# Analysis and Design of a Unique Security Bollard Installment Using LS-DYNA® for a K12 Vehicle Impact

Joseph M. Dulka, Eric R. Dietrich, Kelley S. Elmore,
Kendra D. Jones, Clyde S. Harmes, Robert H. Moyer

Elmore Engineering services, inc.

215 W. Philadelphia Ave.
Boyertown, PA 19512

## Abstract

*This paper presents the design process for a unique security bollard providing protection against a K12* [1] *(M50* [2]*) vehicle crash load. LS-DYNA was used to aid in the design of the security bollard to account for the highly dynamic and inelastic behavior during a vehicle impact. The bollard was installed along the top of a wall for a below-grade courtyard in order to maintain a building security perimeter, providing protection against a potential malevolent vehicle attack. Contrary to typical bollard installations where the foundation is supported on all sides with well compacted soil or other substrata, no significant support was provided on the protected side of the bollard foundation. As a result, this posed significant difficulty in the design of an effective security bollard required to resist a potential K12 (M50) vehicle impact load with zero vehicle penetration. The initial conceptual bollard design originated from the standard Department of State (DoS) DS-22 K-12 rated bollard system* [3]*. Hand calculations were used to develop a preliminary bollard design with equivalent static design stopping forces based upon existing physical K12 test results. LS-DYNA aided the engineering team in observing structural and material responses characteristic of impact loading which may have otherwise not been perceived by method of traditional hand calculations. Utilizing LS-DYNA as not only an analysis tool, but a powerful design tool enabled the engineering team to optimize the design of the security bollard.*

*Keywords: Protective Design, VBIED, Crash Barrier, Security Bollard, Vehicle Impact*

# 1. Introduction

Protective design has steadily increased into a global concern in the post 9/11 world. Protection against explosive threats and vehicular impact threats has developed into a requirement rather than a decision during building and site design phases. Building security starts by defining an exterior perimeter to provide a safe standoff distance for a Vehicle-Borne Improvised Explosive Device (VBIED).

The simplest and most effective way to reduce the blast or impact effects of a VBIED is to provide a further standoff distance. However, in urban settings where standoff is limited this is accomplished by designing a hardened structure for blast loading and a Vehicle Barrier System (VBS) capable of stopping a design malevolent vehicle load within the predetermined safe standoff distance (i.e. building site protection perimeter).

There are many potential barrier options to consider when designing a VBS for protection against a VBIED. Typical VBS designs consist of concrete mass barriers, cable barriers, bollards, crash gates, natural terrain, etc. Selection of a suitable VBS is based upon the requirements which are adherent to the needs of the building site, level of protection, budget, and aesthetics. For the design presented herein, protection is required to resist a K12 (M50) vehicle impact (15,000 lbm. at 50 mph) at the top of a subgrade courtyard. Figure 1 below illustrates the coincidence between the courtyard wall and the required building VBIED security perimeter at the street elevation.

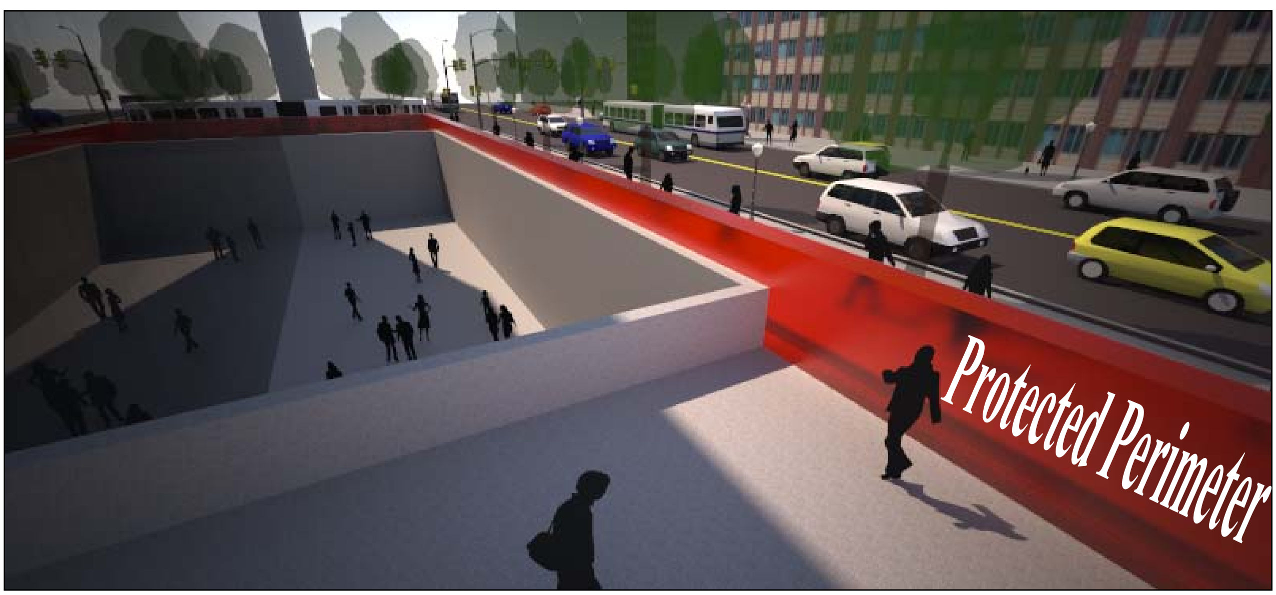


**Figure 1 – Illustrative Description of Site Specific Courtyard Coinciding with the Protected Perimeter**

Inadequate support on the protected side of the prospective barrier system's foundation imposed limitations on the design of the VBS. Additionally, the project scope, as developed by the building owner and architect, required sensitivity to a VBS design which aesthetically complemented a streetscape setting.

Simply idealizing a static load to account for the dynamics of a vehicle impact tends to result in highly conservative and overly robust designs. If this approach alone is applied as the design methodology, the results typically yield overdesigned, uneconomical options for the client. Therefore Finite Element Analysis (FEA) software was used by engineering to account for the behavior inherent to vehicle impact loading (nonlinear, inelastic, dynamic, strain-rate dependent material modeling, etc.).

LS-DYNA is widely used in crashworthiness and vehicle barrier design applications. While physical testing is the ideal method for simulating a VBS's crash effectiveness, this likely will not always be a cost-effective or schedule permitting option. In the case of the courtyard VBS design for a malevolent vehicle, LS-DYNA Explicit Solver was employed to simulate the vehicle impact.

This paper discusses an overview of the methods applied in designing the VBS from concept to construction. Though multiple design iterations were performed, the final design is presented herein for brevity with supporting discussion regarding intermediate design phases. This paper demonstrates the use of LS-DYNA as a powerful design optimization tool.

## 2. Analysis and Development of the Preliminary Design Concept

The client's design criteria required the VBS to halt a K12 (M50) vehicle impact load with essentially zero penetration. Since zero penetration was required, the level of protection needed to surpass the DoS standard K12 L3 rating [1] and ASTM standard M50 P1 [2] crash rating. Figure 2 below provides a comparison between the DoS and ASTM vehicle crash rating standards.

| Stndard | Rating | Vehicle Weight (lbs) | Vehicle Speed (MPH) | Rating | Allowable Truck Bed Penetration (ft) |
|---|---|---|---|---|---|
| DoS K-Ratings | K12 | 15,000 | 50 | L1 | 20 - 50 |
| | K8 | 15,000 | 40 | L2 | 3 - 20 |
| | K4 | 15,000 | 30 | L3 | < 3 |
| ASTM F2656-07 Standard | M50 | 15,000 | 50 | P4 | > 98 |
| | M40 | 15,000 | 40 | P3 | 23.1 - 98.4 |
| | M30 | 15,000 | 30 | P2 | 3.31 - 23 |
| | | | | P1 | < 3.3 |

**Figure 2 – Comparison between DoS and ASTM Crash Barrier Rating [1] [2]**

Additional criteria required limiting bollard rotation to a maximum of 8˚. Existing data from physical bollard crash tests provides basis for concluding that when bollard rotation exceeds 8˚ the vehicle has a tendency to ride up and over a bollard system resulting in vehicle penetration. The obvious challenge facing engineering was providing a cost effective solution meeting the stringent level of protection.

Inception of the preliminary VBS bollard concept stemmed from a previously qualified DoS bollard design. Figure 3 illustrates the DoS DS-22 K12 rated bollard with revisions to highlight specific limitations at the courtyard. Steel section sizes and reinforcement detailing of the DS-22 bollard provided the frame work for the initial conceptual design.

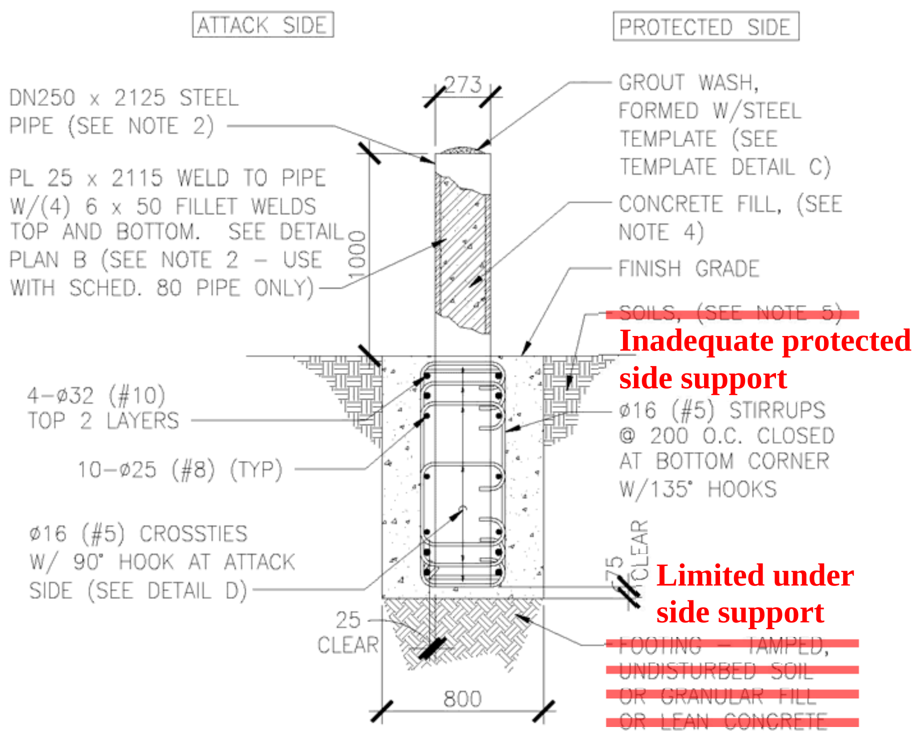


**Figure 3 – DoS Standard DS-22 K12 Rated Bollard [3] with Site Specific Considerations**

The primary concern with the bollard installation at the subgrade courtyard was the non-existence of soil on the protected side and bottom side of the foundation as indicated in Figure 3. This posed the most considerable challenge to develop a bollard system capable of meeting the design criteria.

Early stages of the design started with simplified hand calculations assuming an idealized time duration to stop the K12 vehicle from maximum to zero velocity. Physical crash data shows that typical K12 L3 (M50 P1) crash events will last approximately 0.1 seconds to durations in excess of 1 second, depending upon barrier and vehicle deformation. For the initial design, a conservative stopping time of 0.1 seconds was assumed, yielding an equivalent static stopping force of approximately 340 kips (1520 kN). Figure 4. illustrates the conceptual bollard design.

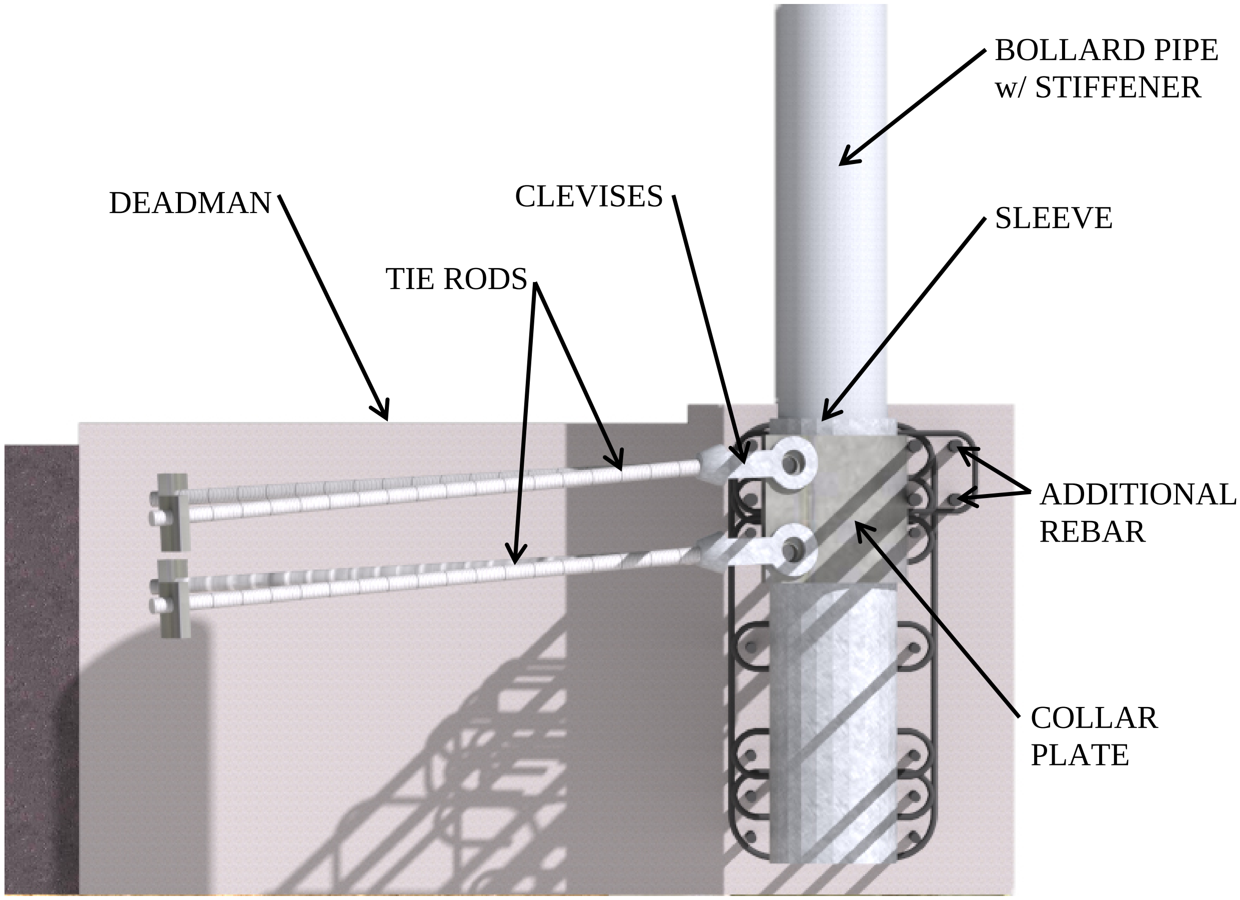


**Figure 4 – Section View of Conceptual Subgrade Courtyard Bollard Design**

To address the absence of support on the protected side of the bollard foundation, a concept was adopted in which a concrete mass (deadman) was integrated into the foundation via tie rods. Upon vehicle impact, load is transferred through contact between the collar plate and bollard assembly. Bolted clevises transfer load from the collar plate to the tie rods and into the deadman, successively resisting the forward momentum of the vehicle. As a precautionary measure, a sleeve was fitted around the bollard in the foundation which provided resistance for plastic hinge development in the bollard below the top of the concrete foundation. As an enhancement, the bollard stiffener was changed to a HSS steel shape. Furthermore, two additional layers of rebar were added at the top most layers on the protected side of the foundation to resist concrete punch-out failure.

## 3. LS-DYNA Bollard Model

Hand calculations provided the conceptual design based upon idealized static loads. LS-DYNA was then used as an analysis and design tool to optimize the bollard system and visualize dynamic response. LS-PrePost® was utilized to generate the VBS geometry and *KEYWORD input file. Figure 5 illustrates the bollard model from LS-PrePost. The bollard, stiffener, and collar plate were assembled using shell elements. The concrete foundation and deadman were constructed using solid elements, while concrete reinforcement and tie rods were represented with beam elements. Shell elements were defined as fully integrated shells, ELFORM 16, with hourglass control IHQ = 8. Solid elements were modeled with constant stress solids, ELFORM 1, and hourglass control IHQ = 3. Beam elements were assigned with Hughes-Liu with cross section integration, ELFORM 1, with CST = 1 for tubular sections.

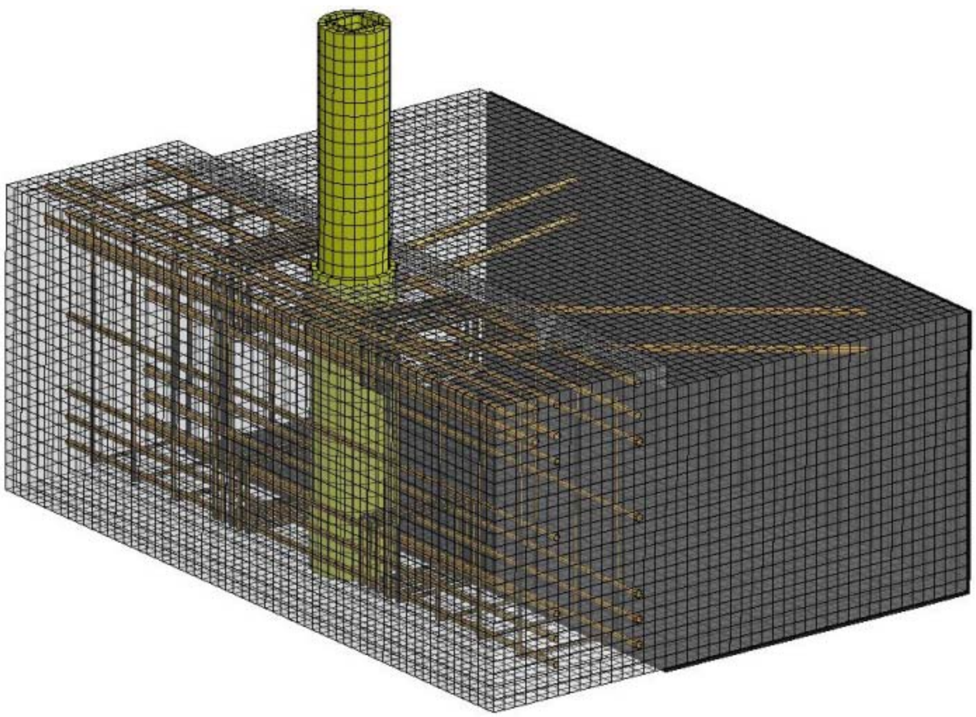

**Figure 5 – LS-DYNA Bollard Model**

Steel material for the bollard, stiffener and collar plate was defined using *MAT_024 *MAT_PIECEWISE_LINEAR_PLASTICITY with Cowper and Symonds strain rate parameters for mild steels to account for strain rate effects on material behavior. Concrete was modeled using the *MAT_159 *MAT_CSCM_CONCRETE material model. Documentation on this material model is readily available from the Federal Highway Administration [4]. Reinforcement and tie rod steel material were defined using material model *MAT_24 *MAT_PIECEWISE_LINEAR_PLASTICITY. *CONSTRAINED_LAGRANGE_IN_SOLID key was used to couple the beam elements (i.e. reinforcement and tie rods) to the solid elements (i.e. concrete) with default CTYPE = 2.

The collar plate-clevis-tie rod assembly was idealized as a plate (shell elements) with connection to the tie rods (beam elements). Bolted connection and clevises were omitted due to complexity and to avoid long run times.

*BOUNDARY_SPC_SET conditions were simulated to account for a continuously poured concrete foundation on the sides of the foundation and deadman. A support boundary on the underside and attack side of the concrete foundation and deadman was modeled with shell elements representing well compacted fill. The model was generated this way to provide resistance against contacting bodies toward the boundary surface only, as opposed to a *BOUNDARY_SPC_SET which resists both positive and negative direction motion.

## 4. LS-DYNA Vehicle Model

The K12 (M50) vehicle model was obtained from the National Crash Analysis Center (NCAC) website [5]. The available model was a typical Ford Single Unit Truck. The mass of the vehicle was increased to accurately conform to the requirement of 15,000 lbm. (~6800 kg). This was accomplished by increasing the payload material density (ballasting shown on truck bed) until the desired mass for the vehicle was obtained. Figure 6 below presents the LS-DYNA vehicle model. Additionally, keyword inputs were revised to eliminate solution errors and early terminations due to spurious modes during the analysis without adversely affecting the bollard system.

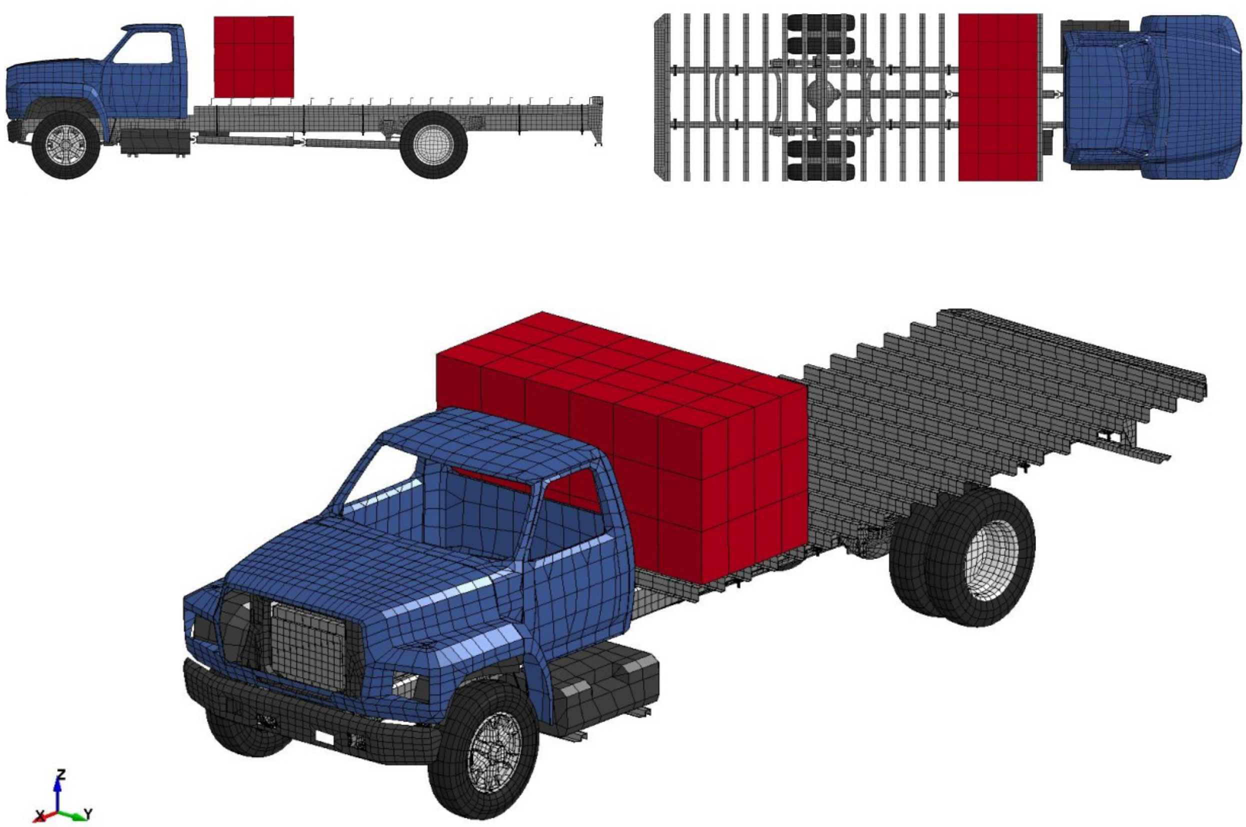

**Figure 6 – LS-DYNA K12 (M50) Vehicle Model**

## 5. LS-DYNA Vehicle Impact Analysis and Results

The vehicle impact with the bollard design was simulated using contact type *CONTACT_AUTOMATIC_SINGLE_SURFACE. Bollards are typically spaced with some minimum clear distance so as to prevent a VBIED from exploiting the security perimeter. However only one bollard was modeled. Qualifying a single bollard for the K12 (M50) load ensured less likelihood of any vulnerability in the VBS design.

In order to reduce run times, the analysis started with the front bumper of the truck a few millimeters away from the bollard (Figure 7). Initial vehicular motion was modeled by defining a *INITIAL_VELOCITY_GENERATION which initiated a velocity of 50 mph (22.35 m/s).

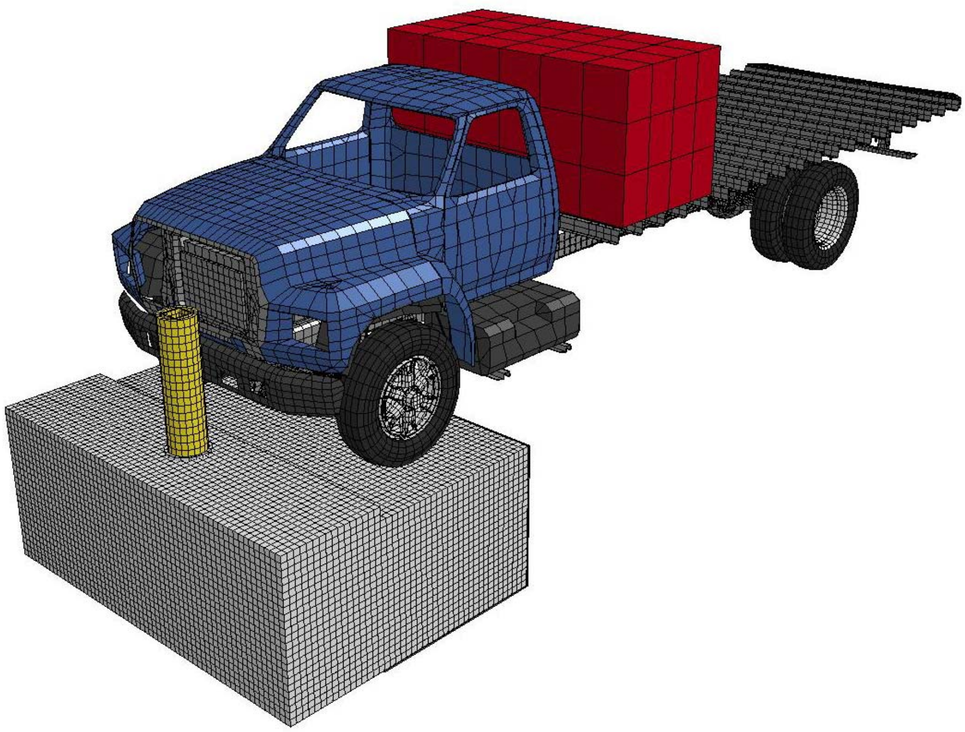

**Figure 7 – LS-DYNA Vehicle Impact Analysis at Initial Time Step**

Screen capture time steps of the impact simulation are presented in Figure 8. The simulation shows the bollard system stopping the K12 (M50) vehicle load with no discernible penetration. It was observed from the simulation results that during the onset of vehicle deformation and bollard rotation, linear horizontal momentum of the vehicle was converted into vertical motion. This is very common behavior in physical crash testing, especially characteristic of barrier systems stopping the vehicle with minor penetrations, i.e. L3 (P1) ratings.

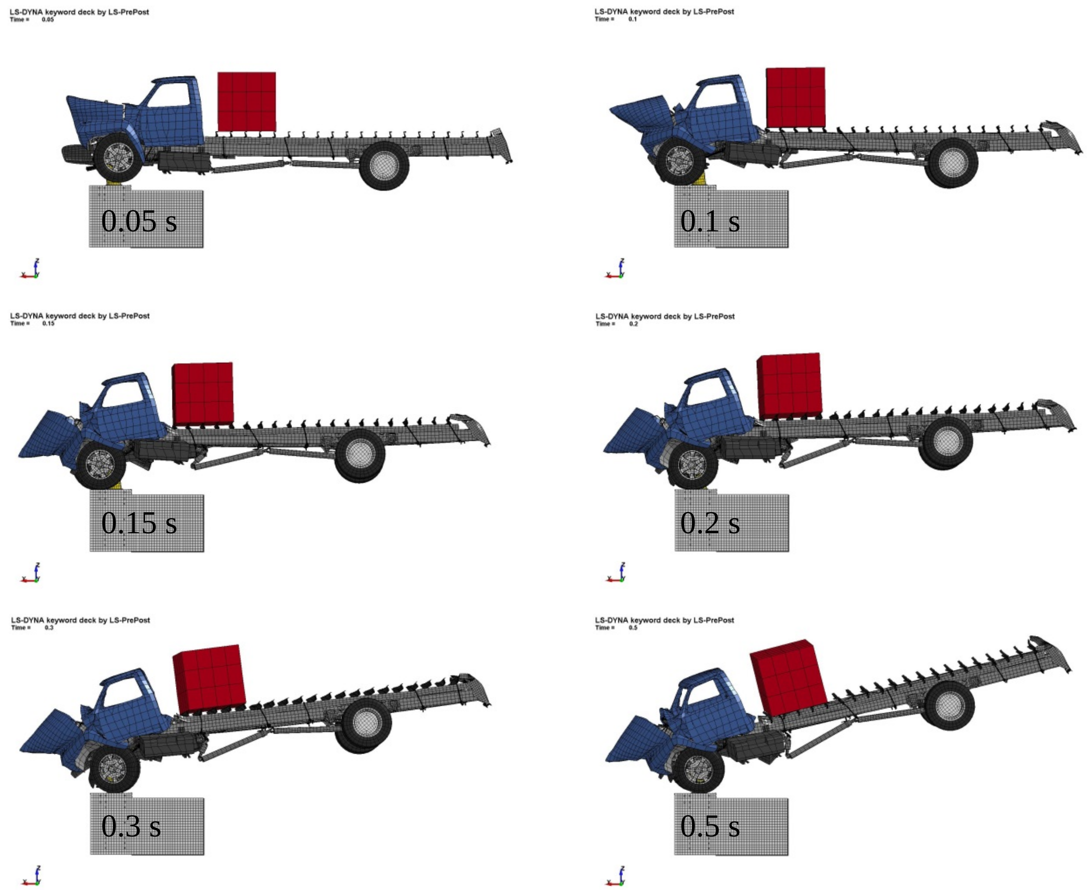


**Figure 8 – Vehicle Impact Time Steps**

The dynamic simulation in LS-DYNA enabled the engineering team to visualize the performance of the bollard system in "real-time". Any unconventional failure mechanisms, design deficiencies, or potential optimizations were easily observed. This accounted for any components that exhibited signs of structural vulnerability or over strength. An extensive number of iterations were conducted, altering components, working towards an optimized design. Once the results from LS-DYNA were accepted with a high level of confidence, additional code based hand calculations were performed to further validate that the bollard system was adequate in resisting vehicle impact.

In contrast to the original DoS DS-22 bollard, the final design consisted of a 10" Sch. 140 pipe bollard with an HSS stiffener. A 12" pipe sleeve was fitted to the bollard in the foundation to drive plastic hinge development above the surface of the concrete. The maximum resultant forces output from the beam elements simulating the tie rods provided the design basis for sizing and detailing the collar plates, clevises and tie rods.

Figure 9 presents the velocity versus time plot from the final bollard system design. The analysis shows that forward motion of the vehicle payload was brought to rest approximately 0.15 seconds after initial collision. It is interesting to note that when the front bumper initially impacts the bollard, there is a short duration from 0 seconds to about 0.05 seconds where the slope of the plot is close to zero, implying that there is a negligible deceleration rate of the vehicle. This describes the "soft" behavior of less stiff components of the vehicle deforming until the impact of the "hard" mass (i.e. engine block, transmission, etc.) on the bollard at 0.05 seconds. Linearly decreasing velocity (constant acceleration) is exhibited from 0.05 seconds to 0.15 seconds. This validated the conservative assumption using a stopping time of 0.1 seconds for preliminary design purposes.

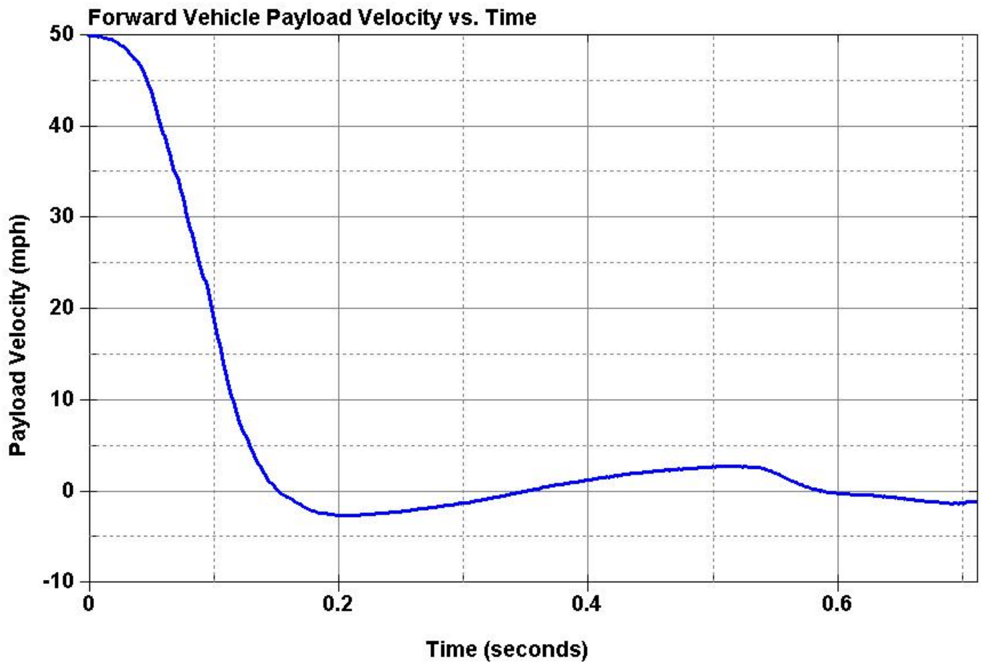


**Figure 9 – Forward Vehicle Payload Velocity vs. Time**

Change in the bollard rotation versus time is plotted in Figure 10 below. The bollard rotation approaches a maximum value of approximately 6˚ thus meeting the 8˚ maximum bollard rotation criteria. As expected this criterion prevented the vehicle from riding over the bollard system.

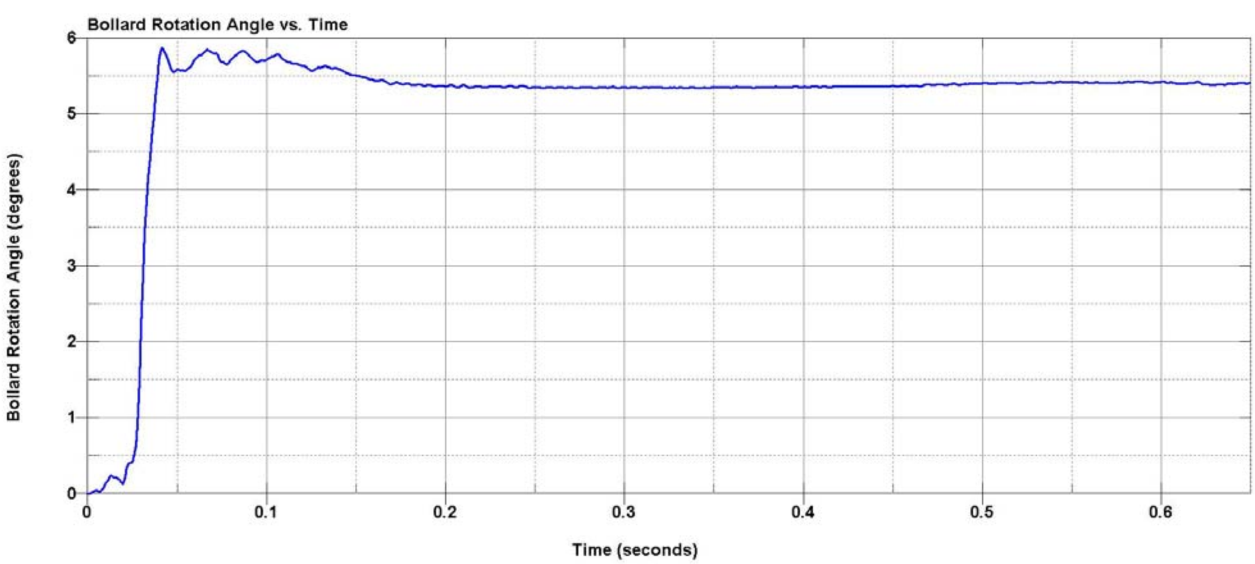


**Figure 10 – Bollard Rotation Angle vs. Time**

## 6. Conclusion

This paper presents a viable solution for a security bollard subjected to a VBIED impact to maintain a building security perimeter. The protected building perimeter coincided with a below-grade courtyard which required a unique design for a K12 (M50) rated VBS requiring zero penetration. Hand calculations were used to develop a preliminary conceptual bollard design. LS-DYNA enabled the engineering team to visualize failure mechanisms that may have otherwise been overlooked with traditional static analysis methods. LS-DYNA was utilized as an analysis and design tool in order to optimize the bollard system design by accounting for inelastic, nonlinear, dynamic behavior inherent to crash simulations.

**Figure 11 – Final Construction of VBIED Perimeter Protection Installed at Top of Subgrade Courtyard**

## References

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