PARAMETRIC STUDY AND DESIGN OF A MODULAR BOLLARD BARRIER

A Thesis

by

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ABSTRACT

This project set out to design a modular security barrier that could be used as an expeditionary system for the construction of new secure areas. It would be flexible enough to curve, both horizontally and vertically, with the ground along the perimeter of the site and still be able to withstand a collision with a 15000 lb vehicle travelling at 30 mph. It could then be installed in the ground for permanent protection and be able to stop the same size vehicle travelling 50mph within 3'-3". All of the tests performed during this project show that this design could meet that desire.

Testing for this design included parametric studies in the behavior of the macrostructure. This included testing how the unit shape and curvature affected the performance of the system. After a design was completed based on these tests, it was analyzed by finding performance curves. These curves compared the displacement of the units with the number of units and their curvature. Next the design was refined to improve assembly and constructability and tested for the connection forces. Using spring and beam connection models data on the connection forces was gathered and used to design how the system would be assembled, completing the design.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Harry Jones (advisor) and Professor William Beason of the Department of Civil Engineering and Professor Anastasia Muliana of the Department of Mechanical Engineering.

All work for the thesis was completed by the student, under the advisement of Dr. Dean Alberson and Dr. Akram Abu-Odeh of the Texas A&M Transportation Institute and Mr. Russell Norris of the U.S. Department of State, Physical Security Division.

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1 INTRODUCTION

With the ever increasing number of attacks on secure areas, there is a constant need to investigate new and/or improved ways to keep intruders out. One example of how people attempt to infiltrate secure areas is by using a vehicle to collide with the physical security system in place. Therefore, there is a need for these systems to be robust enough to obstruct large vehicles traveling at high velocities. The purpose of this study was to solve some of the problems that plague entities attempting to secure an area by designing a modular bollard barrier.

In some cases the physical security system needs to be in place before construction starts on a site. This often results in a temporary barrier system that is subsequently replaced, adding additional cost to the construction. Moreover, most barrier systems are often not very versatile and require more work to install. Another obstacle is the transportation of the materials for the construction of the aforementioned physical system(s). In light of these issues, the U.S. Department of State, Physical Security Division approached the Texas A&M Transportation Institute with a project to address them.

The objective of this project was to produce a design for a modular bollard barrier system for expeditionary purposes. This system can be transported as individual units, quickly assembled, and left on the ground for a quick physical security option. At a later time, a construction crew will be able to return and permanently install the units in the ground for a stronger barrier. The system can also accommodate curved and sloping ground.

To fully define this project the U.S. Department of State issued a set of requirements for the resulting system. These are:

1) The horizontal curvature of the system must have as small a curve radius as possible
2) The bollard is to remain 3’ 3” tall after the unit is installed in the ground with 8” of cover
3) A P2 (Table 2-2) rating or better for an M30 (Table 2-1) crash test with the units arranged on the ground
4) A P1 (Table 2-2) rating for an M50 (Table 2-1) crash test with the units embedded in the ground

A system meeting these criteria would be capable of protecting secure areas. With the criteria set, it was important to determine what had previously been done to provide a starting point for the design. It was also important to validate the use of finite element modeling program LS-DYNA as an appropriate tool for gathering data for designing a system.

2 LITERATURE REVIEW

2.1 Testing Standards

To standardize testing to evaluate the performance of security barriers, ASTM published ASTM Standard F2656. The standard tests combine vehicle weight, the speed at impact, and the tests' designation, as shown in Table 2-1. It also describes the test site, the soil conditions, the test vehicles, how any additional weight is to be added to the test vehicle, as well as how the penetration of the test vehicle is measured. Finally, the penetration rating is given according to how the penetration measurement falls on Table 2-2. The tests and ratings used in this work all follow this standard (ASTM 2015).

Test Vehicle/Minimum Test Inertial Vehicle, kg [lbm]	Nominal Minimum Test Velocity, km/h [mph]	Permissible Speed Range, km/h [mph]	Kinetic Energy, KJ [ft-kips]	Condition Designation
Small passenger car (SC) 1100 [2430]	50 [30]	45.0-60.0 [28.0-37.9]	106 [78]	SC30
1100 + 25 [2420 + 55]	65 [40]	60.1-75.0 [38.0-46.9]	179 [131]	SC40
	80 [50]	75.1-90.0 [47.0-56.9]	271 [205]	SC50
	100 [60]	90.1- above [57.0-above]	424 [295]	SC60
Full-size Sedan (FS) 2100 [4630]	50 [30]	45.0-60.0 [28.0-37.9]	203 [37]	FS30
2100 + 50 [4630 + 110]	65 [40]	60.1-75.0 [38.0-46.9]	342 [247]	FS40
	80 [50]	75.1-90.0 [47.0-56.9]	519 [387]	FS50
	100 [60]	90.1-above [57.0-above]	810 [557]	FS60
Pickup truck (PU) 2300 [5070]	50 [30]	45.0-60.0 [28.0-37.9]	222 [164]	PU30
	65 [40]	60.1-75.0 [38.0-46.9]	375 [273]	PU40
	80 [50]	75.1-90.0 [47.0-56.9]	568 [426]	PU50
	100 [60]	90.1- above [57.0-above]	887 [613]	PU60
Standard Test Truck (M) 6800 [15 000]	50 [30]	45.0-60.0 [28.0-37.9]	656 [451]	M30
11 800-14 970 [26 000-33 000]	65 [40]	60.1-75.0 [38.0-46.9]	1110 [802]	M40
	80 [50]	75.1-above [47.0-above]	1680 [1250]	M50
Class 7 Cabover (C7) 7200 [15873]	50 [30]	45.0-60.0 [28.0-37.9]	673 [497]	C730
11 800-14 970 [26 000-33 000]	65 [40]	60.1-75.0 [38.0-46.9]	1199 [884]	C740
	80 [50]	75.1-above [47.0-above]	1872 [1381]	C750
Heavy goods vehicle (H) 29 500 [65 000]	50 [30]	45.0-60.0 [28.0-37.9]	2850 [1950]	H30
27 000 [60 000	65 [40]	60.1-75.0 [38.0-46.9]	4810 [3470]	H40
	80 [50]	75.1-above [47.0-above]	7280 [5430]	H50

Table 2-1 - Impact Condition Designations (ASTM 2015)

Designation	Dynamic Penetration Rating
P1	≤1 m [3.3 ft]
P2	1.01 to 7 m [3.31 to 23.0 ft]
P3	7.01 to 30 m [23.1 to 98.4 ft]

Table 2-2 - Penetration Ratings (ASTM 2015)

2.2 Similar Products

Shallow mount bollard systems have a short base, reducing the amount of excavation needed, while still providing adequate protection. Below are descriptions of shallow mount bollard designs that are currently available.

APEX Fabrication & Design, INC. sells an M30/P1 rated shallow-mount security bollard that has the option for removable bollards. This rating was given based on the standardized test (Table 2-1 above) carried out and the system's resultant performance rating (Table 2-2 above). The design consists of steel bollards connected to steel W-flange beams embedded in concrete, as shown in Figure 2-1. The advantages of this product is that the bollards and beams are sold as units so the customer can make this barrier as wide as they want to. Also, the removable bollard option allows the barrier to be temporary or permanent (APEX 2016).

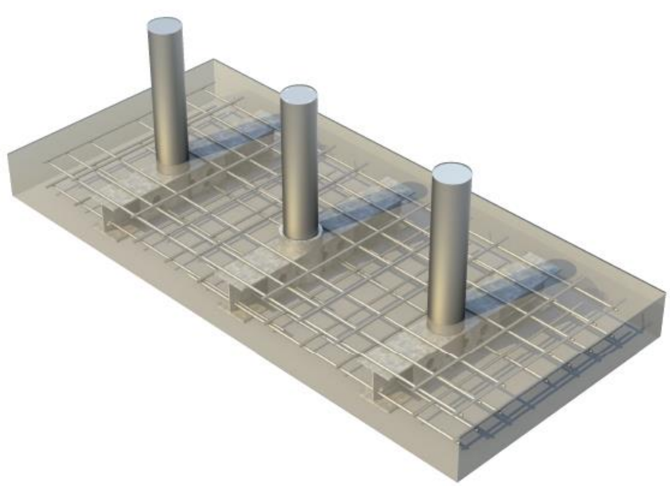

Figure 2-1 - APEX SFB-M30 / SRB-M30 Shallow Bollard Isometric View (APEX 2016)

Calpipe Security Bollards sells an M30/P1 (Table 2-1/Table 2-2) rated fixed shallow-mount bollard. Their design has the bollard connected to two steel W-shapes providing a wider base for the unit. The drawings can be seen in Figure 2-2. Another advantage to this product is that the customer can order any number of units and install them on any spacing (Calpipe 2016).

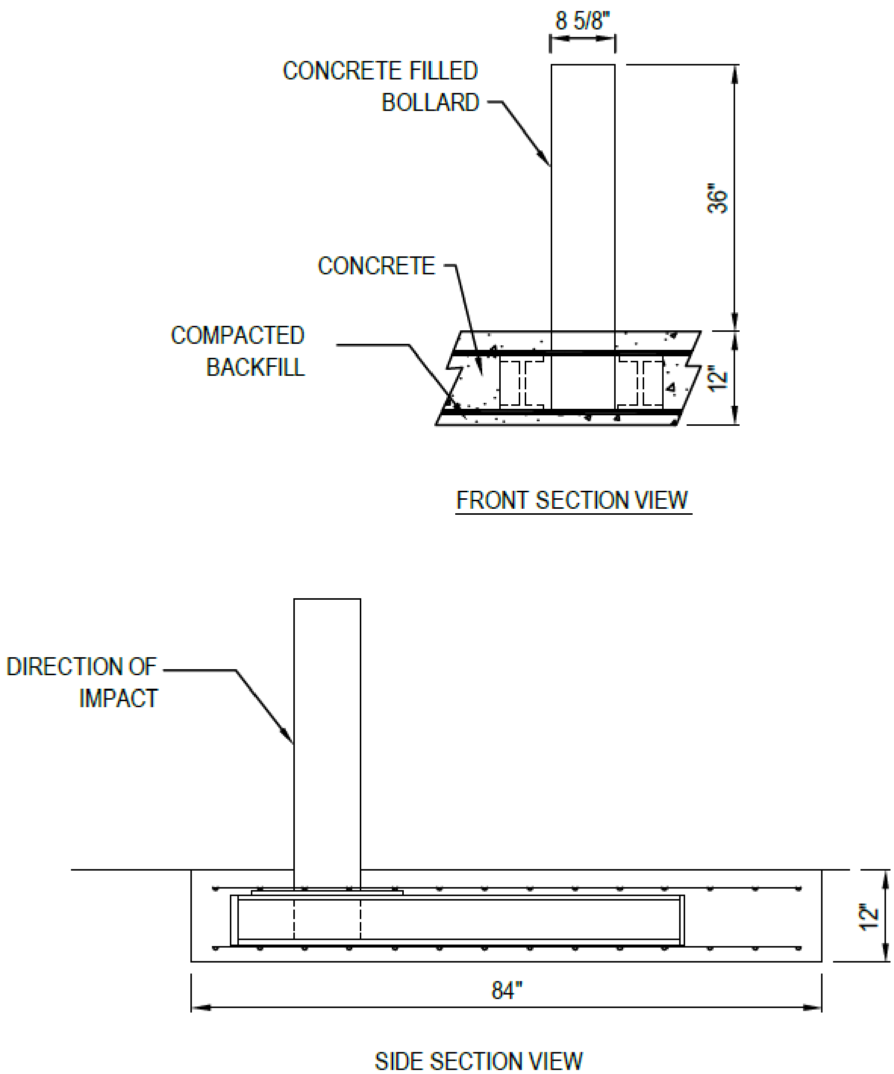

Figure 2-2 - Calpipe Fixed Shallow Mount Bollard (Calpipe 2016)

Ameristar Security Products sells an M50/P1 (Table 2-1/Table 2-2) rated shallow-mount bollard. The system consists of a series of prefabricated units where the bollard is connected to either a T shaped or straight shaped steel base. An example of the T-shaped unit is shown in Figure 2-3. The advantages of this unit include the sturdier M50 rating, the ease of assembling the units and the elimination of concrete reinforcing steel. However, this design also requires a concrete pour and is a permanent fixture (AMERISTAR 2014).

Figure 2-3 - Ameristar Shallow Mount Anti-Ram Bollard T-Shaped Unit (AMERISTAR 2014)

EL-GO Team Security Systems developed a bollard security barrier that allows for curvature. It consists of a series of modular units connected by arms bolted to the units. Each unit is made up of a welded steel frame with two bollards connected to it, as shown in Figure 2-4. The advantages of this design are that the units can achieve any curvature desired. In addition, the units have a removable bollard option so the barrier can be temporary (EL-GO 2012).

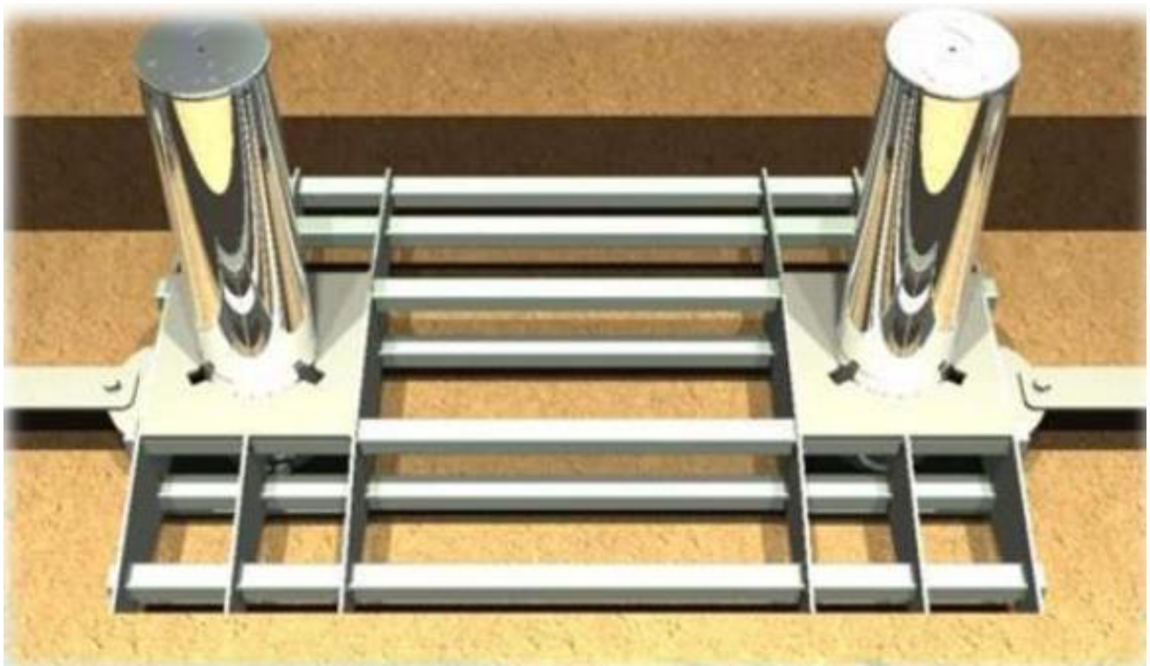

Figure 2-4 - EL-GO Team Shallow Mount Bollard Artist Rendering (EL-GO 2012)

These existing designs, offer many different sets of dimensions and configurations for further exploration. They demonstrate it is possible to create a shallow mount security bollard that is M50/P1 (Table 2-1/Table 2-2) rated provided that it is strong enough. They also show that curvature can be accomodated. These products provide good information for the design of the new bollard system developed in this study.

2.3 Finite Element Modeling

In the past, designing security barriers was an expensive trial and error process. Engineers would create a design based on simplified mathematical models, build their design and then test it. After the test they would change the design based on its performance and retest the new design. This cycle would continue until the engineers obtained the performance they sought, budgetary constraints ended the revision process. Today, finite element modeling (FEM) is used extensively to predict the behavior of complex dynamic systems at a fraction of the cost of full scale crash testing. This section reviews and discusses how FEM simulation has been used to design different vehicle impact systems.

In 2007, the journal *Engineering Failure Analysis* published a paper by M. Borovinšek, comparing the results of FEM simulations with real crash test results to justify the use of computer simulation in the process of developing roadside safety barriers. Comparisons were made between two sets of results using two different methods. The first method was by visual comparison where snapshots of the simulation and photos of the test were compared for similarity (see Figure 2-5). The second method was by comparing numerical results from both tests. To do this, an accelerometer was placed inside the test vehicle in both the real and simulated tests. The accelerations in three principle directions were recorded and combined into a dimensionless parameter, named the Acceleration Severity Index (ASI). The results from the second method are shown in the graph below Figure 2-6). The paper concluded that FEM simulations using LS-DYNA was an acceptable method for developing roadside safety systems because the maximum ASI parameter for the simulation was within a 10% margin of error (Borovinšek, Vesenjak et al. 2007).

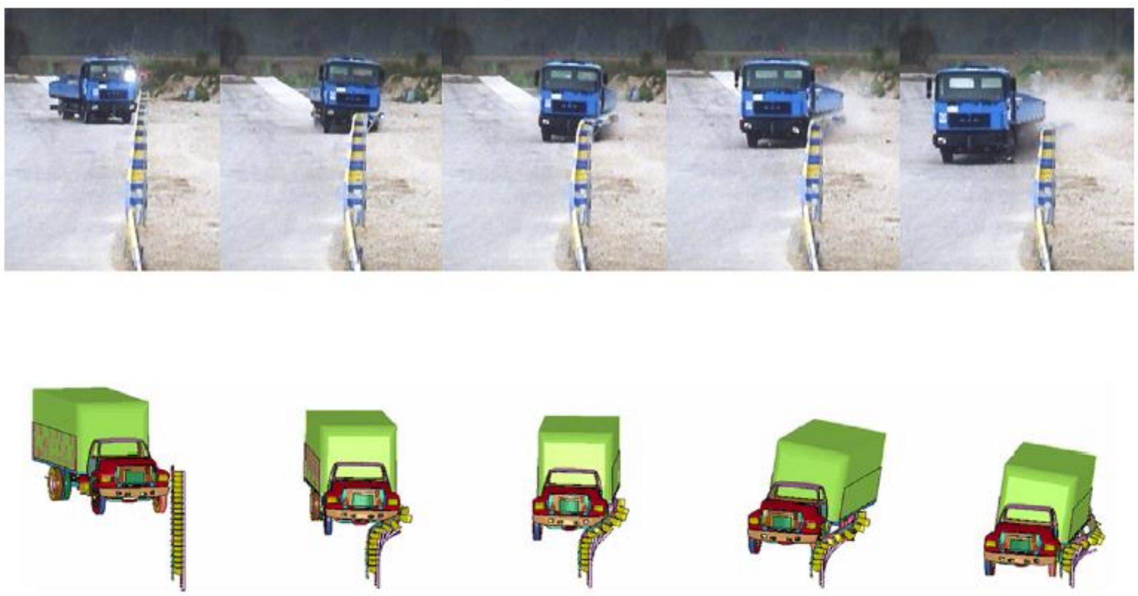

Figure 2-5 - Visual Comparison of Test Results (Borovinšek, Vesenjak et al. 2007)

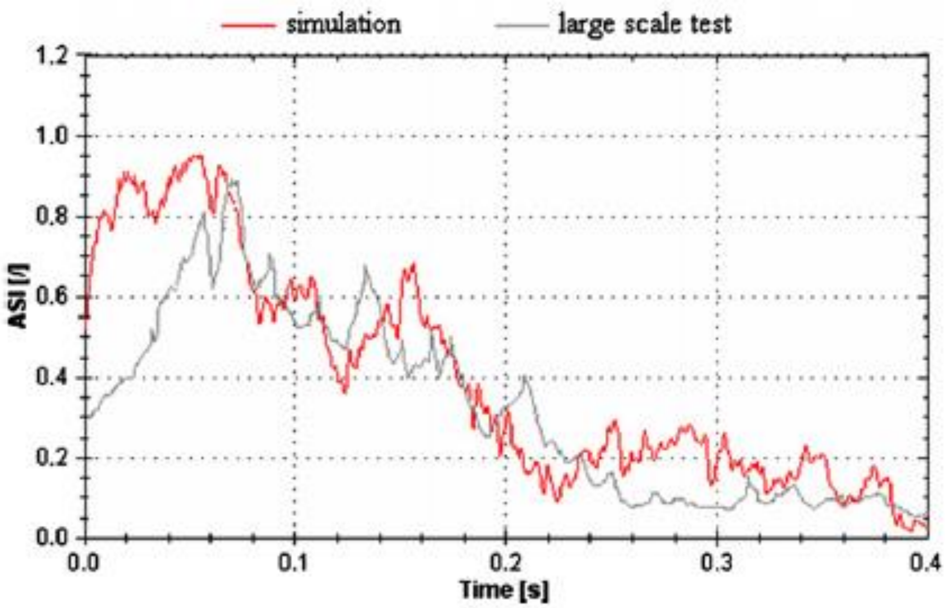

Figure 2-6 - Calculated ASI Parameter over Time (Borovinšek, Vesenjak et al. 2007)

In 2014, a presentation was made by D. Marzougui for the International LS-DYNA Users Conference comparing. The simulated vehicles used were created and verified by the National Crash Analysis Center. The barrier was modeled using rigid shell elements in the shape of the real barrier, assuming that the concrete wouldn't deform or deflect under crash conditions. Three different verification methods were used for the simulations. The first method was a visual comparison between the crash tests and the models. The second was a comparison of the measurements of the roll, pitch, and yaw calculations as shown in Figure 2-7. This was done to make sure the model vehicle behaved similarly to the real vehicle in the crash test. The third verification method used was to look at the energy calculations of the simulations and verify their accuracy. An example of the data output is shown in Figure 2-8. The presentation concluded that there was good correlation between the simulation data and measurements from the crash test. It also concluded that the use of LS_DYNA for FEM simulations is a valid way to predict the outcome of crash tests crash tests, and simulations for two different vehicles impacting a concrete barrier (Marzougui, Kan et al. 2014).

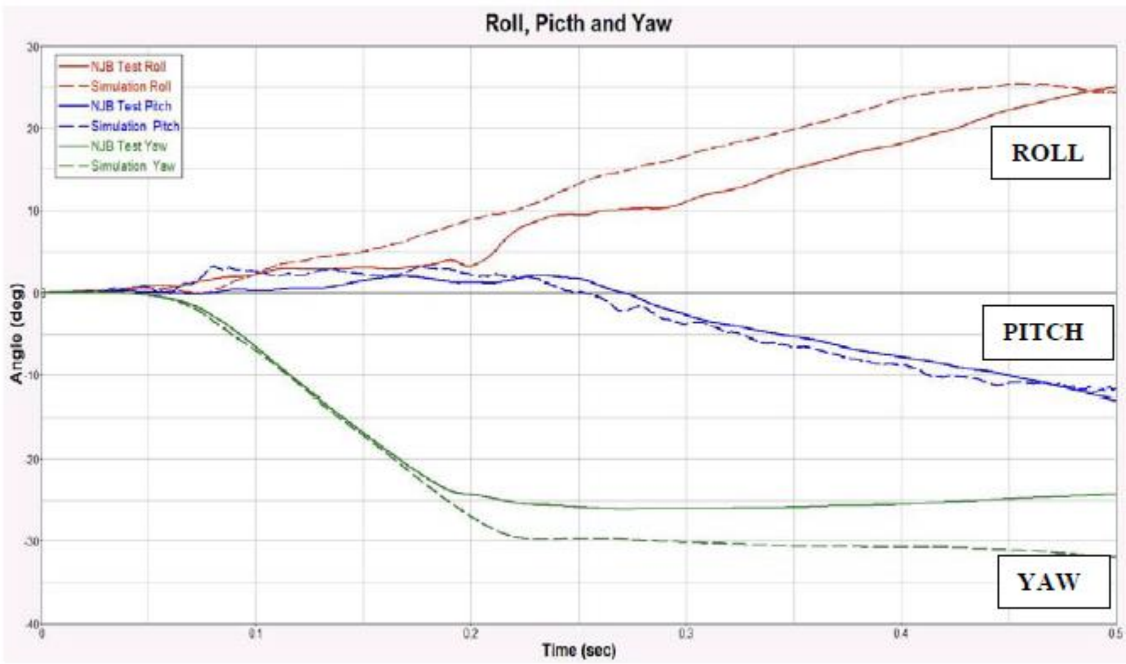

Figure 2-7 - Example Comparison of Roll, Pitch, and Yaw Measurements (Marzougui, Kan et al. 2014)

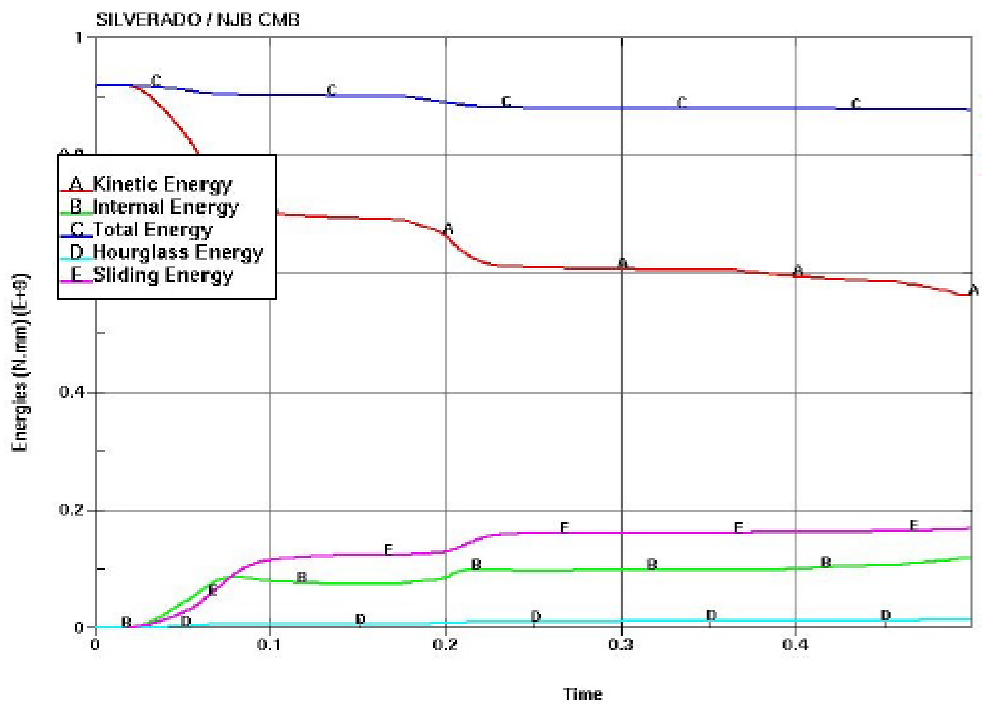

Figure 2-8 - Example LS_DYNA Energy History Output (Marzougui, Kan et al. 2014)

Finally, Hasan Mohammed had a paper published in the KSCE Journal of Civil Engineering about simulation assessment of a concrete barrier design. The purpose of the model was to determine whether the barrier would absorb the impact, and not necessarily to see if the concrete would fail. For this reason, the barrier was modeled as rigid concrete with piecewise linear plastic steel bars. The vehicle model used in this paper was also from the National Crash Analysis Center. The comparison between the simulation and the crash test included a visual comparison and an analytical comparison. The visual comparison in this paper was identical to the ones performed in the two previous papers. The analytical evaluation compared the horizontal accelerations in two principle directions between the model and the real test. This comparison can be viewed in Figure 2-9. Mohammed's paper also concluded the LS-DYNA simulations provide a good estimate of the behavior of a vehicle under crash conditions, and can provide a cursory prediction of a barrier's performance against standard criteria (Mohammed and Zain 2016).

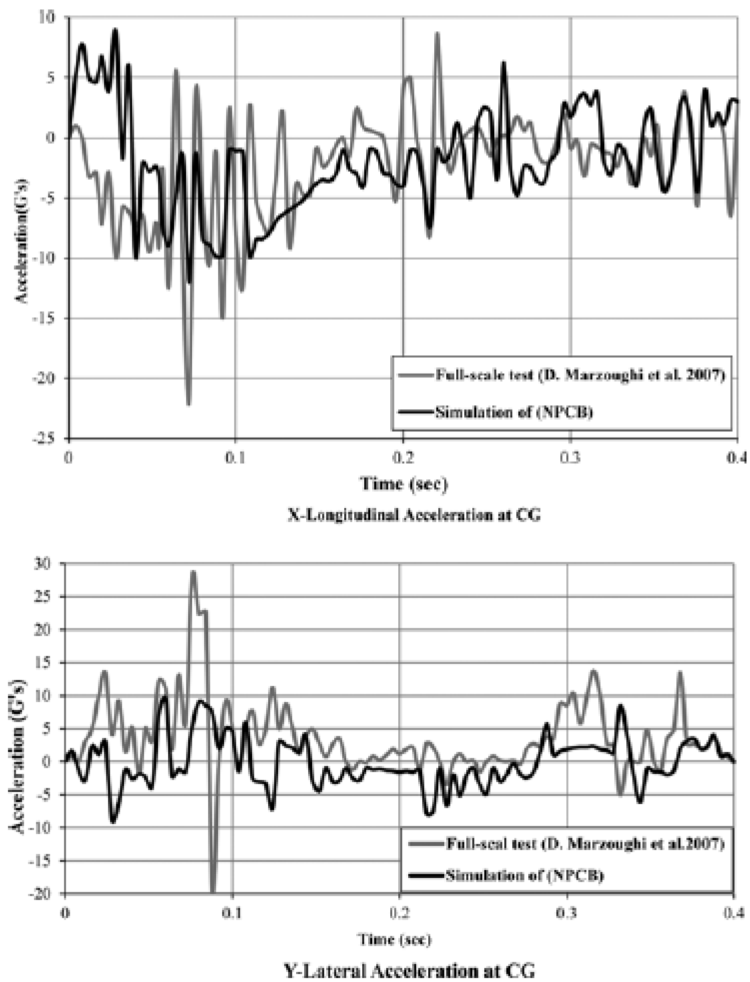

Figure 2-9 - Acceleration Comparison (Mohammed and Zain 2016)

Based on these three papers, it was concluded that FEM simulations using LS-DYNA are a valid means to predict behavior of the system under development in this study. However, care is needed in the construction of the barrier model to ensure that its behavior correctly reflects the events in a real crash test. It is also known that, a good vehicle model will be key to analyzing performance against standard criteria. Finally, any product resulting from this design must be subjected to a full scale crash test before it can be formally rated and offered as a commercial product

3 EARLY MODEL DEVELOPMENT

The FEM simulations for the study and design for this security bollard system were built from scratch. Before testing could begin on how the different parameters would affect the performance of the system, several models were generated to verify the accuracy of the parts of the units. This section describes the evolution of the model so that it could be used with confidence in testing the large scale parameters of the bollard system.

The first models were created to produce a bollard model that is strong enough to resist the impact of a heavy vehicle moving at high speeds. The bollard was modeled as a cylindrical shell made of an elastic steel material. The dimensions of the bollard were made similar to those systems studied in the literature review. To verify if the bollard was modeled correctly, an impact simulation was needed. For this purpose, a rigid steel box was created and given an initial velocity to impact the bollard. The dimensions of the box were 3’-3”x3’-3”x2’ and the velocity set at 20mph. The box was constrained so that it would only move in the direction of impact. The setup is shown in Figure 3-1.

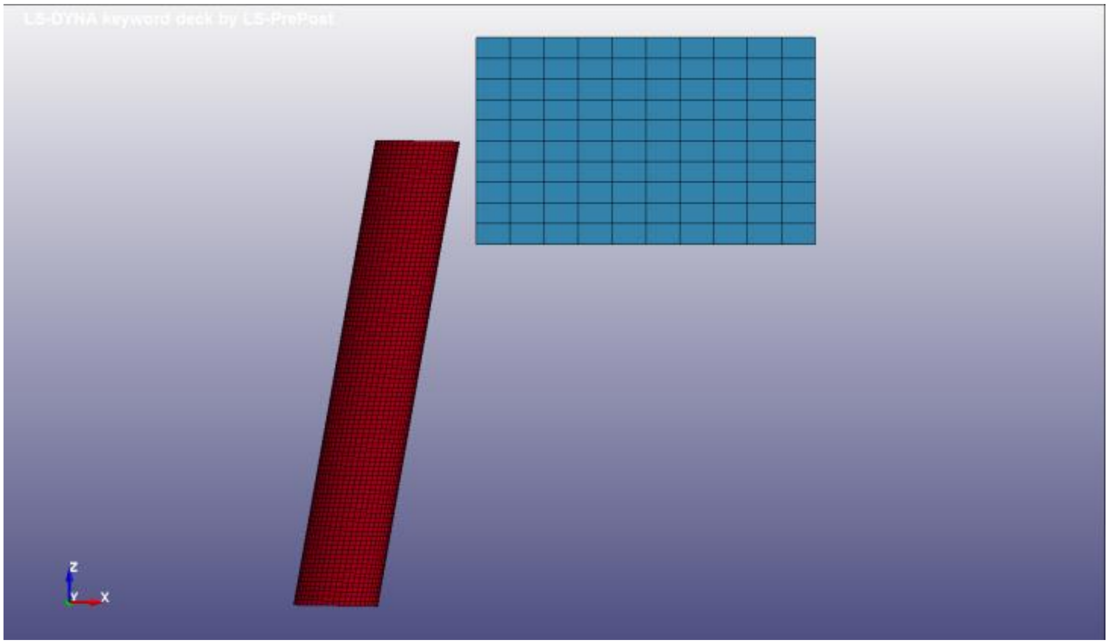

Figure 3-1 - Steel Box Impacting Bollard

With the bollard model verified, the next step was to create a simple model to simulate the vehicle impact without using a full vehicle model. This allowed the initial data to be acquired for the units without the computational expense of using a full vehicle model. This surrogate vehicle model consisted of the same size box with a plate connected to it with springs (See Figure 3-2).

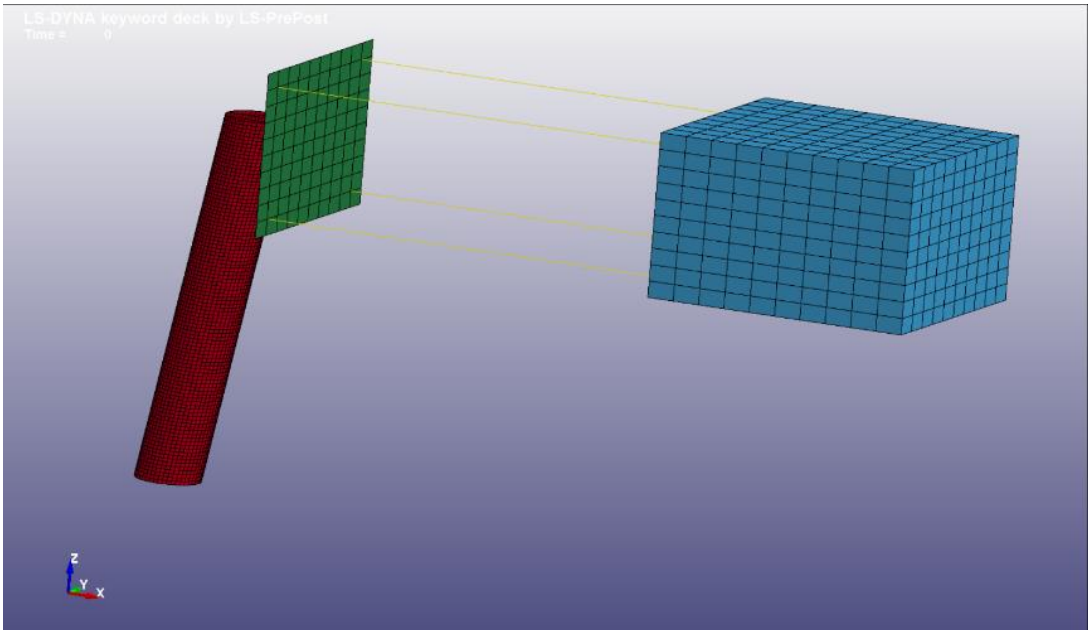

Figure 3-2 - Basic Crash Vehicle Model Impacting Bollard

The weight and initial velocity of the block was adjusted to meet ASTM Standard F 2656-07 Table 2-1, Condition Designation M50. The spring stiffness was adjusted to give a compression in the spring similar to that of the crushing distance of real vehicles. It was also adjusted to give a force on the bollard similar to the impact of a real crash.

The stiffness of the springs was found using the test data from the TTI report “DOS K12 Testing and Evaluation of the Shallow-Mount Bollards” through the energy method (Alberson and Menges 2007). The assumption was made that all of the kinetic energy of the mass would be put into the potential energy for the spring, leading to the equation:

$$\frac{1}{2} * m * v^2 = \frac{1}{2} * k * x^2$$

where:

m = the mass of the vehicle (14940lbm)

v = the velocity of the vehicle just before impact (50mph)

x = the crush of the exterior of the vehicle (60")

k = the stiffness of the spring model

The equation was solved and divided by the number of springs being modeled. The final stiffness for the four springs modeled was found to be 2.06k/in each. The springs were modeled as nonlinear so that they would remain compressed after impact, mimicking the behavior of a real vehicle during impact. This was done so that they would better simulate a crashing vehicle. The error between the model and the real test was 24.6% and 0.8% for the peak force and crushing distance respectively. As this was created to be a simplified crash model these errors were deemed reasonable for testing.

The next step in the model development was to estimate the size needed to model the foundation for the bollard. The same block-spring-plate was used to simulate impact. The ground was added into the model as a large rigid plate. The foundation was placed on top of the ground with static and dynamic friction values of 0.3 and 0.15 respectively. The foundation was modeled as elastic concrete with the density including a 20% steel ratio. The dimensions of the foundation were changed to keep it from overturning, or gaining excessive velocity when the simplified truck model came to a stop. For these tests it was assumed that the upper limit on the foundation's displacement was 3'-3". The controlling factor was the velocity of the foundation, and the upper limit of the velocity was determined by using the following equation:

$$\int v * dv = \int a * dx$$

where:

v = the velocity of the foundation (taken from model)

a = the acceleration needed to stop the foundation within the given distance

x = the displacement the foundation moves (upper limit is 3'-3")

From the model, the velocity of the foundation after the vehicle model stopped moving was 7.61ft/s which would require a deceleration of 8.83ft/s^2 to stop it in 3'-3". By comparing this deceleration to the acceleration due to gravity, the coefficient of friction required to provide this deceleration of the foundation was calculated to be 0.274. The mass of the foundation in the model that produced these results was 131 780 lbm. The dimensions of the model were based on five 15'x4'x2' modular foundations rigidly connected on their long sides. The final model used for this test can be seen in Figure 3-3.

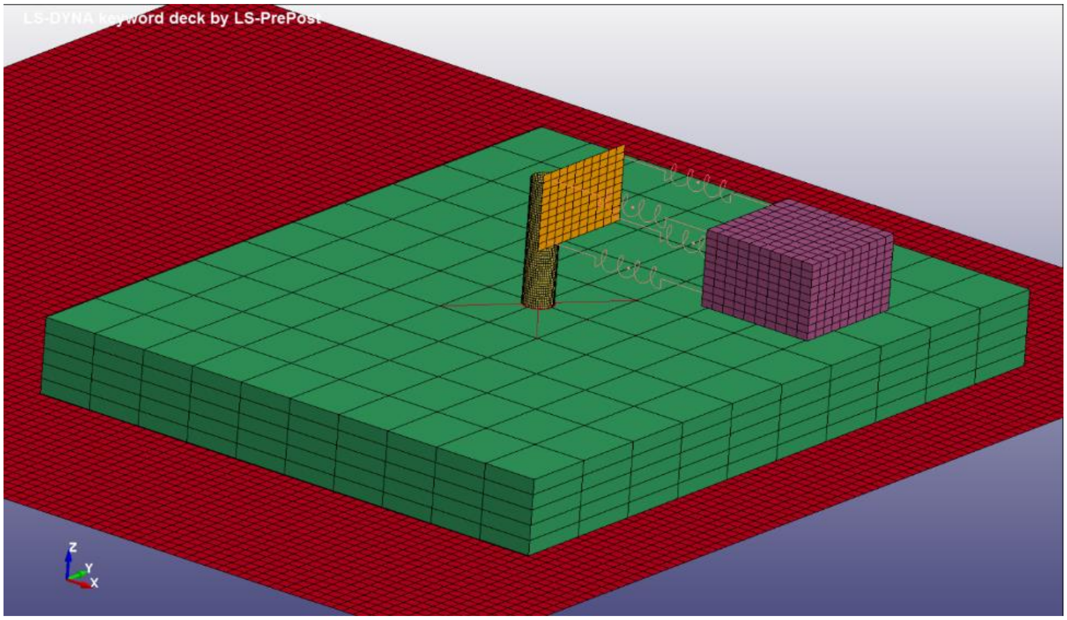

Figure 3-3 - Foundation Mass Simulation

The next model created was to estimate the approximate forces that the connections would need to take. The foundations were modeled as elastic concrete with 20% steel reinforcement for mass. The weight of the base of the units was 22 kips each. They were 10'-10"x4'x2' and were rigidly connected by 2" long, 2" diameter piecewise linear plastic steel rods. Seven foundations were modeled and connected with the bollard rigidly attached at the base to the center foundation. The model is shown in Figure 3-4, with the resulting forces shown in Table 3-1.

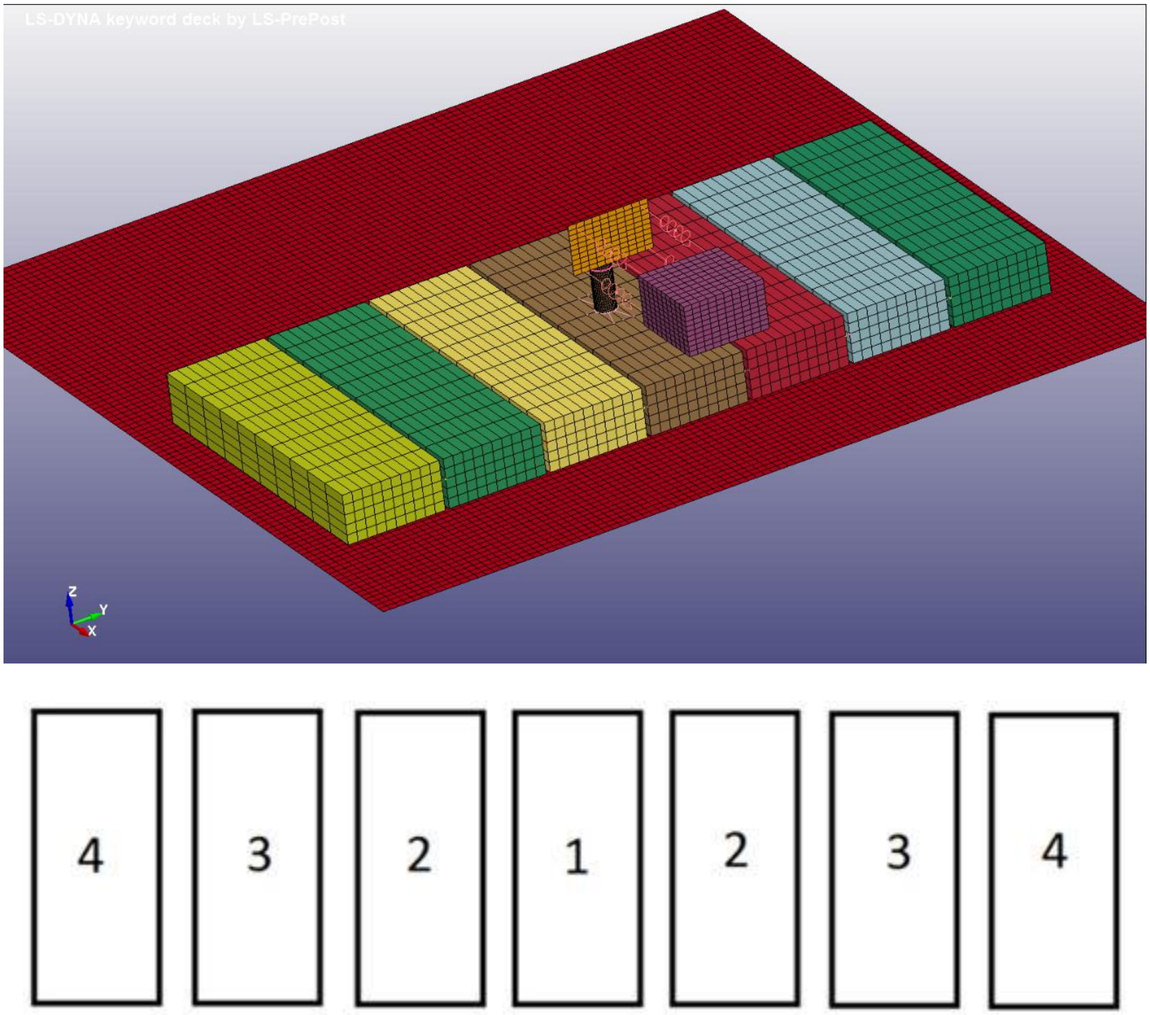

Figure 3-4 - Unit Foundations (top) with Numbering Scheme (Bottom) for Shear Forces

A	B	Shear (k)
1	2	102.96
2	3	135.34
3	4	157.14

Table 3-1 - Shear Forces Between Units

With this last simulation, the model was deemed sufficiently developed to start performing parametric tests. The model was divided into modular units with the approximate size and weight that would be required to meet the penetration requirements. Also, these units were connected together in a way that allows the forces between the units to be extracted for study. This model was used to examine how large scale parameters would affect the performance of the bollard system as a whole.

4 TESTING FOR INITIAL DESIGN

The large scale parameters considered in the initial testing included unit shape, and curvature. These parameters significantly affected the design for the unit, but don’t require much detail to evaluate unit response. That is why these simulations were performed so early in the design process and why the base of the unit could be a simple box. What follows describes how each of these large scale parameters were tested and the resulting data.

4.1 Unit Shape versus Interunit Forces

These tests were designed to study how the unit shape affected the forces connecting the units. They were performed to optimize the shape of the unit for the design of the connection forces. The models for all of these tests were created to have the same total weight of 22 kips so the displacement of the units and the energy dissipation of the impact would be the same across all tests. The density of the base remained constant for all tests so an equivalent mass was achieved by all of the units having the same volume. Also, the vehicle model had the same mass and velocity across all tests. The data collected from each of these tests was the axial and shear forces in the steel connectors. There were a total of five models created and run, one with rectangular foundations, two with triangular foundations, and two with trapezoidal foundations.

The first test that was completed was the rectangular unit test. The units were 10’-10”x4’x2’ and because of their symmetry only one test was needed for this shape. The model configuration and unit numbering scheme are shown in Figure 4-1. The peak forces of the simulation are shown in Table 4-1.

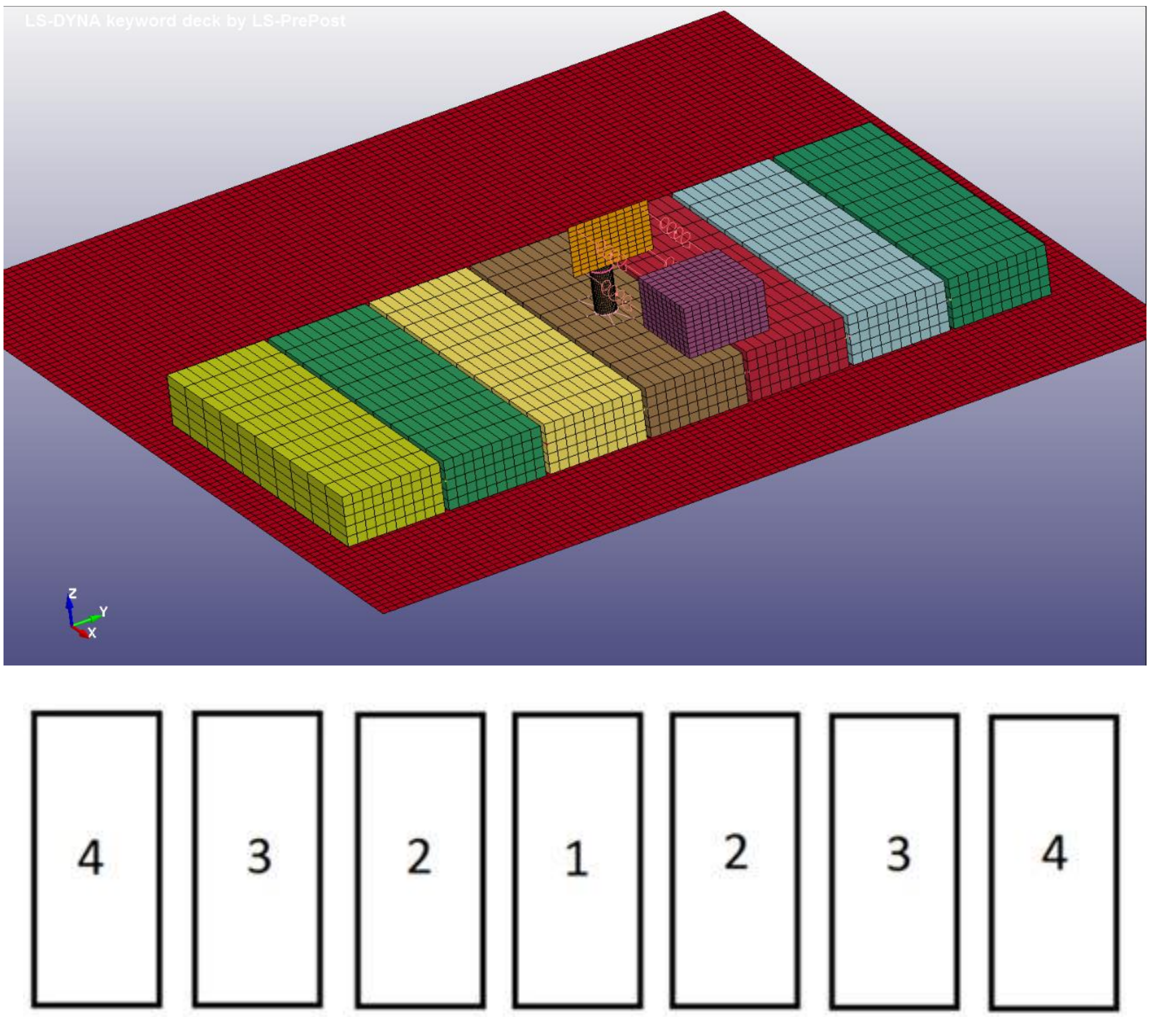

Figure 4-1 - Rectangular Units (Top) with Numbering Scheme (Bottom) for Interunit Forces

A	B	Shear Force (k)	Normal Force (k)
1	2	69.69	-40.24
2	3	135.56	48.56
3	4	75.31	-28.33

Table 4-1 - Interunit Forces for Rectangular Units

Next the triangular units were tested. They were modeled as isosceles triangles with a base of 8’ and a length of 10’-10”. This resulted in the same volume as the rectangular units and thus the same mass. The units were oriented so that the system as a whole would remain straight, and because of this the mass distribution of the units was not symmetric. To circumvent this problem, two tests were run, one in each direction, and the forces collected. The two tests’ orientations and numbering schemes are shown in Figure 4-2 and Figure 4-3, with their results reported in Table 4-2 and Table 4-3.

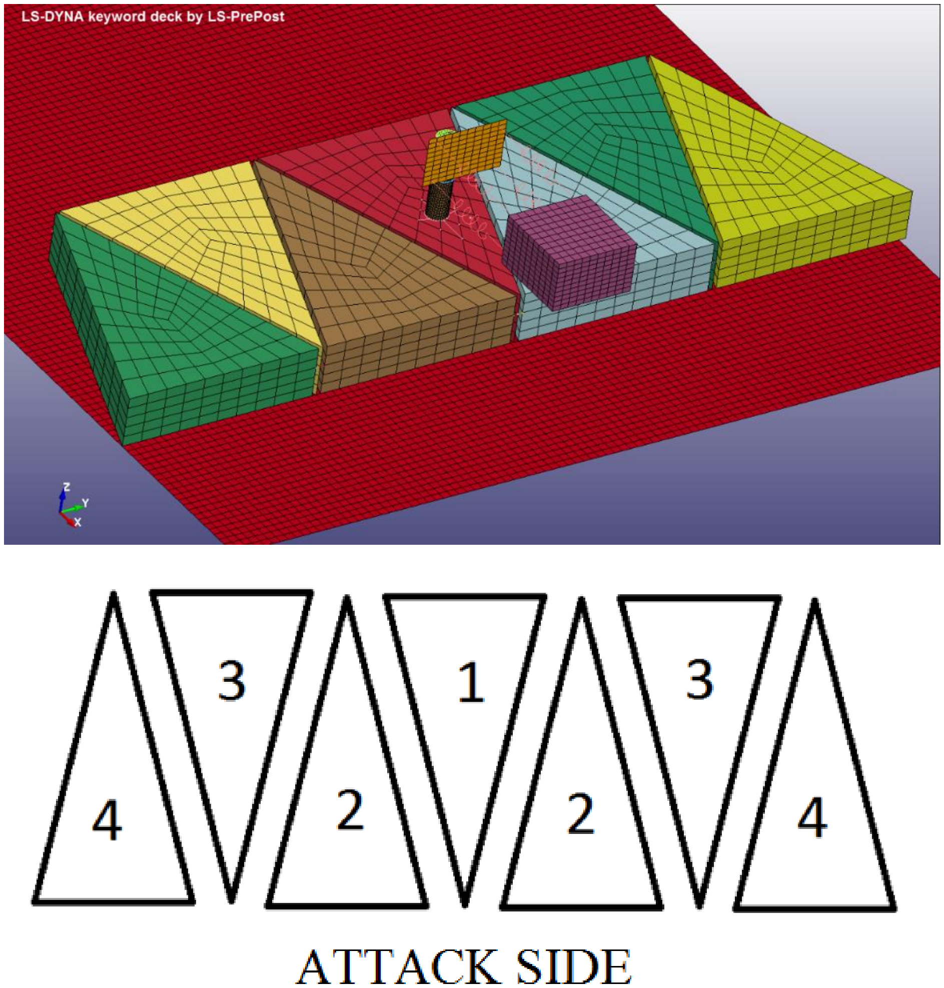

Figure 4-2 - Triangular Units Configuration 1 (Top) with Numbering Scheme (Bottom) for Interunit Forces

A	B	Shear (k)	Normal (k)
1	2	153.55	-258.53
2	3	160.74	-142.53
3	4	74.41	-80.71

Table 4-2 - Interunit Forces for Triangular Units Configuration 1

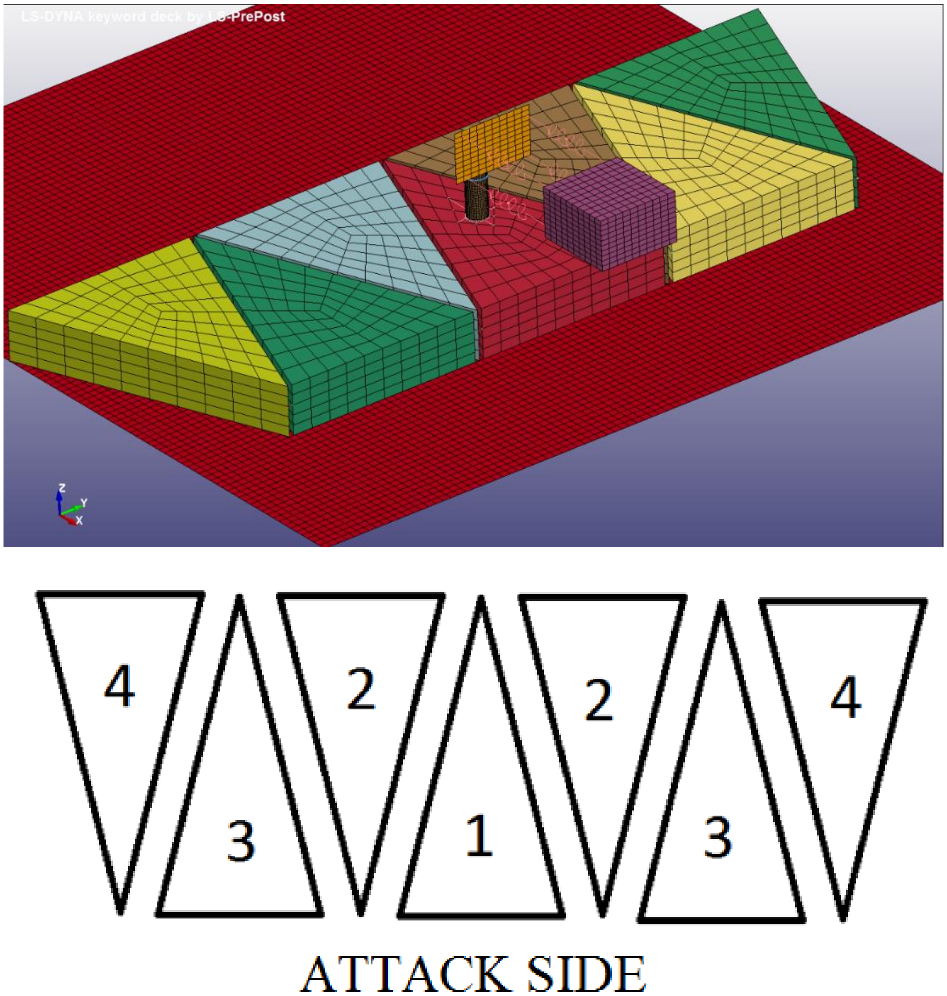

Figure 4-3 - Triangular Units Configuration 2 (Top) with Numbering Scheme (Bottom) for Interunit Forces

A	B	Shear (k)	Normal (k)
1	2	197.61	-249.54
2	3	119.15	-233.80
3	4	79.81	63.62

Table 4-3 - Interunit Forces for Triangular Units Configuration 2

Finally, the trapezoidal unit tests were performed. The foundations were modeled as isosceles trapezoids, with a short end of 2', a long end of 6' and a length of 10’-10”. The volume and mass of these units match those of the triangular and rectangular units. The units were oriented so that the system as a whole would remain straight, and as a result the mass distribution of the units was asymmetric similar to the triangular units. Two tests were run for this unit shape as well, one in each direction, and the forces compared to the rest of the tests. The two tests’ orientations and numbering schemes are shown in Figure 4-4and Figure 4-5, with their results in Table 4-4 and Table 4-5.

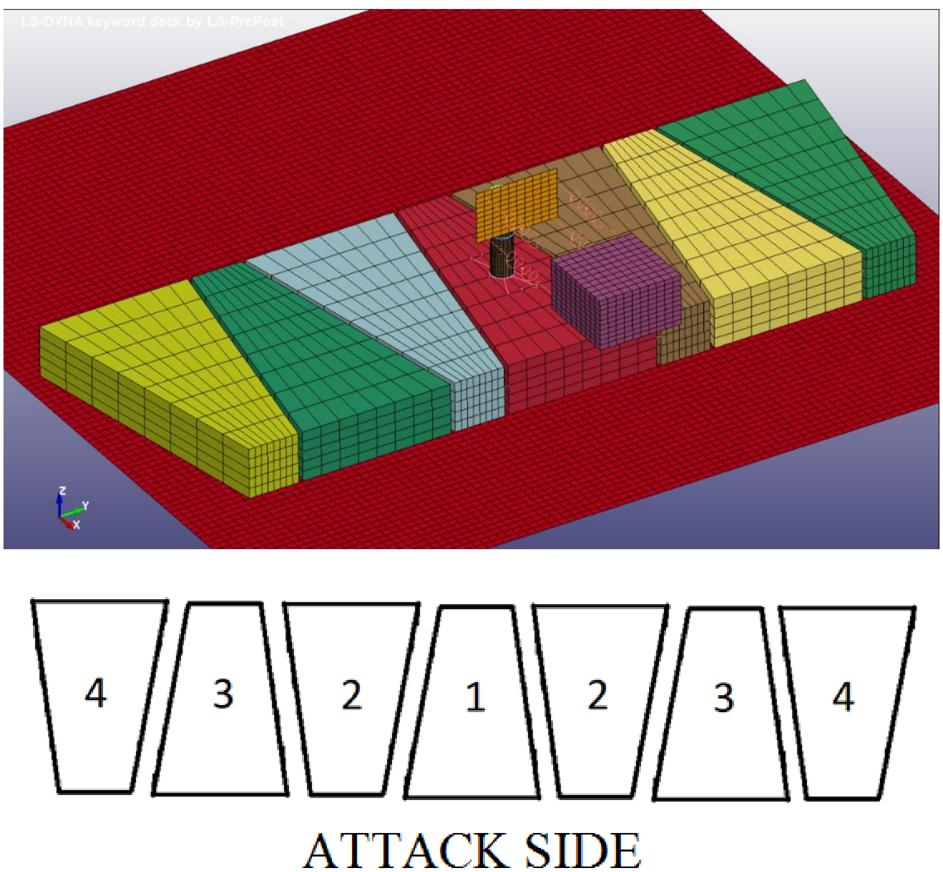

Figure 4-4 - Trapezoidal Units Configuration 1 (Top) with Numbering Scheme (Bottom) for Interunit Forces

A	B	Shear (k)	Normal (k)
1	2	194.46	-42.04
2	3	139.38	82.51
3	4	79.81	-27.43

Table 4-4 - Interunit Forces for Trapezoidal Units Configuration 1

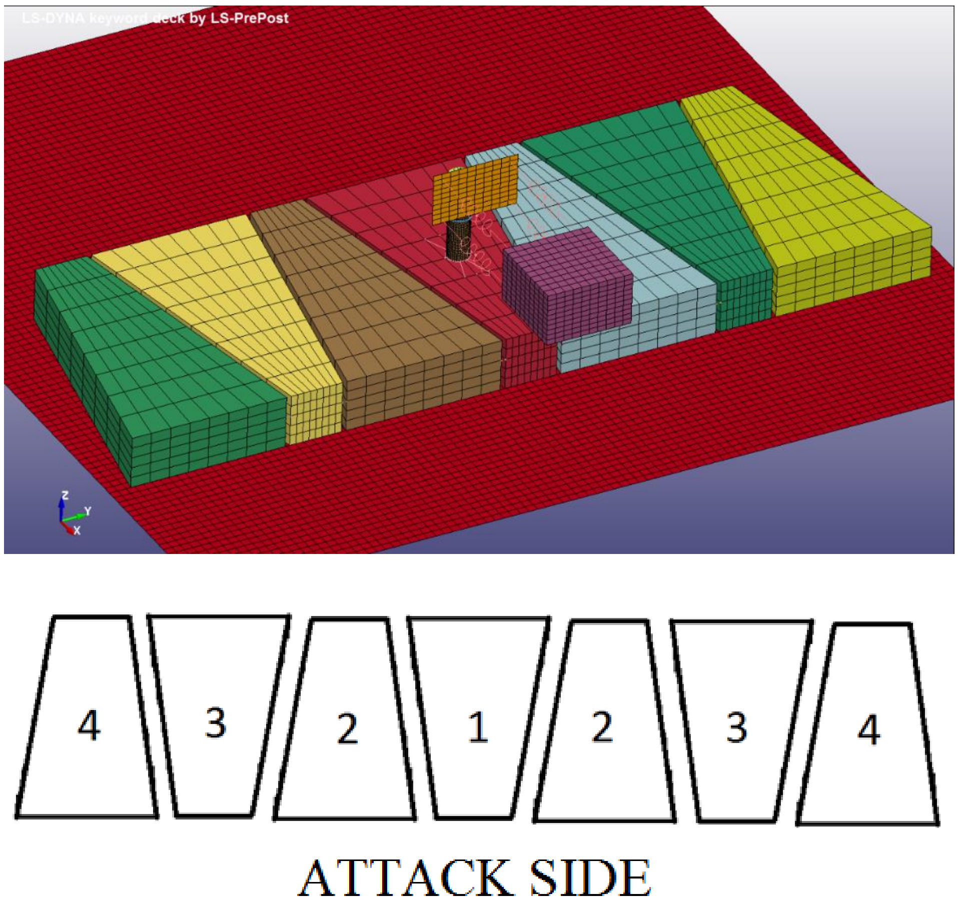

Figure 4-5 - Trapezoidal Units Configuration 2 (Top) with Numbering Scheme (Bottom) for Interunit Forces

A	B	Shear (k)	Normal (k)
1	2	189.74	-81.61
2	3	126.57	-87.23
3	4	89.47	-37.54

Table 4-5 - Interunit Forces for Trapezoidal Units Configuration 2

It was observed that the rectangular units resulted in the lowest shear and normal forces. This was likely a result of the shear plane of the connections being parallel to the direction of impact. As the angle between the shear plane of the connections and the direction of impact increases there is more interaction between the shear and axial forces of the connections. This can be seen in the increase in force from the rectangular to the trapezoidal to the triangular units. From these results, it was decided that the base of the units would be rectangular in shape.

4.2 Curvature versus Interunit Forces

The next set of concept models explored how the foundations interacted when configured for horizontal and vertical curvature. To achieve the desired curvatures the units were modeled as trapezoids. Each curve had a unique trapezoidal unit model that was tailored specifically to meet that curve. However the mass of all of the units remained the same. The unit numbering scheme is shown in Figure 4-6.

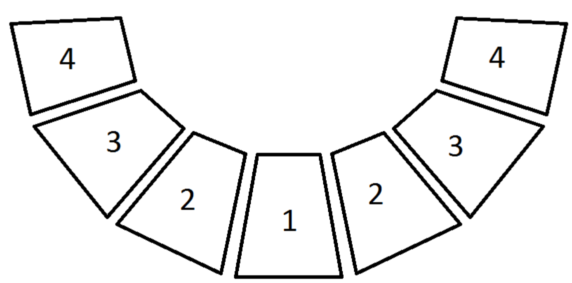

Figure 4-6 – Curvature Configuration Numbering Scheme

The curvatures used were from the American Association of State Highway and Transportation Officials' (AASHTO) Manual for Assessing Safety Hardware (MASH). For the horizontal curvature, curves for created for 30mph and 50mph, for elevations of 4% and 6% each. The units were tapered in the direction of the impact to the proper angle for the curve, and then rotated so that each side was parallel with the side of the unit adjacent to it. The curve radii for the horizontal curvature were 250', 926', 231', and 833' (American 2009). The bollards of the system lined up with these curve radii and were impacted by the simple vehicle crash model. Each horizontal curve underwent two tests, one with the vehicle model impacting the units toward the center of curvature (COC) and one away from the COC. Plan views of the model configurations are shown in Figure 4-7 and Figure 4-8. The peak forces in the connections of the units are displayed in Table 4-6.

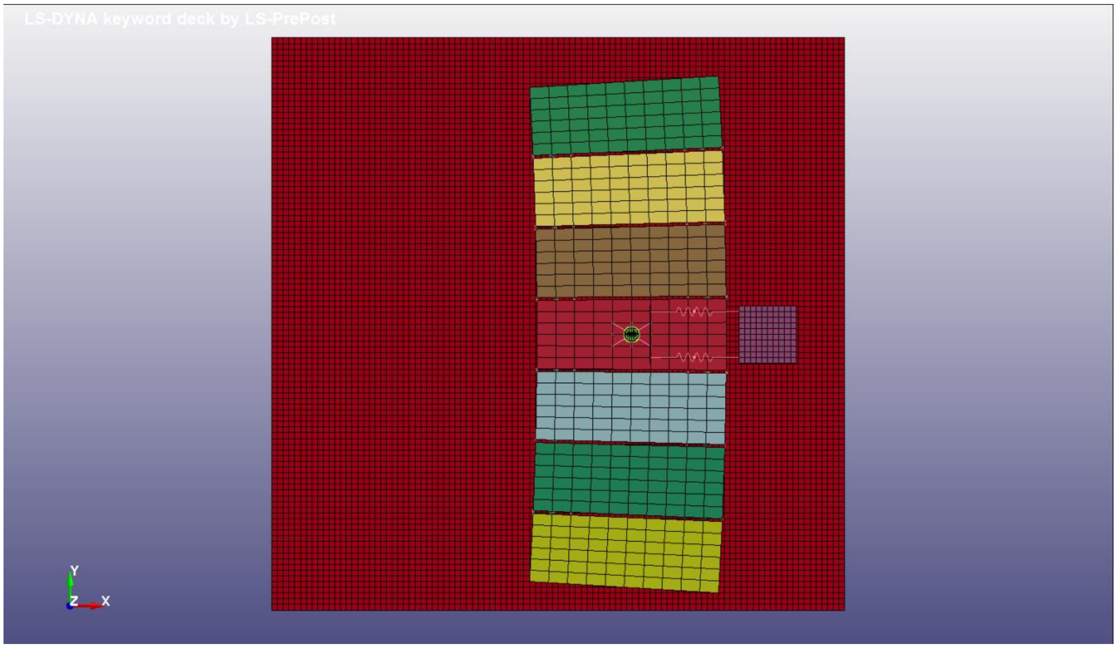

Figure 4-7 - Horizontally Curved Units Impact towards the COC

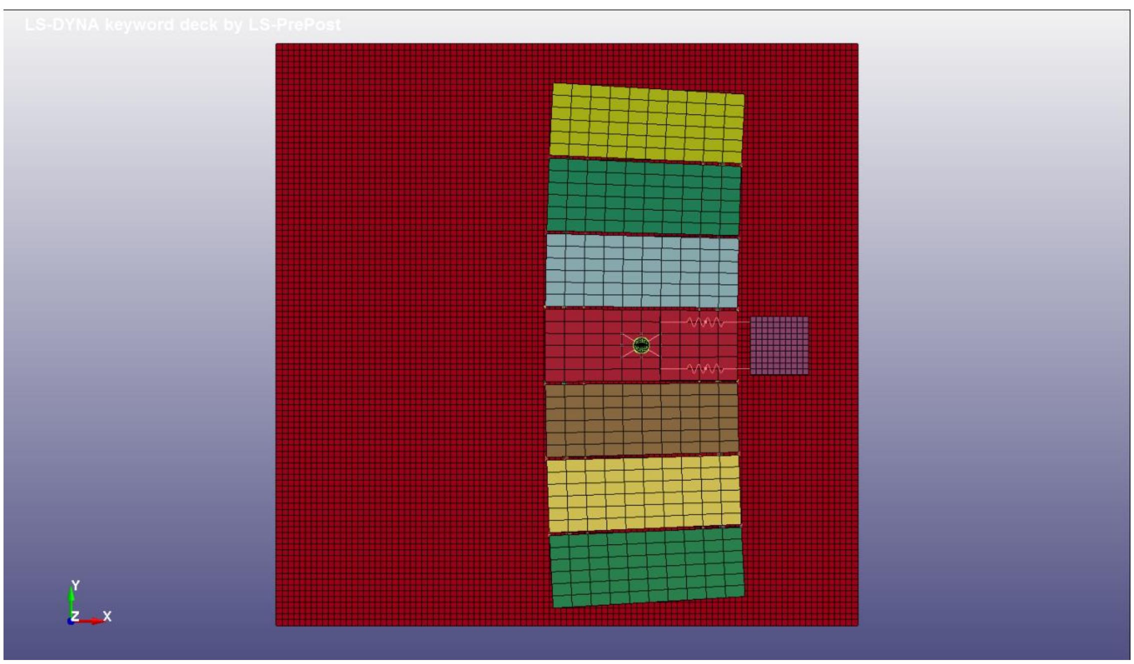

Figure 4-8 - Horizontally Curved Units Impact away from the COC

Horizontal Curvature					
A	B	4% elevation, 30mph, 250ft radius			
		Toward the COC		Away from the COC	
		Shear Force (k)	Normal Force (k)	Shear Force (k)	Normal Force (k)
1	2	116.46	36.65	117.81	32.37
2	3	80.94	-69.92	80.04	53.73
3	4	52.61	61.38	64.52	-39.79
A	B	4% elevation, 50mph, 926ft radius			
		Toward the COC		Away from the COC	
		Shear Force (k)	Normal Force (k)	Shear Force (k)	Normal Force (k)
1	2	183.23	-26.53	187.50	66.10
2	3	125.00	-31.03	133.09	15.78
3	4	73.29	-11.08	66.55	18.64
A	B	6% elevation, 30mph, 231ft radius			
		Toward the COC		Away from the COC	
		Shear Force (k)	Normal Force (k)	Shear Force (k)	Normal Force (k)
1	2	118.26	46.31	118.26	87.90
2	3	79.36	-49.01	81.16	71.49
3	4	56.43	71.04	65.20	52.83
A	B	6% elevation, 50mph, 833ft radius			
		Toward the COC		Away from the COC	
		Shear Force (k)	Normal Force (k)	Shear Force (k)	Normal Force (k)
1	2	205.49	27.43	204.36	15.18
2	3	131.07	14.66	130.40	-17.49
3	4	88.35	19.11	88.80	-24.28

Table 4-6 - Interunit Forces for Horizontal Curve Configurations

For vertical curvature, curves were created for passing distance, stopping sight, and sag, each for 30mph and 50mph. The curvature for the models were achieved by tapering the units in the vertical direction to the proper angle for the curve. The units were then rotated so that each side was parallel with the side of the unit adjacent to it. The model configuration for the passing distance and stopping sight cases can be seen in Figure 4-9 with the peak forces in the connections of the units are displayed in Table 4-7.

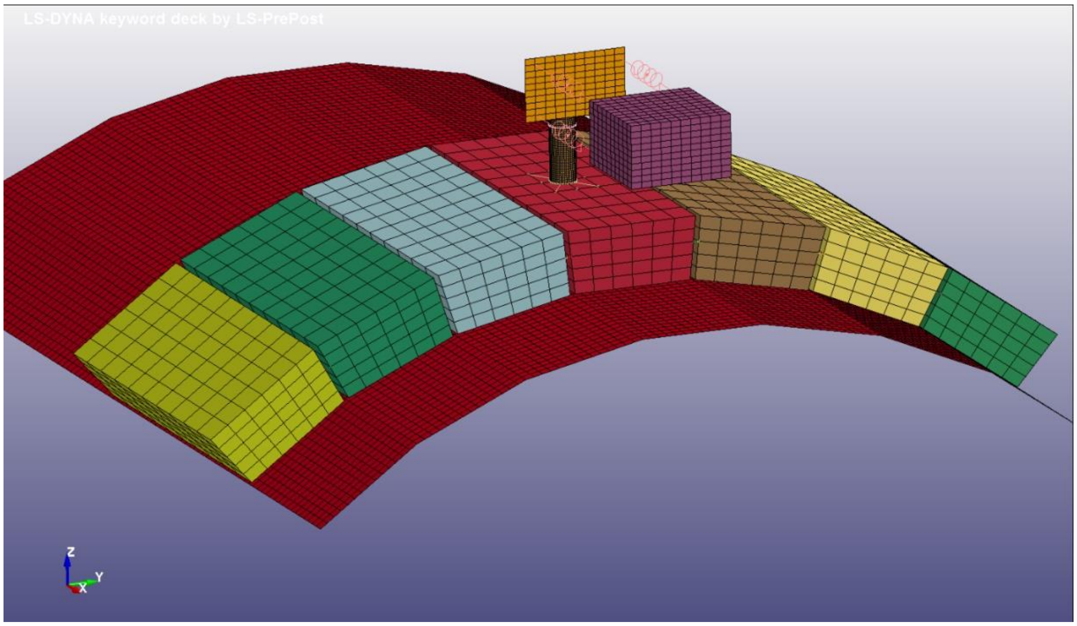

Figure 4-9 - Vertically Curved Units – Passing Distance and Stopping Sight

Vertical Curvature					
A	B	Passing Distance			
		30mph		50mph	
		Shear (N)	Normal (N)	Shear (N)	Normal (N)
1	2	116.23	46.54	19.33	-23.61
2	3	93.30	41.37	144.56	21.04
3	4	55.98	62.28	86.33	16.88
A	B	Stopping Sight			
		30mph		50mph	
		Shear (N)	Normal (N)	Shear (N)	Normal (N)
1	2	114.88	74.64	210.88	33.95
2	3	75.99	46.76	152.65	13.11
3	4	36.65	26.30	83.63	22.48

Table 4-7 - Interunit Forces for Vertically Curved Units - Passing Distance and Stopping Sight

The model configuration for the sag case is shown in Figure 4-10 with the peak forces in the connections of the units are displayed in Table 4-8.

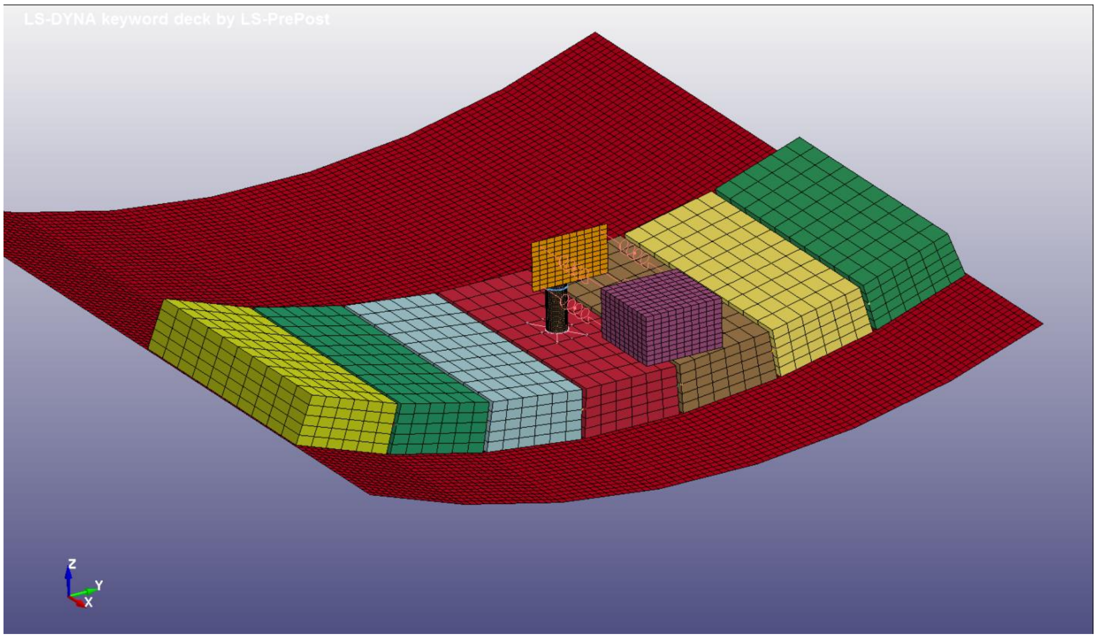

Figure 4-10 - Vertically Curved Units - Sag

A	B	Sag			
		30mph		50mph	
		Shear (N)	Normal (N)	Shear (N)	Normal (N)
1	2	117.81	-85.66	196.27	22.28
2	3	80.49	70.37	131.74	14.21
3	4	57.78	-55.53	84.53	14.12

Table 4-8 - Interunit Forces for Vertically Curved Units - Sag

The purpose of these tests was to determine if there was any relationship between the curvature of the units and the interunit forces. The results show in the horizontal direction the larger curve radii have larger connection forces, and the curvature in the vertical had relatively no affect. From this it was concluded that the worst case for the connection design was when the units were in a straight line.

4.3 Initial Design

With these tests completed an initial design was proposed. From the unit shape tests it was decided that the units would be rectangular. The curvature tests showed that the straight configuration of the units was the worst case. A significant challenge for the initial design was keeping the units rectangular while still allowing for curvature. In addition, the units still need to be strong enough to stop a moving vehicle, while remaining flexible enough to curve. With the main impact forces being transferred from the bollard to the base unit, a large moment is created. Because of these issues, was decided the units would be given a flange type geometry. The base unit would be made up of large steel plates with two webs in the center. The plates on the top and bottom of the unit make it strong against moments, as well as allow for flexibility by having the plates of each unit overlap with the ones next to it. The two webs contain the bollard to the middle of the base and allow the base to be filled for additional mass. To allow for flexibility, the connections in the units would be slotted holes for the bolts. A drawing of the initial design is shown in Figure 4-11.

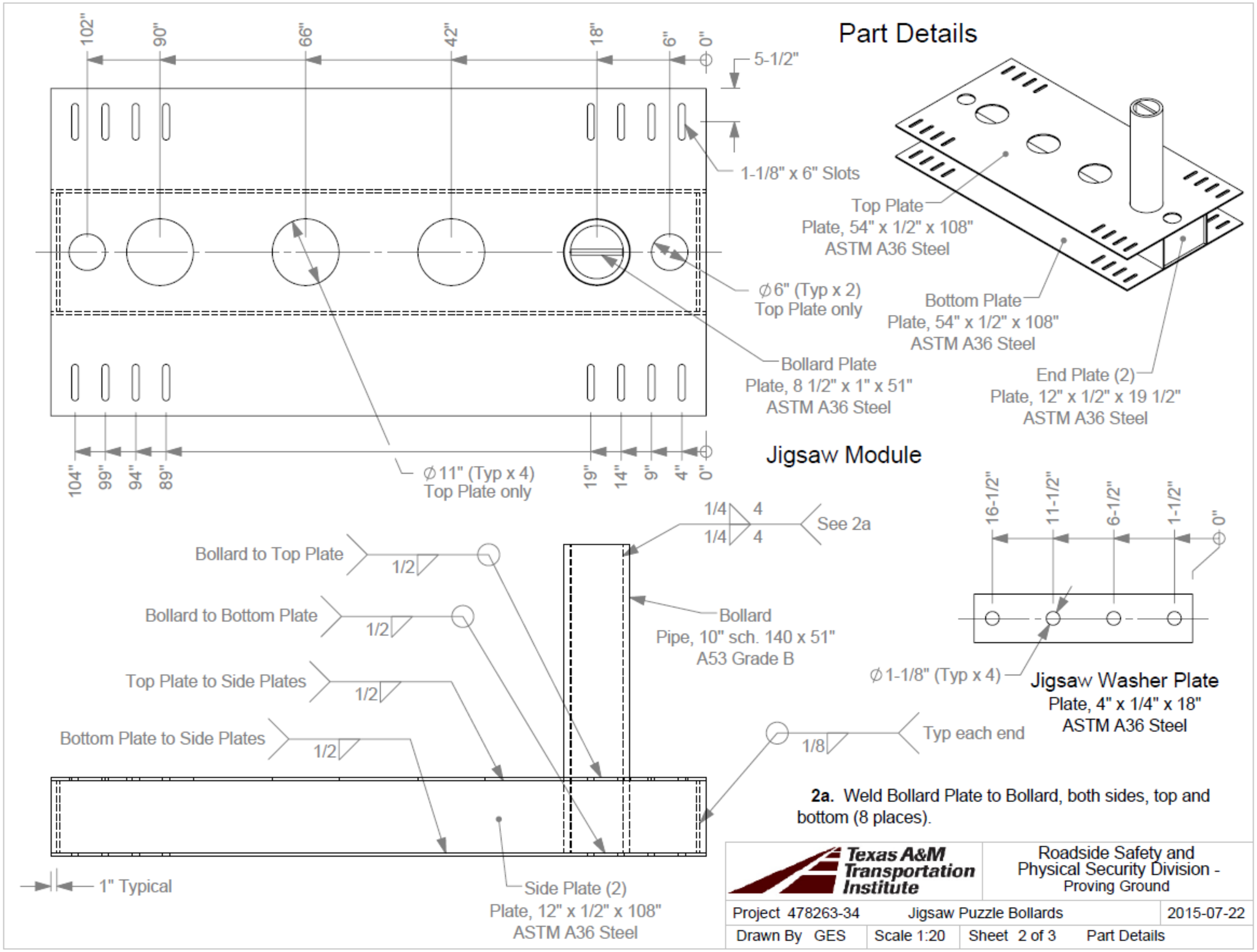

Figure 4-11 - Initial Design Details Drawing

5 UNIT DISPLACEMENT TESTS

With an initial design (Figure 4-11) in hand, another series of simulation tests were undertaken to examine the following issues: (i) system performance as the number of units increased, and (ii) the effects of curvature in the system on performance. The performance measure used in these was a comparison of displacement of the units caused by impact. To reduce the run time in these tests, each simulation was terminated before the units came to rest. Instead, the simulations were run until the units' velocities converged and the whole system was moving at the same speed. From there the total displacement was determined by adding the displacement of the units at the time of the converged velocities to the remaining stopping distance. The stopping distance was found using the equation:

$$x = \frac{v^2}{2g\mu} + x_0$$

where:

x = stopping distance

x_0 = unit displacement at velocity convergence

v = system velocity after convergence (taken from model)

g = gravitational acceleration (32.2ft/s)

μ = coefficient of friction

This equation is derived from the work energy theorem. Two different coefficients of friction, 0.4 and 0.7, were used in these simulations since they are reasonable bounds on typical field conditions. It was important not only to look at performance of the system as it lengthened but also as the friction value changed.

For this series of tests, revised versions of prior models were created. The new unit models were created to the dimensions of the initial design, but using shell elements for the steel plates and solid elements for concrete. The initial solid element bolt models resulted in runtime errors, so they were modeled using springs. The revised models provided more detailed information on the behavior of the system and its materials. To further enhance the quality of these simulations, a model of a single unit truck (SUT) validated by TTI was used to represent the conditions of the required ASTM standard test. This new model allowed the observation of the interaction between the bases of the units with the tires of the truck, as well as how the vehicle would crush on impact with the bollard. The modular unit model and SUT model are shown in Figure 5-1 and Figure 5-2 respectively.

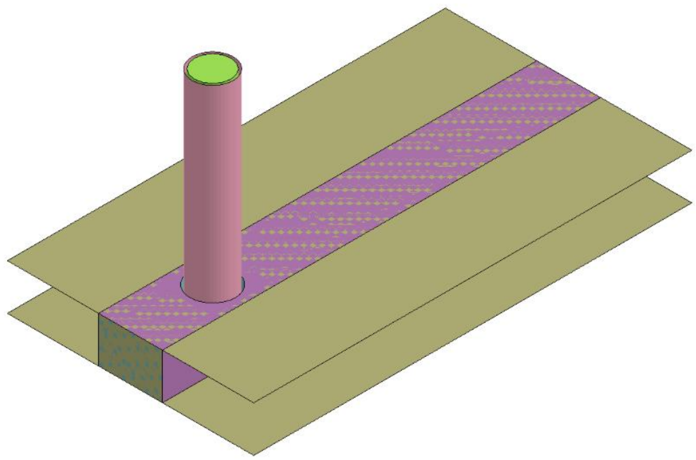

Figure 5-1 - Unit Model for Displacement Curve Testing

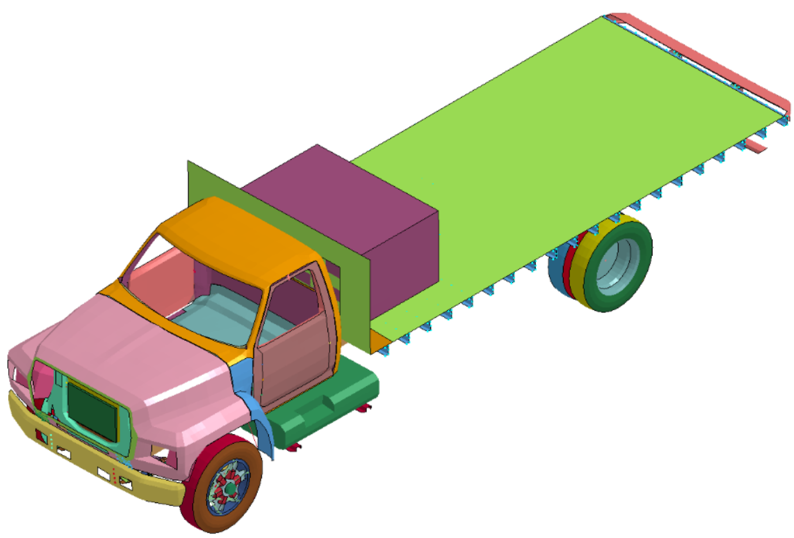

Figure 5-2 - SUT Model

5.1 Number of Units versus Displacement

The first round of tests in this series examined the number of units versus displacement for the extreme curvature cases considered, which included a horizontal curvature and two vertical curvature cases. Each case had 14 tests run, seven numbers of units each with the two different friction coefficients. The number of units tested began with three units and increased by two units with each new test. Testing started with the units oriented in a straight line, the results of which can be seen in Figure 5-3.

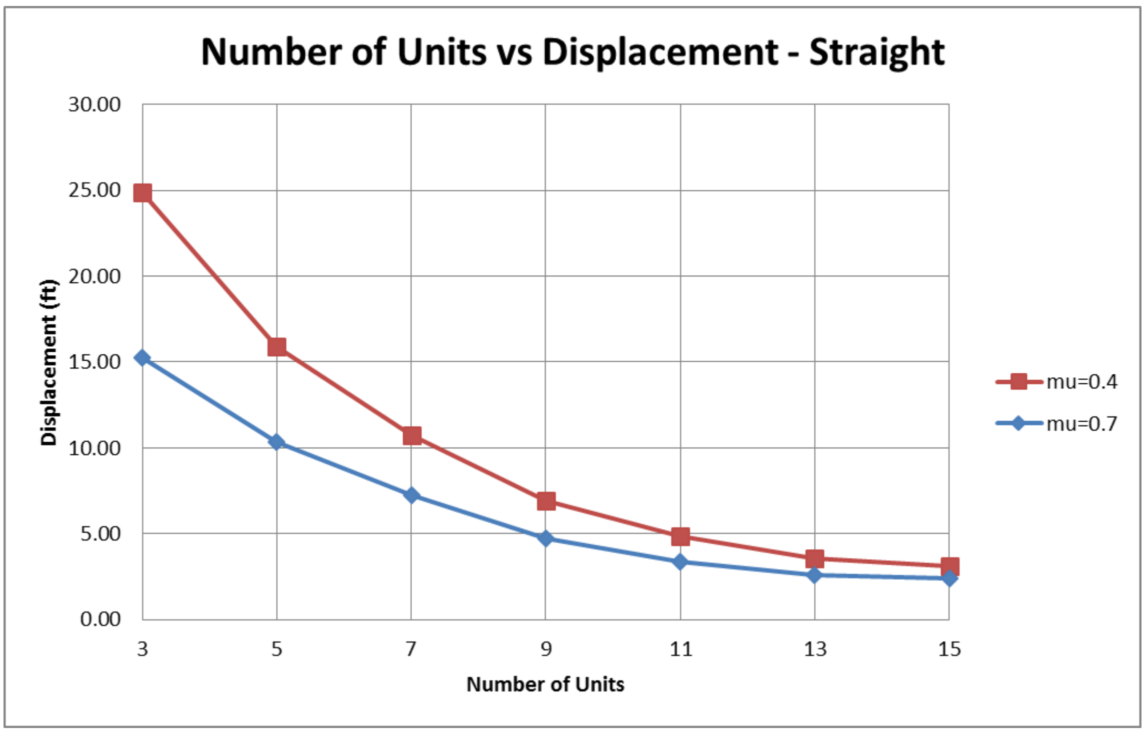

Figure 5-3 - Number of Units vs Displacement for Straight Configuration

The next condition examined was the extreme horizontal curvature. Each units was placed in such a way that it was angled 5° with respect to the units next to it. This created a curve with a radius of 45'-10". Only one impact direction was tested since the mass of the system and the interaction of the units were the only behavior being observed. It was believed the orientation of the units would not have had a significant impact on the results. The final curves are shown in Figure 5-4.

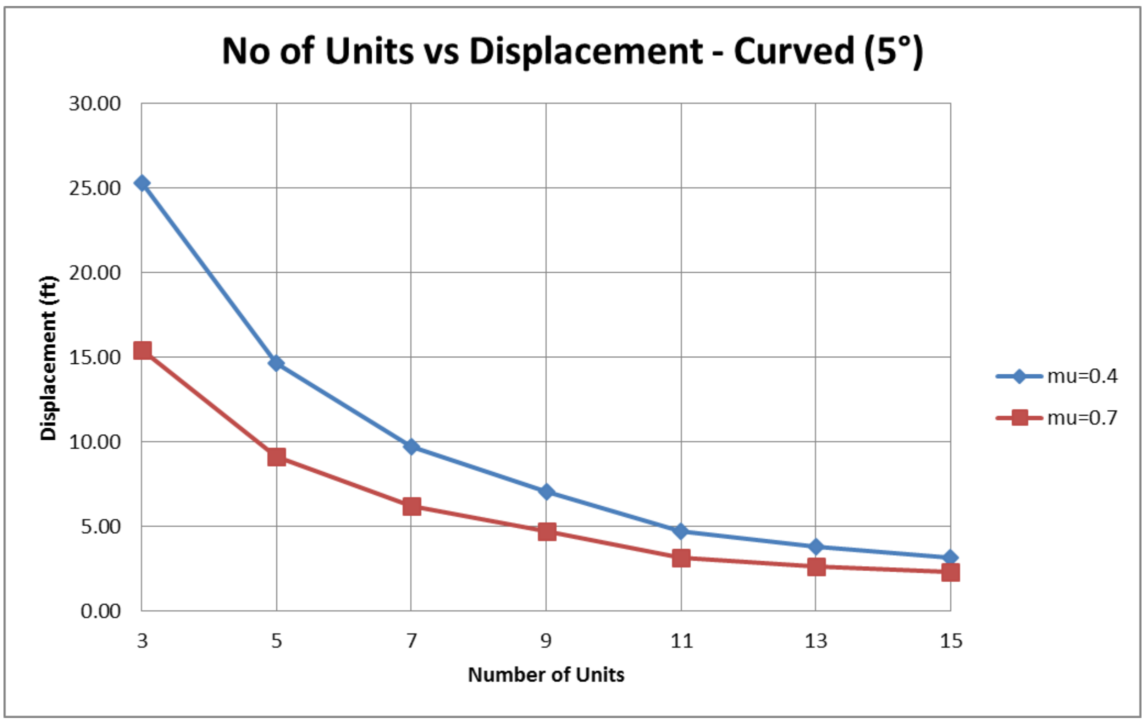

Figure 5-4 - Number of Units vs Displacement for 5° Curved Configuration

The next configuration examined was the vertical curvature of the units in a downward direction. The units for this test were modeled so that each unit was angled 6° in the vertical direction with respect to the ones next to it. This orientation was called the downward direction because the center point of the arc made up by the units is above the units. The results of these tests are shown in Figure 5-5.

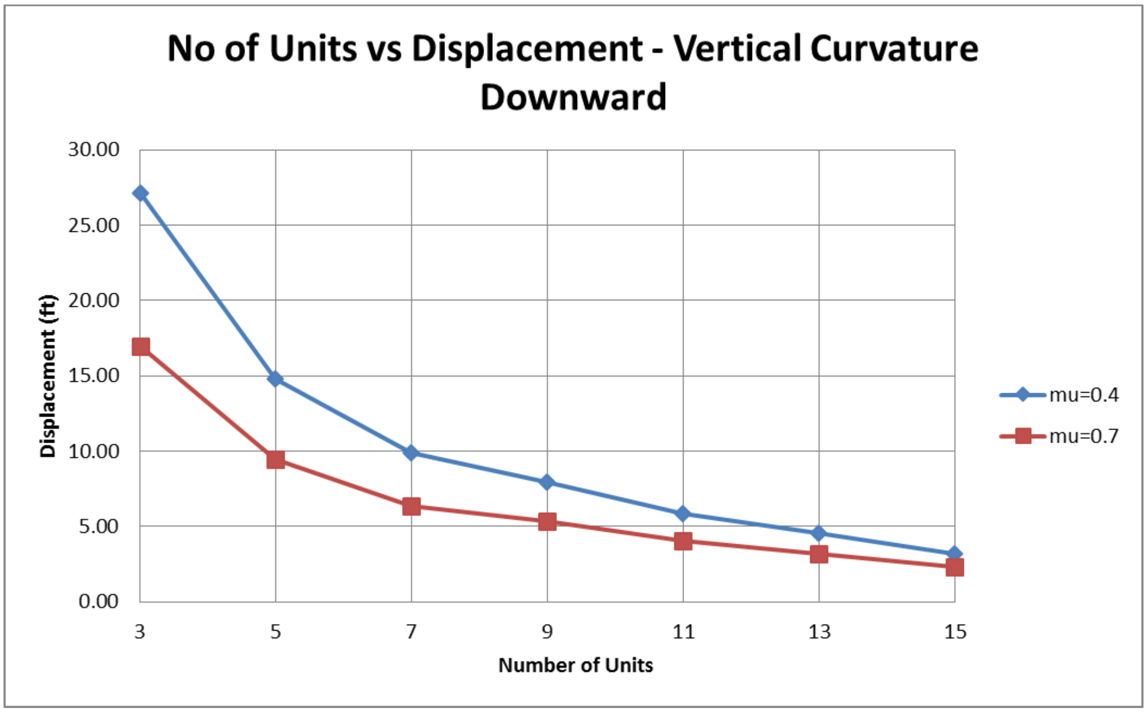

Figure 5-5 - Number of Units vs Displacement for Downward 6° Vertical Curvature

The last configuration examined was the vertical curvature of the units in an upward direction. The units for this test were modeled so that each unit was angled 6° in the vertical direction with respect to the ones next to it. This orientation was called the upward direction because the center point of the arc made up by the units is below the units. The results of these tests are shown in Figure 5-6.

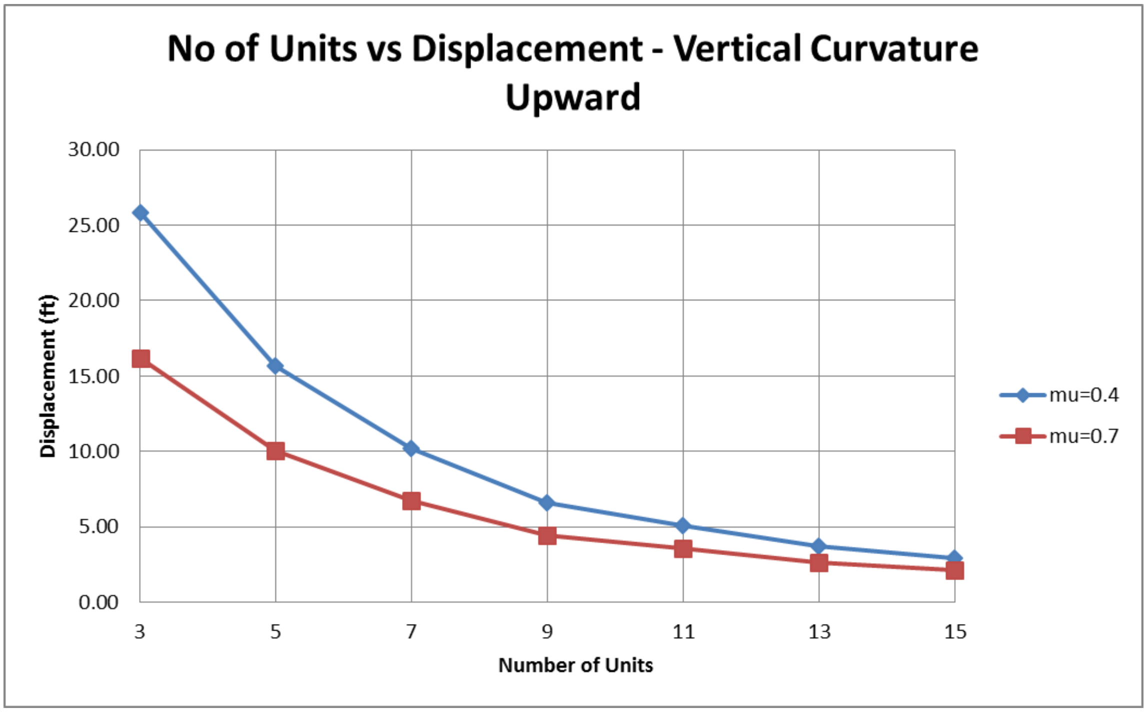

Figure 5-6 - Number of Units vs Displacement for Upward 6° Vertical Curvature

The results of this test are in agreement with all of the cases. The displacement of the units decreases nonlinearly as the number of units increase in the system. Also the displacements with respect to the friction coefficients is converging. From these two observations it was reasoned that there was a point where the displacement was not going to decrease further with the increase in the number of units. However, more testing would be needed to find that point.

5.2 Curvature versus Displacement

In addition to the effect of the number of units on displacement, the curvature of the designed units versus displacement was needed to further quantify performance. Three curvatures were considered; horizontal, vertical downward, and vertical upward. Each of these cases were modeled as before but the angles between the units changed. The tests were run between 0° and the maximum considered case (5° for horizontal and 6° for both vertical cases) at 1° intervals. The results of these tests are shown in Figure 5-7, Figure 5-8, and Figure 5-9 respectively.

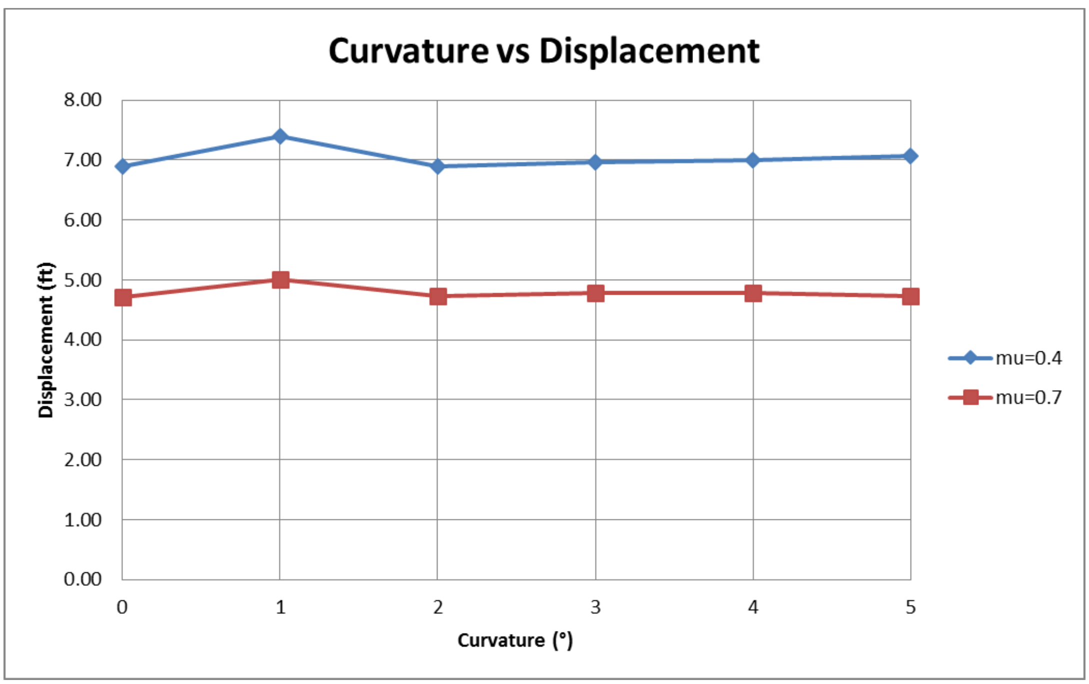

Figure 5-7 – Unit Horizontal Curvature vs Displacement

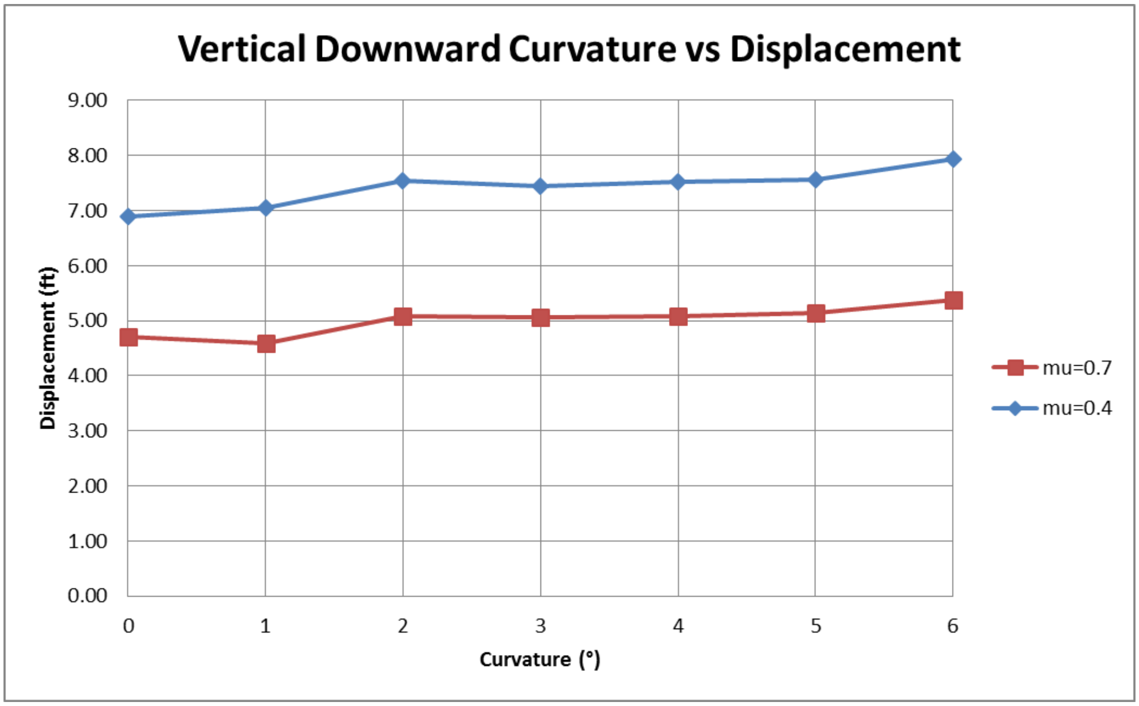

Figure 5-8 - Unit Vertical Downward Curvature vs Displacement

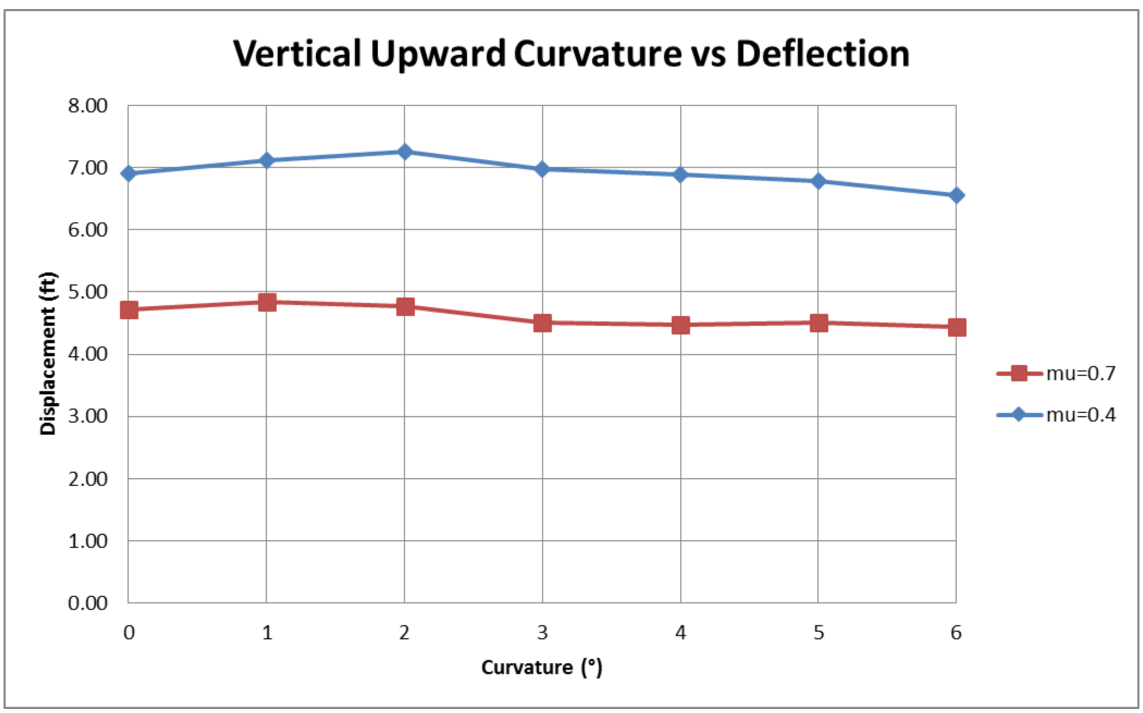

Figure 5-9 - Unit Vertical Upward Curvature vs Deflection

The results of these simulations suggest there is little to no change in the displacement for horizontal curvature, while both vertical curvatures are rather insensitive. The change in the vertical curvature can be explained by the change in the friction forces due to the angle. The normal forces between the units and the ground changed with the angle causing the friction forces to change and thus the displacement. The horizontal curvature had the same normal force regardless of how angled the units were to each other, which was why there was no change there. Because these changes were so small, they were not considered in design.

5.3 Design Changes

After completion of these refined model tests, it was evident that this design was workable. However, if was felt some changes were necessary for the purpose of constructability. The first change that was implemented was the shortening of the units. Initially they were to be 9’ long, but because sheets of steel are only available in 8’ cuts the units were shortened to length of 8’. The second change was the use of a HSS rectangular tube in the unit. The original design of the units were made up of six steel plates welded together. To decrease fabrication costs, the two web plates were replaced with an HSS 10x14x5/8” rectangular steel tube. The top and bottom plates could now be stitch welded to the HSS tube and the end plates welded to close in the center. The next change in the design decreased the number of fasteners at each corner to one, as well as only have the units connected by the top plates. These were implemented to make the assembly of the system easier. Also, it was decided the bolts would be made up of B7 threaded rods or others equivalent or greater in strength. This reduced the size of the connections as much as possible. In addition to the changes, a new design consideration was introduced.

After studying the displacement versus number of units curves, it was decided a new possibility should be explored. This new consideration was the possible use of the units without a concrete fill. This would allow the units to be placed temporarily in an area and then later removed and reused, with the same ease of transport as the original units. With this new usage possibility, it was important that new tests be run to determine its feasibility. It was also important to include the last change to the design, which was to include a bolted connection between the unit and the bollard. With these design changes finalized testing resumed.

5.4 Number of Units versus Penetration

After the design was altered, the performance of the units needed to be tested again. The models were updated to reflect the changes in the design and simulations were run. There were a few changes in these tests. Because the curvature had such a small impact on displacement, it would not be tested again. All additional tests would be performed with the units in a straight line. The second change was time to measure the performance of the units based on the penetration measurements outlined in ASTM Standard F2656. The penetration for this type of system is the distance the front of the truck bed reached past the back side of the bollard. A P1 and P2 rating is given to a system that stops the test vehicle in 3’-3” and 23’, respectively. It was also decided the tests would include systems with a larger numbers of units in an attempt to capture the leveling of the curve. Finally, to keep from increasing the number of tests, the two unit step was abandoned for a 4 unit step. There was also a new design consideration to review; the units without a concrete fill.

The first set of tests were performed with the concrete fill in the units. The number of units in each test started with 5, and then increased to 9, 13, 17, 25, 33, and 41. This was done for two reasons. The first was so that the curve would level out and the minimum penetration found. The second was to determine how many units would be effected by a vehicle crashing into the system. The results of the tests are shown in Figure 5-10.

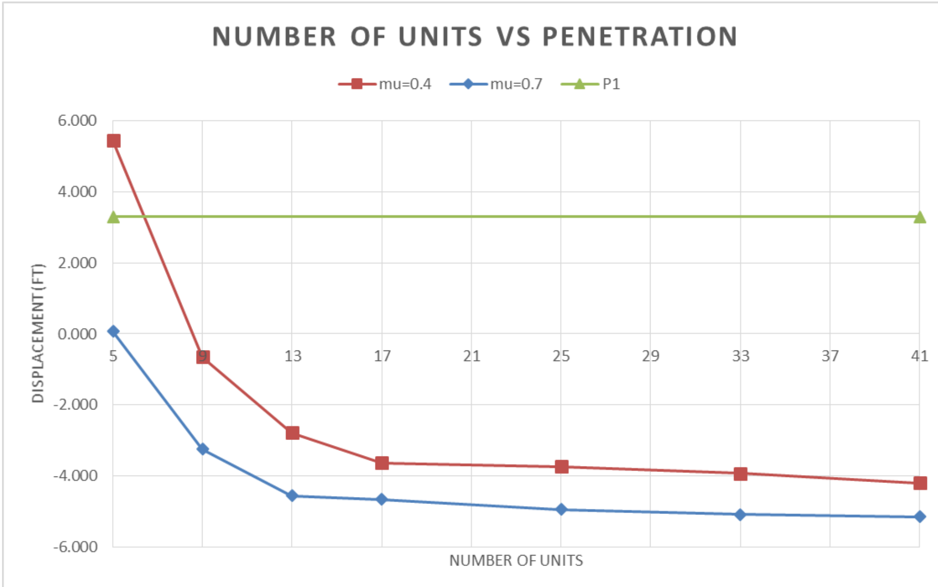

Figure 5-10 - Number of Units vs Penetration for Units Filled with Concrete

It was concluded that for these models the number of units effected by the crash was infinite. There were three reasons for this. Firstly, the design of the units was strong enough to pass the forces onto the next unit with no damage to itself, except for the units directly impacted by the vehicle. Secondly, the connections were modeled as pinned springs between the units to simplify them for testing. This method caused the connection model to be more rigid than the design. Finally the units were modeled as resting on the ground, meaning the only restraining force was friction.

The next tests run explored the behavior of the units when not filled with concrete. The number of units for each test was the same. The results of these tests are shown in Figure 5-11.

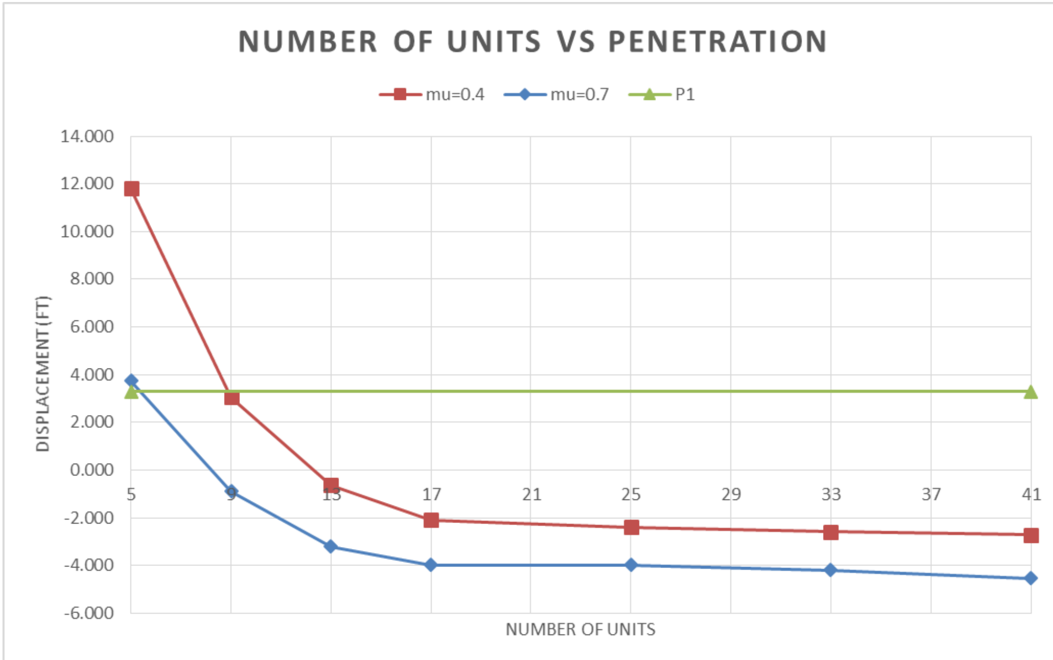

Figure 5-11 - Number of Units vs Penetration for Empty Units

As expected, these results were similar those of the concrete filled unit simulations. The reason the graph levels out later is because the mass per unit is lower. While the mass does not affect the energy dissipation after impact, it does affect the amount of velocity the units have after impact, thus resulting in higher penetrations.

6 CONNECTIONS

The last key component of the design needing more in depth study was the connections for the units. This was delayed until the end of the process for two reasons. First, confirmation of the design worked on a large scale was needed. There was no point in performing detailed design of the connection if the macrostructure of the units might change. The second reason was due to problems with the connections in the initial design testing. The first step was to determine the worst case scenario for the connection forces. Data from previous tests showed that the worst case for the interunit forces was with the units connected in a straight line. Simulations were completed with two different bolt models; spring models and beam models.

6.1 Spring Connection Tests

The spring model tests were completed to determine the trend in the connections forces as the number of units increased. The bolts were modeled as linear springs pinned to the unit, producing only axial force in the spring. Having only a single unidirectional force made it easier to see how the number of units impacted the connection forces. There were two subsets of simulations, those with concrete fill in the units and those without. These models were identical to the penetration versus number of units curves from the previous round of testing. The only change for these tests was the output included specific data about the spring forces to more accurately determine the maximum forces. The results for the units with and without concrete are shown in Figure 6-1 and Figure 6-2 respectively.

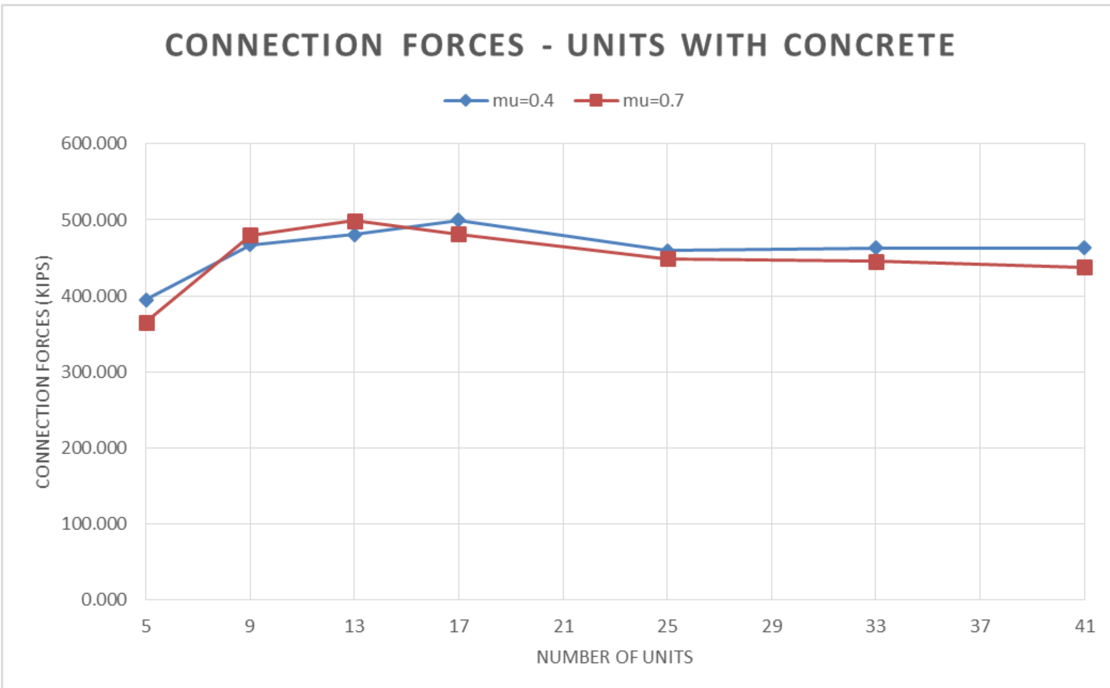

Figure 6-1 - Number of Units vs Connection Forces for Units Filled with Concrete

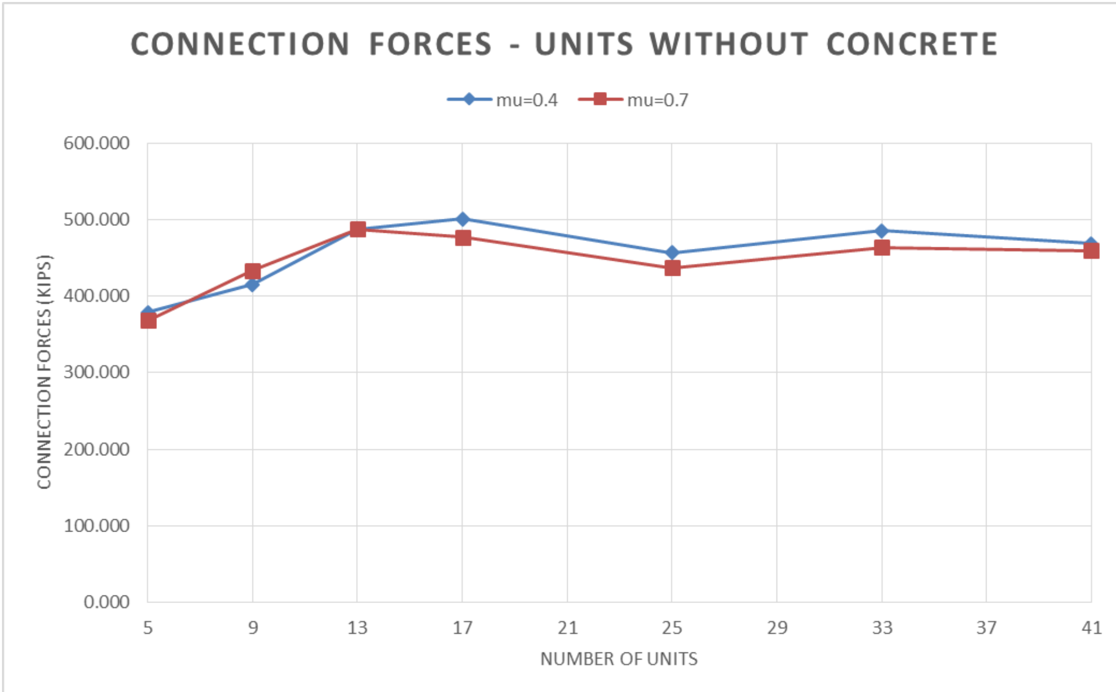

Figure 6-2 - Number of Units vs Connection Forces for Empty Units

From the graphs it was noted that the 17 unit models yielded the highest connection forces. However, there was concern the maximum force of 500 kips, would require at least a 2.3” diameter bolt. Concerned that the simple axial force model might underestimate the forces involved, a more refined connection model was introduced. The information from this force trend was utilized with the more accurate connection model tests to reduce the time spent on simulations. Another conclusion resulting from these graphs was the connection forces’ lack of dependence on whether or not the unit was filled with concrete. The data, with and without concrete fill, follow the same curve, and have the same maximum.

The lack of dependence meant that it would be sufficient to run the beam connection tests only on the units without the concrete fill.

6.2 Beam Connection Tests

The next tests were run with the connections modeled as beams rigidly attached to the units. As discussed previously, only the case of the units without the concrete fill was tested. This allowed data for both the unit-to-unit and bollard-to-unit connections to be collected simultaneously. The output of the simulations was modified to include the beam forces in both connections.

In each case, the maximum loading ratio was found for both the bollard connections and the interunit connections. This was done by taking the sum of the forces divided by the nominal capacities. The maximum loading ratio used to determine if the bolt would hold under the test conditions. The maximum Von Mises stress was also recorded to verify that the loading ratio was accurate. These results were recorded for all test cases.

This round of testing was used to determine the bolt sizing for the connections. All of the previous tests showed that the plate had sufficient strength at the connection point, so how the bolt holes were designed was not a concern. The testing with the spring bolt model showed that the bolts needed to be on the larger end of the available bolt sizes, the two largest standard bolt sizes were tested; 1.5” diameter bolts and 2” diameter bolts. Each test configuration ran both of these cases.

The first test model included 17 units with a coefficient of friction of 0.4 because that was the case that yielded the highest force in the spring bolt tests. The second model also had 17 units, but had a coefficient of friction value of 0.7. This was done to ensure the increase in friction did not increase the connection forces. The third case included 33 units lined up to verify the connection forces with the increase in the number of units. The final case included 33 units, but with the units on the ends fully constrained. This was done to ensure that the largest connection forces were captured, by making the connections transfer the full force to the ends of the units without the units gaining any momentum. The results of all of these tests can be seen in Table 6-1.

Beam Connection Data					
No of units	Bolt Dia	Friction	Max Von Mises (ksi)	Max Loading Ratio - Pipe	Max Loading Ratio - Unit
17	1.5	0.4	215.67	2.032	0.511
17	2	0.4	156.06	1.166	0.35
17	1.5	0.7	220.75	2.179	0.613
17	2	0.7	151.71	1.259	0.426
33	1.5	0.4	215.38	2.002	0.862
33	2	0.4	156.93	1.165	0.534
33+	1.5	0.4	223.79	2.106	0.872
33+	2	0.4	163.60	1.214	0.591

Table 6-1 - Beam Connection Tests Data

The results from these tests show that there was a discrepancy between the spring and beam bolt models. The data showed the bolts were under more stress with 33 units than with 17. It also showed that the increase in friction values did increase the connection forces. This difference was likey the result of resonance in the 17 unit model that was dampened out with the increased number of units. This also may have been the cause behind the difference in the trends with the friction values.

6.3 Connection Design

The results from the beam connection tests provided suitable data for designing the connections. The tests showed that the 1.5” diameter bolts were suitable for the interunit connections while the 2” diameter bolts were just about enough to hold the bollard in place. The tests did show that the maximum loading ratio for the 2” diameter bolts was greater than the one for the bollard connections, however it was deemed sufficient for two reasons. The first reason was that the bolts would not be as rigid as modeled so the resulting stresses may not have been as high in the fully detailed model. The second reason was that the plate might deform under the loading which would also result in slightly lower forces on the bolt. With the bolt sizes decided, the holes in the units needed to be designed.

The driving idea behind the design of the holes for the bolts was the curvature of the units. In all of the previous tests the areas in the plates where the bolts were connected did not deform at all, so it was assumed that the steel plate was strong enough for the bolts. The bollard connection was designed first. There were to be slotted holes cut into the HSS tube and the bollard to allow the bollard to remain vertical while the base tilted. The hole was 1.25” long to allow for an angle up to 5°. The connections of the units were designed next with the same curvature considerations in mind. It was decided that the holes for the connections be but into both the top and bottom plates. This was to make fabrication of the units easier as well as allow the units to be angled along their length. It was also decided that one side of the plate have a regular sized hole while the other had curved slotted holes. This was so that the units could still curve horizontally, but they could also be curved vertically without the need for washers on both sides of the connection. The curved slotted holes were design in such a way that their center of curvature was at the center of the bollard and projected 5° in both directions. They were also oversized by 1/2" to allow for the vertical curvature. The only washers for the connections were 1/2" plate washers for the slotted holes to ensure that the bolts did not slip through. With this, the connections completed the design was finished.

7 DESIGN VERIFICATION

With the connections designed the units were completely detailed and ready for verification. Prior to this point the models for each of the tests had been simplified to gather the data needed for design. For these final two simulations, the units were modeled with as much detail as possible.

The unit models that were refined included the connections, sand fill, and bollard freedom. The holes for the bolts were included in the plates, the HSS tube and the bollard. The washers were modeled as shell elements like the plates and had contact with them. The bolts were modeled as beam segments with null shell elements rigidly constrained to them at cross sections. The beam elements were for the stiffness of the bolt, while the null elements were there to provide the contact between the bolt and the plate. The assumption was made that the bolt would bend in such a way that the cross section would not deform, which was why the ends of the beams were rigidly constrained to the ends of the null shells. To properly simulate any deformation in the beams due to loading each beam and null shell element was very short. A picture of the bolt model is shown in Figure 7-1.

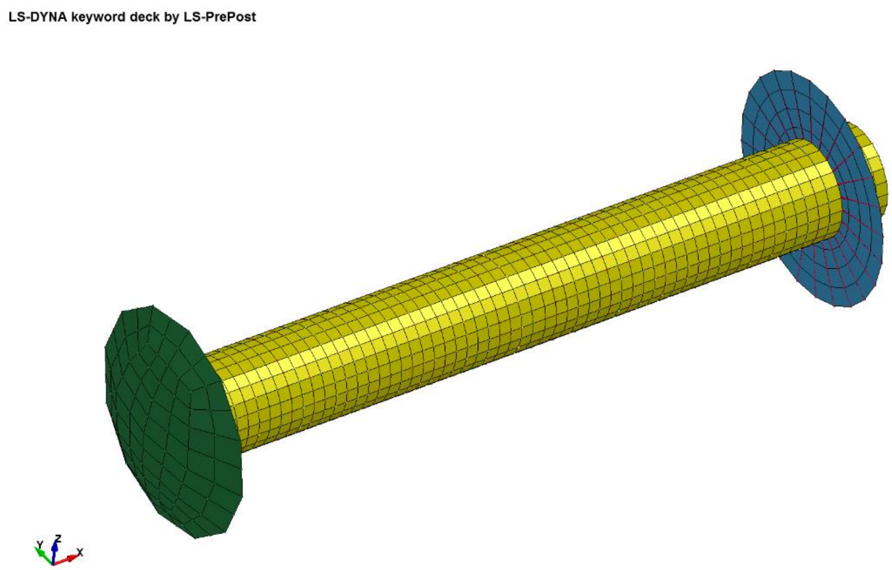

Figure 7-1 - Bolt Model for Design Verification

Modeling the sand fill for the units was challenging. The difficulty with modeling the sand fill was that most property data on sand is gathered using compressed samples. However the sand fill was assumed to be loosely packed and thus wouldn't have the same density or bulk modulus. Utilizing a NASA report on the LS_DYNA modelling of soils (Thomas and Chitty 2011) it was decided to use the MAT-5 Soil and Foam material card for the sand. The sand was modeled as a solid with this material card. To avoid difficulty in modeling the geometry of the sand and including a contact card it was decided that solid elements of the sand would share nodes with the HSS tube and bollard where there was contact. In this way the sand would still behave as if there was contact between them but without increasing the simulation time by adding in a contact card.

After the models were complete with the details described above and displayed in Figure 7-2, the complete units were tested. The beam connection tests showed that the most stress on the bollard and unit bolts was during the 33 unit test with the ends anchored. For this reason a similar test was performed here. 31 units were modeled in a straight line with the end units fully constrained on the outside. The simulation was run for almost the full duration of the crash, but stopped just before the end due to supercomputer run time restraints. The results of the test are shown in Table 7-1.

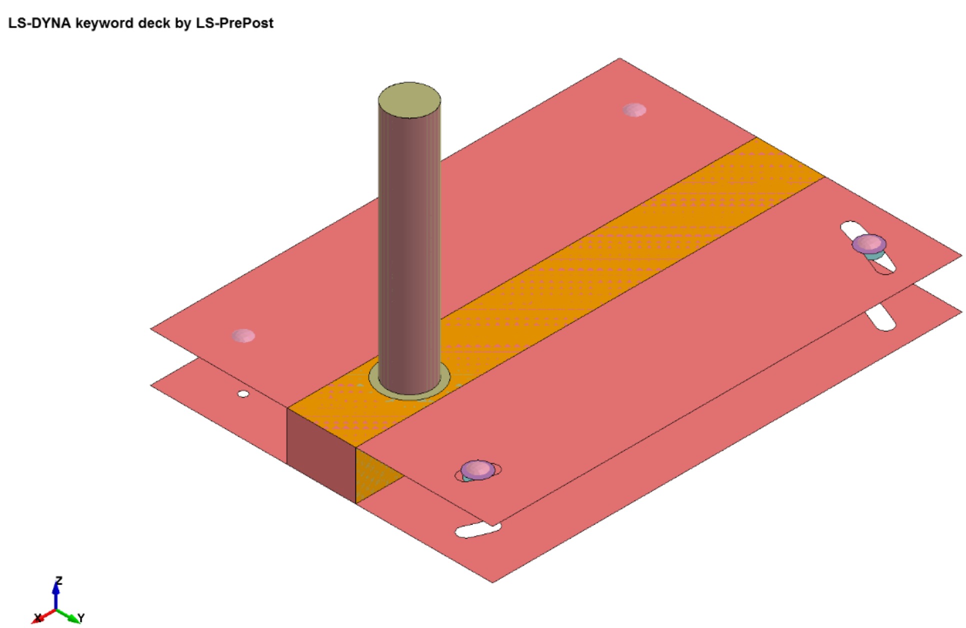

Figure 7-2 - Fully Detailed Unit Model

Maximum Bolt Stress, Strain, and Unit Penetration				
Max Von Mises Stress (ksi)		Max Plastic Strain		Penetration (ft)
Unit Bolts	Bollard Bolts	Unit Bolts	Bollard Bolts	
104.423	120.566	0	0.125	11.910

Table 7-1 - Horizontal Ground Test Results

Finally, there was some concern with the increased size of the hole for the bollard because the extra flexibility might allow the truck to continue moving after the impact with the barrier. The size of the hole for the bollard was adjusted for the plate and HSS tube to the size specified in the design. This was particular concern for the case when the units would be at a five degree incline with the vehicle traveling downhill. For this reason, a five degree incline test was performed with the general horizontal ground case. The results can be seen in Table 7-2.

Maximum Bolt Stress, Strain, and Unit Penetration				
Max Von Mises Stress (ksi)		Max Plastic Strain		Penetration (ft)
Unit Bolts	Bollard Bolts	Unit Bolts	Bollard Bolts	
77.404	134.822	0.000	0.141	11.812

Table 7-2 - 5° Downhill Incline Test Results

As can be seen from the results the design of the modular bollard barrier passed these simulation tests. The slotted holes for the interunit connections gave the system much more flexibility than the simplified models, resulting in a finite number of units being engaged. The oversized hole for the bollard caused the system to vault the truck upwards, however the system slowed the truck down enough that it came back down on top of the system. This allowed some additional penetration but did stop the truck within the desired limits for this case.

8 CONCLUSION

8.1 Research Summary

This project set out to design a modular security barrier that could be used as an expeditionary system for the construction of new secure areas. It would be flexible enough to curve, both horizontally and vertically, with the ground along the perimeter of the site and still be able to withstand a collision with a 15000 lb vehicle travelling at 30 mph. It could then be installed in the ground for permanent protection and be able to stop the same size vehicle travelling 50mph within 3’-3”. All of the tests performed during this project show that this design could meet that desire.

This system is made up of interconnecting modular units bolted together to make up a physical barrier that is able to stop a 15000 lb truck traveling 30mph within 12 ft. It is able to do this with the unit resting on the ground. Each unit is able to rotate in any direction up to 5° while the bollard remains vertical. This gives it flexibility to be able to curve along with the ground with less groundwork than other systems. Further, with the bollard designed to be a separate piece from the base of the units, it allows the units to be much more efficiently transported. The units can be stacked while the bollards can be bundled separately. Finally, both the literature review and the testing indicate that once fully installed the system will be able to stop the truck moving at 50mph within 3’-3”.

8.2 Future Tasks

While testing has shown positive results, there is still much to be done before this design can be called complete and put on the market. Further testing needs to be done to include full design curvature tests, permanently installed unit tests, and off-center crash tests. Under the idealized rigid connection tests for the displacement curves in Section 5.2 the curvature did not affect the performance of the system. However, the slotted hole connections will behave very differently and need to be reviewed to ensure the system meets the penetration requirements for the curvature designed. The reason the permanently installed units need to be tested further is that while the testing and literature review indicate that the units will meet the requirements, there is no conclusive tests indicating that they will.

The last issue with the tests performed in this study is that they focused on the scenario where the vehicle impacted the center bollard. This was acceptable for these tests because of they were done to gather data for the design. With the design completed it is important to test how the system will react when the vehicle does not impact at the center. The off center crash will give the system angular as well as linear momentum and will need to be addressed if the units are to ever be used in a case where they are not assembled in a closed shape. One possible solution for this would be to somehow fix the units to the ground, but that was not within the scope of this research.

Other thoughts for design that were outside the scope of this research was the need to include pedestrian trip hazards and requirements set forth by the American Disabilities Act. Once finished these units could be placed in areas where pedestrian traffic might have to walk over them. In this case the layering of the units and the bolts would present a tripping hazard for anyone trying to access the other side of the barrier. This is why it will be important to look at ways to cover and/or minimize these extrusions. Also, if these units were ever to be used in the United States (or other countries with a similar law) then the units would need to be design to allow disabled peoples to be able to get over them somehow in addition to everyone else.

Finally, after everything else has been considered, real life crash tests need to be performed before this design can be put on the market. FEM simulation is a very useful tool for research and design, but no simulation can match the accuracy of a real life, full scale crash test. The tests would potentially need to cover a variety of numbers of units, curvatures, and positioning on and in the ground but that will need to be decided once the issues presented above have been addressed and testing criteria established.

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APPENDIX

No of Units vs Displacement - Straight		
# of Units	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
3	24.90	15.27
5	15.90	10.36
7	10.74	7.28
9	6.90	4.72
11	4.87	3.36
13	3.55	2.59
15	3.11	2.37

Table A-1 - Numbering of Units vs Displacement for Straight Configuration

No of Units vs Displacement - Curved (5°)		
# of Units	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
3	25.31	15.39
5	14.66	9.10
7	9.69	6.23
9	7.07	4.73
11	4.72	3.12
13	3.77	2.62
15	3.12	2.27

Table A-2 - Number of Units vs Displacement for 5° Curved Configuration

No of Units vs Displacement - Curvature (6°)		
# of Units	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
3	27.15	16.99
5	14.83	9.49
7	9.93	6.40
9	7.93	5.37
11	5.87	4.07
13	4.59	3.17
15	3.17	2.33

Table A-3 - Number of Units vs Displacement for Downward 6 Vertical Curvature

No of Units vs Displacement - Curvature (6°)		
# of Units	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
3	25.84	16.15
5	15.68	10.06
7	10.19	6.76
9	6.56	4.44
11	5.06	3.56
13	3.72	2.65
15	2.89	2.13

Table A-4 - Number of Units vs Displacement for Upward 6 Vertical Curvature

Curvature vs Displacement		
Curvature (°)	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
0	6.90	4.72
1	7.40	5.01
2	6.89	4.72
3	6.97	4.77
4	6.99	4.79
5	7.07	4.73

Table A-5 - Unit Horizontal Curvature vs Displacement

Vertical Curvature (Downward) vs Displacement		
Curvature	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
0	6.90	4.72
1	7.05	4.58
2	7.55	5.08
3	7.45	5.06
4	7.51	5.07
5	7.56	5.13
6	7.93	5.37

Table A-6 - Unit Vertical Downward Curvature vs Deflection

Vertical Curvature (Upward) vs Displacement		
Curvature	Final Displacement mu=0.4 (ft)	Final Displacement mu=0.7 (ft)
0	6.90	4.72
1	7.11	4.84
2	7.25	4.77
3	6.98	4.52
4	6.89	4.47
5	6.78	4.51
6	6.56	4.44

Table A-7 - Unit Vertical Downward Curvature vs Deflection

No of Units vs Penetration		
# of Units	Penetration (ft) mu=0.4	Penetration (ft) mu=0.7
5	5.446	0.066
9	-0.656	-3.248
13	-2.789	-4.560
17	-3.642	-4.659
25	-3.740	-4.954
33	-3.937	-5.085
41	-4.199	-5.151

Table A-8 - Number of Units vs Penetration for Units Filled with Concrete

No of Units vs Penetration		
# of Units	Penetration (ft) mu=0.4	Penetration (ft) mu=0.7
5	11.811	3.740
9	3.051	-0.886
13	-0.623	-3.215
17	-2.100	-3.970
25	-2.395	-3.970
33	-2.592	-4.199
41	-2.723	-4.528

Table A-9 - Number of Units vs Penetration for Empty Units

Connection Forces (kips)		
No Units	mu=0.4	mu=0.7
5	394.892	365.556
9	467.577	479.628
13	480.350	499.243
17	499.873	481.681
25	459.852	449.036
33	463.390	445.463
41	463.306	438.079

Table A-10 - Number of Units vs Connection Forces for Units Filled with Concrete

Connection Forces (kips)		
No Units	mu=0.4	mu=0.7
5	378.750	368.553
9	415.267	433.486
13	487.699	487.879
17	501.208	477.509
25	456.605	437.592
33	486.049	464.273
41	468.644	459.905

Table A-11 - Number of Units vs Connection Forces for Empty Units