LOW-DEFLECTION PORTABLE CONCRETE BARRIER

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ABSTRACT

Temporary barriers are often required to provide positive protection for motorists and workers in a highway work zone. Most highway work zones are restricted in terms of available lateral space for accommodating traffic and the work activity. Consequently, it is desirable to minimize the deflection of work zone barriers in order to minimize the required buffer distance between the barrier and work activity area and, thereby, maximize the space and number of lanes available for traffic.

Under this study, a new connection designed to reduce the dynamic deflection of portable concrete traffic barriers was developed through a program of finite element simulation and full-scale crash testing. The new cross-bolted (or X-bolt) connection utilizes two threaded rods in different horizontal planes across the barrier joint to form a tight, moment connection. It achieves the objective of low dynamic barrier design deflection without sacrificing constructability. In addition to being easy to install, the new barrier system is also perceived to be easy to inspect, and repair.

Crashworthiness and design deflection of the barrier connection were verified through full-scale crash testing using segment lengths of 10 ft and 30 ft. An F-shape barrier with X-bolt connection was demonstrated to have the lowest deflection of any approved portable concrete barrier.

INTRODUCTION

Work-zone traffic barriers have several functions *(1)* including: (1) shielding motorists from hazards in the work area (e.g., pavement edge drops, excavations, equipment, etc.), (2) providing positive protection for workers, and (3) separating two-way traffic. Due to the temporary and frequently changing nature of work zones, work-zone barriers are designed to be easily transported, placed, and relocated. However, this portability and ease of placement does not come without a price. Unlike permanent concrete barriers, free standing temporary barriers can undergo large displacements when subjected to a vehicular impact.

A “buffer space” is typically required behind a work zone barrier to accommodate barrier deflection. The buffer space provides a recovery area for errant vehicles and separates traffic flow from workers or potential hazards (e.g., drop offs) in the work activity area.*(2)* As a general rule, no work activity should occur and no equipment should be stored within this space.

Most work zones, besides those associated with new construction, are commonly restricted in terms of available space. Depending on the design deflection of the work zone barrier being used, an extra travel lane may have to be incorporated into the work activity area simply to provide the desired buffer distance. Consequently, it is desirable to minimize the deflection of work zone barriers in order to minimize the required buffer distance and maximize the space and number of lanes available for traffic.

When the work zone is so restrictive that lateral displacement of the work zone barrier cannot be tolerated, the movement of the barrier must be strictly limited by pinning, staking, or otherwise tying the barrier to the deck, pavement or soil.

The primary objective of the research effort described herein, which was sponsored by the Texas Department of Transportation (TxDOT), was to develop a work zone traffic barrier that has a low lateral deflection (i.e., ≤2 ft) when impacted under design impact conditions. It was additionally desirable that the barrier be easy to install, inspect, and repair. Ease of installation includes provision for adequate tolerance for field erection as well as placement on curves. Various analyses were performed to help assess the ability of the selected barrier system to meet impact performance criteria prior to conducting full-scale crash tests.

REVIEW OF PORTABLE CONCRETE BARRIERS

Portable concrete barriers (PCBs) are the most widely used type of work zone barrier. PCBs are free-standing, precast, concrete segments that are connected to one another through various means of external connections. The segment length of PCBs ranges from 8 ft (2.4 m) to 30 ft (9.1 m).*(1)* Adequate longitudinal reinforcement and positive tensile connections are needed to help ensure the segments function together as a continuous unit.

The impact performance of portable concrete barriers is influenced by a number of variables which include but are not limited to: barrier shape/profile, barrier height, segment length, joint rotation slack, joint moment capacity, joint tensile strength, and barrier-roadway friction. The design of the joint connection plays a particularly critical role in the impact performance of portable concrete barriers (PCBs). The design of the joint has a direct influence on the magnitude of lateral barrier deflection and degree of barrier rotation during a vehicular impact event. A joint with inadequate strength and/or stiffness can induce instability of the vehicle, result in failure of the connection and penetration of the vehicle through the barrier, and/or produce greater than desired deflection.

Methods for connecting PCB segments vary widely.*(1)* Since October 2002, the Federal Highway Administration (FHWA) has required that new barriers used in construction projects meet the impact performance guidelines for temporary barriers contained in National Cooperative Highway Research Program (NCHRP) *Report 350*.*(3)* For high-speed roadways, the basic strength test (Test 3-11) involves a 4,400-lb (2000-kg) pickup truck impacting the barrier at a speed of 62 mph (100 km/h) and an angle of 25 degrees. Many types of PCB connections have been successfully crash tested under these conditions and approved for use by FHWA.

Texas is the only state known to use barrier segments as long as 30 ft (9.1 m). Although heavy equipment is required to move these segments, their length and mass help reduce dynamic deflections once they are in place. Other State Department's of

Transportation (DOTs) typically use segments that range from 10 ft (3.0 m) to 20 ft (6.1 m) in length.

When a barrier is reviewed and approved by FHWA, an acceptance letter for the barrier is issued. FHWA maintains a list of acceptance letters issued on successfully crash-tested portable concrete barriers on its website at the following address: http://safety.fhwa.dot.gov/roadway_dept/road_hardware/listing.cfm. This list is not necessarily all inclusive as some state DOTs may not submit information on their generic barrier(s) for formal review.

The majority of these designs utilize some form of pin-and-loop connection. The pin-and-loop connection involves inserting a vertical pin through two or more sets of overlapping loops that extend from the ends of the barrier segments. The designs differ in regard to gap width between segments, pin diameter, manner in which the pin is secured, loop embedment length, and material used to form the loops.*(1)* While this type of connection provides positive barrier tensile capacity, it initially acts as a hinge and typically requires considerable deflection and rotation of the barrier segments before providing any moment resistance about the vertical axis of the barriers. Consequently, the design deflections associated with pin-and-loop connections can be quite large. This is illustrated by three pin-and-loop barriers tested at the Texas Transportation Institute (TTI).*(4,5,6)* These barriers, which had segment lengths ranging from 10 ft to 20 ft had deflections ranging from 4 ft to 6 ft.

Figure 1 presents a distribution of barrier deflections for successfully crash tested, FHWA-approved portable concrete barriers. The FHWA list was supplemented with two other PCB designs.*(4)* The lowest deflection of any NCHRP Report 350 compliant PCB is 2.5 ft (0.76 m). The majority of PCBs have deflections greater than 3.5 ft (1.07 m), and 25% have design deflections greater than 5.5 ft (1.68 m).

DEVELOPMENT OF THE X-BOLT CONNECTION

An efficient way to reduce barrier deflection is through the use of a strong, tight connection. During impact, any deformation of the connection members or slack in the connection will result in increased dynamic deflection. A strong, tight connection, which minimizes construction slack and component deformation during impact, will effectively decrease deflection. However, practical tolerances must be maintained in the connection to provide reasonable construction tolerance in the field and the ability to accommodate vertical and horizontal curvature. Thus, the objectives of limiting deflection and providing a barrier that is easy to construct and replace tend to work against each other and must be properly balanced to achieve an effective barrier design.

With the project objectives and constraints in mind, numerous new connection designs were conceptually developed for consideration by TxDOT engineers. After a preliminary assessment and prioritization of the design concepts, a cross-bolted (or X-bolt) connection was selected for further design, analysis, testing, and evaluation. The

cross-bolted connection system utilizes two threaded rods/bolts to form the connection. The bolts are placed in different horizontal planes in the barrier at a prescribed angle with respect to the longitudinal axis of the barrier. The bolts pass through guide pipes cast into the ends of the barrier segments. The bolts exit one barrier segment and enter the adjacent barrier segment at the vertical center line of the barrier section. In plan view, the two connection rods/bolts form an "X" across joint between adjacent barrier segments. The guide pipes through which the cross bolts pass are oversized to provide connection tolerance for barrier fabrication, installation, and placement of the barrier on horizontal and vertical curves. An illustration of the X-bolt connection concept is shown in Figure 2. The tight moment connection provided by the cross-bolted design was considered to have the most promise for minimizing overall barrier deflections while maintaining constructability.

In addition to low deflection, the X-bolt barrier is also perceived to offer easier inspection and repair than many other connection options. The presence of the cross bolts that comprise the connection are readily apparent from drive by inspections. The connection components associated with some other barrier systems are not readily visible from the roadside. The cross bolts can also be readily replaced if damaged (e.g., bent) during an impact, whereas damage to other barrier connection systems with integral, cast-in-place components (e.g., loops or plates), often requires replacement of the entire barrier segment.

Various analyses were performed to help design the X-bolt connection and assess the ability of this barrier system to meet *NCHRP Report 350* impact performance criteria and other design constraints prior to conducting a full-scale crash test. The moment capacity of the connection was initially analyzed in a manner analogous to a reinforced concrete beam. The couple at the end of the barrier is comprised of a tensile force taken as the horizontal component of the bolt tensile capacity and a compressive force acting at the centroid of an area of concrete in compression in the "toe" of the safety-shape barrier. Nominal moment capacity of the connection was computed as a function of bolt diameter, material strength, and cross angle. The connection configuration selected for further evaluation was a 7/8-in. diameter, high strength (A325) bolt at an angle of 25 degrees. This configuration has a nominal moment capacity of 70 kip-ft. The strength of the connection, its dynamic deflection, and other aspects of the connection system were further evaluated using finite element analysis as described below.

FINITE ELEMENT ANALYSES

Computer simulation techniques were used to support the analyses efforts. The code utilized in the computer modeling efforts was LS-DYNA.*(7)* LS-DYNA is a general-purpose, implicit-explicit finite element code used to analyze the nonlinear dynamic response of three-dimensional inelastic structures. This code is capable of capturing the complex interactions that occur when a vehicle impacts a roadside safety structure. In recent years, LS-DYNA has been used extensively for crashworthiness simulations of automobiles and their components by automobile manufacturers and by

researchers in the roadside safety community in the design and evaluation of roadside safety features.

30-ft Barrier Segments

In order to evaluate the cross-bolted connection design concept, full-scale finite element computer model was developed. The 32-in. (813-mm) tall precast, free standing, concrete barrier segments were modeled with an F-shape profile. TxDOT elected to use an F-shape barrier profile for the new barrier in lieu of the New Jersey-shape profile used on current TxDOT barriers because the F-shape is widely considered to provide improved impact performance over the N.J.-shape. Full-scale crash testing indicates that vehicles experience less climb and remain more stable during impacts with barriers having an F-shape profile compared to those with a New Jersey-shape profile.

Initially, the barrier segments were modeled with a top width of 8 in. (203 mm) and a length of 30 ft (9.1 m), both of which were TxDOT standards. The reduction in the number of joints/connections associated with the long segment length helps support the primary objective of reducing dynamic barrier deflection. Subsequent simulations and a full-scale crash test were also performed on an X-bolt barrier with 10-ft (3 m) segments as described later in this paper.

With the exception of the bottom layer of solid elements in contact with the ground surface, the elements comprising the barrier segments were assigned a rigid material definition. The lowest layer of solid elements was assigned elastic material properties to provide a reliable account of friction in the contact between the PCB segments and the ground. A friction coefficient of 0.4, as determined from barrier pull tests on a concrete pavement, was used between the CMB and the ground.

A limitation to this type of rigid CMB model is that concrete failure is not incorporated. Modeling concrete failure requires a reliable, validated concrete material model that considers fracture. Although the Federal Highway Administration has sponsored the development of such a material model, the research effort was not complete during the time when simulations were conducted under this project. Without incorporating concrete failure into the analysis, it should be noted that the results of the simulation represent a lower bound estimate of the overall CMB system deflection. If concrete fracture and spalling occurs at the ends of one or more barrier segments during an actual impact, additional joint rotation can occur and deflections can increase. Conversely, a rigid barrier representation is conservative in regard to stress and deformation of the connection bolts. Concrete fracture and spalling near the ends of the barrier segments will help relieve the loads transferred to the connection bolts. With these aspects of the model understood, valuable design and performance information was gleaned from the predictive simulation results.

The selected cross-bolted connection system utilizes two 7/8-in. diameter, A325 bolts or equivalent strength threaded rods to form the connection. The bolts pass through nominal 1 ¼-in. diameter, schedule 40 guide pipes cast into the ends of the barrier

segments. The selected guide pipe supplies sufficient tolerance around the bolt shaft to provide a minimum radius of curvature of approximately 400 ft for the 30-ft barrier segments.

The cross-bolt connection was modeled by first creating rigid, cylindrical shafts with shell elements to represent the guide pipes embedded in the concrete through which the cross bolts pass. These shafts were rigidly constrained to the concrete such that motion of the shafts relative to the barriers was prohibited. The bolts inside the shafts were modeled using beam elements. The mechanical properties of the bolts were defined using a bilinear stress strain curve representing ASTM A325 high-strength steel. A325 bolts have a yield strength of 92 ksi and a tensile strength of 120 ksi.

The vertical location of the connection bolts and the spacing between them were determined through parametric simulations. The vertical spacing of the bolts dictates the torsional capacity of the cross-bolt connection. The connection must provide sufficient torsional capacity to prevent vehicle snagging on the end of a barrier segment due to the relative rotation of one barrier with respect to another. Three different vertical bolt spacings were evaluated via a parametric simulation study. The vertical bolt spacings considered were 3 in., 8 in., and 10 in. In addition to assessing barrier rotation, the lateral barrier deflection and stress in the cross bolts was determined for each design case.

The initial full-scale simulations replicated Test Designation 3-11 of *NCHRP Report 350*. This test involves a 2000-kg pickup truck (2000P) impacting the barrier at a speed of 100 km/h and an angle of 25 degrees. This is considered to be the critical test for evaluating the structural integrity of the connection and the maximum dynamic deflection of the barrier. A total of 6 CMB segments were modeled to provide a barrier length of 180 ft. A public domain finite element pickup truck model develop to represent the 2000P design test vehicle was used in the simulations.*(8)*

Selected results from the simulations are presented in Table 1. In each case, the vehicle was successfully contained and redirected in a stable manner. As previously discussed, the predictive deflection estimates were viewed as lower bound estimates that would likely be exceeded depending on the degree of concrete damage encountered.

TABLE 1. Simulation results for cross-bolted barrier connection

Vertical Bolt Spacing (in)	Torsional Capacity (kip-ft)	Lateral Barrier Deflection (ft)	Max. Bolt Stress (ksi)
3	5.3	1.50	86.9
8	12.0	1.34	86.6
10	15.0	1.34	N/A

For each design case, the stress in the bolts was below yield. The vertical spacing of the bolts appears to have little effect on the maximum bolt stress. In addition, the lateral barrier deflection showed little change with respect to the bolt spacing.

The torsional twisting or rotation of the barriers relative to one another about the longitudinal axis of the barrier was also investigated. The worst-case scenario for barrier twisting/rotation would occur at the minimum vertical bolt spacing, which offers the lowest torsional capacity for the connection. After reviewing the simulation results, barrier rotation did not appear to be a problem, regardless of the vertical spacing between the cross bolts. Thus, the vertical bolt spacing for the final design configuration was selected to be 6 in. (152 mm) based on other considerations such as fabrication clearances, etc.

10-ft Barrier Segments

While TxDOT's 30-ft barrier segments serve their intended functions well once they are in place, many consider them to be only minimally "portable" because heavy equipment such as cranes are usually required to lift and place them on and off the trailers used to deliver them to a job site. Because maintenance sections do not typically have the heavy equipment capable of moving and setting these long, heavy rail sections, they must contract for these services. TxDOT recognized a need to develop a more portable rail system that TxDOT maintenance crews could transport and place with readily available equipment such as a front-end loader with a fork attachment. In addition to addressing emergency situations, such as damaged bridge railing, there are other routine maintenance and construction operations that would benefit from such a barrier system.

To accommodate this need, the F-shape barrier with X-bolt connection was further evaluated with 10-ft segments. While reducing the length of the barrier segments is an effective means of decreasing the weight and enhancing portability, it also generally results in increased barrier deflections due to the added number of joints. A benefit of the additional joints is that they decrease the minimum radius of curvature along which the barrier can be placed. The connection tolerance combined with the added joints permits the barrier with 10-ft segment length to achieve a minimum radius of curvature of approximately 125 ft.

Additional simulations were conducted to investigate the effect of segment length on barrier deflection. The finite element models were modified to obtain a barrier with 10-ft segments. A total of 19 PCB segments were modeled to provide a barrier length of 190 ft.

The initial full-scale simulation of the X-bolt barrier system with 10-ft segments replicated Test Designation 3-11 of *NCHRP Report 350*. This test involves a 4,409-lb (2000-kg) pickup truck impacting the barrier at a speed of 62 mph (100 km/h) and an angle of 25 degrees. The simulation was terminated at 0.5 seconds, at which time the vehicle was exiting the barrier system. The pickup truck was successfully contained and redirected in a relatively stable manner with only moderate climb and roll. Top views of

the simulated impact event as the vehicle enters and exits the barrier (i.e., t = 0 sec and t = 0.5 sec) are shown in Figure 3.

The maximum dynamic deflection of the barrier system was 20 in. As previously discussed, this deflection estimate was considered to be a lower bound estimate. Previous simulations of the X-bolt barrier with 30-ft segments indicated a lower bound deflection of 16 in. In a subsequent full-scale crash test, details of which will be described in the following sections of this paper, some concrete fracture and spalling occurred at the base of the barrier at several joint locations. The concrete damage resulted in a measured dynamic barrier deflection of 19 in.*(9)* Using the ratio of the actual and simulated deflections (1.19) as a factor to account for concrete damage at the joints provides an estimated deflection of approximately 24 in. for the X-bolt connection with 10-ft barrier segments.

Prior to conducting the full-scale crash test on the X-bolt barrier with 10-ft barrier segments, TxDOT engineers and TTI researchers received information regarding proposed revisions to the impact conditions used to evaluate longitudinal barriers. Under NCHRP Project 22-14(2), the guidelines and procedures contained in *NCHRP Report 350* for testing and evaluation of roadside safety features are being updated. After successful crash tests on a W-beam guardrail and a portable concrete barrier under Project 22-14(2) and feedback received from the project panel, the principle investigator of the research effort expressed a high degree of confidence that the weight of the pickup truck design vehicle will increase from 4,409 lb (2000 kg) to 5,000 lb. Further, a minimum center-of-gravity (c.g.) height of 27 in. would be adopted as part of the new vehicle specification.

With a progressive attitude toward safety, TxDOT decided to test and evaluate the X-bolt barrier system with 10-ft segments following the revisions to the impact conditions proposed under NCHRP Project 22-14(2). The increase in vehicle weight results in a 13% increase in impact severity. To determine the effect of this change on the predicted barrier deflection, another finite element impact simulation was conducted.

The full-scale simulation replicated the impact conditions proposed for the update to *NCHRP Report 350*, and involved a 5,000-lb pickup truck impacting the barrier at a speed of 100 km/h and an angle of 25 degrees. Additional mass was added to the finite element vehicle model to increase its weight to the prescribed value. The mass was added throughout the vehicle in such a way that the c.g. height of the pickup was 27 in.

The heavier pickup truck was successfully contained and redirected. The factored dynamic barrier deflection, which accounts for some concrete damage, increased to 27 in.

FULL-SCALE CRASH TESTING

Two tests are required to evaluate longitudinal barriers to Test Level 3 (TL-3) in accordance with *NCHRP Report 350*. These tests are:

***NCHRP Report 350* test designation 3-10**: An 1,806-lb (820 kg) passenger car impacting the barrier at the critical impact point (CIP) of the length of need at a nominal speed and angle of 62.2 mi/h (100 km/h) and 20 degrees, respectively. The test is intended to evaluate occupant risk and post-impact trajectory.

***NCHRP Report 350* test designation 3-11**: A 4,409-lb (2000 kg) pickup truck impacting the barrier at the CIP of the length of need at a nominal speed and angle of 62.2 mi/h (100 km/h) and 25 degrees, respectively. The test is intended to evaluate strength of the barrier and its connections.

The test conducted on the X-bolt barrier with 30-ft segments corresponds to *NCHRP Report 350* test designation 3-11. The pickup truck test is generally the most discerning for portable concrete barriers in terms of evaluating vehicle stability, occupant compartment intrusion, and maximum dynamic barrier deflection. A rigid barrier with F-shape profile has demonstrated acceptable performance when impacted by a small car under test 3-10 impact conditions.*(4)* Due to the small deflection expected for the precast F-shape CMB with cross-bolt connection when subjected to Test 3-10, the behavior is expected to be similar to that obtained in the rigid barrier test and this test was, therefore, not deemed necessary.

As mentioned previously, the guidelines and procedures contained in *NCHRP Report 350* for testing and evaluation of roadside safety features were being updated during the course of this project. Prior to conducting the full-scale crash test on the X-bolt barrier with 10-ft segments, it was learned that it was being proposed to increase the weight of the pickup truck design vehicle from 4,409 lb (2000 kg) to 5,000 lb to reflect a continuing increase in the weight of light trucks. It was further proposed to adopt a minimum center-of-gravity (c.g.) height of 27 in. as part of the new vehicle specification. *NCHRP Report 350* currently recommends that the c.g. height fall within a range of 25.5 in. to 29.5 in.

Based on the high degree of confidence expressed by the researchers preparing the update to *NCHRP Report 350* that the 5,000-lb pickup would be adopted and a progressive attitude toward roadside safety, TxDOT elected to test and evaluate the X-bolt barrier with 10-ft barrier segments using the heavier pickup truck. Thus, the impact conditions used were a modified version of *NCHRP Report 350* Test 3-11 with a 5,000-lb, standard cab, ¾-ton pickup truck impacting the barrier at a speed of 62.2 mi/h (100 km/h) and an angle of 25 degrees.

30-ft Barrier Segments

The precast segments used to construct the test installation for the cross-bolt concrete median barrier system were 30 ft in length and had a standard F-shape profile. The barrier segments were 32 in. in height, 23 5/8 in. wide at the base, and 9 ¼ in. wide at the top. The top width of the barrier was increased from 8 in. to 9 ¼ in. at the request of TxDOT to more conveniently accommodate barrier mounted lighting hardware.

Horizontal barrier reinforcement consists of eight #5 bars spaced liberally within the vertical reinforcement. Vertical barrier reinforcement in the barrier segments consists of #5 bars spaced 12 inches on center. These vertical bars are bent in a "hairpin" fashion to conform to the F-shape barrier profile. Within 5 ft of the barrier ends, the spacing of the vertical bars is reduced to 6 inches. A U-shaped bar is tied to the bottom of the vertical bars to provide closed stirrups in this region.

Sections of 1 ¼-inch diameter, schedule 40 pipe are cast into the ends of the barrier segments at an angle of 20 degrees to the barrier axis to serve as a guide shaft and reinforcement for the cross bolts. The angle of the cross bolts was decreased from 25 degrees to 20 degrees to address clearance issues identified during the rebar detailing process. The centers of the guide pipes are vertically spaced 6 inches apart. A 4 in. ×4.5 in. × 3/8 in. thick, A36 steel plate is welded to one end of each pipe section. A 1 3/8-inch diameter hole, which matches the inside diameter of the guide pipes, is drilled through the center of the plate to permit passage of the cross bolts. Two #6 bars are bent in an "L" shape and welded to the inside surface of each end plate. Triangular wedges are cast into the barrier to permit the exposed ends of the cross bolts to be recessed and, thus, prevent vehicle snagging. Due to space restrictions, the spacing of the vertical reinforcement is adjusted and a slightly modified vertical bar is used in the immediate vicinity of the guide pipes and triangular wedges.

The cross-bolts are fabricated from 7/8 inch diameter, SAE Grade 5 threaded rod. The lengths of the upper and lower cross bolts were 25 ¼ inches and 29 inches, respectively. The barriers segments are placed end to end and the cross bolts are inserted through aligning guide pipes between adjacent barrier segments. A 3 in. ×3 in. × 3/8 in. thick, A36 steel plate washer is used under the nut at each end of the cross bolts.

The completed test installation consisted of seven barrier segments connected together for a total length of approximately 210 ft. Photographs of the completed test installation are shown in Figure 4.

A 2000 Chevrolet 2500 pickup truck with a test inertia weight of 4531 lb (2057 kg impacted the concrete barrier installation 4.2 ft (1.27 m) upstream of joint 3-4 at a speed of 62.3 mi/h (100.3 km/h) and an angle of 25.7 degrees. The pickup was successfully contained and redirected in a stable and upright manner. At 0.404 s, the vehicle lost contact with the barrier while traveling at a speed of 51.6 mi/h (83.1 km/h) and an exit angle of 5.1 degrees. Occupant risk measures were below desirable levels, and the maximum roll angle was 23.3 degrees. Damage to the vehicle was moderate. Maximum exterior crush to the vehicle was 17.7 in (450 mm) and maximum occupant compartment deformation was 2.6 in (65 mm).

Damage to the barrier is shown in Figure 5. Some cracking and spalling was observed in the vicinity of the three joints nearest the point of impact. Maximum dynamic deflection during the test was 19.0 in (482 mm), and maximum permanent deflection was 18.1 in (460 mm). After the test, the nuts on the cross bolts in the impact

region were removed with an impact wrench. After the nuts were removed, the bolts could be readily removed by hand without having to move or reposition the barrier segments. The two bolts at the joint directly downstream from impact required replacement. The other bolts were reusable. Of the four barrier segments damaged in the impact, two could be readily repaired and reused while two would likely need to be replaced. Further description and details of the test can be found in reference *(9)*.

10-ft Barrier Segments

Other than the segment length, details of the X-bolt barrier with 10-ft segments were similar in detail to the system described for the X-bolt barrier with 30-ft segments. The completed test installation consisted of 20 barrier segments for a total installation length of approximately 200 ft.

A 2001 Chevrolet 2500 pickup truck with a test inertia weight of 4960 lb (2252 kg) was used for the crash test. The height to the upper edge of the bumper it was 27.6 in. (700 mm), and the vertical center-of-gravity (c.g.) height of the vehicle was measured to be 27.5 in. The pickup truck contacted the barrier 3.5 ft upstream of the joint between segments 8 and 9 at a speed of 62.0 mph and an angle of 24.5 degrees. The pickup was successfully contained and redirected in an upright manner. At 0.0351 s, the vehicle moved out of view of the overhead camera and was traveling at a speed of 52.6 mph and an angle of 2.1 degrees.

Occupant risk measures were below desirable levels. The maximum roll angle was 30 degrees. Damage to the vehicle was moderate. Maximum exterior crush to the vehicle was 20.9 in (530 mm) and maximum occupant compartment deformation was 1.8 in (46 mm) in the firewall area.

Damage to the portable concrete barrier installation with 10-ft segments is shown in Figure 6. Spalling was noted on the lower front corners of both ends of segments 8 and 9 at the joints, and also on the lower rear corner of segment 5 at the joint with segment 6. When disassembling the barrier, permanent deformation to some of the connection bolts was noted. Five bolts were bent sufficiently to require replacement. Four other bolts were only slightly bent and were considered reusable. Maximum movement of the barriers was 27.0 inches (685 mm). Further description and details of the test can be found in reference *(11)*.

CONCLUSIONS

Under this study, a new connection for portable concrete traffic barriers was developed through a program of simulation and full-scale crash testing. The new barrier system achieves the objective of low dynamic barrier design deflection without sacrificing constructability. In addition to being easy to install, the barrier is also perceived to be easy to inspect, and repair.

Predictive LS-DYNA computer simulations were performed to help design the barrier, quantify its deflection characteristics, and assess its ability to meet *NCHRP Report 350* impact performance criteria. The simulation effort provided a more detailed understanding of the three-dimensional impact response of the barrier prior to conducting full-scale crash testing. Once factored to account for an expected level of concrete damage, predicted deflections for the barrier with 10-ft segments agreed with the deflections measured in the crash test.

Subsequent to its design and simulation, the new X-bolt connection was subjected to two full-scale crash tests to assess impact performance and quantify the design deflection of the cross-bolted F-shape barrier for two different segment lengths. In both tests, the structural integrity of the barrier and its connections was maintained, and the barrier successfully contained and redirected the test vehicle in an upright manner. The occupant risk factors were within the preferred limits specified in *NCHRP Report 350,* and all relevant evaluation criteria were met.

The test of the X-bolt connection with 10-ft barrier segments involved a 5,000-lb pickup truck, which is an increase of approximately 13% from the current weight of 4,409 lb (2000 kg) specified for the design test vehicle in *NCHRP Report 350*. This is a proposed change being considered as part of the update to *NCHRP Report 350* that is in progress under NCHRP Project 22-14(2).

Even though the impact severity was 13% greater than required in *NCHRP Report 350*, the dynamic deflection the 10-ft barrier segments with X-bolt connection was only 27 in. (686 mm). This is the lowest deflection of any free-standing, portable concrete barrier approved to *NCHRP Report 350* requirements other than the X-bolt barrier with 30-ft segments, which had a dynamic deflection of 19 in. (483 mm). The low deflections associated with the X-bolt connection make it ideal for use in restricted work zones where it is desirable to minimize the required buffer space between the barrier and the work activity area.

The tolerance available in the X-bolt connection assists with barrier constructability and placement of the barrier on horizontal and vertical curves. Field trials with the barrier test sections verified that the minimum radii of curvature upon which the barriers can be placed is 125 ft and 400 ft for the 10-ft and 30-ft barrier segments, respectively.

Design details for the X-bolt barrier with 10-ft segments are shown in Figure 7. Additional details for the 10-ft and 30-ft segment barrier systems are be found in references (11) and (9), respectively. It should be noted that the X-bolt connection can be readily adapted to other barrier shapes/profiles such as the New Jersey safety shape, single or constant slope barrier, and vertical profile barriers.

REFERENCES

1. *Roadside Design Guide*. AASHTO, 2002.

2. Lewis, R. M., *Work Zone Traffic Control Concepts and Terminology*, in Transportation Research Record 1230, Transportation Research Board, National Research Council, Washington, D.C., 1989.

3. H. E. Ross, Jr., D. L. Sicking, R. A. Zimmer and J. D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, D.C., 1993.

4. C. E. Buth, N. M. Sheikh, R. P. Bligh, W. L. Menges, and R. H. Haug. *NCHRP Report 350 Testing of Montana Portable Concrete Safety Shape Barriers*. Report FHWA/MT-03-002/8162, Texas Transportation Institute, College Station, TX, April 2003.

5. W. L. Menges, C. E. Buth, R. A. Zimmer, and W. F. Williams. *NCHRP Report 350 Test 3-11 of Georgia Temporary Concrete Barrier*. Research Report No. 404821-1, Texas Transportation Institute, College Station, TX, August 1999.

6. C. E. Buth, W. L. Menges, and S. K. Schoeneman. *NCHRP Report 350 Test 3-11 of the Modified Virginia DOT Portable Concrete Barrier*. Research Report No. 402041-1, Texas Transportation Institute, College Station, TX, January 1999.

7. J. O. Hallquist. *LS-DYNA*. Livermore Software Technology Corporation, 2002.

8. A. K. Zaouk, N.E. Bedewi, C. D. Kan, and D. Marzougui. "Development and Evaluation of a C-2500 Pick-Up Truck Model for Roadside Hardware Impact." *Federal Highway Administration Simulation Conference*, Langley, VA, 1997.

9. R. P. Bligh, N. M. Sheikh, W. L. Menges, and R. R. Haug. *Development of Low-Deflection Precast Concrete Barrier*. Report 0-4162-3. Texas Transportation Institute,College Station, TX, January 2005.

10. C. E. Buth, T. J. Hirsch, and W. L. Menges, *Testing of New Bridge Rail and Transition Designs, Volume VII: Appendix F, 32-inch (813 mm) F-shape Bridge Railing*, Report No. FHWA-RD-93-064, Federal Highway Administration, McLean, VA, June 1997.

11. R. P. Bligh, N. M. Sheikh, W. L. Menges, and R. R. Haug. *Portable Concrete Traffic Barrier for Maintenance Operations.* Report 0-4692-1. Texas Transportation Institute, College Station, TX, May 2005.

DISCLAIMER

The contents of this paper reflect the views of the authors who are solely responsible for the facts and accuracy of the data, and the opinions, findings and

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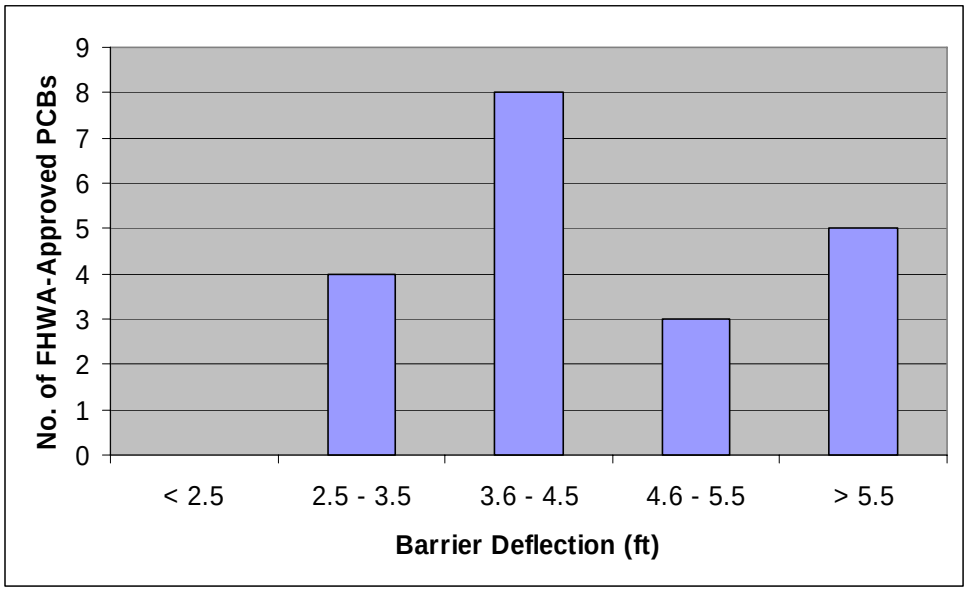
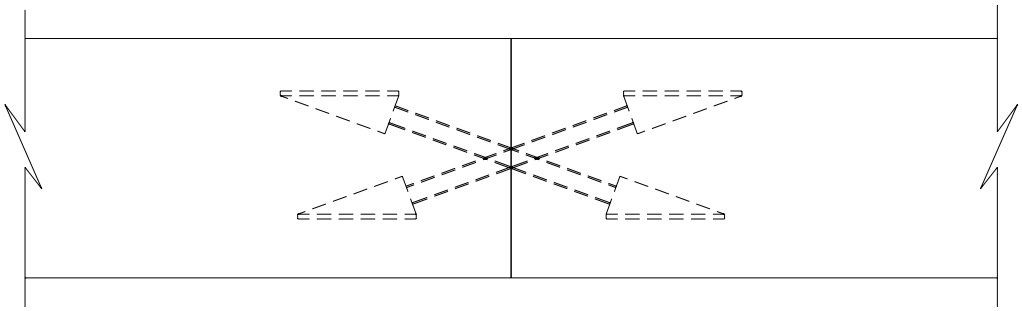
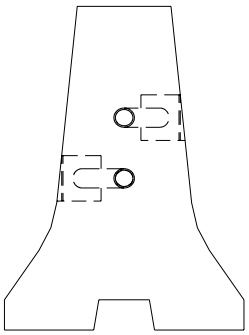


FIGURE 1. Distribution of Barrier Design Deflection for Approved PCBs



(a) Plan



(b) End View

FIGURE 2. X-bolt Connection Concept

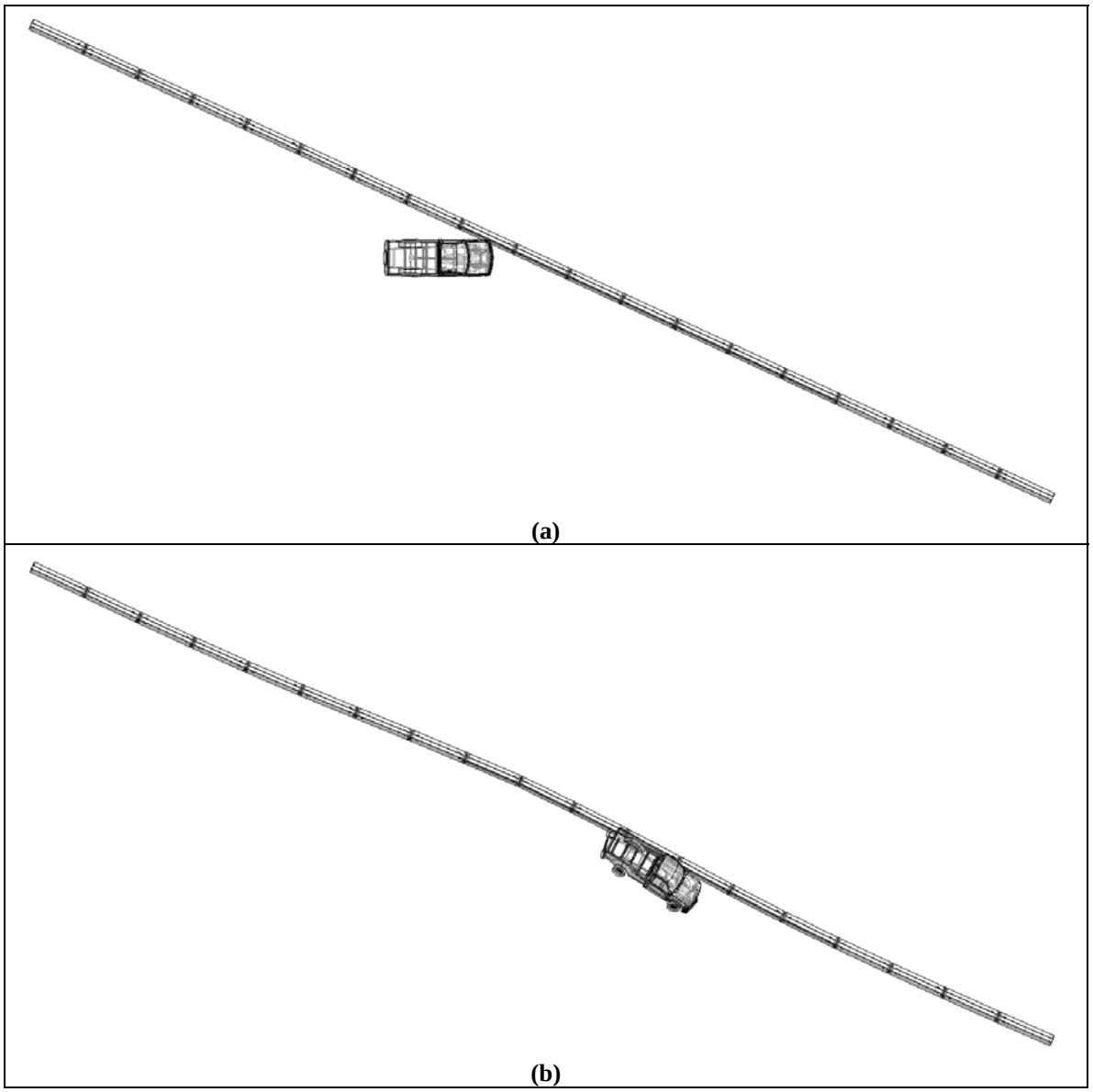


FIGURE 3. Plan view of impact simulation, (a) before impact (b) after impact.

FIGURE 4. X-Bolt Barrier Test Installation

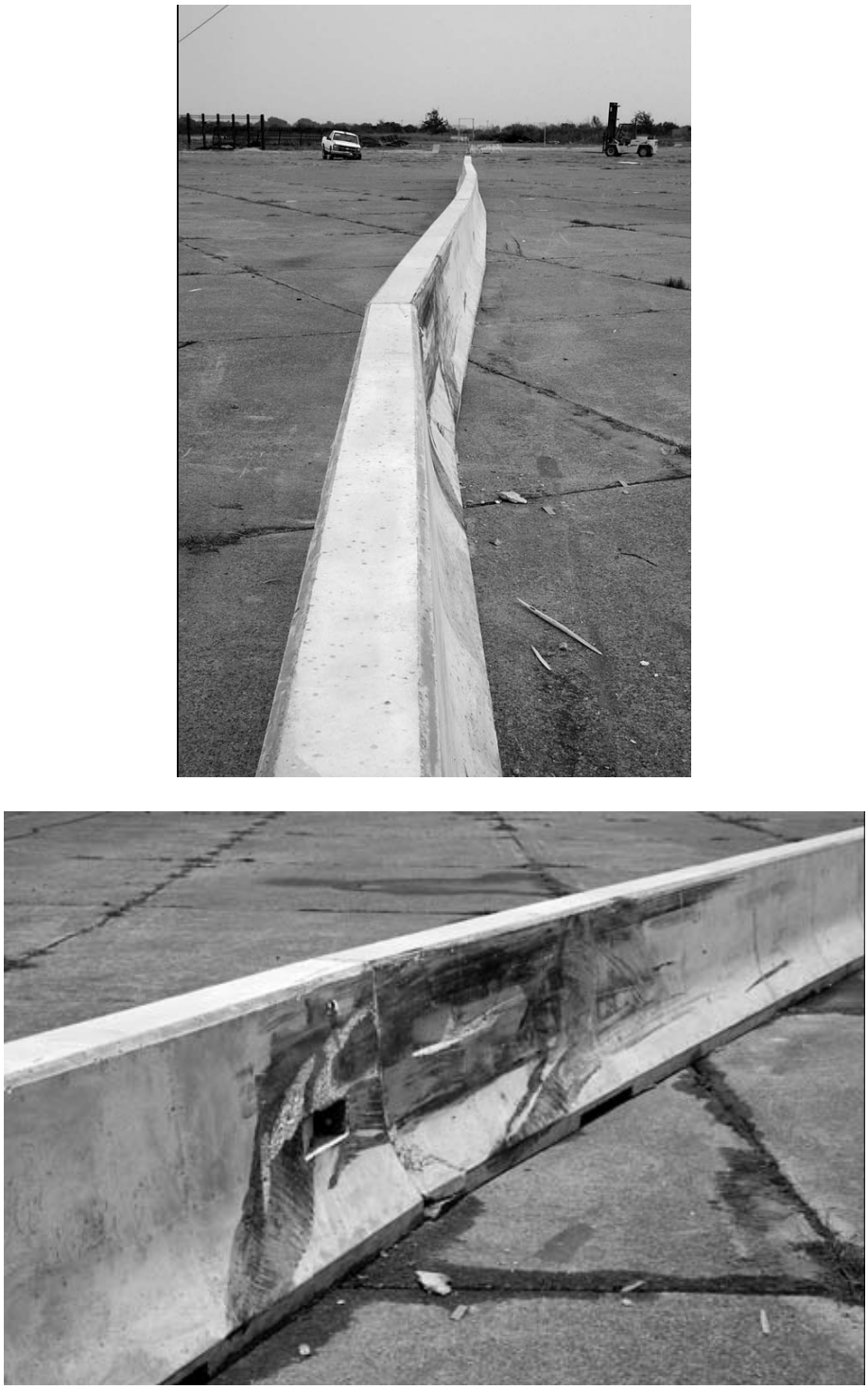


FIGURE 5. Damage to X-Bolt Barrier with 30-ft Segments

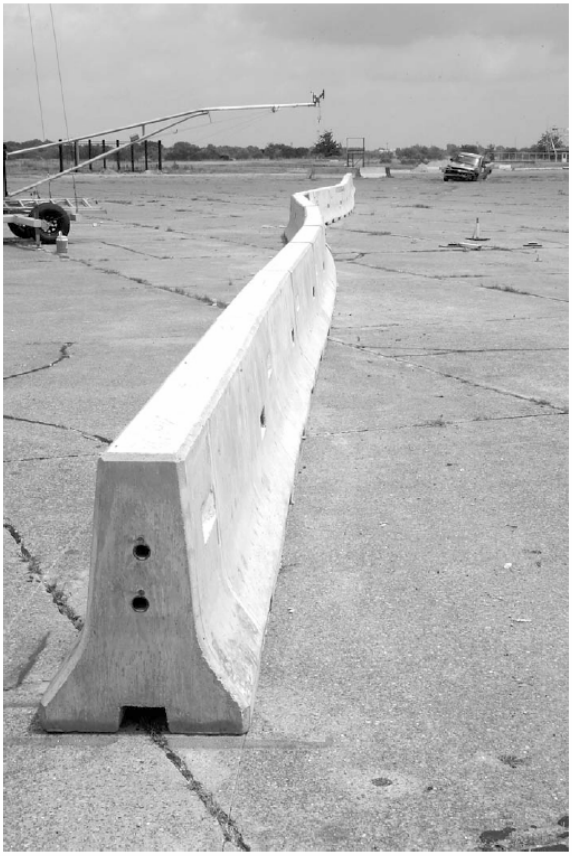


FIGURE 6. Damage to X-Bolt Barrier with 10-ft Segments

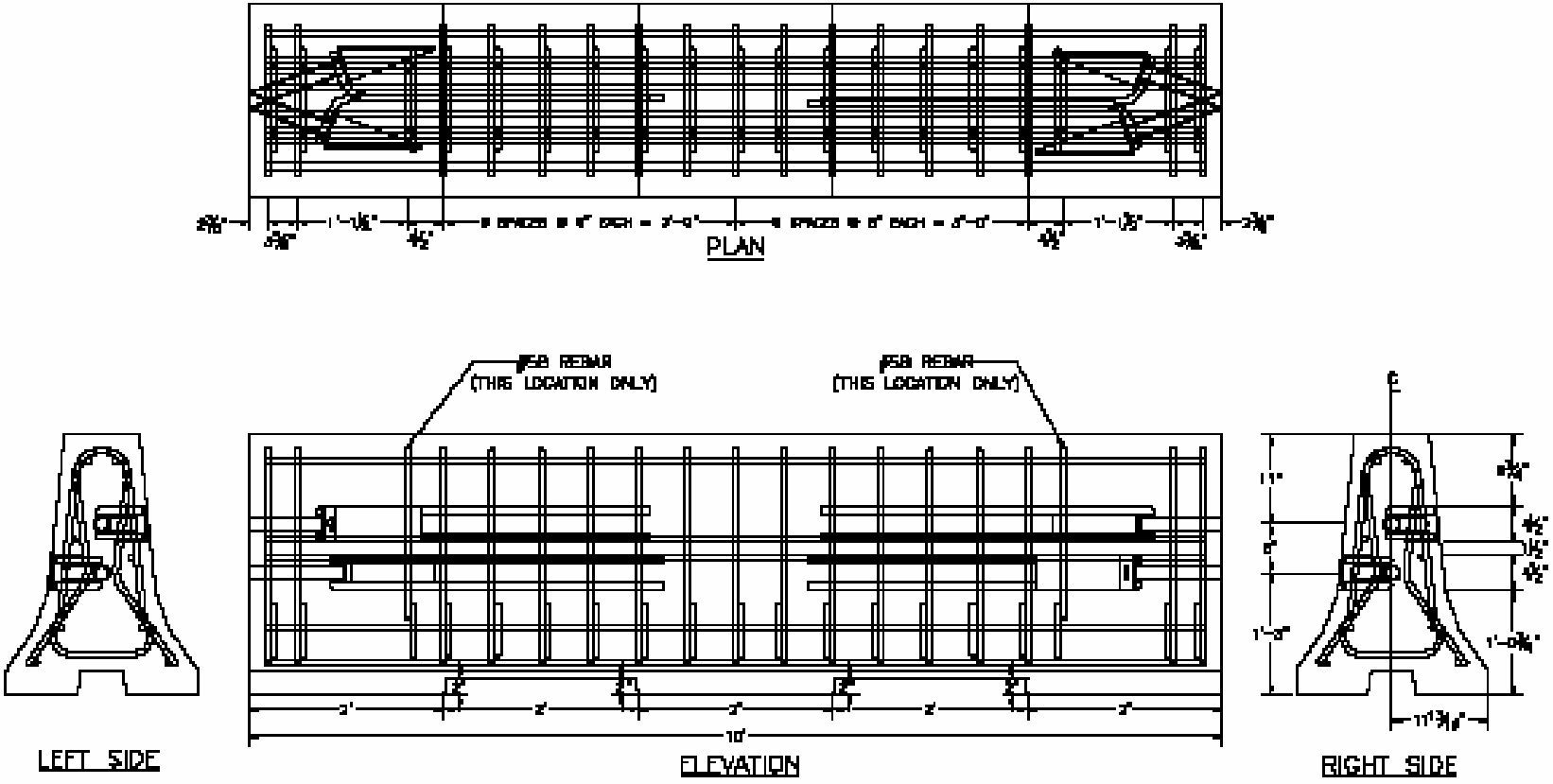


FIGURE 7. Details of 10-ft, F-Shape Barrier Segment with X-Bolt Connection