier System Details

of a 76 mm x 6.4 mm x 914 mm piece of ASTM A36 steel that was bent at four points along the strap to form a trapezoidal shape. A 22-mm diameter hole, punched 51 mm from each end of the plate, was used to accommodate the two Red Head 19-mm diameter drop-in anchors and the 19-mm diameter x 57-mm long ISO Class 8.8 bolts which constrained the strap. The drop-in anchor's embedment was 81 mm into the concrete surface. In addition, 76-mm x 6.4-mm x 83-mm steel plates with identical size holes were welded to the strap at the hole locations to reinforce the strap. A third 35-mm diameter hole was also punched in the center of the strap to accommodate the vertical pin used to connect the barrier segments. This center hole in the plate was reinforced by a 76-mm x 12.7-mm x 83-mm ASTM A36 steel plate.

In the full-scale crash test installation, a series of sixteen Iowa F-shape temporary barriers were constructed 305 mm from a simulated bridge deck edge at the MwRSF test facility, as shown in Figures 27 through 29. The tie-down straps were installed at eleven of the joints along the barrier system beginning at barrier no. 2 and ending at barrier no. 13, as shown in Figure 29.


Figure 27. Tie-Down Temporary Barrier System

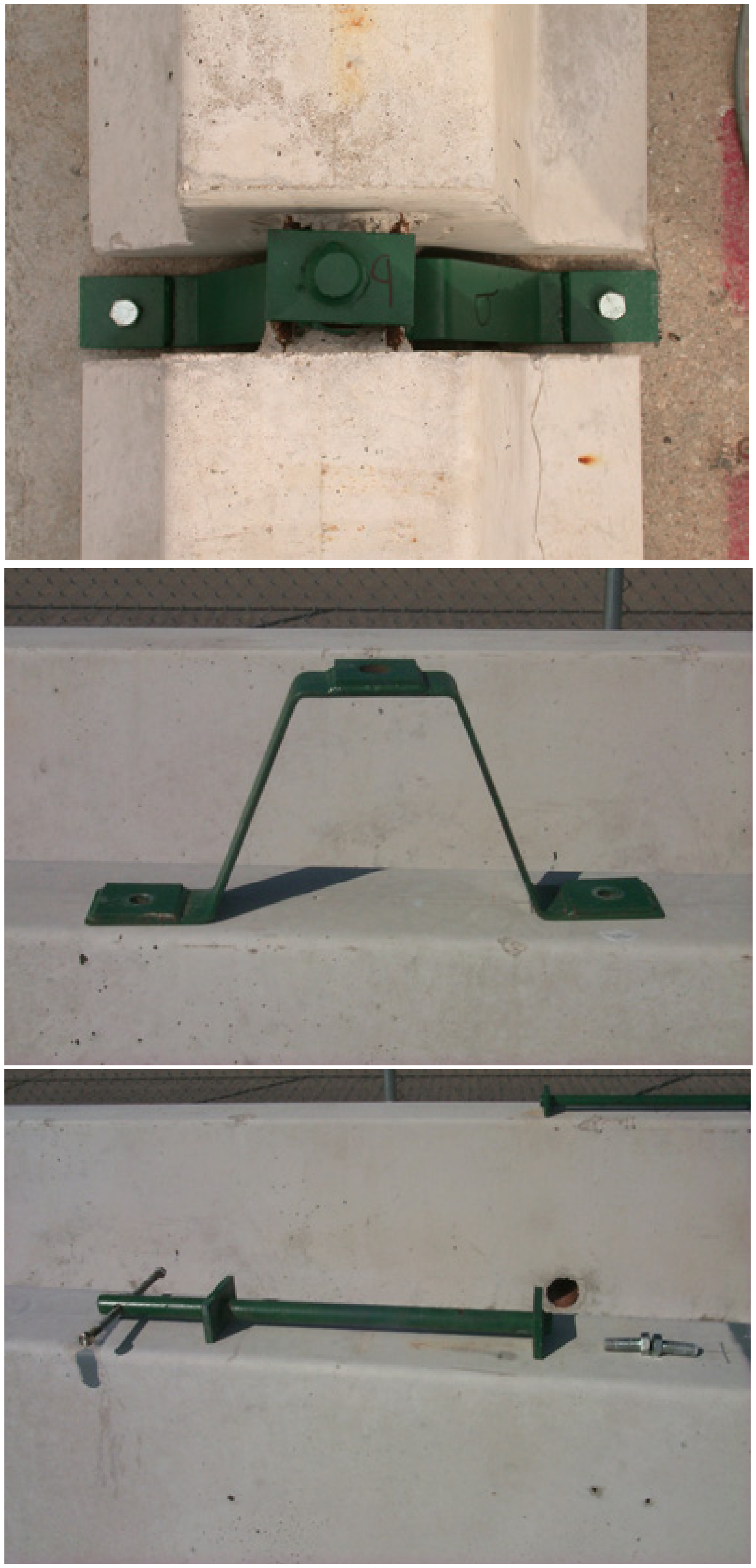


Figure 28. Tie-Down Temporary Barrier System

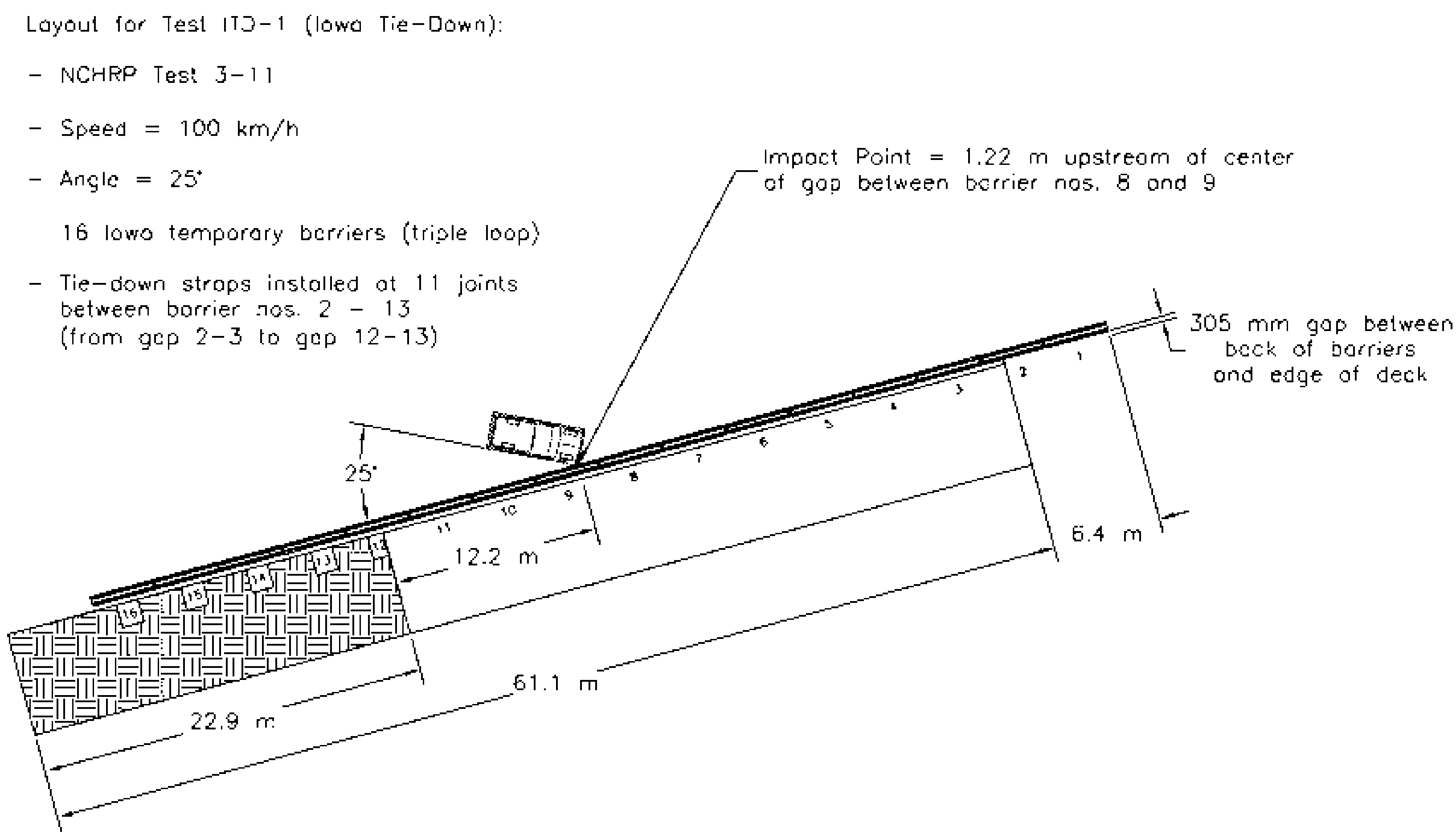


Figure 29. Tie-Down Temporary Barrier System Layout, Test ITD-1

6 TEST REQUIREMENTS AND EVALUATION CRITERIA

6.1 Test Requirements

Longitudinal barriers, such as temporary concrete barriers, must satisfy the requirements provided in NCHRP Report No. 350 in order to be accepted by the Federal Highway Administration (FHWA) for use on new construction projects or as a replacement for existing designs not meeting current safety standards.

According to Test Level 3 (TL-3) of NCHRP Report No. 350, longitudinal barriers must be subjected to two full-scale vehicle crash tests: (1) Test 3-10, an 820-kg small car impacting at a speed of 100 km/hr and at an angle of 20 degrees; and (2) Test 3-11, a 2,000-kg pickup truck impacting at a speed of 100 km/hr and at an angle of 25 degrees. However, test 3-10 was deemed unnecessary for several reasons. First, rigid New Jersey safety shape barriers have been shown to meet safety performance standards when impacted by small cars (8-9). Second, small car crash tests conducted on temporary New Jersey safety shape concrete median barriers resulted in little barrier movement (10). Third, computer simulation modeling of safety shape barriers has revealed that the F-shape concrete median barrier offers a slight improvement in safety performance over the New Jersey safety shape (11). Finally, a small car crash test was successfully conducted on a rigid, F-shape bridge rail; and therefore, it was reasoned to be a valid indicator of the safety performance of F-shape tie-down temporary barrier system (12). As a result, test 3-11 was conducted as the only compliance test for the tie-down temporary barrier system described herein.

6.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the barrier to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents, thereby subjecting occupants of other vehicles to undue hazards or to subject the occupants of the impacting vehicle to secondary collisions with other fixed objects. These three evaluation criteria are defined in Table 1. The full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in NCHRP Report No. 350

Table 1. NCHRP Report No. 350 Evaluation Criteria for NCHRP Test 3-11 (3)

Structural Adequacy	A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
	F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.
	M. The exit angle from the test article should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with the test device.

7 TEST CONDITIONS

7.1 Test Facility

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

7.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the longitudinal barrier. A digital speedometer was located on the tow vehicle to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (13) was used to steer the test vehicle. A guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact with the longitudinal barrier. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and supported laterally and vertically every 30.48 m by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground. The vehicle guidance system was approximately 304.8-m long.

7.3 Test Vehicles

For test no. ITD-1, a 1995 GMC 2500 pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,012 kg and 2,012 kg, respectively. The test vehicle dimensions are shown in Figure 30.

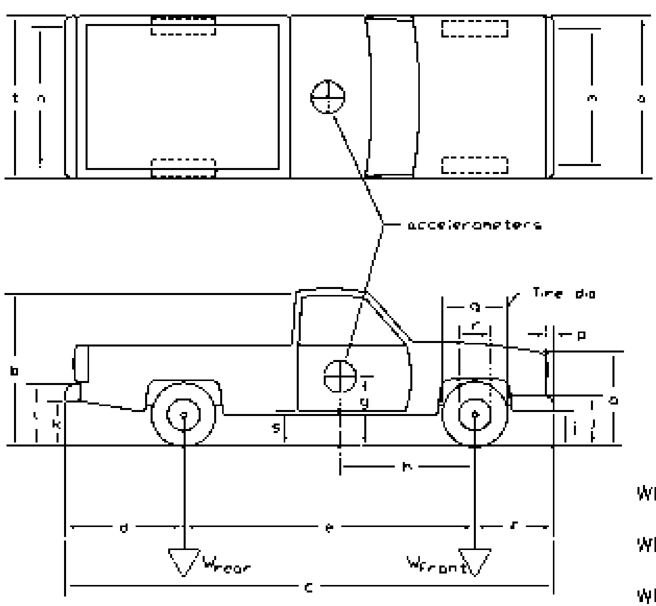
The longitudinal component of the center of gravity was determined using the measured axle

Date: 9/6/01 Test Number: ITD-1 Model: 2000P/2500PU

Make: GMC Vehicle I.D.#: 1GDGC24K85Z560694

Tire Size: LT 245/75 R16 Year: 1995 Odometer: 206962

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - mm

a	1908	b	1841
c	5537	d	1321
e	3327	f	889
g	667	h	1387
i	470	j	683
k	584	l	768
m	1591	n	1622
o	1045	p	83
q	768	r	445
s	502	t	1867

Wheel Center Height Front 371

Wheel Center Height Rear 375

Wheel Well Clearance (FR) 917

Wheel Well Clearance (RR) 959

Engine Type 8 CYL. GAS

Engine Size 5.7 L 350 CID

Transmission Type:

(Automatic) or Manual

FWD or (RWD) or 4WD

Weights - kg	Curb	Test Inertial	Gross Static
W_{front}	1115	1173	1173
W_{rear}	834	839	839
W_{total}	1949	2012	2012

Note any damage prior to test: NONE

Figure 30. Vehicle Dimensions, Test ITD-1

weights. The location of the final centers of gravity are shown in Figures 30 through 31.

Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film and E/cam video, as shown in Figure 31. Round, checkered targets were placed on the center of gravity on the driver's side door, the passenger's side door, and on the roof of the vehicle. The remaining targets were located for reference so that they could be viewed from the high-speed cameras for film analysis.

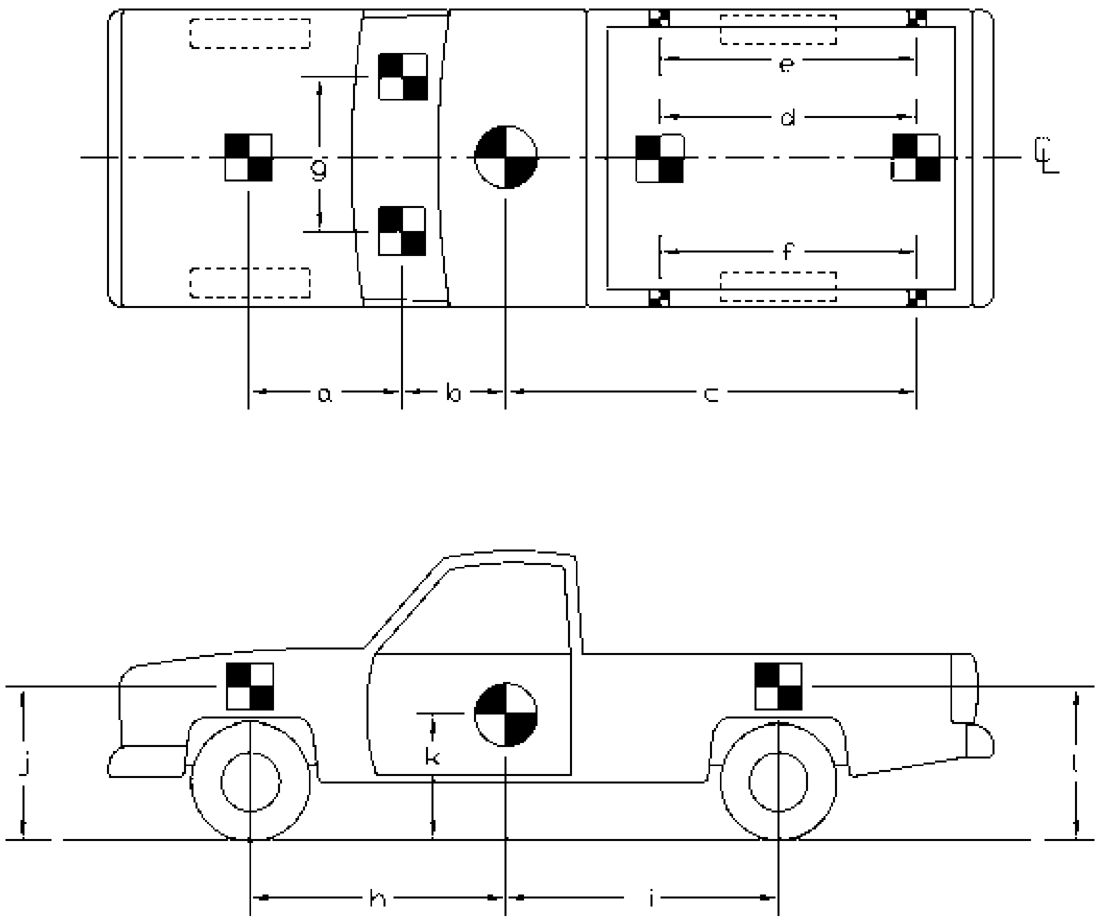
The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs were mounted on both the hood and roof of the vehicle to pinpoint the time of impact with the bridge rail on the high-speed film and E/cam video. The flash bulbs were fired by a pressure tape switch mounted on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

7.4 Data Acquisition Systems

7.4.1 Accelerometers

One triaxial piezoresistive accelerometer system with a range of ±200 G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 10,000 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-4M6, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan and includes three differential channels as well as three single-ended channels. The EDR-4 was configured with 6 Mb of RAM memory and a 1,500 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the accelerometer data.

A backup triaxial piezoresistive accelerometer system with a range of ±200 G's was also



TEST #: ITD-1

TARGET GEOMETRY (mm)

a	908	d	1967	g	1149	j	1016
b	692	e	2153	h	1387	k	667
c	2832	f	2153	i	1940	l	1054

Figure 31. Vehicle Target Locations, Test ITD-1

used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 3,200 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-3, was developed by Instrumental Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the accelerometer data.

7.4.2 Rate Transducers

A Humphrey 3-axis rate transducer with a range of 360 deg/sec in each of the three directions (pitch, roll, and yaw) was used to measure the rates of motion of the test vehicle. The rate transducer was rigidly attached to the vehicle near the center of gravity of the test vehicle. Rate transducer signals, excited by a 28 volt DC power source, were received through the three single-ended channels located externally on the EDR-4M6 and stored in the internal memory. The raw data measurements were then downloaded for analysis and plotted. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the rate transducer data.

7.4.3 High-Speed Photography

For test no. ITD-1, five high-speed Red Lake E/cam video cameras, with operating speeds of 500 frames/sec, and two 16-mm Red Lake Locam cameras, with operating speeds of approximately 500 frames/sec, were used to film the crash test. Four Canon digital video cameras, with a standard operating speed of 28.97 frames/sec, were also used to film the crash test. Two E/cam high-speed video cameras and a Locam with a wide angle 12.5-mm lens were placed 16.05-m above the installation to provide a field of view perpendicular to the ground. An additional E/cam high-speed video camera, a Nikon F5 camera, and a Locam camera were placed on the downstream of the impact point to provide a field of view downstream of the impact point. Another E/cam high-speed video camera and a Canon digital video camera were placed downstream and offset to the right of the impact point and had an angled view of the impacts. An E/cam high-speed video camera and a Canon digital video camera were placed upstream and to the right of the impact point to provide a second angled view of the impact. A Canon digital video camera and a Nikon 995 camera were placed to the left of the impact point to provide a view perpendicular to the impact. A final E/cam digital video camera was placed upstream of the impact point to provide an upstream view. A schematic of all of the camera locations for tests ITD-1 is shown in Figure 32.

The Locam films and E/cam videos were analyzed using the Vanguard Motion Analyzer and the Redlake Motion Scope software, respectively. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

7.4.4 Pressure Tape Switches

For test no. ITD-1, two sets of three pressure-activated tape switches, spaced at 2-m intervals, were used to determine the speed of the vehicle before impact with the barrier system. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the vehicle's front tire passed over it. For no. test ITD-1, the right-front tire passed over the tape switches. Test vehicle speed was determined from electronic timing mark data recorded using the "Test Point" software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

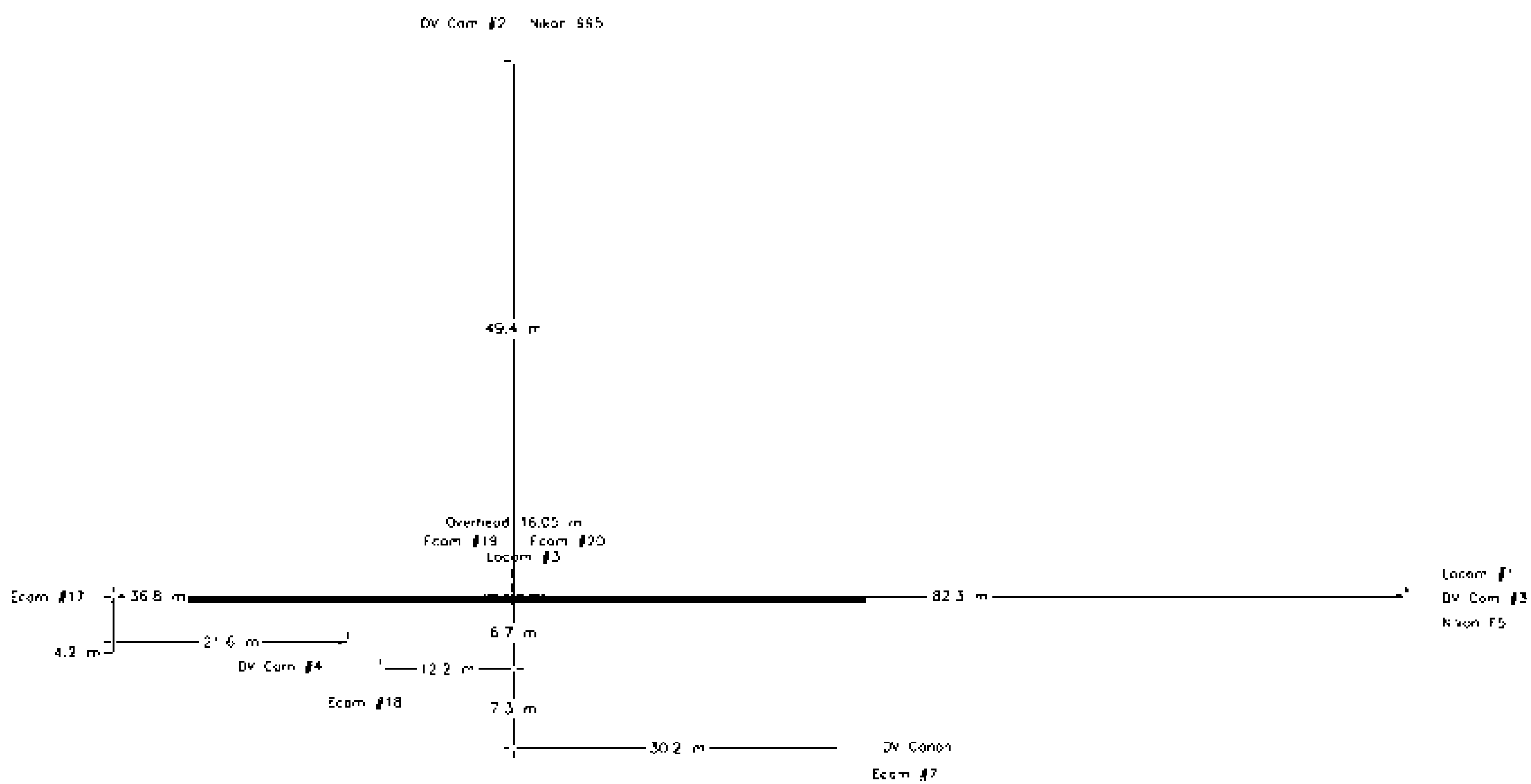


Figure 32. Location of High-Speed Cameras, Test ITD-1

8 FULL-SCALE CRASH TEST NO. ITD-1

8.1 Test No. ITD-1

Test no. ITD-1 was conducted according to NCHRP Report No. 350 Test Designation 3-11. The 2,012-kg pickup truck impacted the tie-down temporary barrier system at a speed of 97.6 km/hr and at an angle of 24.3 degrees. The critical impact point was 1.2-m upstream of the joint centerline between barrier segment nos. 8 and 9. A summary of the test results and the sequential photographs are shown in Figure 33. Additional sequential photographs are shown in Figure 34. Documentary photographs of the crash tests are shown in Figures 35 and 38.

It should be noted that the Impact Severity (IS) for this impact was slightly lower than the NCHRP Report No. 350 recommended target value. NCHRP Report No. 350 recommends a nominal IS value of 138.1 kJ with an acceptable range between 127.3 kJ and 149.4 kJ. In addition, NCHRP Report No. 350 recommends a vehicle speed tolerance of ± 4 km/h and an angle tolerance of ± 1.5 degrees. While both the speed and angle for this test fall within the NCHRP 350 recommended values, the IS value of this impact was 124.7 kJ and slightly below the recommended IS lower bound. However, because both the speed and angle of the test impact were within the accepted ranges and the IS value was only marginally less than the recommended range, it was believed that test no. ITD-1 was a valid indicator of the safety performance of the tie-down temporary barrier system.

8.2 Test Description

The test vehicle impacted the tie-down temporary barrier system at a location 1.2-m upstream of the joint between barrier segment nos. 8 and 9, as shown in Figure 39. Immediately after impact, barrier segment no. 9 began to deflect backward, and the right-front corner of the pickup truck was deformed inward. At 0.030 sec after impact, the right-front tire of the pickup truck was ruptured and deflated as it climbed the barrier. By 0.048 sec, the right-front corner of the pickup truck impact had reached the joint between barrier segment nos. 8 and 9. As the vehicle traversed this joint, the tie-down strap at this joint was deformed, and both of the drop-in anchors were pulled out of the concrete. The pickup truck then continued to move downstream and redirect back towards the roadway. At 0.130 sec, the right-front corner of the pickup truck reached the midspan of barrier segment no. 8, and the front of the vehicle began to climb the barrier. Additionally, cracks were formed at this time on the backside of barrier segment no. 8 and near the top of the backside of barrier segment no. 7 on the upstream end. By 0.224 sec, the pickup truck had redirected parallel to the barriers at a speed of 82.1 km/hr, and barrier segment nos. 8 and 9 were partially deflected off of the bridge deck. At 0.296 sec, the right-rear side of the pickup truck slapped the face of barrier segment no. 8, thus causing it to deflect backwards even farther. Barrier segment no. 7 also began to show significant deflection at this time, causing the tie-down strap at the joint between barrier segment nos. 7 and 8 to deform and pullout.

As vehicle redirection continued, the pickup truck rode up the sloped face of the barrier and all four wheels of the vehicle left the road surface. At 0.584 sec, the vehicle was airborne as it exited the barrier system at a speed of 85.2 km/hr. After exiting the barrier, the pickup truck continued to move downstream and to the left along the exit trajectory until the front wheels returned to the concrete at 0.718 sec. Before coming to rest, the pickup truck turned right after it returned to the pavement due to the damage to the right-front wheel. The final position of the pickup truck was 59.8 m downstream and 20.7 m to the left. The trajectory and final position of the pickup truck are shown in Figure 33.

8.3 System and Component Damage

Damage to the tie-down temporary barrier system was moderate, as shown in Figures 40 through 42. Tire marks and scrapes were visible on the front face of barrier segment nos. 7 through 9. Spalling of the concrete and tire marks were also observed on the upstream end of barrier segment no. 8 at the joint between barrier segment nos. 8 and 9. Barrier no. 7 showed concrete damage on the top of its upstream end in the form of a small concrete piece broken off of the front face and a larger piece broken off of the backside. Four major vertical cracks were observed on the back side of barrier segment no. 8.

In addition to the concrete damage, damage was also noted with respect to the barrier joints and the tie-down straps. Deformation of the vertical pins occurred to the joint between barrier segment nos. 3 and 4 and through the joint between barrier segment nos. 12 and 13. While most of the pin deformations where small, the pins at the joints between barrier segments nos. 6 through 11 showed larger flexural deformations. Several of the rebar loops at these locations also were deformed, but all of the loops remained solid and intact.

Deformation of the tie-down strap was observed at the joints located between barrier segment nos. 6 through 11. The deformation of the straps at the joints between barrier segment nos. 7 through 10 was very extensive. In addition, the straps at the joints between barrier segment nos. 7 through 9 were pulled completely out of the concrete. The drop-in anchors restraining these straps all failed due to the pullout of the drop-in anchor, except for the front strap anchor of the strap between barrier segment nos. 7 and 8. This front-side anchor was sheared and/or cut off by the steel rim of the right-rear wheel as the vehicle passed by the joint. All of the other straps remained effectively anchored to the concrete.

The maximum permanent set and dynamic barrier deflections were measured to be 0.85 m and 0.96 m, respectively.

8.4 Vehicle Damage

Vehicle damage was moderate, as shown in Figures 43 through 44. The majority of the damage to the pickup truck was focused on the right-front corner and right side where the impact occurred. The right side of the front bumper was bent inward around the frame horn. The right-front fender was crushed inward and dented as well. Damage was observed to the right-front suspension components which consisted of bent control arms and a disengaged tie rod. The right-front tire and the outside of the steel rim were disengaged from the main body of the wheel assembly during impact. The right-rear tire was torn open and deflated but was still attached to the rim. Scrapes and dents from the vehicle contact with the barriers was observed on the bottom of the truck bed and right side door. No damage to the engine hood nor roof was observed. There was no broken glass on the vehicle.

Minor damage was observed in the interior occupant compartment of the vehicle, including a tear along the weld on the forward passenger-side floor pan and deformation of the passenger-side floor pan. The occupant compartment deformations were measured and recorded for the floorboard and dash. A maximum vertical deflection of 70 mm was found near the center of the floor on the driver side. Maximum lateral and longitudinal deflections of the floor pan were measured as 57 mm and 146 mm, respectively. Maximum dash deflection was reported to be approximately 6 mm. Although modest deflections were observed, they were not believed to pose as serious hazard to the occupants of the vehicle. Complete occupant compartment deformation details are given in Appendix F.

8.5 Occupant Risk Values

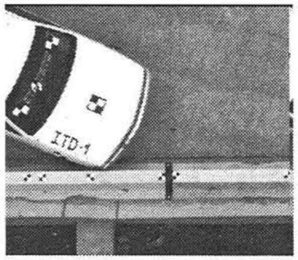
The longitudinal and lateral occupant impact velocities (OIV) were determined to be 4.51 m/s and 4.82 m/s, respectively. The maximum 0.010-sec average occupant ridedown decelerations (ORD) in the longitudinal and lateral directions were 5.44 g's and 7.86 g's, respectively. It is noted that the occupant impact velocities and the occupant ridedown decelerations were within the suggested limits provided in NCHRP Report No. 350. The results of the occupant risk data are summarized in Figure 33. Results are shown graphically in Appendix G. The results from the rate transducer are also shown graphically in Appendix G.

8.6 Discussion

Following test no. ITD-1, a safety performance evaluation was conducted, and the tie-down system for temporary barrier applications was determined to be acceptable according to the NCHRP Report No. 350 criteria. The test article contained and redirected the vehicle, and the vehicle did not penetrate, underride, or override the barrier. Detached elements and debris from the barrier did not penetrate nor show potential for penetrating the occupant compartment or present undue hazard to the other traffic, pedestrians, or personnel in the work zone. Deformations of, or intrusion into, the occupant compartment that could have caused serious injury did not occur. The vehicle remained upright during and after the collision. The vehicle's trajectory did not intrude into adjacent traffic lanes. The occupant impact velocities and ridedown accelerations were within the suggested limits imposed by NCHRP Report No. 350.

It should be noted that insignificant pitch or roll motions were observed as the vehicle climbed the barrier, which is contrary to what has been observed in most free-standing temporary barrier tests. The reduced pitch and roll were attributed to the reduced deflection and rotation of the barrier due to the tie-down straps.

It should be restated that the IS level for this test was slightly below the recommended lower bound given in NCHRP Report No. 350. As such, it is realized that the barrier deflections seen in this impact may be marginally less than those that would be observed in an vehicle impact with a slightly higher impact severity. However, the researchers believe that the results of this test remain a valid indicator of the safety performance of the barrier for several reasons. First, the speed and angle of the test impact are both within the NCHRP Report No. 350 recommended values. Second, the IS value for the test was only slightly less than the recommended lower bound. Third, the dynamic performance of the tie-down system for temporary barriers was very good, and the vehicle trajectory observed was very smooth and stable. In addition, the tie-down straps were designed to support the dead weight of three temporary barriers that were deflected off of the bridge deck edge and performed as intended. In test no. ITD-1, one barrier was deflected completely off the deck and with the two adjacent barriers only partially deflected off the deck. This result suggests that there is more than sufficient capacity remaining in the system to contain an impacting vehicle at a marginally higher speed, angle, or combination thereof.



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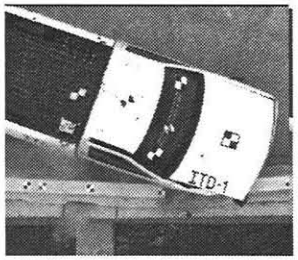

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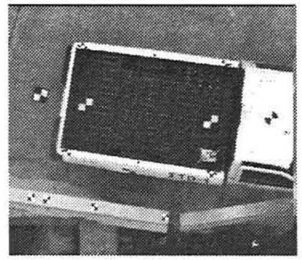

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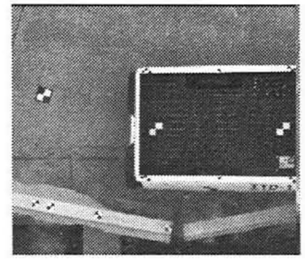

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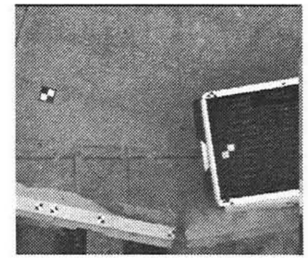

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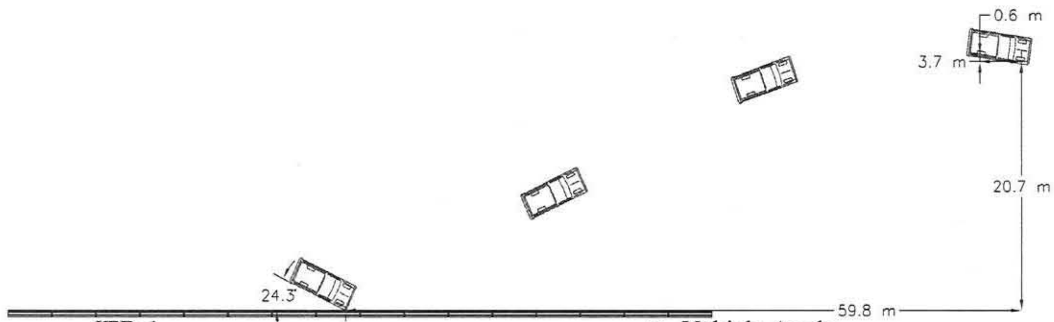

- Test Number ITD-1
- Date 9/6/01
- Test Article
  - Type .... Tie-Down Temporary Barrier System
  - Key Elements .... Sixteen 3810-mm long Iowa F-shape temporary barriers; Eleven 76x6.35x914-mm A36 steel tie-down straps
  - Orientation .... Angled impact 1.2-m upstream of joint between barrier nos. 8 and 9
- Soil Type .... On dry pavement
- Vehicle Model .... 1995 GMC 2500
  - Curb .... 1,949 kg
  - Test Inertial .... 2,012 kg
  - Gross Static .... 2,012 kg
- Vehicle Speed
  - Impact .... 97.6 km/hr
  - Exit .... 85.2 km/hr
- Vehicle Angle
  - Impact .... 24.3 deg
  - Exit .... NA
- Vehicle Stability .... Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal .... 5.44 g's/-4.67 g's < 20 g's
  - Lateral (not required) .... 7.86 g's/-2.58 g's
- Occupant Impact Velocity
  - Longitudinal .... 4.51 m/s < 12 m/s
  - Lateral (not required) .... 4.82 m/s
- Vehicle Damage
  - TAD[14] 1-FR-3
  - SAE[15] 01RFEW5
- Vehicle Stopping Distance .... 59.8 m downstream; 20.7 m left
- Test Article Damage .... Moderate
- Maximum Deflections
  - Dynamic .... 0.96 m
  - Permanent Set .... 0.85 m
- Working Width .... 1.46 m

Figure 33. Summary of Test Results and Sequential Photographs, Test ITD-1

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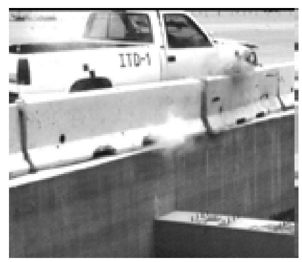

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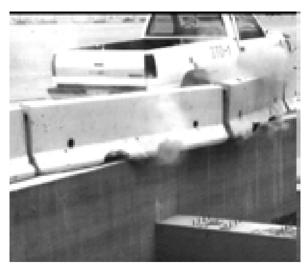

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Figure 34. Additional Sequential Photographs, Test ITD-1

Figure 35. Documentary Photographs, Test ITD-1

Figure 36. Documentary Photographs, Test ITD-1

Figure 37. Documentary Photographs, Test ITD-1

Figure 38. Documentary Photographs, Test ITD-1

Figure 39. Impact Location, Test ITD-1

Figure 40. System Damage, Test Test ITD-1

Figure 41. System Damage, Test ITD-1

Figure 42. System Damage, Test ITD-1

Figure 43. Vehicle Damage, Test ITD-1

Figure 44. Vehicle Damage, Test ITD-1

9 SUMMARY AND CONCLUSIONS

A tie-down system for use with temporary F-shape concrete barriers was developed and successfully full-scale crash-tested according to Federal impact safety standards. Development of the new tie-down system began with the brainstorming of several design concepts. Following a preliminary analysis of the initial design concepts and discussions with the sponsoring states, MwRSF researchers focused on a steel strap concept for reducing barrier deflections and restraining the deflected barriers from falling off of the bridge deck edge. The final tie-down concept selected for study consisted of a steel strap that connected to the barrier joint and then bolted to the concrete deck. For the development of the tie-down strap concept, LS-DYNA computer simulation modeling and simple engineering calculations were utilized for determining the capacity of the steel straps. As a result of this analysis, researchers adopted a two-sided steel strap tie-down concept which incorporated an additional drop-in anchor as well as provided increased energy absorption.

A component test of the steel strap tie-down design was then conducted by loading a temporary barrier joint. A single F-shape barrier joint was fitted with a tie-down strap and loaded using a bogie vehicle. The results of this test demonstrated that the tie-down strap was capable of absorbing a significant amount of energy with the potential for reducing barrier deflections and restraining barriers deflected off of the bridge deck edge.

One full-scale vehicle crash test, test no. ITD-1, was conducted according to TL-3 test no. 3-11 found in the NCHRP Report No. 350. The results of this test are summarized in Table 2. The test consisted of a 2,012-kg pickup truck impacting the temporary barrier system at a speed of 97.6 km/h and at an angle of 24.3 deg. The impact point was located 1.2 m upstream of the barrier joint. As observed in the test, the barrier system safely redirected the pickup truck and successfully met

Table 2. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test ITD-1
Structural Adequacy	A	S
Occupant Risk	D	S
	F	S
Vehicle Trajectory	K	S
	L	S
	M	S
NCHRP Report No. 350 Test Level		TL-3
NCHRP Test No.		3-11
Pass/Fail		Pass

S - Satisfactory
M - Marginal
U - Unsatisfactory
NA - Not Available

all of the NCHRP Report No. 350 safety performance criteria.

10 RECOMMENDATIONS

A tie-down system for use with F-shape temporary barriers, as described in this report, was developed and successfully crash tested according to the criteria found in NCHRP Report No. 350. The results of this test indicate that this design is suitable for use on Federal aid highways. However, it should be noted that any significant modifications made to the tie-down design would require additional analysis and possible full-scale crash testing to insure that it would provide an acceptable safety performance.

The tie-down system for F-shape barriers was tested with a clear gap of 305 mm between the backside of the barriers and the bridge deck edge. As observed in test no. ITD-1, one full barrier segment was deflected completely off of the bridge deck, while the two adjacent barrier segments were only partially deflected off the deck. As mentioned previously, the tie-down strap was originally designed to safely support the dead weight of three barriers deflected off of the bridge deck. As such, it is believed that the 305-mm gap located behind the barrier could be slightly reduced and still allow for the safe redirection of impacting vehicles while constraining the deflected barriers to the bridge. Analysis of the test results, combined with additional engineering calculations suggest that the gap between the backside of the barriers and the bridge deck edge may be reduced to 150 mm and still provide acceptable performance. With the reduction of the gap, an increased number of barriers would be deflected off of the bridge deck. However, the adjacent tie-down straps and their anchorage are believed sufficient to safely redirect impacting vehicles and contain the deflected barriers on the bridge deck even with the reduced gap. Therefore, it is recommended that the tie-down system for use with F-shape barriers can be safely installed with a 150-mm gap between the bridge deck edge and the backside of the barriers.

The tie-down system described herein was developed to utilize press-fit or drop-in type concrete anchors, as per the request of the sponsoring states. While these anchors performed well in the physical testing of the tie-down system, some state DOT's may prefer to use alternative anchoring methods. Other possible anchorages for the tie-down strap include the use of epoxied, threaded rods or vertical bolts placed through the bridge deck. These alternative anchorage methods can be safely used as long as they provide a structural capacity equal to or greater than that provided by the ISO class 8.8 bolts and drop-in anchors used in the original tie-down system.

It should also be noted that the tie-down system described herein was designed and tested for use on a concrete bridge deck or roadway. As configured, the steel strap tie-down is not intended for use on installations involving asphalt roadways nor shoulders since the drop-in anchors would not be capable of developing sufficient structural capacity. Therefore, further research would be recommended in order to determine the dynamic barrier performance of alternative anchorage methods when used on asphalt roadway surfaces.

Free-standing temporary barrier systems are often placed in front of or connected to an existing rigid bridge railing system. For this scenario, there exists a potential for vehicle snag or pocketing on the upstream end of the bridge railing due to the differences in lateral stiffness and allowable barrier deflections between the rigid barrier and the free-standing temporary barrier systems. The tie-down temporary barrier system discussed herein could potentially be developed to provide a stiffness transition between the standard temporary barriers and the bridge rail. Consequently, the details of such a transition, using the tie-down design concept, have not been considered nor developed. Further research is recommended in order to investigate the feasibility of the tie-down concept for this application.

11 REFERENCES

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12 APPENDICES

APPENDIX A
DEVELOPMENT OF BACKUP TOWER TIE-DOWN CONCEPT

CONCEPT DEVELOPMENT OF A TIE-DOWN TEMPORARY CONCRETE BARRIER SYSTEM

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Midwest Roadside Safety Facility

John D. Reid
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ABSTRACT

Design for safety includes not only the vehicle and occupant protection system but also the structures that vehicles hit. One such example includes temporary concrete barriers. Often in work zones on bridges there is very little room available for barrier deflections when impacted by errant vehicles. Thus, deflections of the barriers must be severely restricted to prevent the barrier from being deflected off of the deck, followed closely by the striking vehicle.

A tie-down design was generated consisting of a steel base plate with two vertical steel tubes, each with a crosshead tube blockout. Nonlinear finite element analysis of the new design focused on gauging the performance of the design as well as optimizing the structural requirements and anchor loads. Results of simulating a full-scale crash test predicted that the proposed design would be capable of safely constraining the barriers during an impact event.

INTRODUCTION

Roadway construction zones are a common site along almost all federal and state highways. In most cases these zones involve the redirection of traffic around or through the construction zone. Temporary concrete barriers are often used to separate the flow of traffic from the construction area. Temporary concrete barriers are segmented, precast concrete barriers connected by some form of load bearing connection. The segmentation of the barriers allows them to be easily moved and repositioned in the construction zone. The barrier is designed to protect equipment and workers in the work zone and to safely redirect vehicles impacting the barrier.

A common installation of temporary barriers is placement of the barriers on the edge of a bridge deck that is under construction, as shown in Figure 1. However, installations such as this pose a major safety hazard to errant vehicles impacting the temporary barriers. Previous testing of temporary barriers, such as the one shown in Figure 1, have shown deflections of over 1 meter [1,2]. Deflections of that magnitude, when combined with the narrow gap behind the barriers, would prove sufficient to push the barriers off of the deck along with the impacting vehicle.

Figure 1. Temporary Barrier Installation on Bridge Deck

Researchers at the Midwest Roadside Safety Facility at the University of Nebraska-Lincoln were approached to develop a tie-down temporary barrier system for this type of installation. The design had to meet five basic requirements:

(1) Severely limit the deflection and rotation of the barrier during impact while limiting the damage to the bridge deck.
(2) 3.81-m barrier segments were to be used in the design.
(3) No permanent attachments were allowed on the deck, like epoxied rods.
(4) Anchors used in the system could penetrate no further than 127-mm into the bridge deck.
(5) All of the components of the tie-down system must be placed on the backside (non-traffic side) of the barrier.

This paper details the use of non-linear finite element simulation to develop and refine a design prototype to meet the above design objectives and prove suitable for full-scale testing.

Previous research has been done in the area of temporary barrier tie-down systems. The most notable effort in this area was the development and testing of a limited-slip portable concrete barrier by the Texas Transportation Institute (TTI) [3]. This system used steel pins, that slid through the front of the barrier at an angle and into the bridge deck to a depth of 127-mm, 9.1-m long barriers and stiff barrier segment connections. During full-scale testing 0.4-m of dynamic deflection of the barriers was observed.

The TTI system was not the optimum design for the researchers' current needs. The barrier connections used in this system were significantly stiffer than those used for many other barrier designs. The researchers also believed that the angled pins would potentially cause spalling of the concrete bridge deck during impact. It was desired that a new tie-down barrier be developed that further reduced the deflection of the system while not damaging the bridge deck. The new design would also be applicable to barriers with less stiff connections.

INITIAL DESIGN CONCEPT

After thorough review of the requirements for the tie-down temporary barrier, an initial design concept for the design was developed, as shown in Figure 2. The design concept consisted of a steel backup tower bolted to the bridge deck behind the barrier. The tower was comprised of a pair of 127-mm x 127-mm x 375-mm vertical tubes connected by a 127-mm x 127-mm x 813-mm crosshead tube. Tube height was set to place the crosshead slightly above the vertical center of gravity of the barrier to reduce the potential for the barrier to tip over. The vertical tubes were welded to a 1016-mm x 203-mm x 19-mm steel base plate. Connection of the base plate to the bridge deck was accomplished using 19-mm diameter drop-in anchors with a depth of 127-mm into the deck. Two of these tie-downs were placed behind the ends of each barrier segment to absorb the impact.

While this initial design concept met all design criteria, the researchers did not know with any certainty if the design would prove capable of restraining the temporary barriers upon impact. It was very difficult to accurately determine the loading of the tie-down during an impact event. This in turn prevented a reasonable estimation of the structural requirements of the design as well as approximation of the drop-in anchor loads. Thus, it was decided that non-linear finite element analysis should be applied to aid in the design process.

SIMULATION OF THE INITIAL PROTOTYPE

Computer simulation of the tie-down temporary barrier design concept was performed using LS-DYNA, a transient, nonlinear finite element analysis program [4]. The analysis of the design was focused on the investigation and refinement of the initial design prototype. Deflection and rotation of the barrier were observed in the simulation to gauge the performance of the tie-down. Simulation results were also used to determine the size of the structural elements in the design as well as approximate the drop-in anchor loads.

Three Barrier Model

Initial modeling of the tie-down concept was performed using a simple model consisting of three temporary barriers,

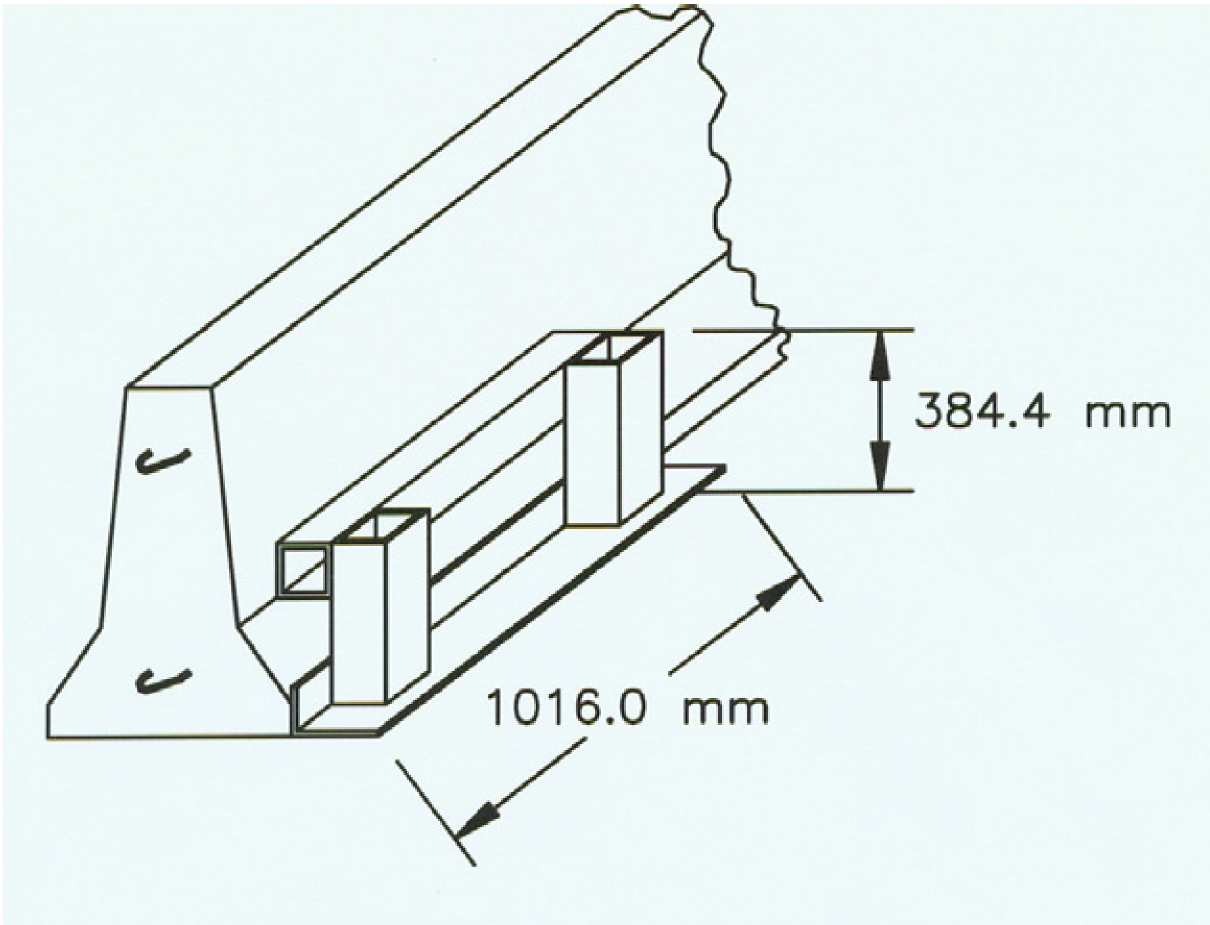


Figure 2. Initial Design Concept

as shown in Figure 3. All three of the 3.81-m long barrier segments were modeled using solid elements. Each barrier segment was defined using a rigid material because the concrete barriers themselves were not expected to deform significantly during impact, this also saved considerable CPU time. Connection of the barrier segments was done with a deformable pin and loop connection equivalent to the connection used on the actual barriers. The connection consists of a steel bar that passes through a pair of steel loops cast into the end of each barrier. The bar is then constrained with steel plates on the top on bottom to prevent the bar from pulling out of the loops during the impact. There were no additional constraints placed on the three barriers at this time other than gravity.

Modeling of the tie-down anchor concept itself was done entirely with shell elements employing a piecewise linear plasticity model with the appropriate steel properties. Initially the base plates were considered rigid and fixed. Constraining the tie-down in this manner assumed that the base plate would not deform, thus forcing the vertical tubes and crosshead tube to absorb the impact. This assumption was considered conservative, however, the base plate and anchor system were examined in more detail later in the project.

The pickup truck model used in the simulation was set up to impact the middle barrier at a speed of 100-km/h and an angle of 25-deg. That impact condition was derived from compliance test criteria for temporary barrier systems set forth in NCHRP Report 350 [5].

Simulation and analysis of the three barrier model focused on the investigation of the structural requirements and limits of the tie-down anchorage, specifically the vertical tubes. To this end, a series of models were run that varied the vertical tube thickness between 3.175-mm and 12.7-mm.

Three Barrier Model Results

Analysis of the three barrier model simulations yielded valuable information about the structural requirements of the tie-down design. Figure 4 shows a graph of the moment in the base of the vertical tubes for three different thicknesses. By reducing the thickness of the vertical tubes to 3.175-mm, the moment in the tube was reduced by half and was able to maintain a relatively constant load. This was due to the tube undergoing plastic deformation. The plastic deformation of the tube absorbs energy which reduces the moment in the vertical tube and consequently lowers the loading of the base plate and the drop-in anchors. The thicker tubes in the simulation models displayed no plastic deformation.

Based on these results, it was decided that the tie-down design would need to incorporate deformable vertical tubes in order to reduce the loads in the system to manageable levels. The loads developed in the tie-down with the thicker, more rigid tubes would have required a large number of drop-in anchors and would have made the system too bulky and heavy. By allowing the vertical tubes to have some compliance the loads would be brought down, thus reducing the number of anchors. The high loads seen in the simulation also led researchers to believe that the drop-in anchors would be the limiting factor in the design due to their limited load capacity.

DROP-IN ANCHOR TESTING

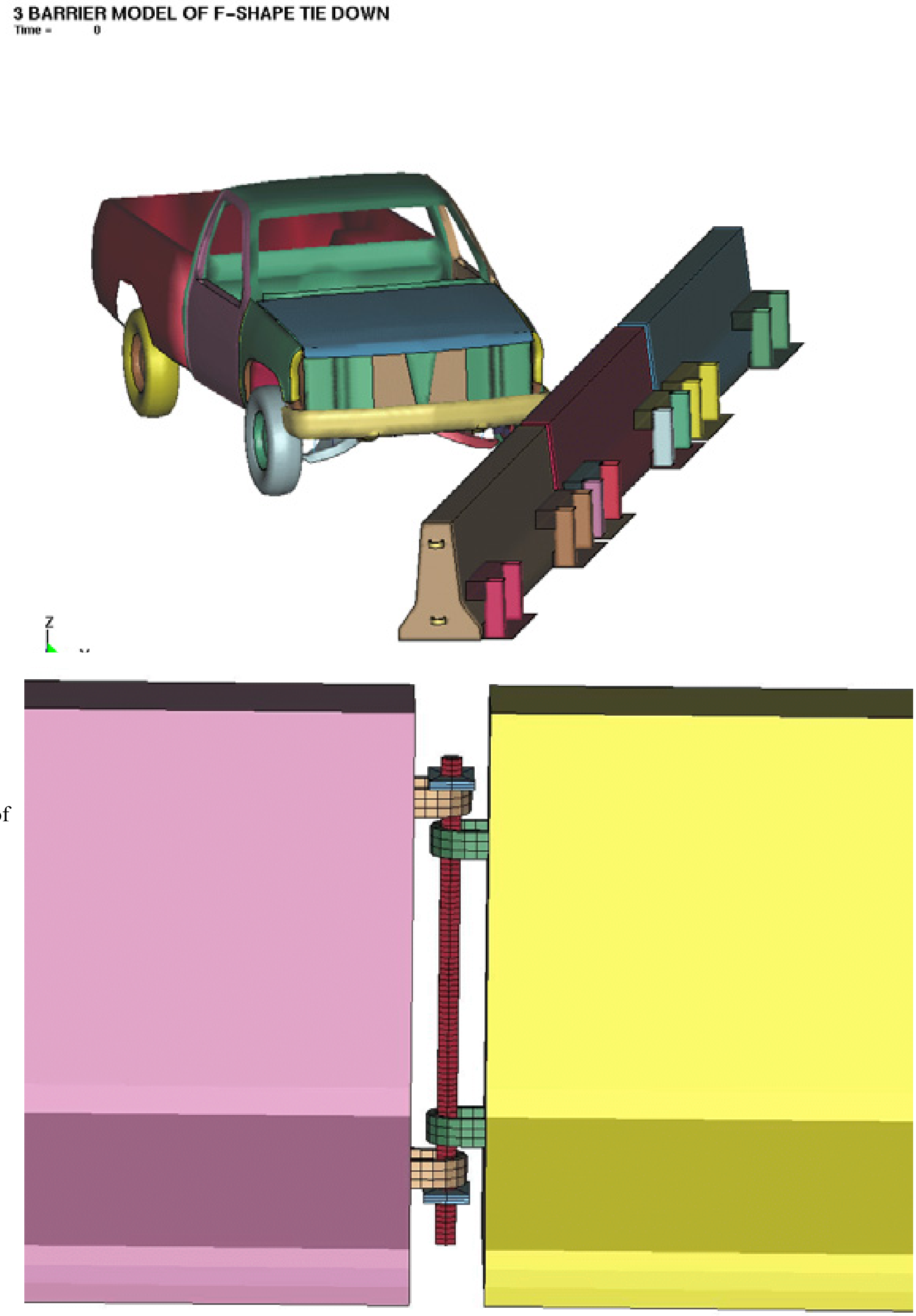
Due to the large loads and moments observed in the simulation, it was important to collect accurate data on the dynamic pullout strength of the drop-in anchors being used in the tie-down concept. Since only static properties of drop-in anchors was available, a simple test was set up to measure the dynamic pullout loads. These loads would then be used in conjunction with simulation to refine the design.

Dynamic testing consisted of a W150x37.1 steel post welded to a 25.4-mm thick steel base plate impacted by a 2161-kg bogie vehicle at a speed of 32.2-km/h (see Figure 5). Two drop-in anchors were bolted through the plate in front of the post. Analysis of the accelerometer data from the impact found a maximum pullout load of 76.2-kN per anchor.

MODELING OF THE IMPROVED TIE-DOWN DESIGN

Improved Tie-down Model

Using previous simulation results and bogie testing results, an improved version of the tie-down barrier concept was developed, as shown in Figure 6. The new design was modified to use 311-mm tall vertical tubes with a reduced cross



Details of pin and loop.

Figure 3. Three Barrie Model of Initial Tie-Down Concept

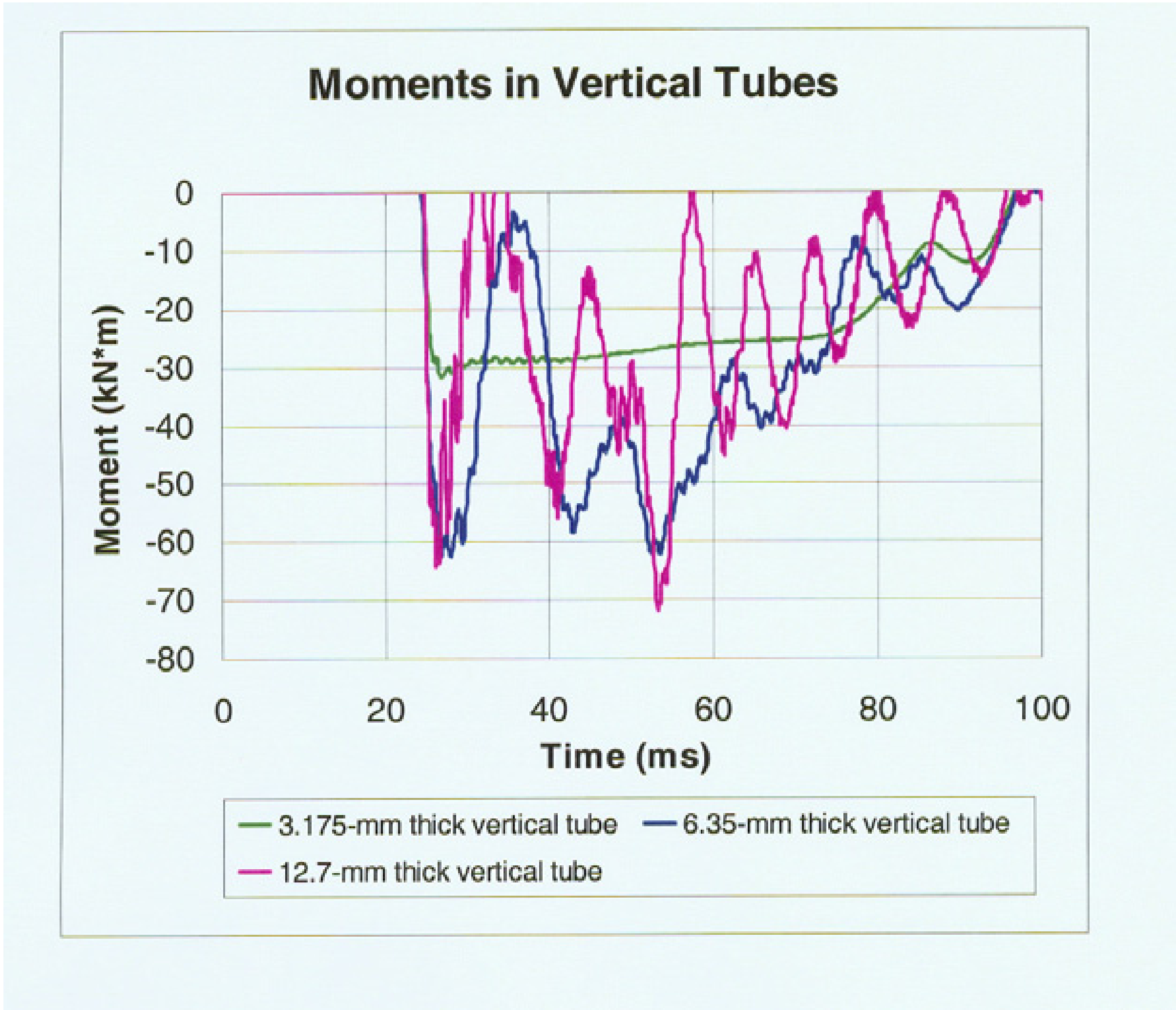


Figure 4. Comparison of Vertical Tube Moments

Figure 5. Drop-In Anchor Component Testing

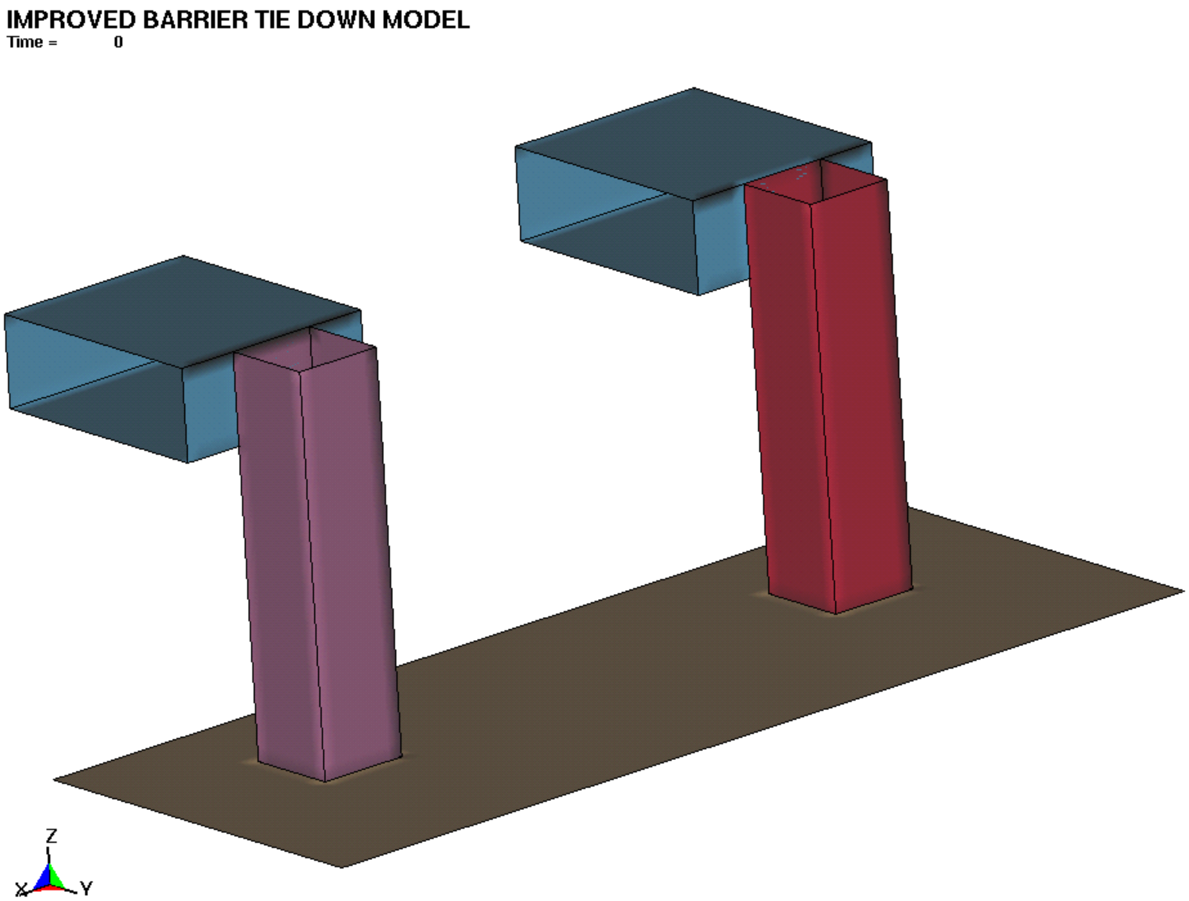


Figure 6. Improved Tie-Down Design

section to allow plastic deformation and to reduce the loads in the design, however the exact size of theses tubes was not yet set. Vertical tubes were repositioned on the base plate to allow more room for eight drop-in anchors spaced at 254-mm apart. Additionally, to reduce weight, the single crosshead tube was replaced with smaller individual spacer blocks on each vertical tube. The thickness of the spacer blocks was increased to 9.525-mm to prevent their deformation and isolate the deformation to the vertical tubes.

To increase accuracy of the simulation, a few changes were made to the model. Mesh size was reduced on the tie-down components to improve the load and deformation predictions. The base plate was effectively made deformable and the constraints modeling the anchors were changed. Instead of constraining the entire base plate, the new model constrained the plate only at the drop-in anchor locations. This method more effectively approximated the loading of the plate during the impact, and it also allowed the forces at the anchor locations to be recorded. Predicted loads were then compared with physical testing to determine whether the anchors would be capable of affixing the tie-down to the bridge deck.

In order to optimize the size of the vertical tubes a parameter study was performed by varying the cross section between 76.2-mm x 51-mm x 6.35-mm and 127-mm x 127-mm x 6.35-mm. The results of the parameter study found that variation of vertical tube size reduced the loads in the tie-down to desired levels, as shown in Table 1. It was determined that the 76.2-mm x 76.2-mm vertical tubes with 6.35-mm thickness provided the optimum performance. Simulation results from of this tube size are shown in Figure 7. These tubes allowed plastic deformation which reduced the loads and moments in the tie-down, however barrier deflection and rotation were kept within satisfactory limits. No potential for tipping of the barriers was observed. The drop-in anchor loads found from simulation were reduced to 52-kN per anchor. This was only 68% of the tested anchor load limit.

Vertical Tube Size (mm)	Maximum Load per Anchor (kN)
127 x 127 x 6.35	83.6
127 x 51 x 6.35	76.6
101.6 x 76.2 x 6.35	72.1
76.2 x 76.2 x 6.35	52.0
76.2 x 51 x 6.35	40.9

Table 1. Effect of Vertical Tube Size on Anchor Load

SEVEN BARRIER MODEL

While the simulation data for the tied down design looked promising, the temporary barriers themselves were displaying some undesirable behavior. Recall that the temporary barriers in the system were unconstrained except for gravity loads. During simulation of the three barrier model, the end barriers showed a degree of rotation that was deemed a little too excessive, as shown in Figure 8. It was believed that this excessive rotation was due to the lack of additional upstream and downstream barriers in the model. Therefore, an extended model of the tie-down temporary barrier design was developed that incorporated a total of seven barriers to produce a more realistic barrier response.

The seven barrier model is shown in Figure 9. The model's four additional barriers were modeled in the same manner as the original barriers in terms of the materials used and the deformable pin and loop connection used. The two end barriers in the model were modified to have six times the mass of a normal temporary barrier. This additional mass served to approximate the response of the remaining un-modeled barriers.

Simulation of the seven barrier model yielded promising results. The relatively high end rotation of the temporary barriers seen in three barrier model was eliminated. The tie-down anchor worked equally well with the additional barriers. Deflection of the barriers was almost completely limited by the tie-down and no potential tipping of the barriers was observed. The loads developed in the tie-down and the anchors loads were nearly identical to those found in the

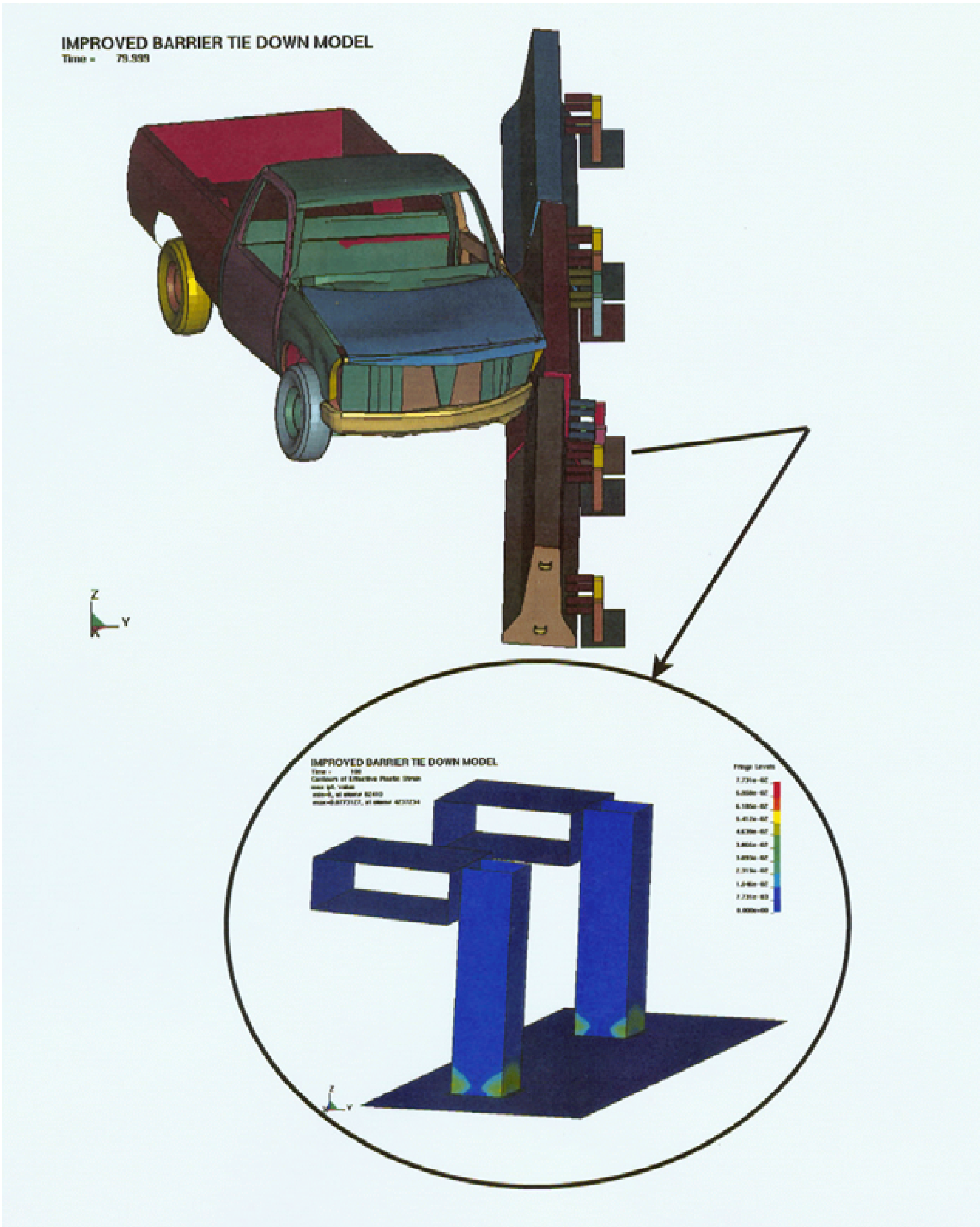


Figure 7. Improved Tie-Down Simulation Results

Figure 8. Excessive Rotation Due to Limited Model Length

Figure 9. Seven Barrier Tie-Down Model

three barrier model. Based on these simulation results, it was believed that the tie-down design concept was capable of restraining a system of temporary barriers.

In order to demonstrate the effect of the tie-down system on the behavior of the temporary barrier system, a simulation of the seven barrier model was run without the tie-down anchors in place. A comparison of the behavior of this system with the tie-down restrained system is shown in Figure 10. Results clearly show the need for a tie-down in a bridge deck installation, as well as demonstrate the effectiveness of the proposed tie-down system in constraining barrier motion.

SUMMARY AND CONCLUSIONS

Design for safety includes not only the vehicle and occupant protection system but also the structures that vehicles hit. To that end, a new design concept for a tie-down anchor for temporary concrete barrier installations used on bridge construction projects was developed. The key components of the tie-down system include the anchorage, base plate, vertical tubes and crosshead blockouts.

Simulation using LS-DYNA, along with limited component testing of drop-in anchors, played a significant role in optimizing the key components. Simulation of the prototype design found that the vertical tubes would have to be allowed to plastically deform in the design in order to absorb energy and reduce the loads in the tie-down to manageable levels. The high loads found in the simulation also suggested that the drop-in anchors used to mount the tie-down to the deck would prove critical in the design.

A system model consisting of seven concrete barriers and the proposed tie-down system was used to predict a satisfactory performance of the design. However, before such a system is installed on actual construction projects, it should be crash tested according to NCHRP Report 350 specifications. It is believed that the number of full-scale tests will have been reduced due to the preliminary refinement of the design through simulation.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Midwest States Pooled Fund Program for sponsoring this project, Dean Sicking, John Rohde, Ron Faller, Jim Holloway and the rest of the MwRSF staff, and Livermore Software Technology Corporation, the developers of LS-DYNA.

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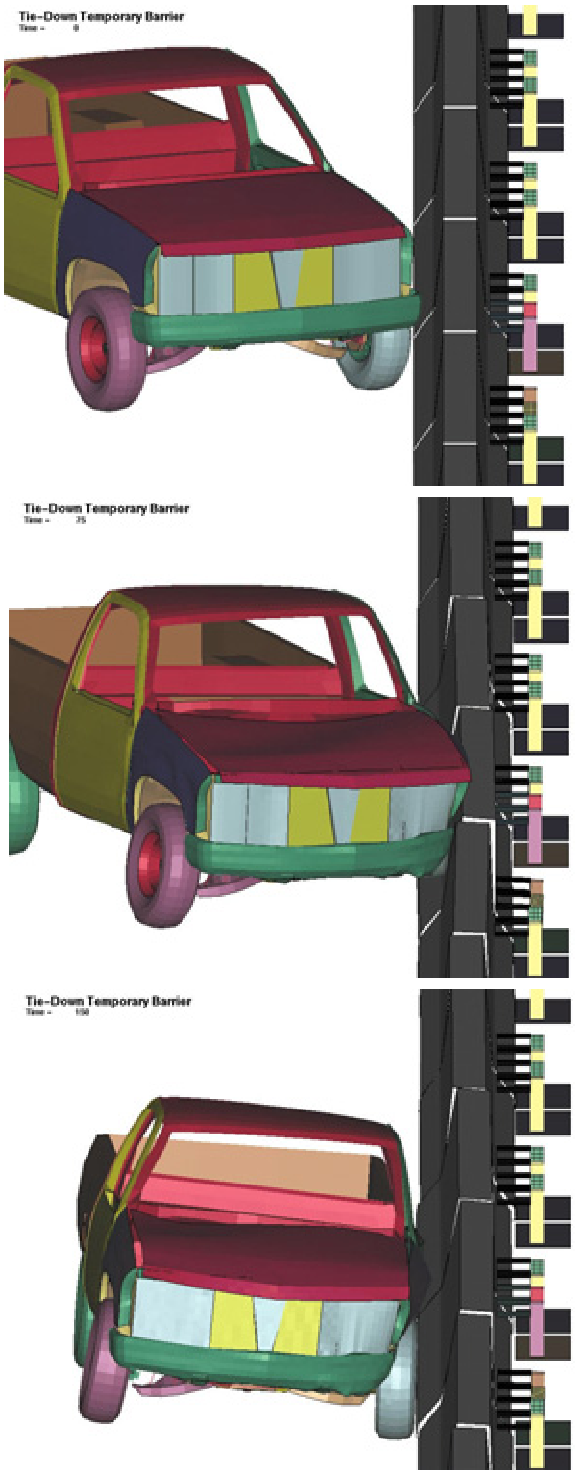


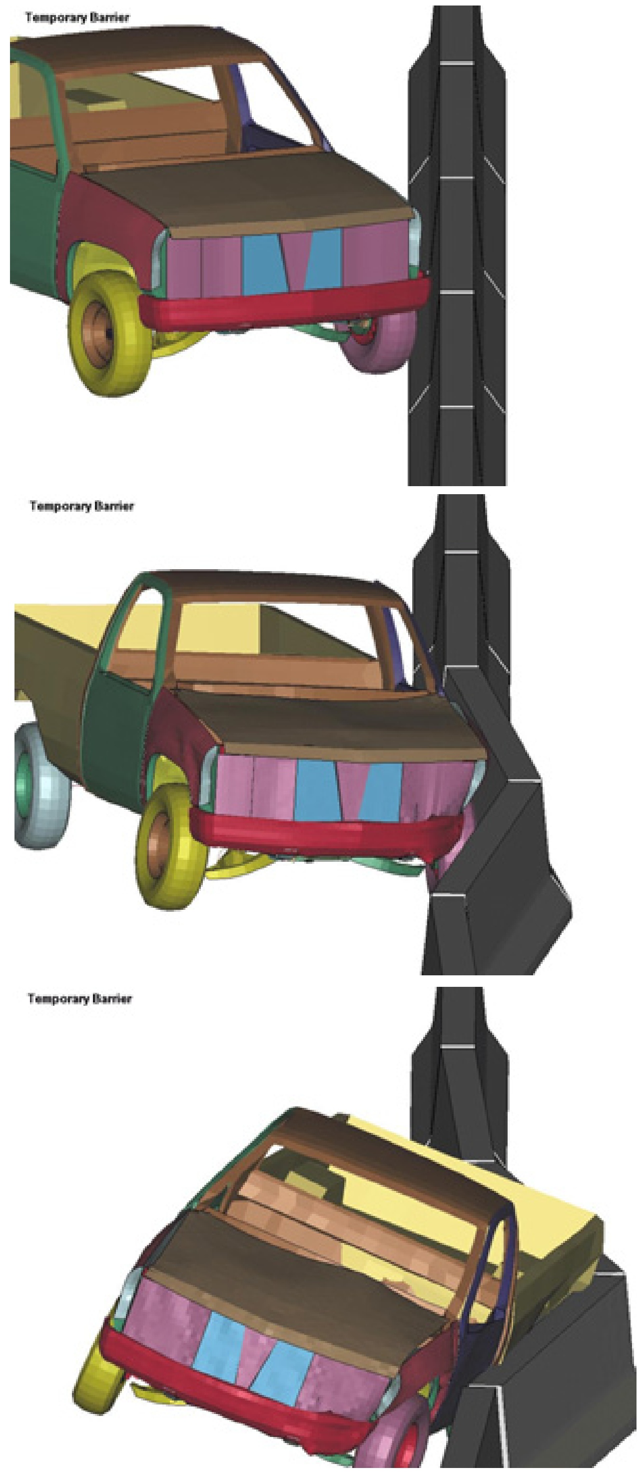


Figure 10a. With Tie-Down Anchors

Figure 10b. Without Tie-Down Anchors

APPENDIX B
MwRSF LARGE BOGIE DETAILS

B.1 Bogie Structural Details

The main frame of the bogie vehicle is comprised of two 3,875-mm long by 203-mm x 152-mm x 6-mm steel tubes on the sides and a pair of 1829-mm long by 457-mm x 152-mm x 13-mm steel tubes on the front and back. Details of the bogie vehicle are provided in Figures B-1 through B-5. The front and back tubes of the bogie are filled with concrete and drilled with a series of holes for mounting various impact heads and other attachments to the frame. In addition to these main tubes, the bogie frame is reinforced with six 203-mm x 152-mm x 6-mm steel tubes, six C 254 x 29.8 pieces of channel iron, and a 254-mm x 51-mm x 6-mm steel tube. The bogie vehicle rolls on standard-size pickup truck wheels and tires that are mounted on independent axles and outfitted with radio-controlled drum brakes.

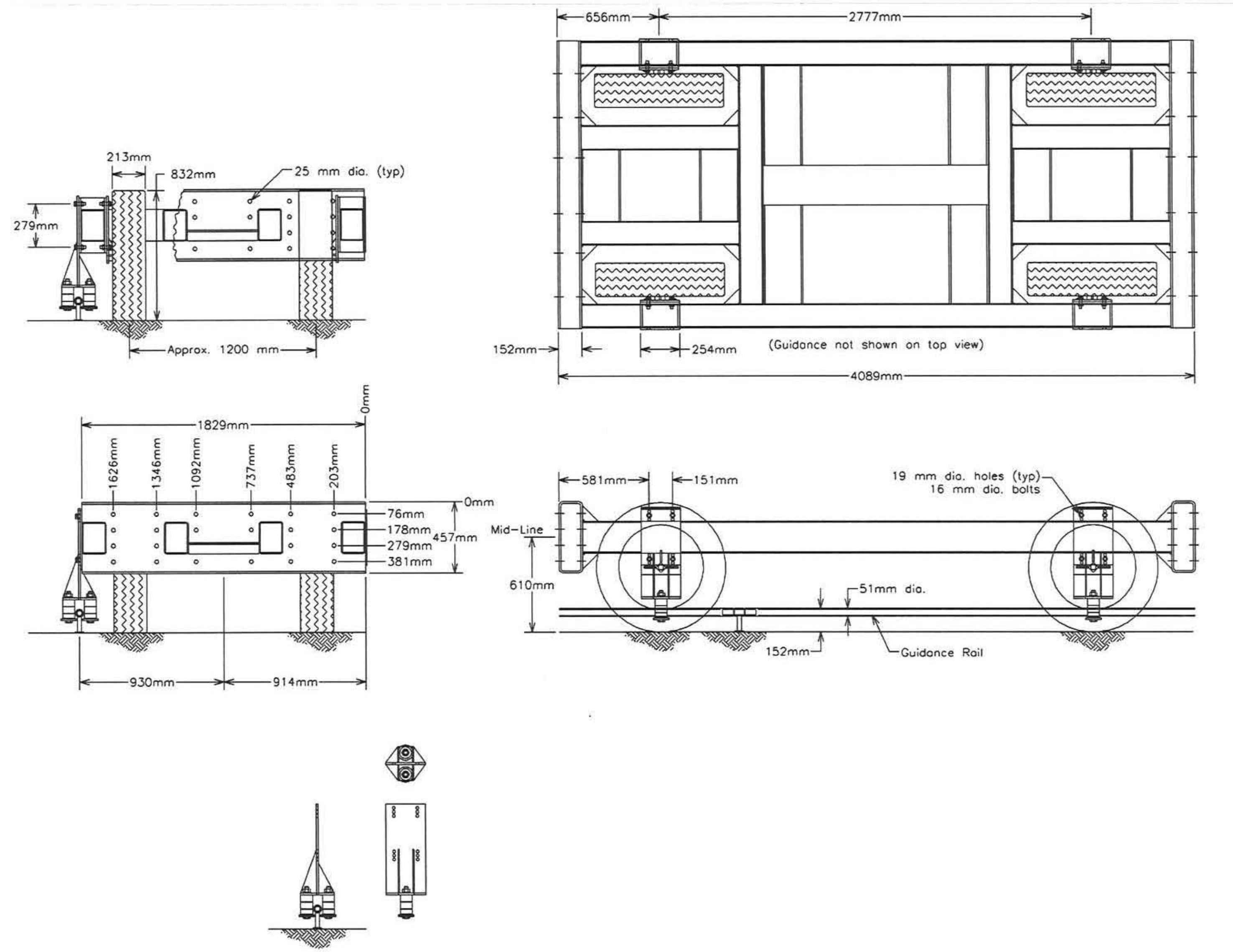


Figure B-1. Bogie Vehicle Details

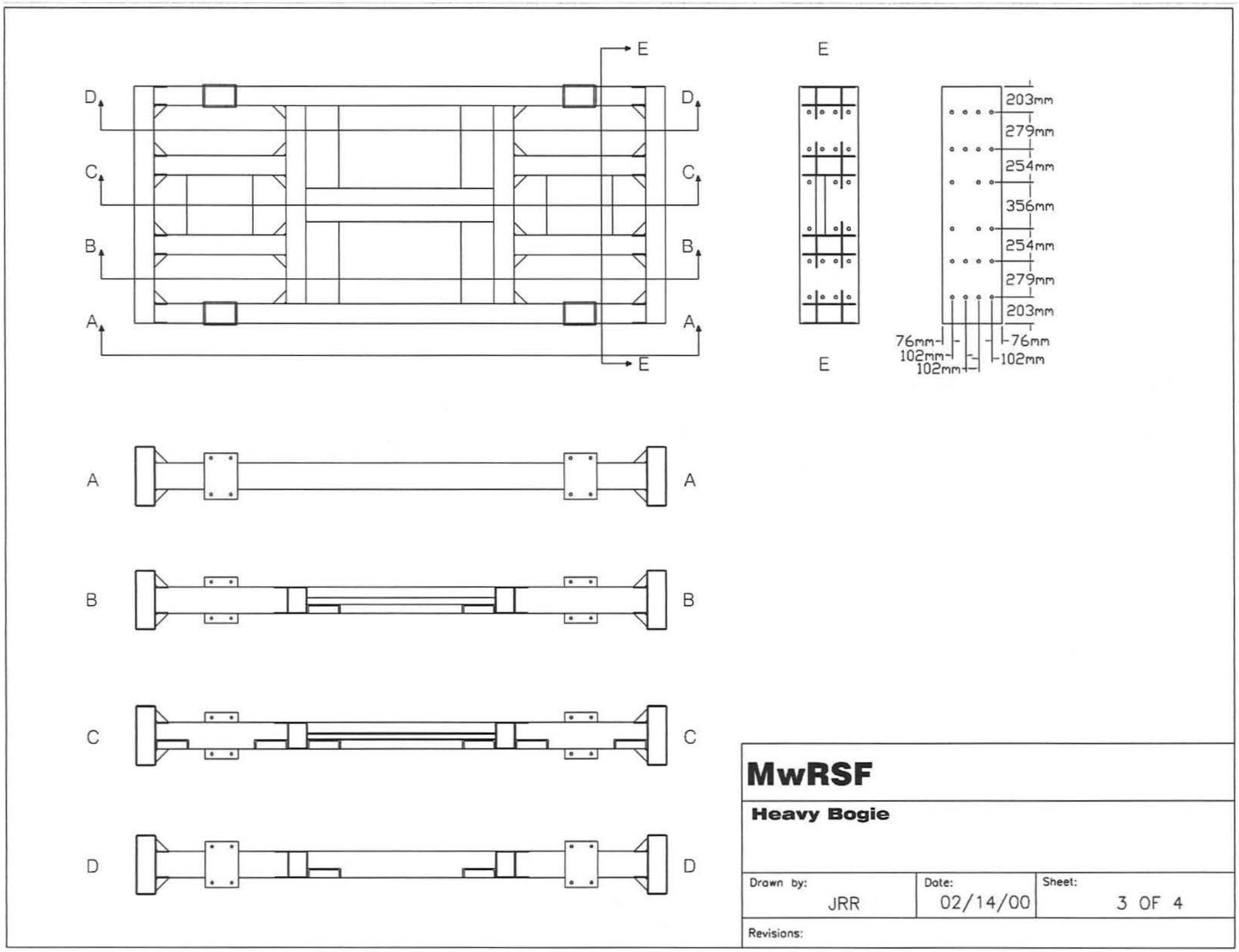


Figure B-2. Bogie Vehicle Details

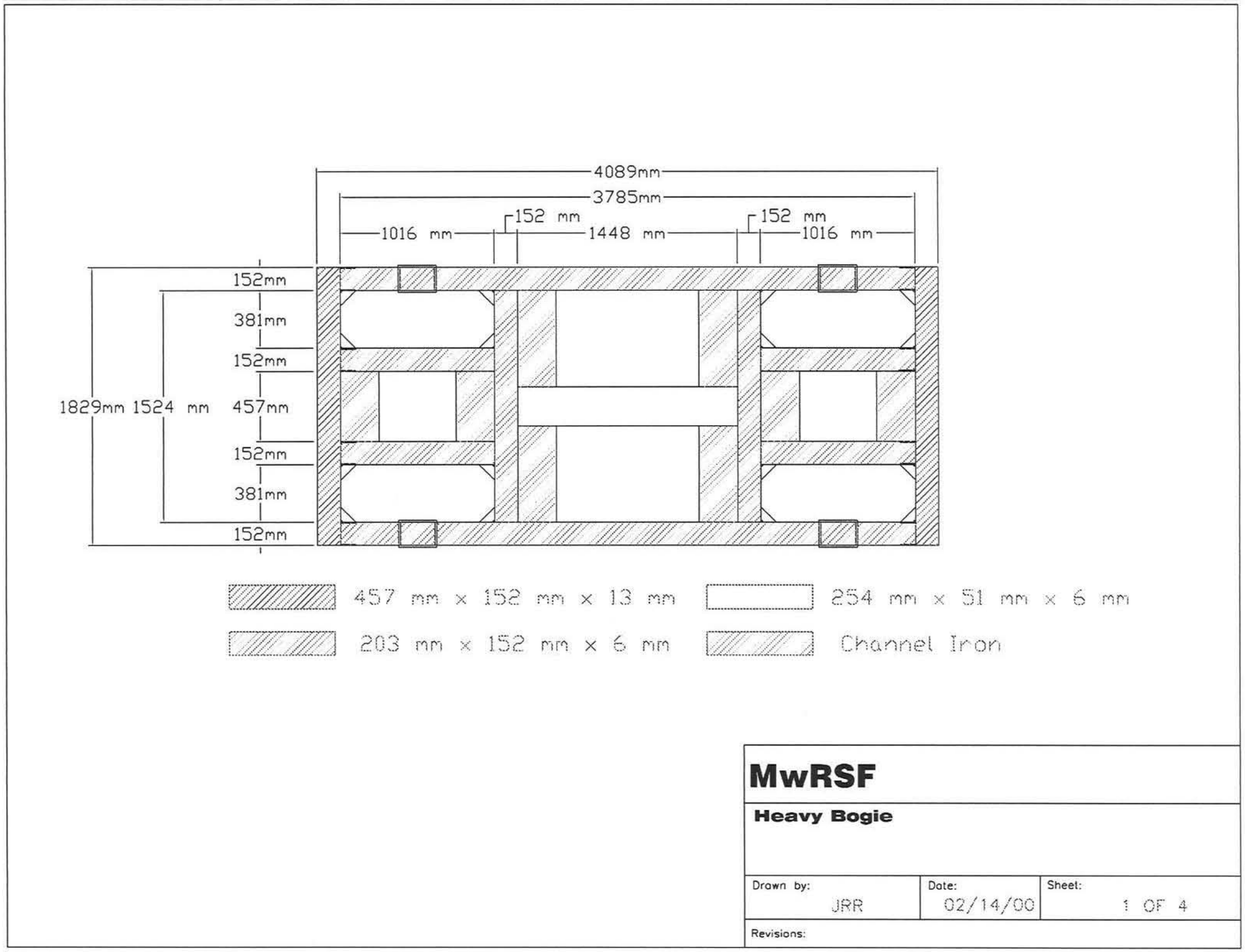


Figure B-3. Bogie Vehicle Details

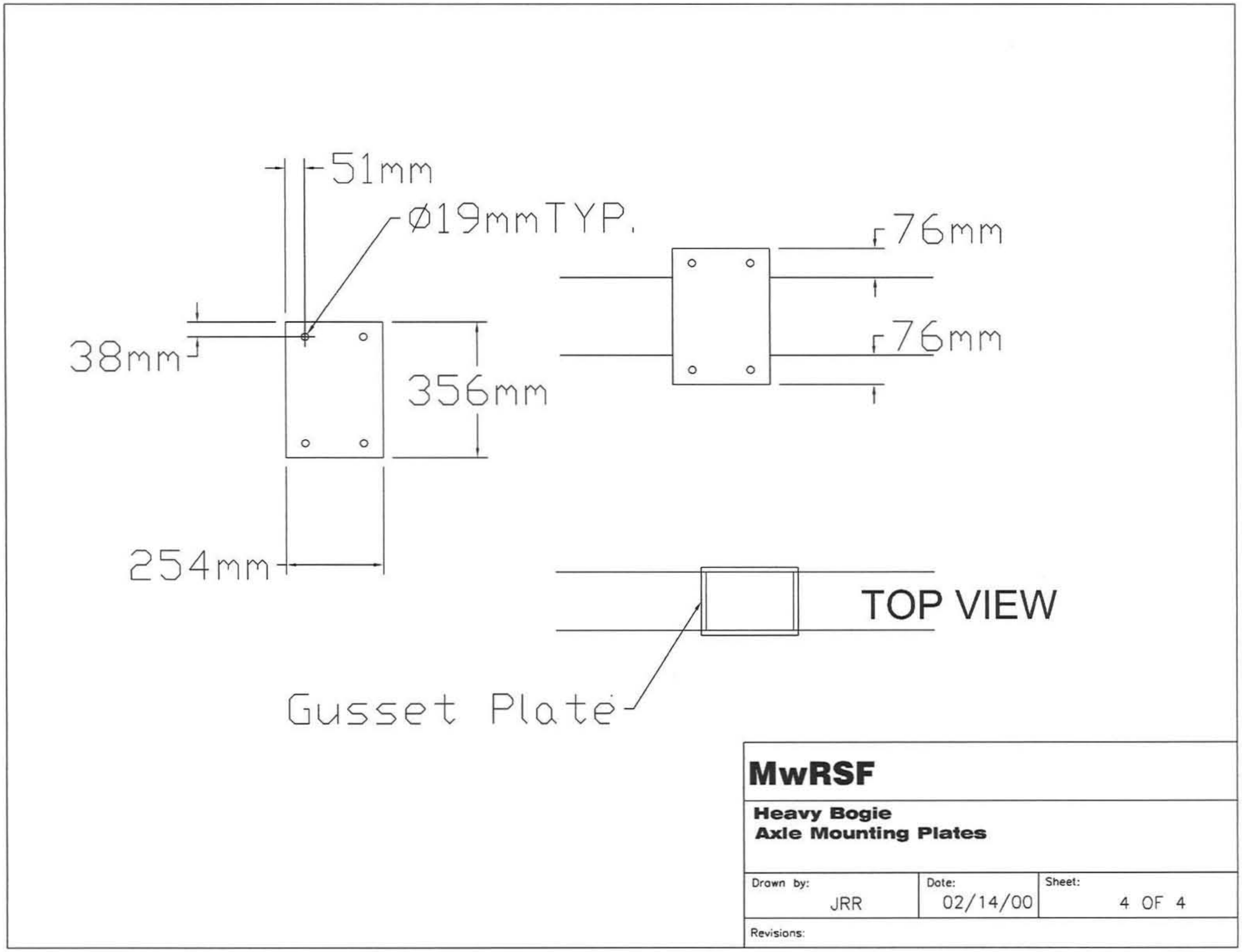
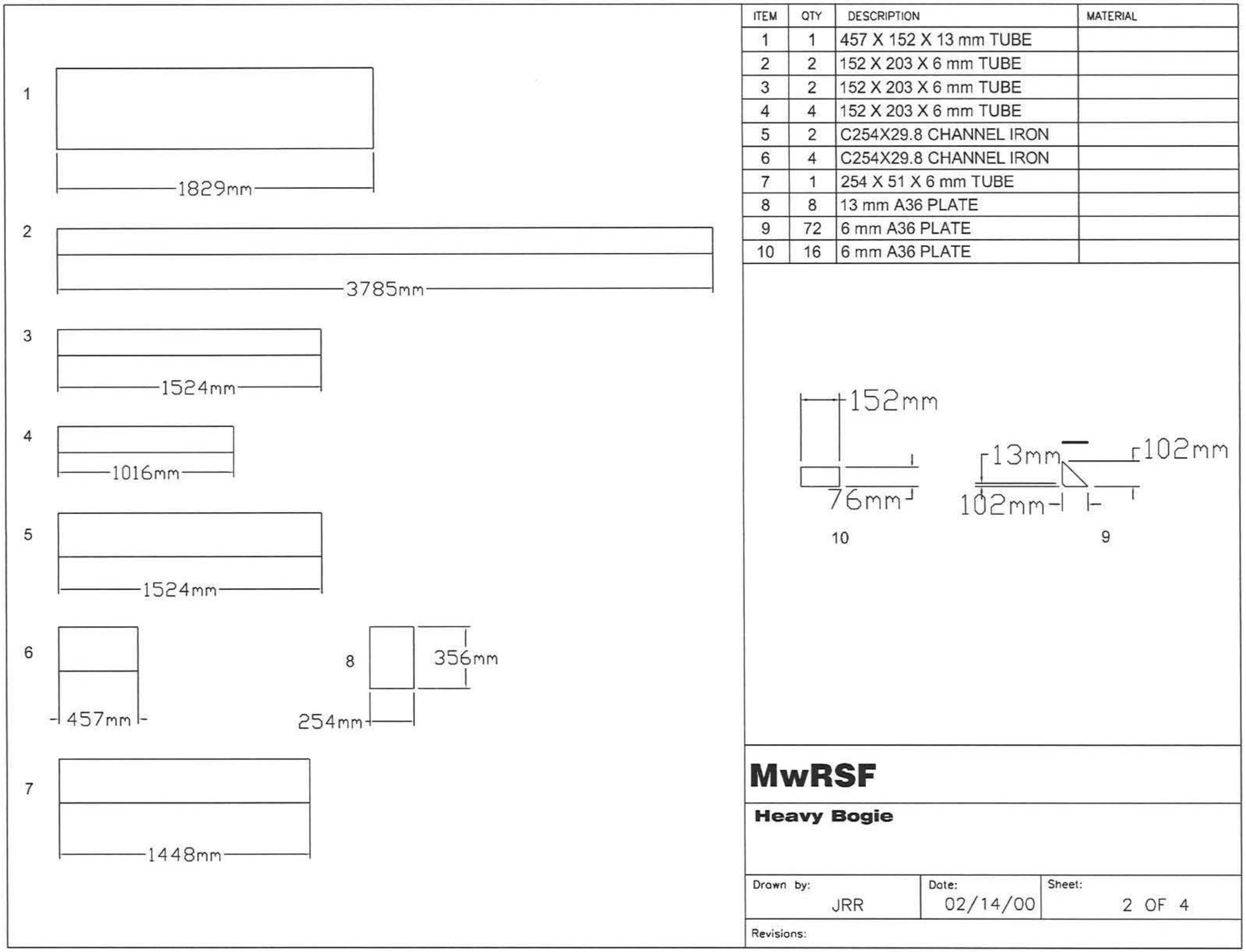


Figure B-4. Bogie Vehicle Details



ITEM	QTY	DESCRIPTION	MATERIAL
1	1	457 X 152 X 13 mm TUBE	
2	2	152 X 203 X 6 mm TUBE	
3	2	152 X 203 X 6 mm TUBE	
4	4	152 X 203 X 6 mm TUBE	
5	2	C254X29.8 CHANNEL IRON	
6	4	C254X29.8 CHANNEL IRON	
7	1	254 X 51 X 6 mm TUBE	
8	8	13 mm A36 PLATE	
9	72	6 mm A36 PLATE	
10	16	6 mm A36 PLATE	

Figure B-5. Bogie Vehicle Details

APPENDIX C
ACCELEROMETER DATA ANALYSIS, TEST ITDB-2

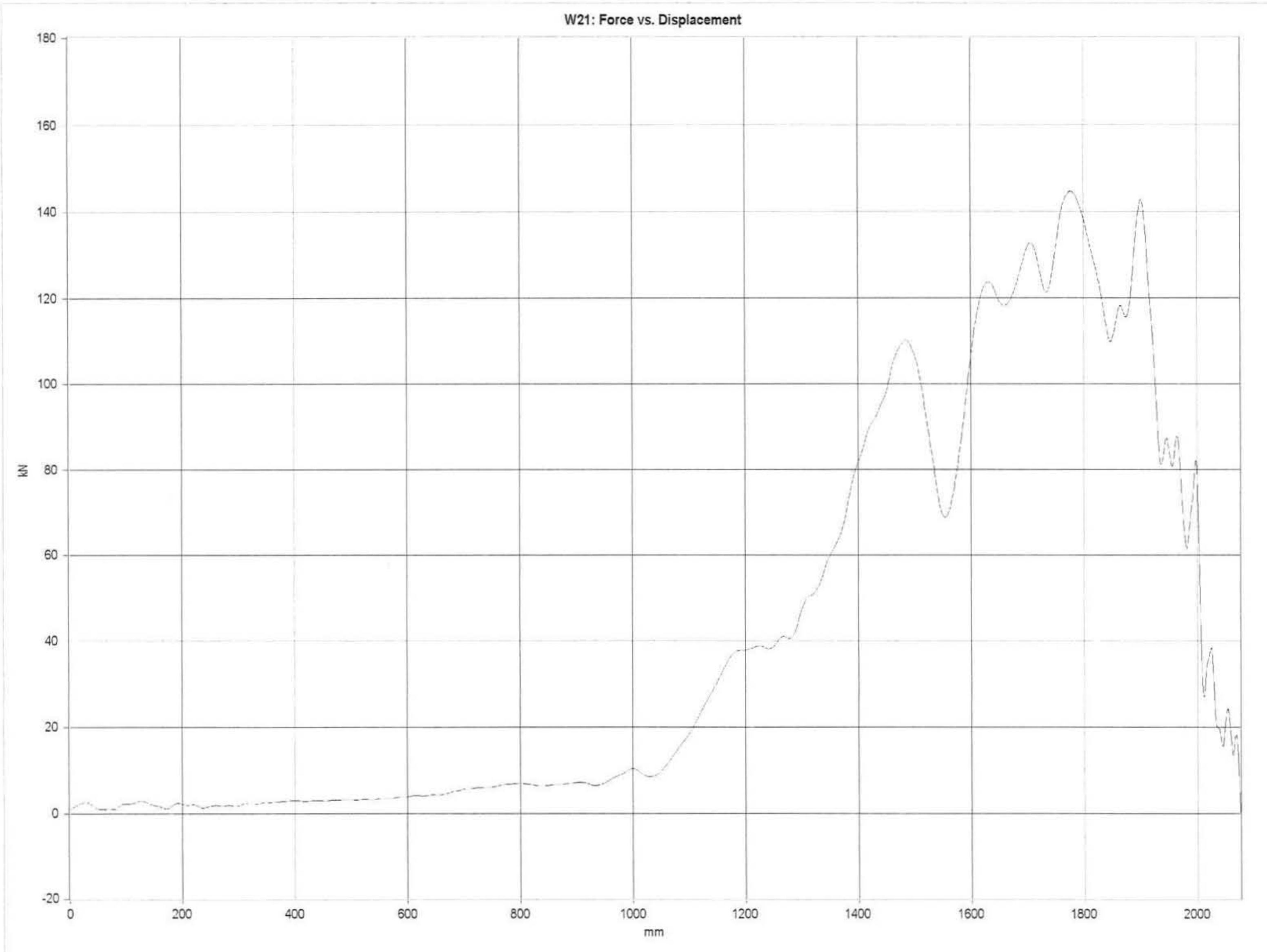


Figure C-1. Force vs. Deflection, Test ITDB-2

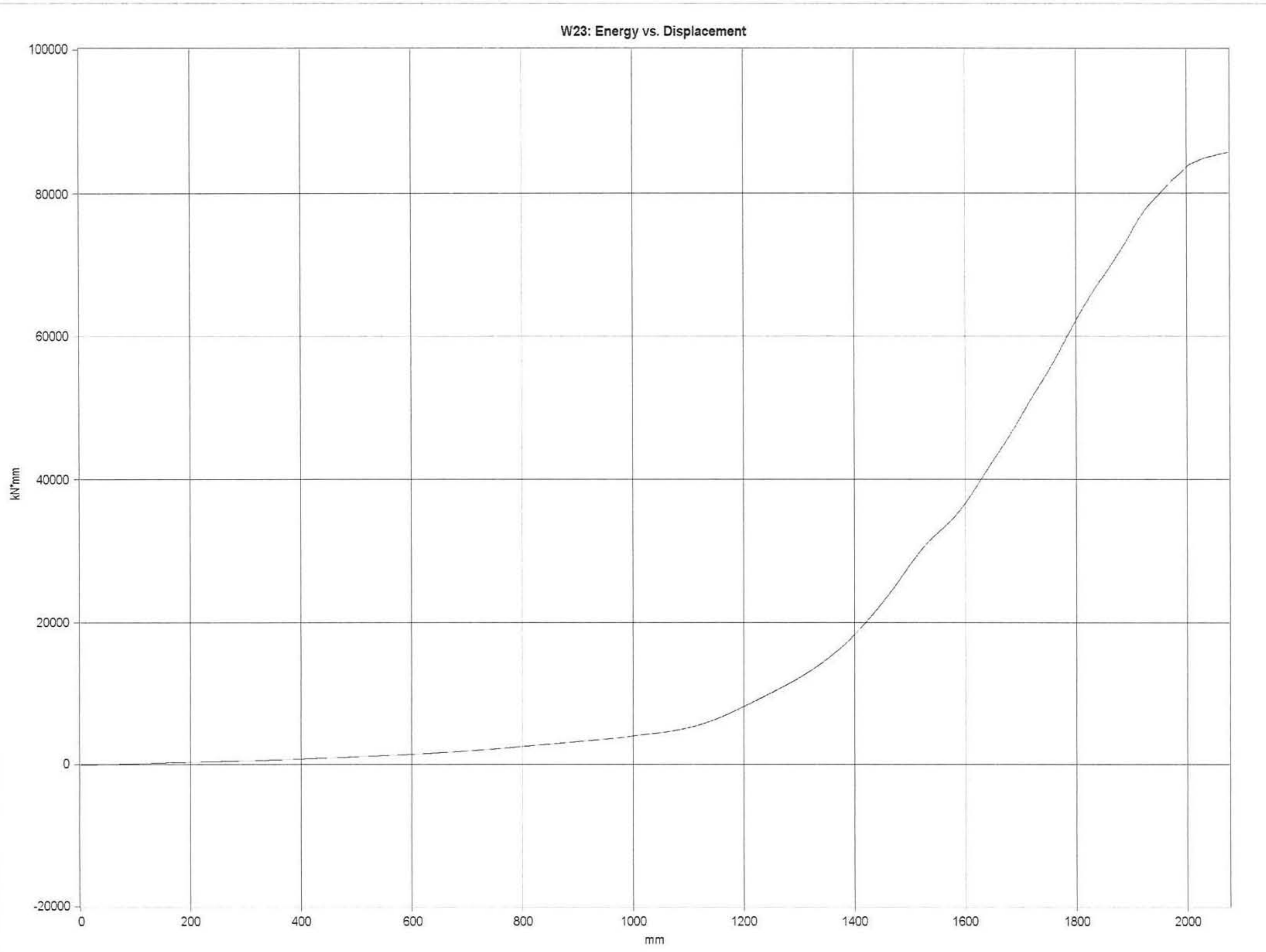


Figure C-2. Energy vs. Deflection, Test ITDB-2

APPENDIX D
STRAIN GAUGE DATA ANALYSIS, TEST ITDB-2

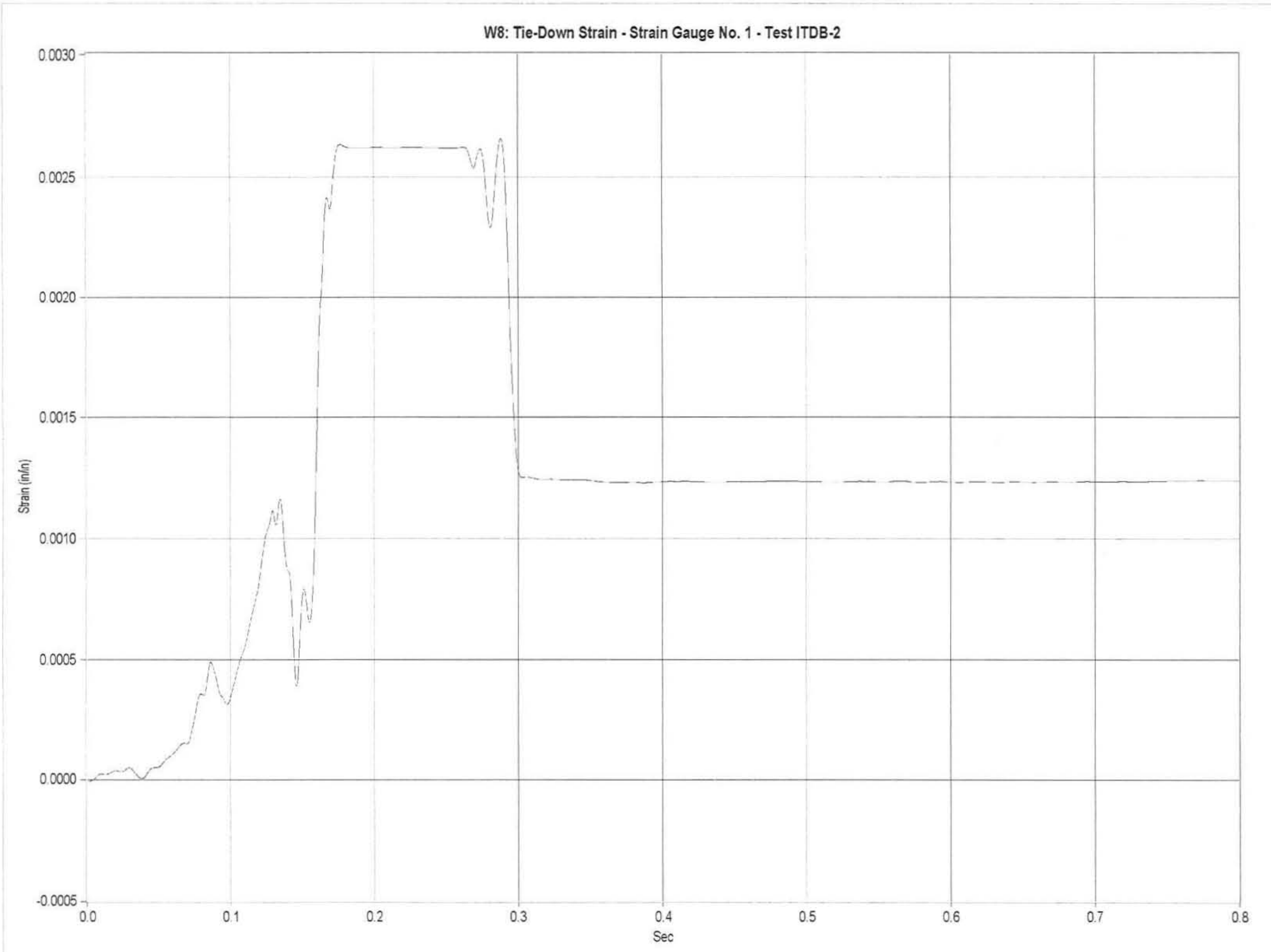


Figure D-1. Graph of Inner Flange Gauge No. 1 Top Peak Strain, Test ITDB-2

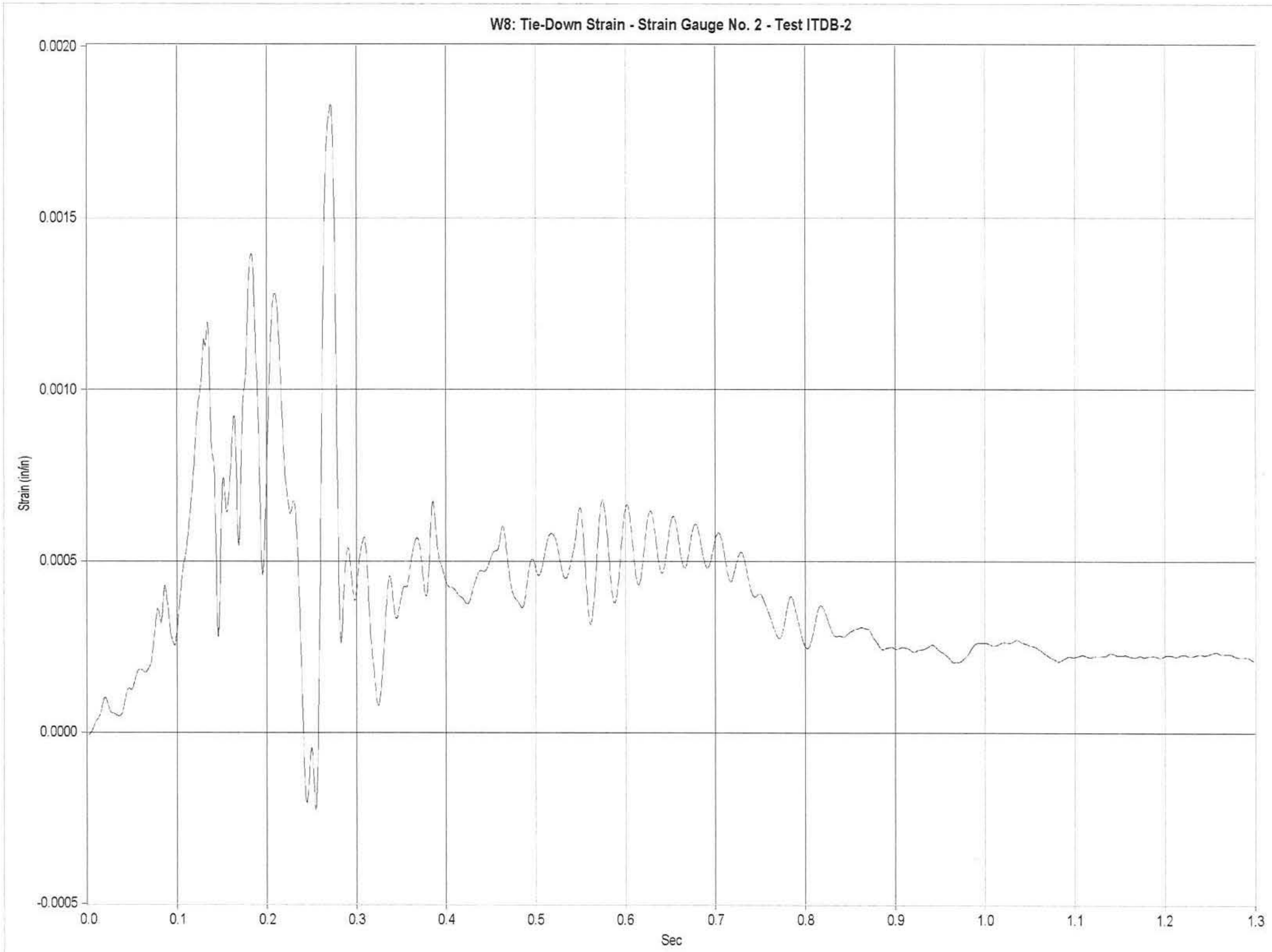


Figure D-2. Graph of Inner Flange Gauge No. 2 Top Peak Strain, Test ITDB-2

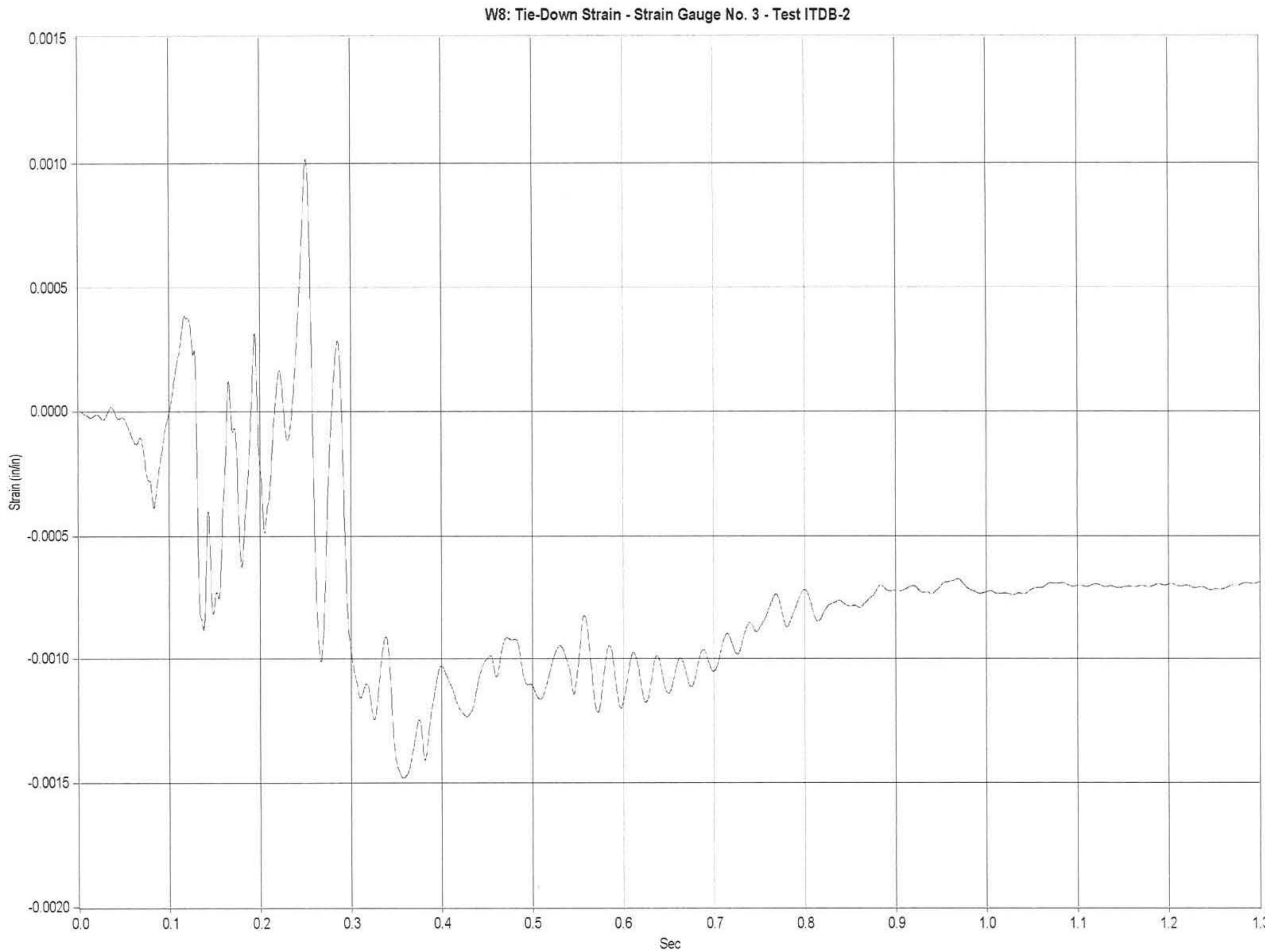


Figure D-3. Graph of Outer Flange Gauge No. 3 Top Peak Strain, Test ITDB-2

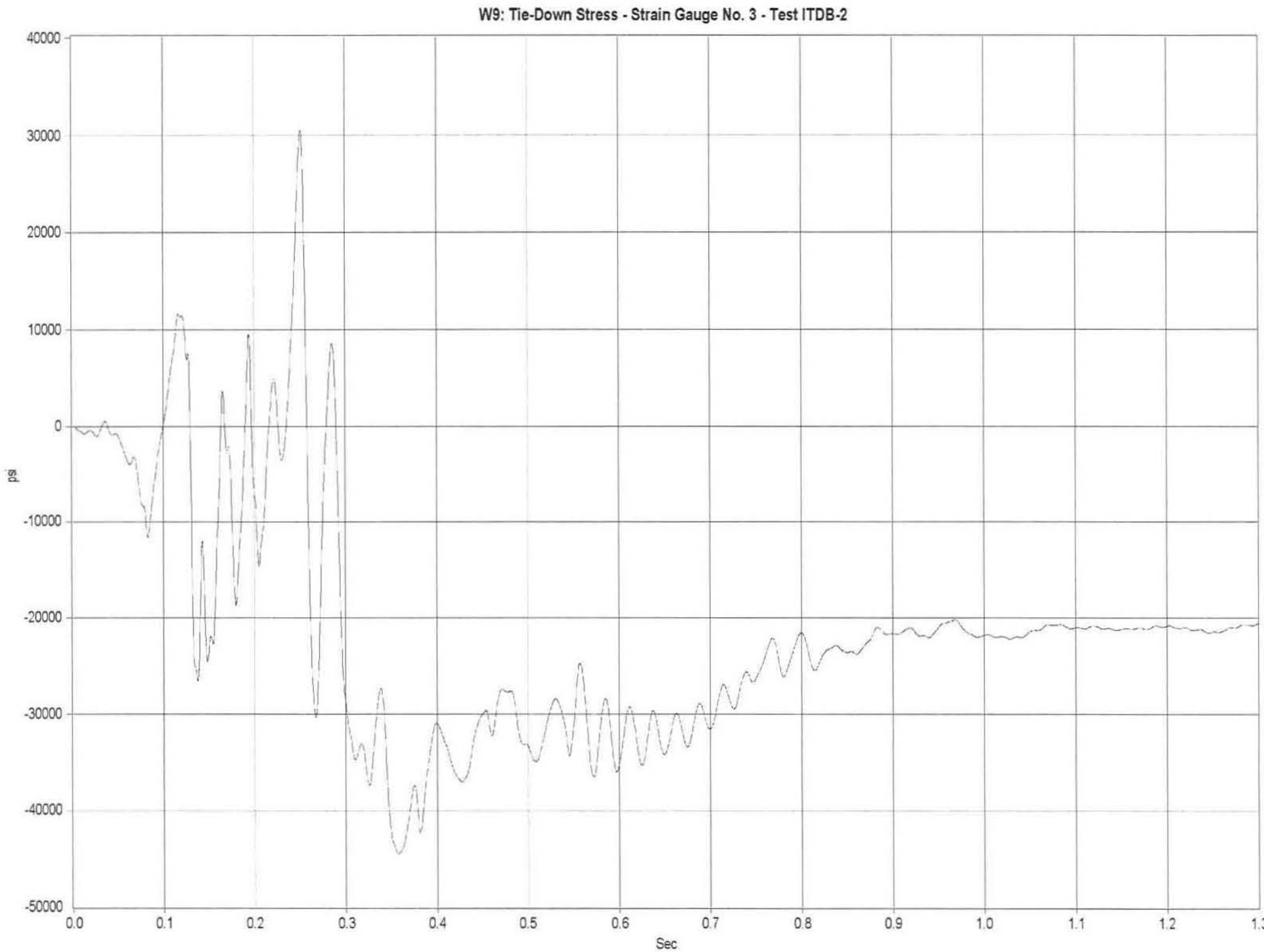


Figure D-4. Graph of Outer Flange Gauge No. 3 Top Peak Stress, Test ITDB-2

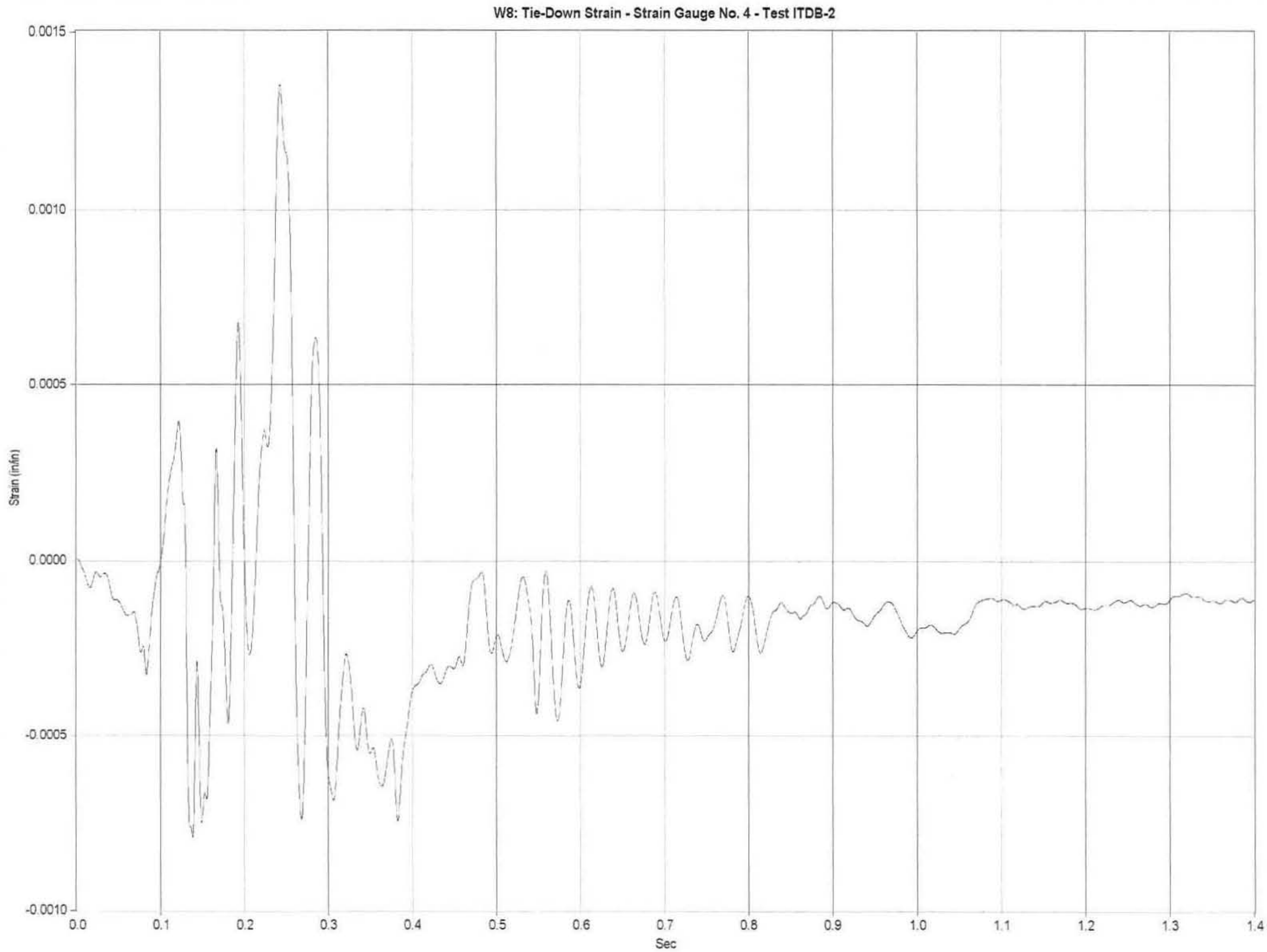


Figure D-5. Graph of Outer Flange Gauge No. 4 Top Peak Strain, Test ITDB-2

APPENDIX E
F-SHAPE BARRIER TIE-DOWN DETAILS

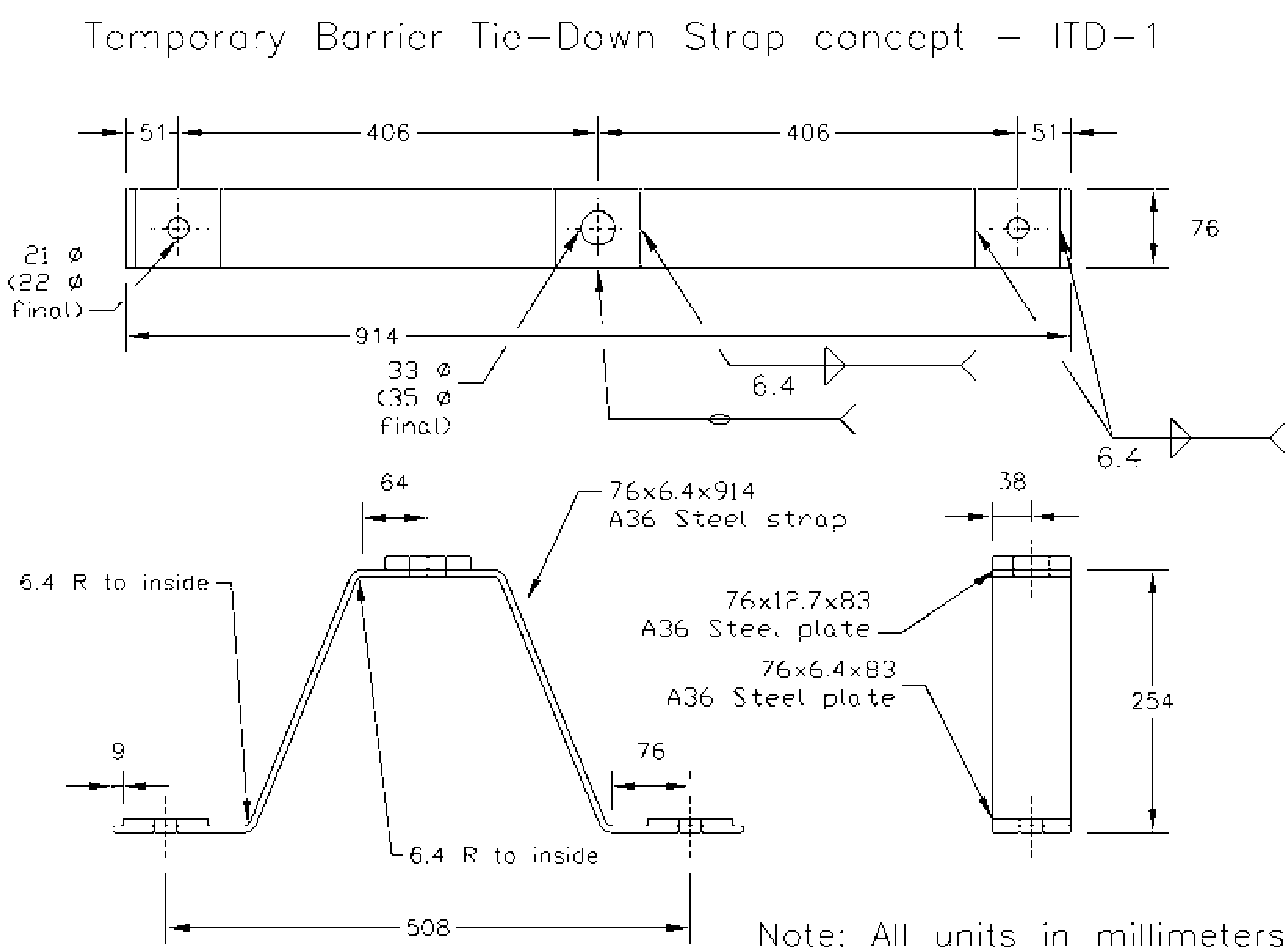


Figure E-1. Tie-Down Temporary Barrier System Details

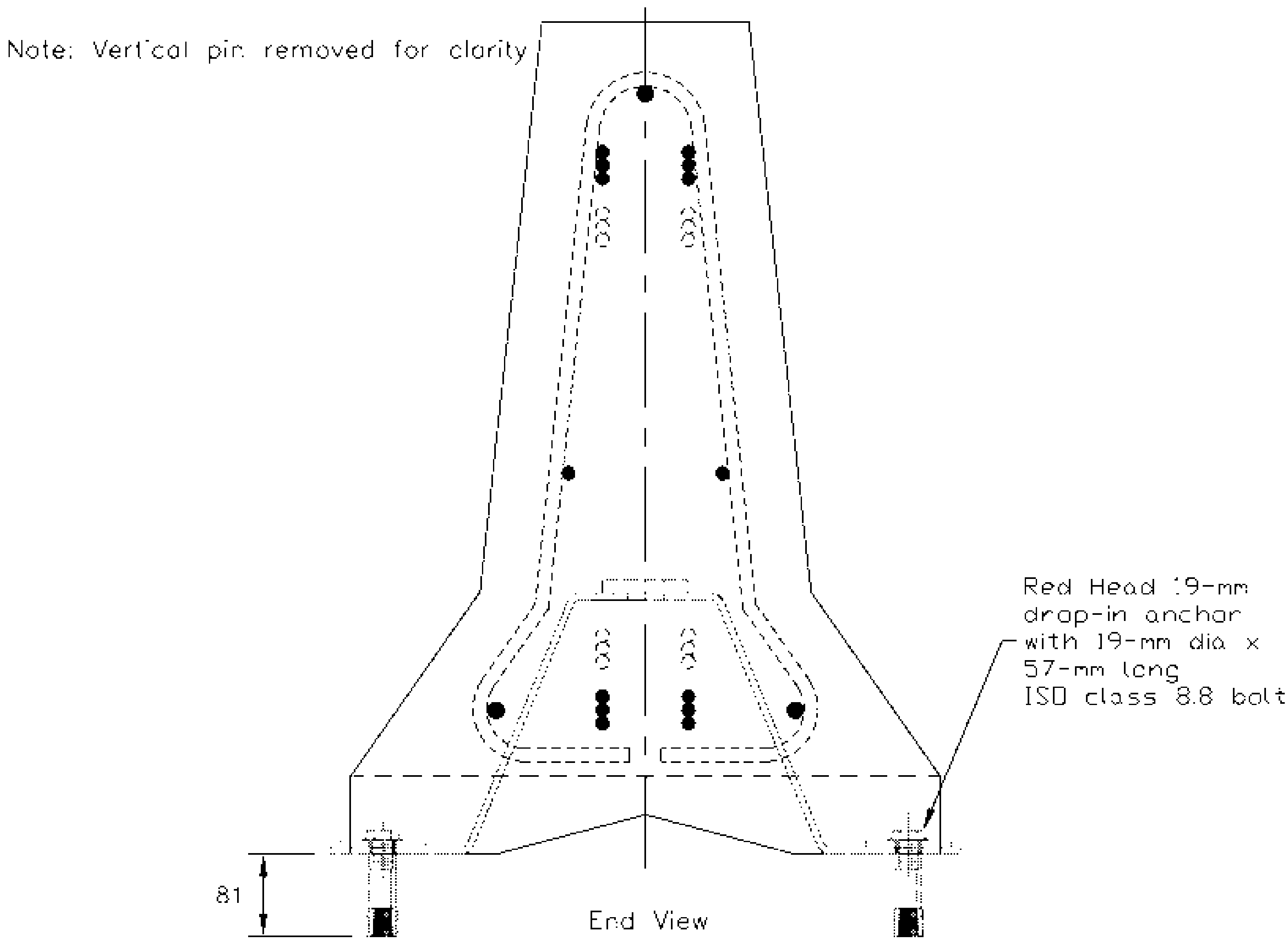


Figure E-2. Tie-Down Temporary Barrier System Details

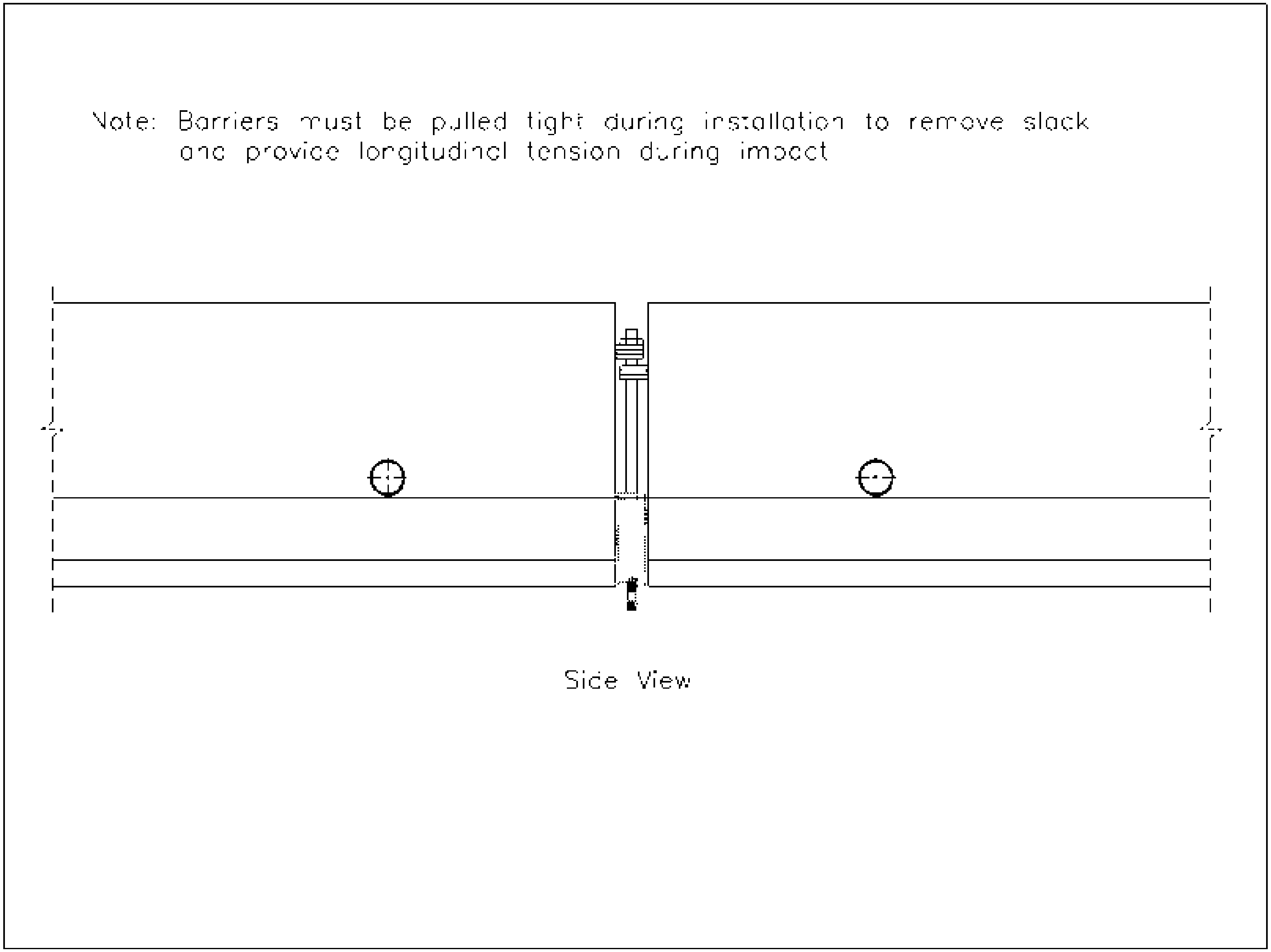


Figure E-3. Tie-Down Temporary Barrier System Details

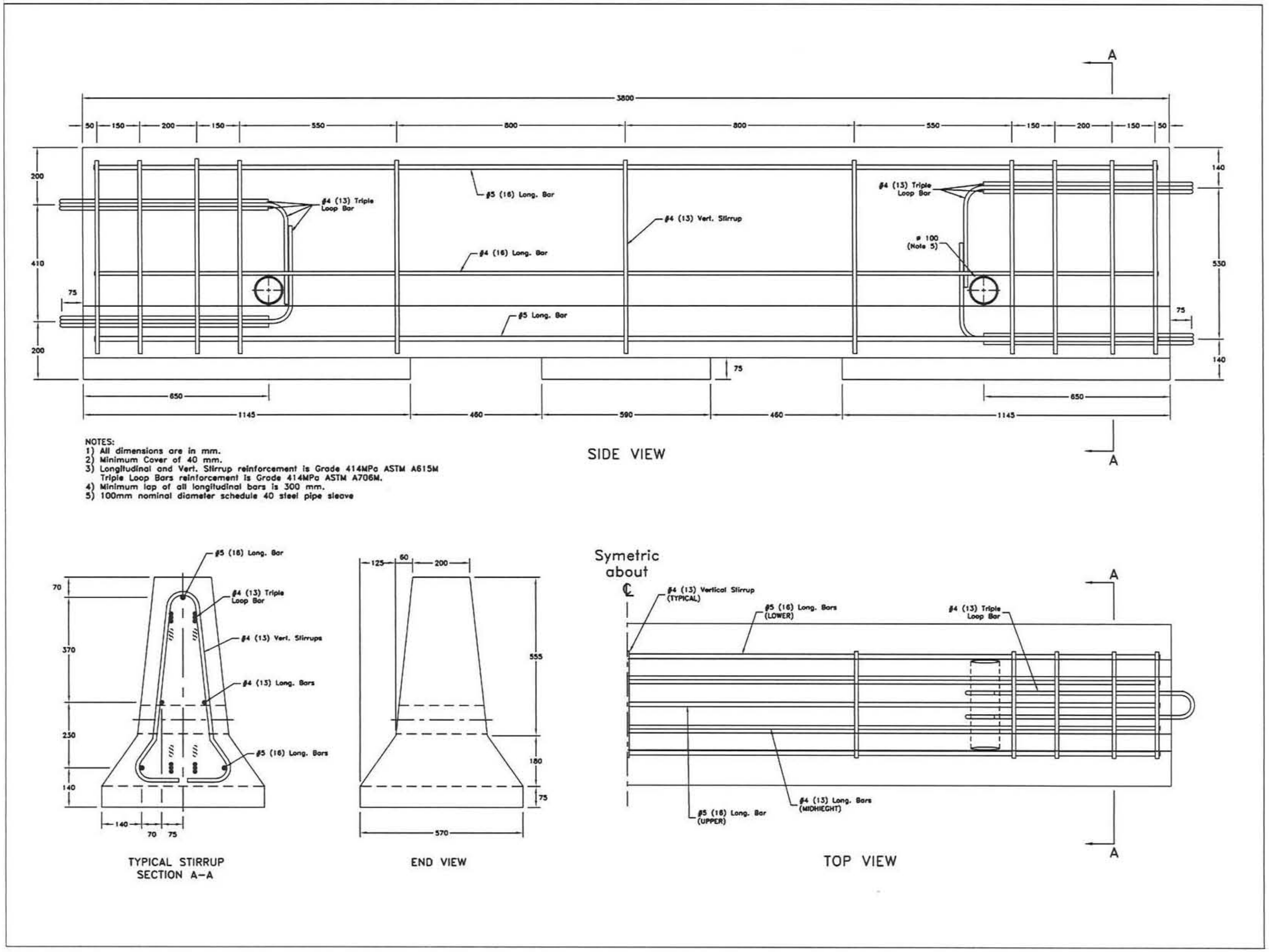


Figure E-4. Tie-Down Temporary Barrier System Details

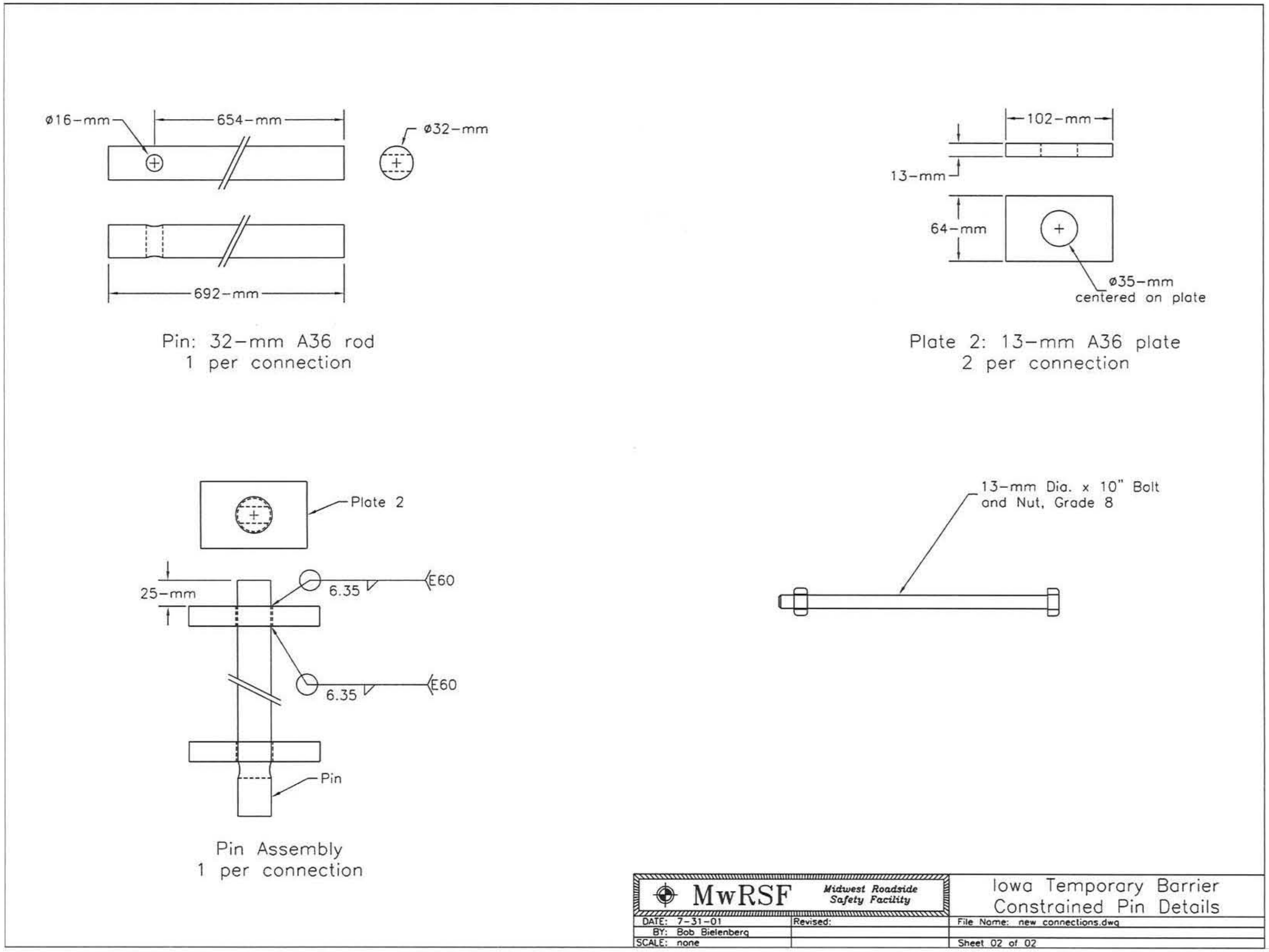


Figure E-5. Tie-Down Temporary Barrier System Details

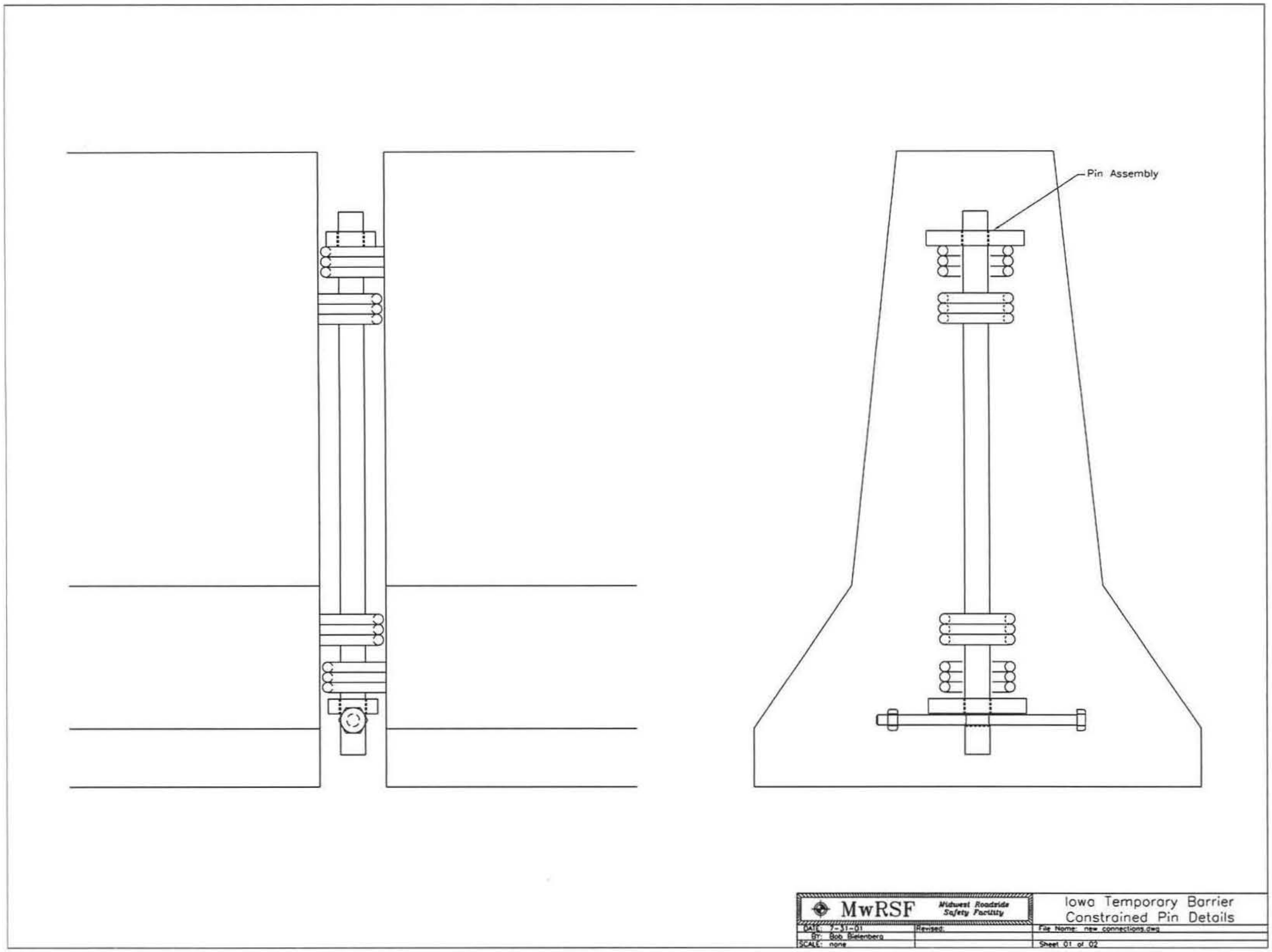


Figure E-6. Tie-Down Temporary Barrier System Details

APPENDIX F
OCCUPANT COMPARTMENT DEFORMATION, TEST ITD-1

Figure F-1. Occupant Compartment Deformation, Test ITD-1

VEHICLE PRE/POST CRUSH INFO

TEST: ITD-1
VEHICLE: 1995/GMC/2500/WHITE

POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z
1	1.75	53	0.75	1.75	53	1.25	0	0	0.5
2	8.125	54.25	-0.75	8	54	0	-0.125	-0.25	0.75
3	13.25	56.75	-1	13.5	56	-0.5	0.25	-0.75	0.5
4	23.25	59	-2.5	22	53.25	0.25	-1.25	-5.75	2.75
5	31.25	55.75	-1.25	29	54.75	-1	-2.25	-1	0.25
6	2.5	45.75	-1.5	2.75	45.75	-1	0.25	0	0.5
7	7.25	48.5	-2	7.25	48.25	-1.25	0	-0.25	0.75
8	10.25	52.25	-7	10.25	52	-6.75	0	-0.25	0.25
9	17.75	52.75	-7.25	17	52.25	-7.25	-0.75	-0.5	0
10	26	52.5	-7	24.25	51	-5.75	-1.75	-1.5	1.25
11	2.25	41.25	-1.75	2.25	41.5	-1.25	0	0.25	0.5
12	8.25	42.5	-3.125	8.25	42.75	-2.5	0	0.25	0.625
13	11.5	44	-7.25	11.25	44.25	-7.25	-0.25	0.25	0
14	18.75	44.125	-7.75	17.75	44.25	-7.5	-1	0.125	0.25
15	25.5	44.5	-8	25	44	-7.75	-0.5	-0.5	0.25
16	1.5	37.25	-2	1.5	37.25	-1.5	0	0	0.5
17	10.75	36.75	-6.25	9.75	36.5	-6.5	-1	-0.25	-0.25
18	16.75	38.25	-7.25	15.75	38	-7.25	-1	-0.25	0
19	26.25	39	-8	25.25	39	-7.75	-1	0	0.25
20	1.5	31.25	-2.25	1.5	31	-2	0	-0.25	0.25
21	15.5	31.5	-7	14.75	31.25	-7	-0.75	-0.25	0
22	26.25	31	-7	25.25	31.25	-7.25	-1	0.25	-0.25
23	14.5	22.5	-6.75	14.25	22.5	-7	-0.25	0	-0.25
24	32.25	29.25	-2	31.75	28.75	-2	-0.5	-0.5	0
25	2.75	43.5	24.5	2.75	43.75	25.25	0	0.25	0.75
26	16.5	49.5	19.75	16.5	49.25	19.5	0	-0.25	-0.25
27	28.5	46.75	20.25				-28.5	-46.75	-20.25
28									
29									
30									

ORIENTATION AND REFERENCE INFO

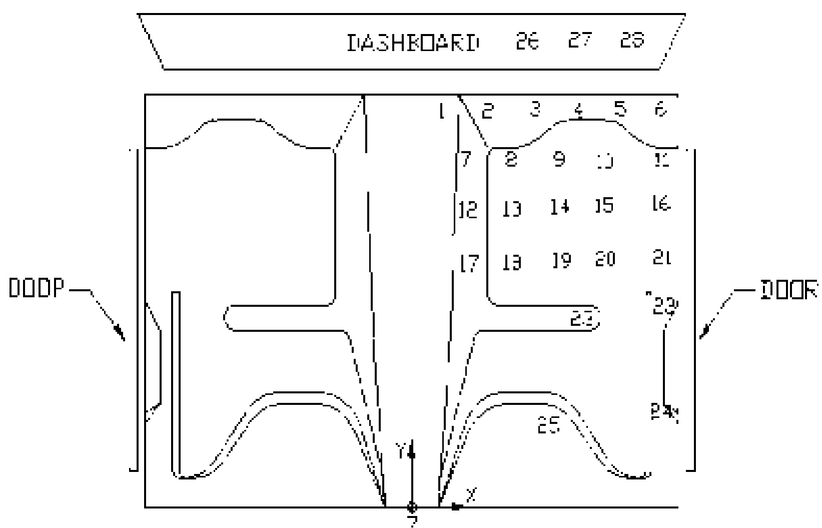


Figure F-1. Occupant Compartment Deformation, Test ITD-1

APPENDIX G
ACCELEROMETER DATA ANALYSIS, TEST ITD-1

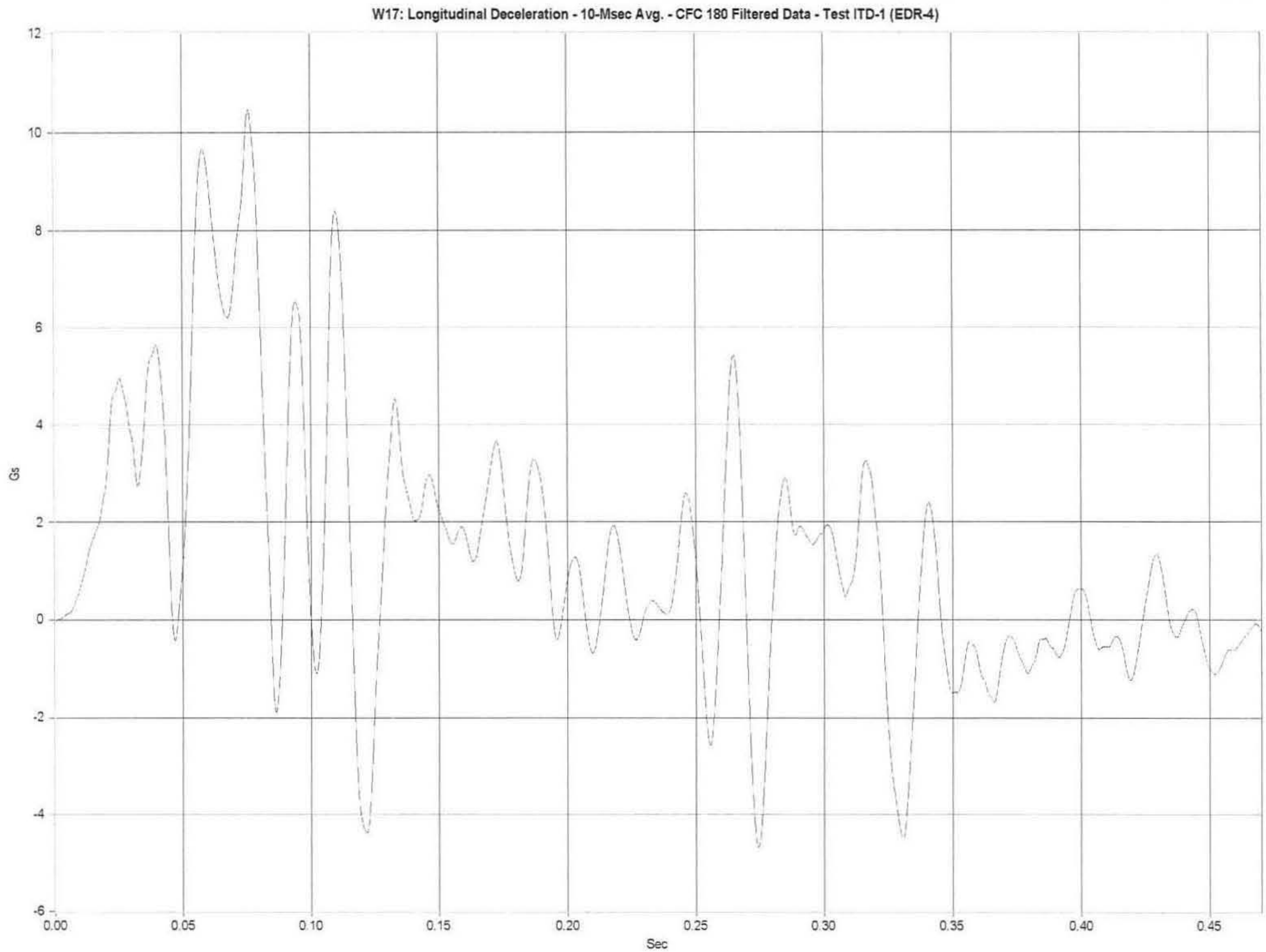


Figure G-1. Graph of Longitudinal Deceleration - Filtered Data, Test ITD-1

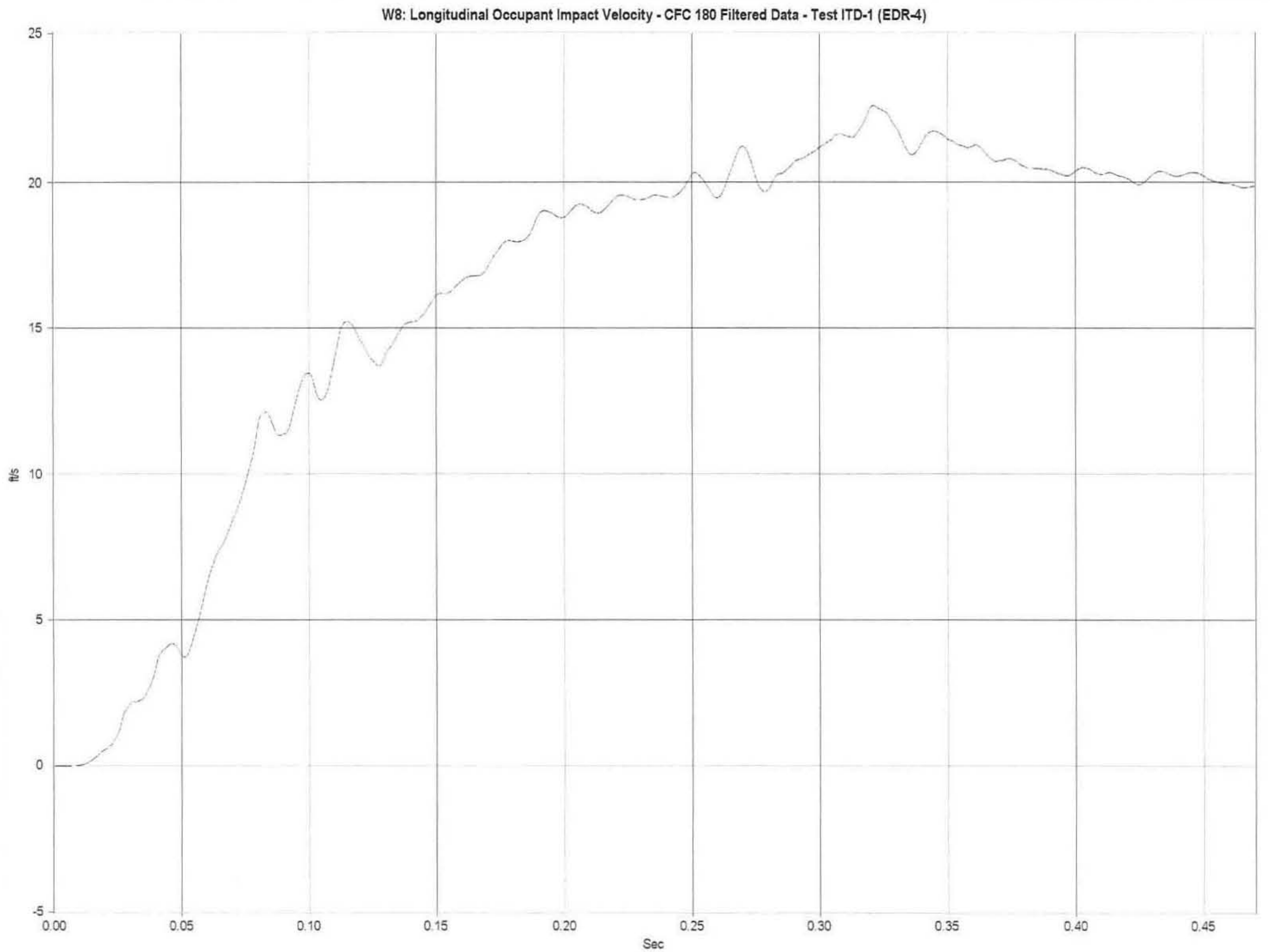


Figure G-2. Graph of Longitudinal Occupant Impact Velocity - Filtered Data, Test ITD-1

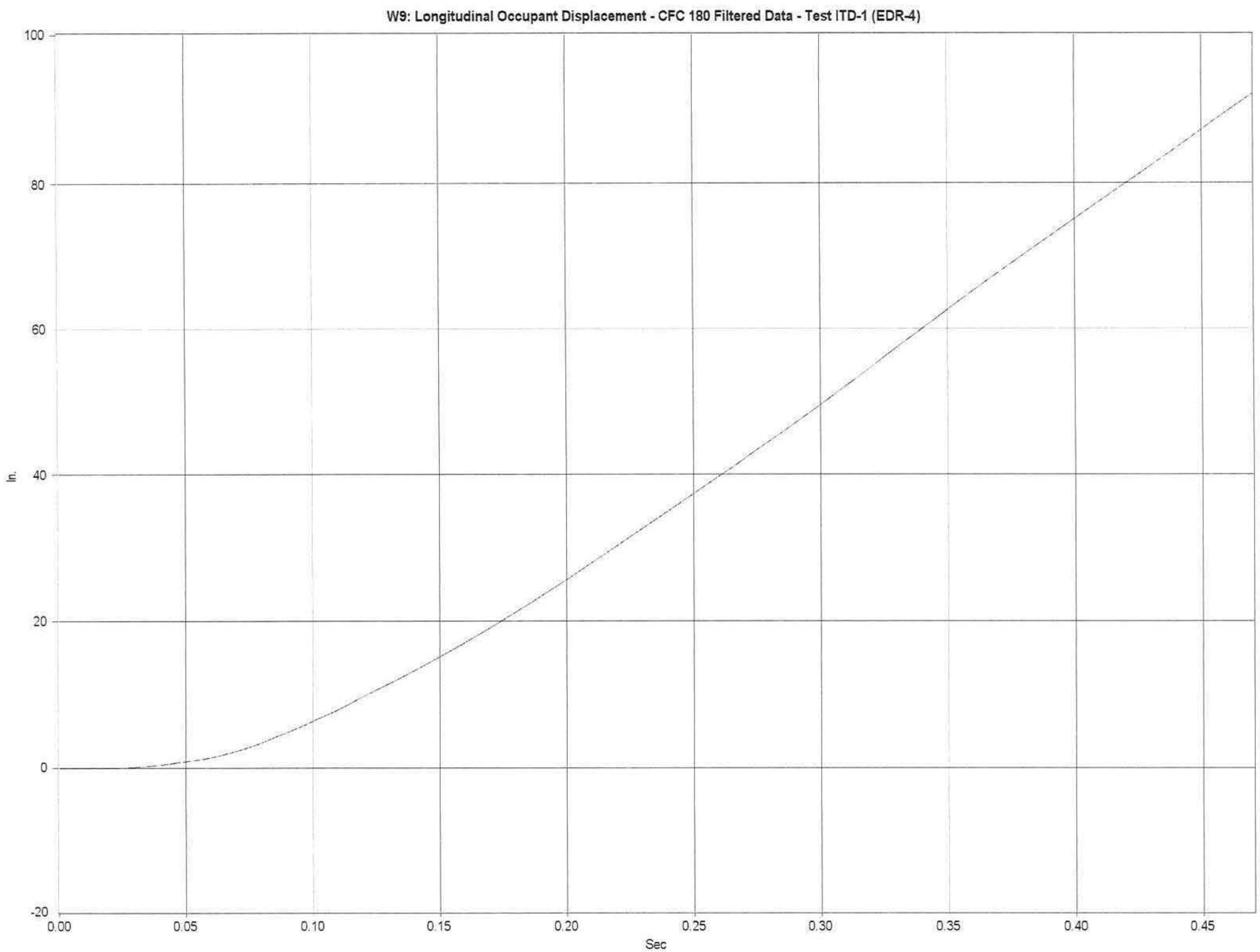


Figure G-3. Graph of Longitudinal Occupant Displacement - Filtered Data, Test ITD-1

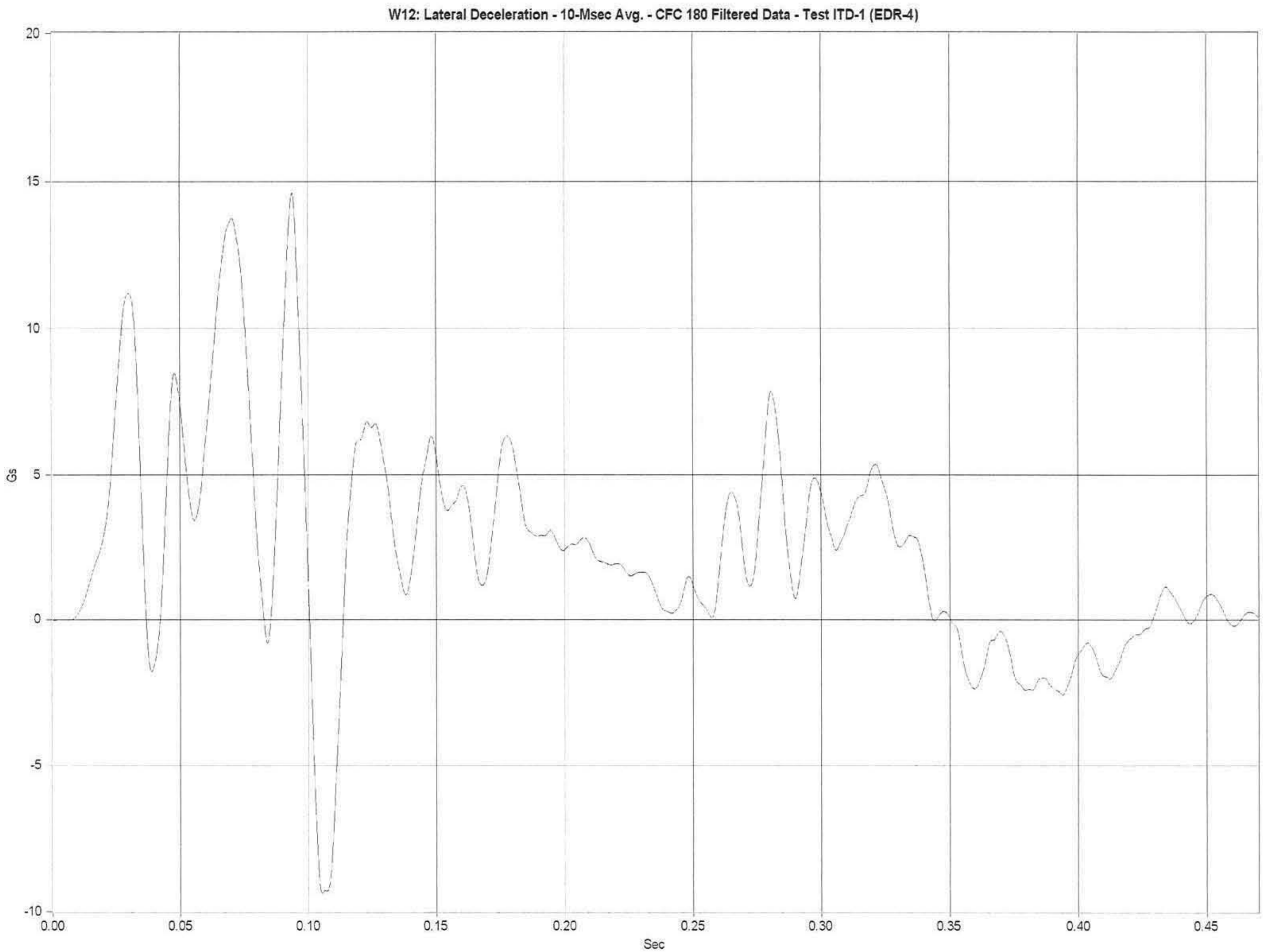


Figure G-4. Graph of Lateral Deceleration - Filtered Data, Test ITD-1

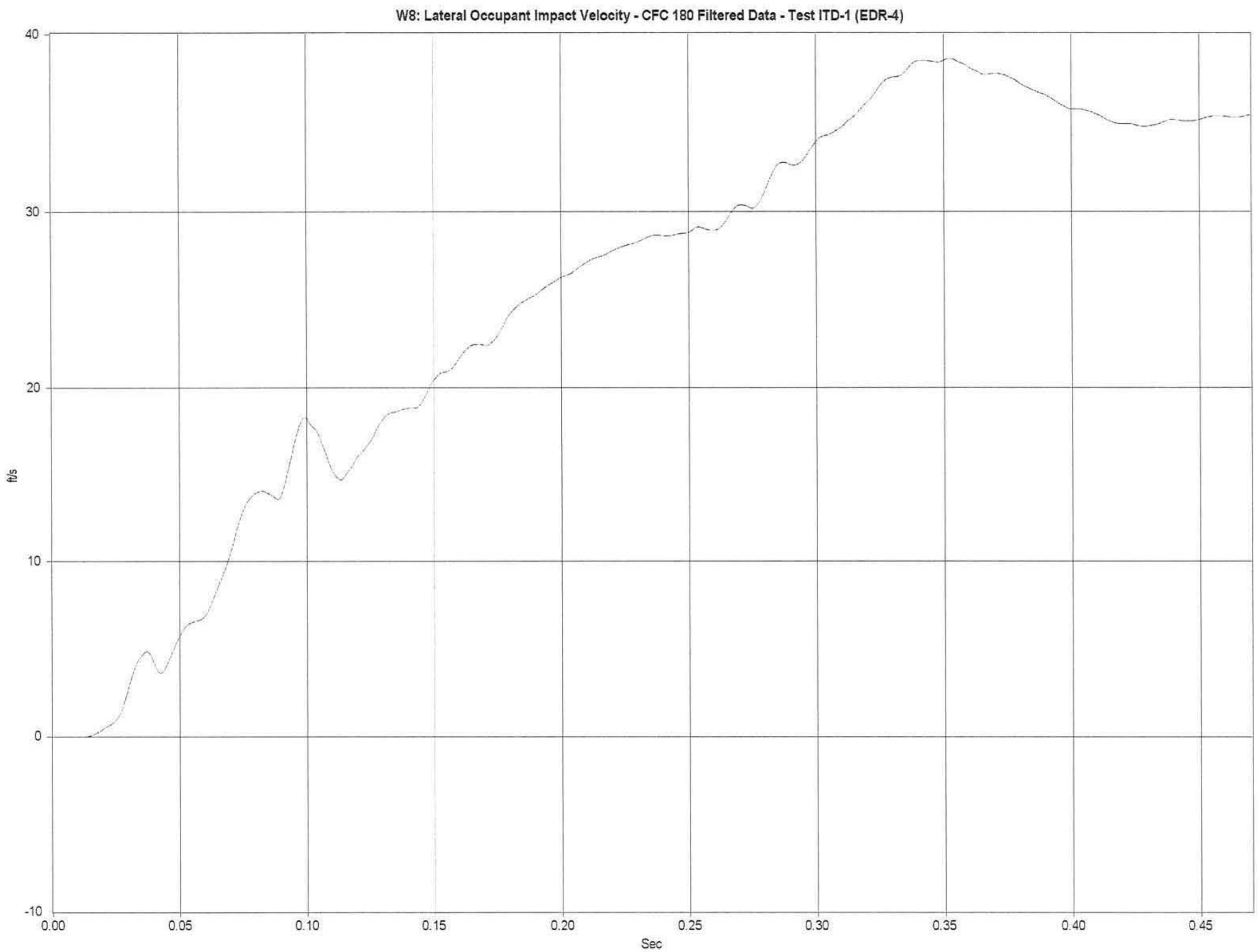


Figure G-5. Graph of Lateral Occupant Impact Velocity - Filtered Data, Test ITD-1

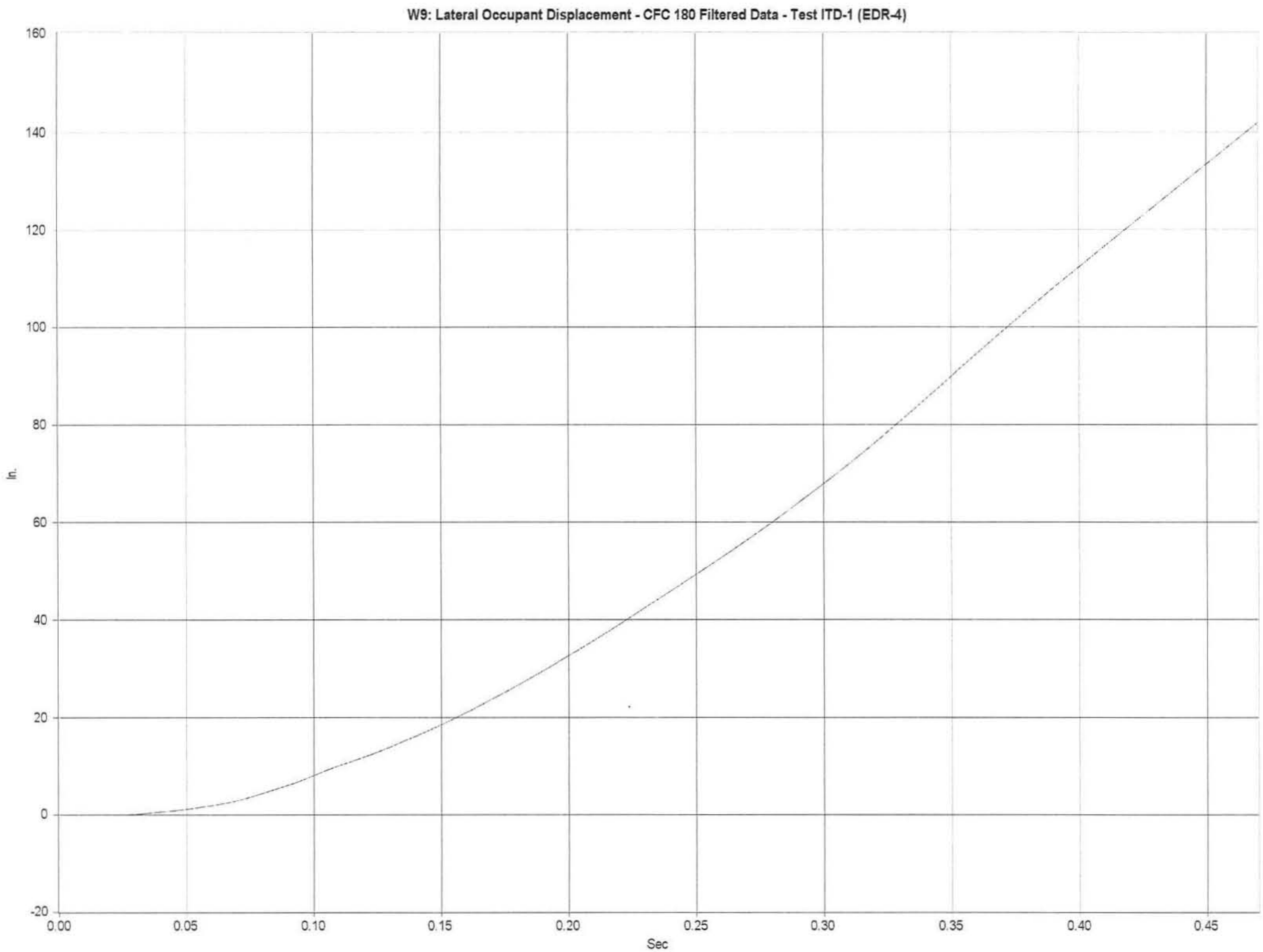


Figure G-6. Graph of Lateral Occupant Displacement - Filtered Data, Test ITD-1

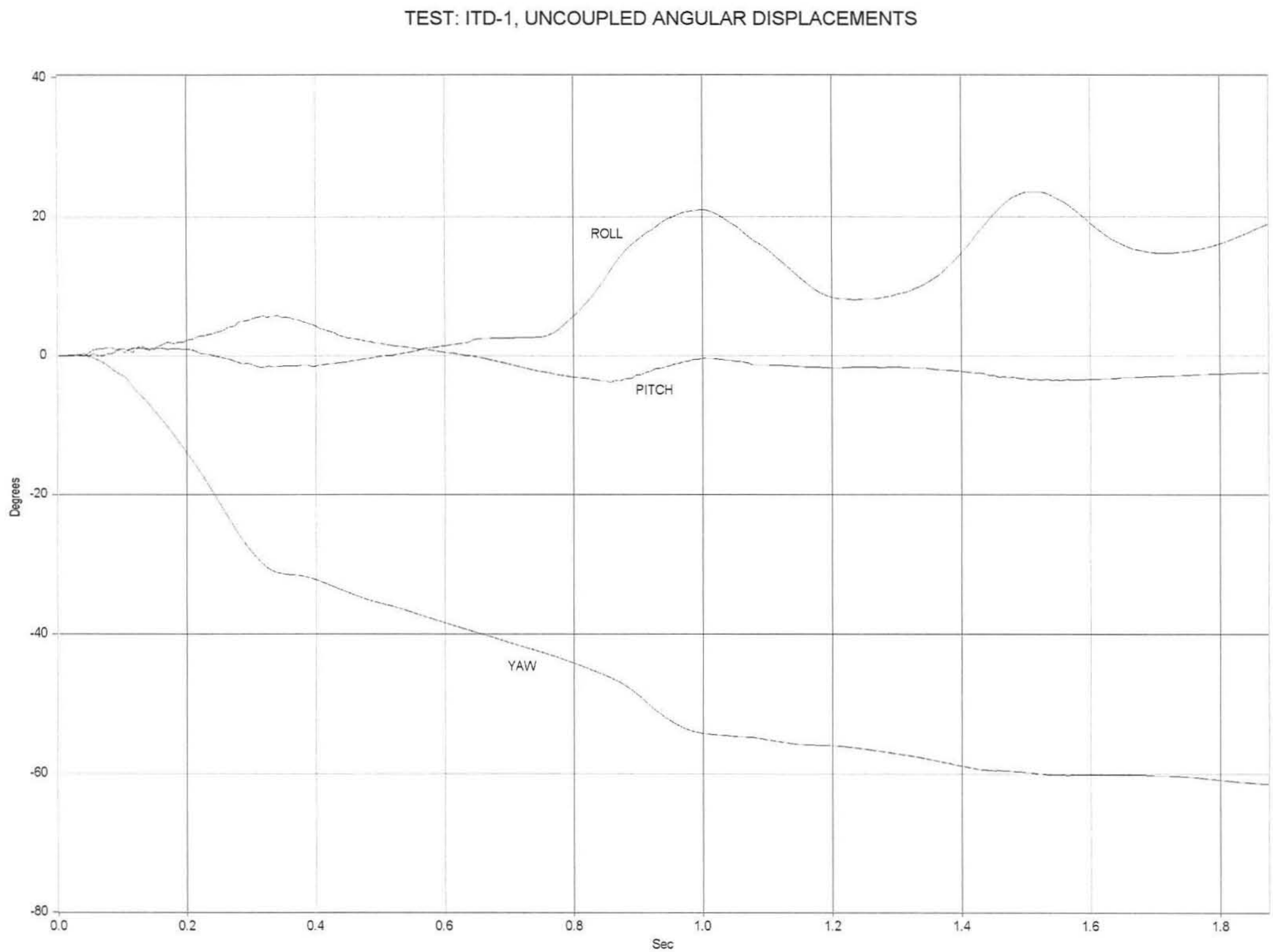


Figure G-7. Rate Transducer Data, Test ITD-1