2014

Assessment of Load Sharing Members in an Anti-ram Bollard System

Scott Kinney

Hinman Consulting Engineers, Alexandria, Virginia, skinney@hce.com

Daniel Linzell

University of Nebraska-Lincoln, dlinzell@unl.edu

Edward O'Hare

Pennsylvania State University, evo101@psu.edu

Follow this and additional works at: <http://digitalcommons.unl.edu/civilengfacpub>

Part of the [Civil Engineering Commons](#), and the [Transportation Engineering Commons](#)

Kinney, Scott; Linzell, Daniel; and O'Hare, Edward, "Assessment of Load Sharing Members in an Anti-ram Bollard System" (2014).
Civil Engineering Faculty Publications. 146.
<http://digitalcommons.unl.edu/civilengfacpub/146>

This Article is brought to you for free and open access by the Civil Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Civil Engineering Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Assessment of Load Sharing Members in an Anti-ram Bollard System

Scott Kinney¹, Daniel Linzell² and Edward O'Hare³

¹Hinman Consulting Engineers, 1800 Diagonal Road, Alexandria, VA. 22314, United States. E-mail: skinney@hce.com

²Voelte-Keegan Professor and Chair, Department of Civil Engineering, University of Nebraska-Lincoln, N104 SEC/PO Box 886105, Lincoln, NE. 68588, United States. E-mail: dlinzell@unl.edu, 402-472-8036

³Graduate Research Assistant, Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA 16802, United States. E-mail: evo101@psu.edu

Received on 04 March 2014, Accepted on 10 Oct 2014

ABSTRACT

Due to the increased frequency, scale, and danger of malicious attacks carried out by Vehicle Borne Improvised Explosive Devices (VBIEDs), anti-ram bollards have become a key element in the protection of critical structures. This study focused on the evaluation of above grade load sharing members in a steel anti-ram bollard system in an attempt to develop efficient load sharing mechanisms that improve the structure's ability to resist vehicle impacts, while concurrently remaining aesthetically pleasing to the general public. A computational assessment was completed using calibrated LS-DYNA finite element models to determine if effective load sharing member configurations and designs could be established so that further optimization of the entire anti-ram system was possible. It was determined that efficient above-grade load sharing could improve the crashworthiness of the anti-ram bollard systems that were studied. Of the configurations that were investigated, the most effective load sharing member design was a single HSS member connecting the vertical bollards near their exposed free ends.

Key words: Perimeter security, finite element modeling, crash testing, load sharing, impact design

1. INTRODUCTION

Due to increased frequency and danger of malicious attacks on buildings and infrastructure carried out using Vehicle Borne Improvised Explosive Devices (VBIEDs), there is an emergent need to protect important structures on both domestic and foreign soil. A large contributor to effective defense against casualties and property damage from such an attack

*Corresponding author: skinney@hce.com

is maintaining an adequate standoff distance between the structure and explosive device using effective perimeter protection. A variety of structural systems, collectively called anti-rams, have been utilized to keep dangerous vehicles away from important facilities and maintain safe standoff distances.

While effective anti-ram systems have been designed in all shapes and sizes, many are imposing and can be aesthetically unappealing. Therefore, there is a need for anti-ram system designs that are effective at stopping high-speed impacts while concurrently being easily integrated into urban environments. Anti-ram bollards, in addition to being efficient impact absorbers, are a preference of building owners and architects because they can be easily blended into architectural features and can be less visually imposing than other anti-ram systems, such as fences or walls [1]. Anti-ram bollards are quite common and typically consist of upright steel tubes embedded in a large concrete foundation. They are designed and spaced so that most vehicles would be unable to fit between them while concurrently being stopped before reaching their intended target.

While many researchers have studied successful anti-ram bollard designs that involve upright steel sections and large foundations [2–6], no public study has been identified that evaluates the benefits of above-grade load sharing between bollards. Therefore, there is a need to evaluate the effectiveness of framed, bollard systems that utilize above-grade load sharing to resist high-velocity impacts. The primary objective of this study was to optimize the design of above grade load sharing members in an idealized anti-ram bollard system.

The simplified anti-ram frame structure that was studied consisted of two hollow structural steel (HSS) vertical bollards embedded in a composite foundation containing HSS members and reinforced concrete (Figure 1). Variations of this structure, which has no welded connections, have been investigated and found to be effective at arresting impact vehicles, but the two-post anti-ram bollard system was selected for this study because its success is most dependent on sharing of impact load between the bollards. In addition to below grade load sharing members that are between HSS members in the foundation, vertical HSS members were also connected using above grade load sharing members, as shown in Figure 1. The efficiency and crashworthiness of these above grade members was the focus of the current study.

Figure 1. Anti-ram device

2. BACKGROUND

A previously developed and calibrated finite element model, created using LS-DYNA [7], was modified and used to simulate the anti-ram system under vehicular impact. Calibration occurred via comparisons between model predictions and results from full-scale experimental impact testing of the structure shown in Figure 1 [8]. All impact tests were completed following criteria from *ASTM F2656-07: Standard Test Method for Vehicle Crash Testing of Perimeter Barriers* [9]. The experimental crash test used for model calibration was performed with an M50 impact designation and a desired penetration level of P1 [8]. A P1 penetration level is obtained by arresting the impact vehicle with less than one meter of dynamic penetration as measured from the leading edge of the truck's bed, where explosive payload would be stored.

The tested anti-ram article consisted of two vertical steel tube bollards embedded in a composite steel and concrete foundation [8]. The two vertical bollards were HSS $203.2 \times 203.2 \times 15.9$ (HSS $8 \times 8 \times 5/8$) A500 Gr. B steel tubes that penetrated through horizontal, below grade HSS $304.8 \times 304.8 \times 15.9$ (HSS $12 \times 12 \times 5/8$) A500 Gr. B foundation members. As shown in Figure 1, this two-post anti-ram bollard design utilized three, above-grade, A36 transverse steel plates in an attempt to provide load-sharing between the vertical bollards.

An appropriate test vehicle meeting *ASTM F2656-07* [9] criteria for a medium-duty truck was used for the impact test. According to ASTM requirements, vehicle impact should be centered on the most vulnerable section of the test article. To adhere to this requirement, the truck was centered on the left vertical bollard when viewed from the direction of impact. Data was taken during the crash test using high-speed video, bonded strain gages, radar and site surveys.

The tested two-post anti-ram bollard system arrested the impact vehicle with a dynamic penetration of -0.24 meters (-0.79 feet), measured from the lower leading edge of the cargo bed to the pre-test inside edge of the barrier, as specified in *ASTM F2656-07* [9]. A negative dynamic penetration measurement signifies that the leading lower edge of the cargo bed did not cross the pre-test inside edge of the anti-ram bollard device. This meant that the barrier succeeded in obtaining a P1 penetration rating under an M50 impact condition.

3. MODEL DEVELOPMENT AND CALIBRATION

In addition to having extensive site requirements, crash tests cause destruction of the test vehicle and bollard system, making full scale tests expensive. Therefore, it is desired to supplement experimental crash tests with computational simulations of vehicle-barrier impacts. Many projects have shown that finite element models, especially those validated with crash test data, can predict the outcome of extreme impact events well enough to draw significant conclusions from simulations [3, 6]. This study utilized fully non-linear finite element LS-DYNA software to develop and validate anti-ram bollard models under high velocity vehicular impacts. A previously developed computational model of the two-bollard anti-ram structure that was crash tested was calibrated and modified to help identify beneficial, above grade, load sharing member design features [8].

The vertical HSS bollards and horizontal HSS steel foundation members, along with the three load sharing plates between the bollards, were modeled using four-node shell elements. Steel reinforcing bars and shear studs were modeled with three-node beam elements. Concrete in the foundation and filling the vertical bollards was represented with constant stress solid elements. Solid elements were also used to model a tributary volume of soil surrounding the foundation. The soil dimensions were based on previous impact tests of similar anti-ram devices that included pressure cells in the soil. The maximum soil pressures

recorded at these locations were small enough to be negligible for the purposes of the finite element model [11]. A general view of the finite element anti-ram device model is shown in Figure 2.

One of the features that makes LS-DYNA effective at simulating dynamically loaded structural systems is the software's extensive material model libraries [7]. Material Type 24, which is a piecewise linear plasticity model, was used to model the steel HSS members, transverse plates, shear studs, and reinforcing bars. This constitutive model has been shown to accurately simulate steel material response under high strain rates, and is the most commonly used elastic-plastic material model in LS-DYNA for modeling structures under vehicle impact [12]. Material testing was performed on all steel types used in the design of the device in accordance with *ASTM E8: Standard Test Methods for Tension Testing of Metallic Materials* [13]. Stress-strain data was collected and converted to effective true stress-strain curves for implementation into LS-DYNA Material Model 24.

The solid concrete elements were modeled using Material Type 159, which is a continuous surface cap model for concrete. Material Type 159 can simulate damage-based softening with erosion of failed elements and rate effects [14]. It is reported to be the most robust and widely used concrete material model for vehicular impact applications [7]. The soil surrounding the anti-ram system's foundation used Material Type 173, which is a constitutive model for soil that utilizes a Mohr-Coulomb yield surface.

In the past, vehicle models for computational crash simulations were created by researchers that were not vehicle experts, which affected their accuracy [1]. For this reason,

Figure 2. General view of the finite element model

the National Crash Analysis Center (NCAC) at George Washington University developed a series of finite element vehicle models for LS-DYNA [15]. One of the provided vehicle models is for a Ford F800 single unit truck, which is comparable to the medium-duty flatbed truck test vehicle specified by *ASTM F2656-07*. A modified version of the Ford F800 truck model was used to apply the simulated impact load in the finite element model.

Model calibration was a collaborative process involving members of the research team and additional calibration details are presented elsewhere [10, 16]. First, the interaction between the foundation and soil was examined. The as-built condition of the foundation was quite different from the smooth-edged, sliding contact that was used to model the boundary between the foundation and soil. The rough cut foundation allowed for the concrete to mechanically interact with the surrounding soil, which enhanced compatibility at the interface. To more closely establish the bond between the foundation and soil as observed from the crash test, interaction between the foundation and surrounding soil was changed to a tiebreak contact [10].

In accordance with a low-cohesive well-graded gravel that was used as the surrounding “soil” in the experimental anti-ram crash test, a realistic range of soil properties were examined in the finite element model. Using allowable ranges of properties, a qualitative calibration was completed for the soil’s cohesion, angle of dilation, and bulk modulus, which are inputs for the Mohr Coulomb (Material Type 173) constitutive material model. Global rotation at the completion of each model iteration was measured by tracking vertical nodal displacements on the front (impact) edge of the foundation. The uplift in the crash test was measured by tracking points on the front edge of the foundation in high speed video of the impact test. Because less global rotation was observed in the experimental crash test than in the finite element model, the soil was stiffened within allowable limits to minimize global rotation. After the update to the finite element model soil properties, the uplift of the front of the foundation was measured to be 56.4 mm (2.22”) in the finite element model, compared to 44.5 mm (1.75”) in the crash test. This difference was attributed to failure to measure the crash test site soil properties and inadequacy of the soil material model to accurately represent the compaction of the well-graded gravel used in the crash test.

Due to the sheer quantity of possible variable combinations and ranges in the developed finite element models, an important initial step with respect to calibrating the model was identifying which items were of most importance with respect to model adequacy. Uncertain variables were selected to be examined, and a sensitivity study was performed to determine how each variable affected finite element model results. Bollard displacements, vehicle dynamic penetration, and peak strains at gage locations were used to evaluate the effect of each variable on model accuracy.

After the sensitivity study was completed, three significant finite element model variables were identified and used to complete model calibration: (1) tube-to-foundation contact friction; (2) steel-to-steel contact friction; and (3) impact-vehicle-to-barrier contact friction. Realistic limits for these coefficients were established from the literature [17–24] and are shown in Table 1.

Table 1. Coefficients of friction used for parametric study

	Lower bound	Middle value	Upper bound	Calibrated value
Steel-to-Steel	0.3	0.45	0.6	0.45
Tube-to-Foundation	0.4	0.55	0.7	0.55
Vehicle-to-Barrier	0.45	0.75	1.0	1.0

Examining all possible combinations of the values in Table 1 gave 27 model permutations. The coefficient combination providing the best agreement between experimental data and model results was one that utilized the middle value for steel-to-steel friction (0.45), the middle value for steel-to-foundation friction (0.55), and the high value for vehicle-to-barrier friction (1.0). These changes were used by the calibrated finite element model [10].

The calibration process improved agreement between finite element model predictions and measured crash test values for vehicle penetration, bollard displacements and strain values at critical locations on the anti-ram system. The calibrated finite element model predicted a maximum dynamic penetration of the impact vehicle of -0.54 meters (-1.77 feet), compared to -0.24 meters (-0.79 feet) measured during the crash test, as shown in Figure 3. As stated earlier, a negative penetration measurement indicates that the lower leading edge of the truck bed did not cross the pre-test reference line, parallel to the back (protected) edge of the bollards as indicated in the figure. Disagreement between vehicle dynamic penetration values was attributed to variations in vehicle properties between the finite element truck model and the test vehicle, as dynamic penetration is largely dependent on the stiffness of the impact vehicle's components. Additionally, in the crash test, the truck's cargo bed became detached from the vehicle and moved forward, which added uncertainty to the measurement.

A comparative strain time history from a representative gage on front side of the top transverse plate member is shown in Figure 4. The peak experimental strain was $11,497$ microstrain ($\mu\epsilon$), compared to a peak strain in the calibrated finite element model of $11,784$ $\mu\epsilon$. This gave a percent difference of 2.5% , compared to 23.8% in the initial finite element model. After initial impact, the predicted strain value at this location responded completely plastically; it did not return elastically to a lower permanent set as observed during the actual crash test. The discrepancy beyond peak strain was most likely due to both element and material formulations in the finite element model. Shell elements used for load sharing members in this study only contained three through-thickness integration points. If the upper and lower integration points reached their plastic limit, almost the entire section is assumed to have plasticized due to the higher computational weighting of the three through-thickness points, which could affect the strain gradient of the shell element. Adding additional through-thickness integration points would allow outer points to reach their plastic limit while

Figure 3. Impact vehicle dynamic penetration comparison

Figure 4. Representative strain time-history

maintaining lower stresses towards the center of the member's cross-section, which would permit more elastic recovery of the element. Additionally, Material Model 24, used for the load sharing member, was not given a damage model that softens response after ultimate capacity is reached. The addition of a damage model to Material Model 24 may improve post capacity predictions. Overall, because the ultimate objective was to track global, system response and maximum vehicle penetration during the impact event, the discrepancy in material elastic rebound was deemed acceptable.

4. PARAMETRIC STUDY

Calibrated finite element models were used to evaluate various above grade load sharing configurations using a parametric study. The study focused on two different designs that varied the number and location of load sharing members, termed Configurations 1 and 2 as shown in Figure 5. Configuration 1 utilized three horizontal load sharing members to spread member stiffness along the height of the anti-ram bollards. This was similar to the configuration of load sharing members in the tested two-post anti-ram system described earlier. Configuration 2 was used to investigate if load sharing and subsequent performance would be more efficient using a single, stiffer member at the top (free end) of the vertical

Figure 5. Elevation view of studied load sharing member configurations

bollards. This design uses less material and consolidates load sharing member strength and stiffness at the free end of the bollards, which may improve energy dissipation in the structural system and help optimize its design. Since the single member in this configuration was located at the top of the anti-ram system, it could also theoretically avoid local failures caused by direct vehicular impact.

In addition to changing the design configurations as shown in Figure 5, above grade load sharing member cross sections were also varied within each configuration to study how different member shapes and stiffness influenced the crashworthiness of each parametric model. Selection of trial member cross sections was based on engineering principles, practical considerations and design criteria from AISC's *Steel Construction Manual* [25]. Adjustment of the trial member cross sections was based on appropriate AISC design limit states for steel members and sections were chosen so that they were controlled by independent failure modes or, in some cases, by interaction of failure modes. By addressing multiple limit states during member design, trial sections were representative of a range of possible above grade load sharing member sizes and types. The combination of the load sharing member configurations, cross sections, and potential failure modes produced 14 different parametric designs. A flowchart describing the member parametric design combinations is shown in Figure 6.

Even though load sharing members were initially assumed to act as tension members to engage the non-impacted bollard, they could also experience bending, shear, torsion, and connection zone failure during impact. Because of the high combined loads and multiple member failure modes that could occur during a vehicular impact, the member cross section selected for each design in Figure 6 corresponded to a controlling limit state for that member type. Internal member forces used to help size the members were taken from the calibrated finite element model discussed in Section 3.

Preliminary calculations were completed to determine controlling load sharing member AISC design limit states. While completing the preliminary calculations, it became apparent that plate members were controlled by tension and flexure, HSS members were controlled by tension and shear and round bar members were controlled by tensile failure. Subsequently, each member type and configuration combination had three trial member sections designed, one for each of the two controlling limit states and one for a combined limit state. This allowed for investigation of a variety of member responses within the anti-ram system and permitted evaluation of the studied member types under different failure modes. The resulting load-sharing members that were examined are summarized in Table 2 along with their identifying designations. Here, C1 represents Configuration 1 and C2 Configuration 2, while T, F, S, and C represent tensile, flexural, shear, or combined failure modes,

Figure 6. Parametric study flowchart

Table 2. Load sharing member designs and abbreviations

Section	Configuration/failure	Cross section (SI)	Cross section (English)
Plate	C1	T	152.4 mm × 25.4 mm
		C	254 mm × 15.9 mm
		F	355.6 mm × 12.7 mm
	C2	T	152.4 mm × 38.1 mm
		C	254 mm × 22.2 mm
		F	457.2 mm × 15.9 mm
HSS	C1	T	76.2 × 127 × 6.4 (LSH)
		C	101.6 × 101.6 × 6.4
		S	127 × 76.2 × 9.5 (LSV)
	C2	T	76.2 × 127 × 12.7 (LSH)
		C	101.6 × 101.6 × 12.7
		S	152.4 × 76.2 × 12.7 (LSV)
Bar	C1	63.5 mm Ø	2–1/2" Ø
	C2	88.9 mm Ø	3–1/2" Ø

respectively. Therefore, the Configuration 1 plate member controlled by tensile failure would be designated as Plate_C1_T. All plate members were oriented with their strong axes vertical, while rectangular HSS members were oriented as specified in the table. Note that LSH and LSV stand for Long Side Horizontal and Long Side Vertical, respectively, with horizontal and vertical being defined relative to the top of soil.

5. RESULTS AND DISCUSSION

Simulated vehicle impact was centered on a single bollard in each finite element model. Therefore, one of the most effective ways to evaluate success of the load sharing members was by tracking how much of the impact energy was transferred to the non-impacted bollard. To do this, bollard displacements and internal moments were evaluated to determine the most efficient load sharing mechanisms and configurations. Another common means of assessing anti-ram system design effectiveness is based on the ability to stop an impacting vehicle within a specified penetration distance as discussed earlier. Therefore, minimization of vehicle penetration was an additional evaluation method implemented for this study with an understanding that any device not obtaining a P1 penetration rating, as defined by *ASTM F2656-07* [9], would be considered an inadequate design. A final evaluation criterion was related to global rotation of the entire anti-ram system out of its surrounding soil as it is recognized that a critical part of the anti-ram barrier design process is to maintain overall stability of the device by accurately accounting for the site conditions [6]. A failure caused by the global rotation of the entire anti-ram system out of the surrounding soil could render that design inadequate.

Comparing displacements at the top of each bollard revealed two different load sharing mechanisms in the anti-ram system, with the exhibited mechanism being dependent on the flexural resistance of the load sharing members. HSS load sharing members, which have a higher resistance to bending and torsion when compared to the plate and round bar members, displayed a flexure-controlled load sharing mechanism. The additional flexural stiffness of the steel tubes allowed for the load to be transferred via moment into the non-impacted bollard in the direction parallel to impact, as shown in Figure 7. The studied plate members, which had less flexural resistance in the primary axis of bending, acted as a tension-controlled mechanism during the impact event, developing plastic hinges near the bollards and relying on their tensile strength to engage the non-impacted bollard and largely pull it in a direction perpendicular to impact. Round bars exhibited a combination of these two distinct load sharing mechanisms.

Maximum internal moments were taken at the base of each bollard and, in general, these values quantified the magnitude of inter-bollard load transfer for different load sharing mechanisms, as shown in Figure 7. HSS members were more effective at transferring the impact energy to the non-impacted bollard in the direction of impact, as evidenced by maximum moments being higher parallel to impact, while plate members and round bars were more effective at engaging the non-impacted bollard in a direction perpendicular to the impact, as evidenced by larger moments in that direction.

To more clearly identify the member type that most efficiently shared load with the non-impacted bollard, a resultant moment was calculated at the base of each bollard. In an ideal load sharing mechanism, it was surmised that the resultant moment of the impacted bollard would be minimized, while the resultant moment of the non-impacted bollard would be maximized. Therefore, the ratio of resultant moment in the non-impacted bollard to resultant moment in the impacted bollard was calculated and was used to assess load sharing effectiveness in each anti-ram system. These “load sharing ratios,” as well as the maximum

(a)

(b)

Figure 7. Prominent load sharing mechanisms. (a) HSS members – flexure-controlled, (b) plate members – tension-controlled

resultant moment at the base of each bollard, are shown in Table 3. The highest ratios were observed for the HSS load sharing member cases, especially in the Configuration 2 cases, highlighted in bold in Table 3. This implied that the HSS members were more effective than plates and round bars with respect to sharing load within the two-post anti-ram system used in this study.

As stated earlier, penetration of the vehicle in each model case was also evaluated. *ASTM F2656-07* [9] specifies that dynamic penetration of the impact vehicle should be measured from the lower leading edge of the truck bed, where any explosive payload would commonly be stored. For the current study, this dynamic penetration was measured by tracking nodes on the front corners of the truck bed in the vehicle finite element model. All fourteen of the finite element anti-ram systems stopped the impact vehicle before the truck bed nodes crossed the failure line [10], indicating that all studied two-post bollard systems would obtain an M50-P1 rating.

However, dynamic penetration as defined by ASTM 2656-07 does not fully represent the effectiveness of each anti-ram design at limiting the displacement of the entire vehicle. Since the finite element model utilized an asymmetric impact, maximum penetration of the truck bed was dependent upon the vehicle geometry and dynamics. The dynamic measurement from the front of the truck bed was used in the calibration of the finite element model, but to further study the ability of each anti-ram design to limit penetration of the impact vehicle, maximum displacement of the vehicle's center of gravity was examined for the load sharing member study, as depicted in Figure 8. This eliminated some variation in vehicle penetration measurements and provided a better estimate of the global response throughout the crash event. The maximum center of gravity displacements for the fourteen parametric models are shown in Figure 9. The figure indicates that, in general, HSS load sharing members allowed less penetration than other member types. In addition, Configuration 2 cases limited vehicle penetration more effectively than Configuration 1 cases, especially for the plate member designs. It was also determined that the HSS member cases stopped the truck more rapidly than the other designs [10].

Table 3. Load sharing performance summary - HSS, configuration 2 members highlighted

	Impacted bollard moment (kN-m)	Non-impacted bollard moment (kN-m)	Load sharing ratio
Plate_C1_T	580	354	0.611
Plate_C1_C	580	341	0.588
Plate_C1_F	591	368	0.622
Plate_C2_T	604	434	0.719
Plate_C2_C	586	433	0.739
Plate_C2_F	578	425	0.736
HSS_C1_T	581	463	0.798
HSS_C1_C	589	426	0.722
HSS_C1_S	584	484	0.829
HSS_C2_T	558	460	0.824
HSS_C2_C	553	466	0.843
HSS_C2_S	550	462	0.840
Bar_C1	588	397	0.675
Bar_C2	529	349	0.660

Figure 8. Impact vehicle center of gravity maximum displacement

Figure 9. Maximum nodal displacements of impact vehicle center of gravity

To better quantify the effectiveness of each load sharing member design and study the ability of each design to limit dynamic penetration of the impact vehicle, a relationship between load sharing ratio and maximum penetration of the truck's center of gravity was established. The maximum displacement of the impact vehicle's center of gravity was plotted against the load sharing ratio for each of the fourteen design cases as shown in Figure 10. In general, anti-ram designs with higher load sharing ratios were more effective at limiting dynamic penetration of the impact vehicle. A linear regression of the data did indicate a level of correlation between load sharing ratio and impact vehicle penetration, with higher load sharing ratios leading to lower penetration, as expected.

Global rotation, which relates to the tendency of the anti-ram system to rotate out of the surrounding soil, is also of concern when designing anti-ram systems. The effectiveness of each of the fourteen load sharing design models with respect to global rotation resistance was assessed by studying vertical displacement at the front (impact) edge of the foundation as shown in Figure 11. Overall, more global rotation was observed in HSS member cases than

Figure 10. Relationship between load sharing effectiveness and impact vehicle penetration

Figure 11. Anti-ram global rotation diagram

in plate member and round bar cases, performance that was attributed to the load sharing mechanisms shown in Figure 7. Since HSS load sharing members transferred more energy in the direction of impact, this can lead to a larger overturning moment on the entire structure. Conversely, plate members pull the non-impacted bollard in a direction perpendicular to impact and caused less global rotation. In addition, load sharing member cases using Configuration 2, which employed a single, stiffer member, exhibited more global rotation than those using Configuration 1, which used three members. Since load transfer occurred higher on the non-impacted bollard for the Configuration 2 cases, the overturning moment arm on the bollard increased, which, in turn, increased global rotation of the anti-ram system.

6. CONCLUSIONS

Anti-ram bollards can be an effective and unobtrusive design solution to protect buildings and their occupants from vehicle impacts. This study focused on the evaluation of above grade load sharing members with the intention of developing more efficient and inconspicuous anti-ram bollard system designs that could still effectively withstand a high speed vehicular impact. Load sharing members were used to connect two bollards in a representative anti-ram system and their effectiveness was studied by impacting one bollard and examining bollard displacements, the magnitude of load transferred to the non-impacted bollard, the amount of dynamic vehicle penetration and overall foundation stability through global rotation. A previously constructed finite element model of a representative two-post anti-ram bollard system was updated and calibrated against experimental crash test data. This calibrated model was subsequently used to evaluate fourteen load sharing member designs, with the numbers and types of designs consisting of: six with above grade plate members that behaved predominantly as tension members; six with above grade HSS members with higher flexural stiffness; and two with above grade round bars that had high flexural and tensile strength. Half of the anti-ram systems utilized three sharing members that distributed load along the height of the vertical bollard, termed “Configuration 1” designs, while half employed a single, stiffer load sharing member at the top of the bollards that were termed “Configuration 2” designs.

Evaluation of the effectiveness of each parametric anti-ram design occurred via the examination of four items: (1) bollard top (free end) displacements; (2) bollard base moments; (3) levels of impact vehicle dynamic penetration; and (4) global rotation of the anti-ram system. The displacements at the top of each the impacted and non-impacted bollard were investigated to ascertain load sharing behavior and effectiveness in the studied anti-ram systems. This investigation showed the existence of two load sharing mechanisms that were dependent on load sharing member flexural stiffness.

To determine how various load sharing member designs and mechanisms influenced the magnitude of internal forces in the anti-ram bollard systems and, subsequently, load sharing effectiveness, moments were calculated at the base of both the impacted and non-impacted bollards. The non-impacted bollard experienced higher moments in the direction of impact for models containing HSS load sharing members, but higher moments perpendicular to impact in models containing plates and round bars, affirming the dependence of load sharing mechanisms on member flexural stiffness. To help determine which of these mechanisms was most effective at distributing impact energy to the non-impacted bollard, resultant moments at the base of each bollard were calculated and were normalized to the impacted bollard resultant moment. The resultant moment ratios showed that the HSS load sharing

members, especially those using Configuration 2, were most effective at transferring impact energy to the non-impacted bollard.

Dynamic penetration of the impact vehicle was also examined to study how each load sharing member design affected system crashworthiness. Designs that contained HSS load sharing members were found to be more effective than plate or round bar load sharing members at preventing vehicle penetration. Configuration 2 designs, which, again, used a single, stiffer load sharing member at the tops of the bollards, arrested the impact vehicle more quickly than Configuration 1 cases. In addition, designs that exhibited more effective load sharing tended to be more successful at limiting the dynamic penetration of the impact vehicle.

Due to the relative uncertainty of boundary conditions, global rotation is an important limit state when designing vehicle barriers. It was determined that anti-ram systems using HSS load sharing members experienced more global rotation due to the mechanism that transferred more load to the non-impacted bollard in the direction of impact. In addition, Configuration 2 cases exhibited more global rotation than Configuration 1 cases due to impact load transfer between bollards occurring higher on the non-impacted bollard.

Even though HSS member cases were shown to be most effective at sharing loads between bollards and subsequently limiting vehicle penetration, they were also vulnerable to global rotation. The examined two-post anti-ram system utilized well-defined boundary conditions that consisted of a saw cut foundation surrounded by soil and a concrete slab. If these devices were placed in a site having poor soil conditions, limited soil confinement, or unknown boundary conditions, there is no guarantee that HSS members would be the most effective choice to limit vehicle dynamic penetration. In those situations, a designer might prefer a load sharing design that produces less global rotation, such as the Configuration 1 cases that used plates as load sharing members. These designs more gradually dissipated the impact energy and transferred load in a fashion that diminished overturning moment on the anti-ram system, leading to decreased vulnerability to global rotation.

For the anti-ram designs that were studied under vehicle impact, study conclusions and design recommendations can be summarized as follows:

- Anti-ram designs that utilized a single, stiffer load sharing member located at the top of the bollards showed improvement over designs using multiple load sharing members. This was attributed to engagement of the full height of the non-impacted bollard, which effectively utilizes the entire anti-ram system to dissipate the impact energy of the vehicle.
- Rectangular HSS members were shown to be the most effective cross section in terms of load sharing efficiency, impact resistance, and minimization of required material, due to their enhanced flexural and torsional resistance.
- Designs that exhibited more effective load sharing tended to be more successful at limiting the dynamic penetration of the impact vehicle.
- Anti-ram designs using multiple, less stiff load sharing members demonstrated lower global barrier rotation than other designs by transferring the impact load lower on the bollards and in a direction perpendicular to impact.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Thomas D. Larson Pennsylvania Transportation Institute and the U.S. Department of State's Bureau of Diplomatic Security for assisting with this research.

REFERENCES

- [1] Hu, B., Li, G., Chen, S., and Shi, W., State-of-the-Art Review on Anti-ram Bollards, *AMM Paper* 2011, 90–93.3206.
- [2] Crawford, J. E. and Lan, S., Design and Implementation of Protective Technologies for Improving Blast Resistance of Buildings, *Proc. Enhancing Building Security Seminar*, Singapore. 2005.
- [3] Omar, T., Bedewi, N., and Hylton, T., Cost-effective Structural Anti-Ram Security Barriers – New Design, Computer Modeling and Test Validation, *Proc., 2007 ASME International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineering, Seattle, Washington. 2007.
- [4] Krishna-Prasad, B., *Protective Bollard Design for High Speed Impact Energy Absorption*, M.S. Thesis, Wichita State University, 2006.
- [5] Dawson, H. and Tennant, D., Inelastic Dynamic Finite-Element Design of Bollard Systems to Impact Loading, Structures Congress, 2008, 1–10, Vancouver, Canada.
- [6] Chunlin, L., Guoquiang, L., Siew Kheong, P., and Jianyun, S. Effects of Boundary Conditions on the Design of Anti-Ram Bollards, *Transactions of Tianjin University*, 2008, 14(5), 384–386.
- [7] Livermore Software Technology Corporation (LSTC), LS-DYNA Keyword User's Manual, 2007, Livermore, CA.
- [8] O'Hare, E. V., *DS-SVAR Sign-M50 Report*, The Thomas D. Larson Pennsylvania Transportation Institute. The Pennsylvania State University, University Park, PA, 2012a.
- [9] American Society for Testing and Materials (ASTM), Standard Test Method for Vehicle Crash Testing of Perimeter Barriers, *F2656-07 American Society for Testing and Materials, Committee F12*, 2007.
- [10] Kinney, S., *Assessment of Load Sharing Members in an Anti-ram System Subjected to Vehicle Impacts*, M.S. Thesis, The Pennsylvania State University, 2013.
- [11] O'Hare, E. V., *DS-SVAR Shallow Bench-M40 Report*, The Thomas D. Larson Pennsylvania Transportation Institute. The Pennsylvania State University, University Park, PA, 2012b.
- [12] Du Bois, P. A., Kolling, S., Koesters, M., Frank, T., Material Behavior of Polymers Under Impact Loading, *International Journal of Impact Engineering*, 2006, 32, 725–740.
- [13] American Society for Testing and Materials (ASTM), Standard Test Methods for Tension Testing of Metallic Materials, *E8/E8M-11 American Society for Testing and Materials*, 2012.
- [14] Federal Highway Administration (FHWA), User's Manual for LS-DYNA Concrete Material Model 159, *FHWA-HRT-05-062. Turner-Fairbank Highway Research Center*, 2007.
- [15] National Crash Analysis Center (NCAC), Finite Element Model Archive, George Washington University, Washington, D.C. <<http://www.ncac.gwu.edu/vml/models.html>> 2011.
- [16] O'Hare, E. V., Linzell, D., Rado, Z., 2013., Development of Shallow Foundation Streetscape Vehicular Anti-ram Systems Through Modeling and Testing, *Proc., Shock and Vibration Symposium*, SAVE, Arvonion, VA., 64
- [17] Blau, P. J., *Friction Science and Technology*, Marcel Dekker, Inc., New York, NY, 1996.
- [18] American Society for Metals (ASM) International, *ASM Handbook V.18: Friction, Lubrication, and Wear Technology*, The Materials Information Society, Materials Park, OH, 1992.
- [19] Serway, R. A., *Physics for Scientists & Engineers*, 4th Edition, Saunders College Publishing, Philadelphia, PA, 1995.
- [20] Grigoriev, I. S., Meilikhov, E. Z. Radzig, A. A., *Handbook of Physical Quantities* CRC Press, New York, NY, 1997.
- [21] Rabbat, B. G., Russell, H. G., Friction Coefficient of Steel on Concrete or Grout *Journal of Str. Engr.*, ASCE, 1985, 111, 505–515.
- [22] American Concrete Institute, ACI 318-08: *Building Code Requirements for Structural Concrete and Commentary*, Committee 318, Farmington Hills, MI, 2008.
- [23] Precast/Prestressed Concrete Institute (PCI), *PCI Design Handbook: Precast and Prestressed Concrete: 5th Edition*, PCI Industry Handbook Committee, Chicago, IL, 1999.
- [24] United Facilities Criteria (UFC), *UFC 4-022-02: Selection and Application of Vehicle Barriers*, Department of Defense, Washington, D.C., 2009.
- [25] American Institute of Steel Construction (AISC), *Steel Construction Manual*, 14th Edition, Chicago, IL, 2010.