Finite Element Modeling of Cable Hook Bolts

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ABSTRACT

Component analysis of any complex system is frequently required to determine the true accuracy of a finite element model. Although a composite system may yield the "correct" final results, the system is not truly accurate unless individual components are performing correctly.

The purpose of this paper is to describe the component testing and finite element modeling of a standard 5/16"-18 x 2" galvanized shoulder hook bolt used in cable barrier systems. These bolts hold the cable to the post of a cable barrier system. During a vehicle impact with the system, the cable loads many of the restraining hook bolts in different directions. Several of the hook bolts will reach their bending yield limits and "open up," allowing the cable to disengage. This is designed behavior which allows the cable to capture the impacting vehicle. Successful modeling of these bolts is essential to have an accurate finite element model of a complete cable barrier system.

INTRODUCTION

3-strand cable barrier systems are versatile and economical barriers that are often used along non-recoverable slopes and in locations where the relatively large dynamic deflections of the barrier is acceptable. Because of the advantages of 3-strand cable barriers, the Midwest States Pooled Fund Program has initiated three projects with the Midwest Roadside Safety Facility. These projects include the design and testing of modified 3-strand cable roadside and median barriers in order to expand the number of applications approved for cable barriers.

Figure 1. South Dakota 3-Strand Cable System

Finite element simulation, using LS-DYNA, of 3-strand cable barrier systems is projected to be a key element in the success of these projects. Before a complete system can be simulated, critical components must first be tested and simulated. One such critical component is the cable hook bolt. Hook bolts are used to support the cables against the steel posts of the system. During an impact, several of the steel posts will bend and rotate towards the ground. During this process it is imperative that the cables be released from the post. If not released, the cables could be pulled towards the ground with the post, allowing the vehicle to ride over the cables. This would result in the vehicle penetrating the barrier, which is unacceptable. Modeling the critical cable and hook bolt interaction is the focus of this paper.

PHYSICAL TESTING

Physical testing was performed to determine the actual physical behavior of the bolt. Testing was performed in both horizontal and vertical directions, relative to the installation direction of the hook bolts. Testing was performed using an MTS machine with custom-manufactured loading devices. A 19-mm (¾) A36 steel dowel was used to simulate the cable while the bolt was fastened rigidly to the loading platform. Testing configurations are shown in Figure 2.

Both static and dynamic tests were performed. Static loading was performed at 0.20 mm/sec while dynamic loading was performed at 185 mm/sec. Dynamic loading rates were determined by the maximum loading rate of the MTS machine.

Force-deflection data was acquired through a load cell and a linear position transducer, respectively. The forces were then integrated over the displacements using the trapezoidal rule to determine the energy. Variables of interest included peak loads and corresponding displacements, and energy absorption at 15-mm and 25-mm of deflection.

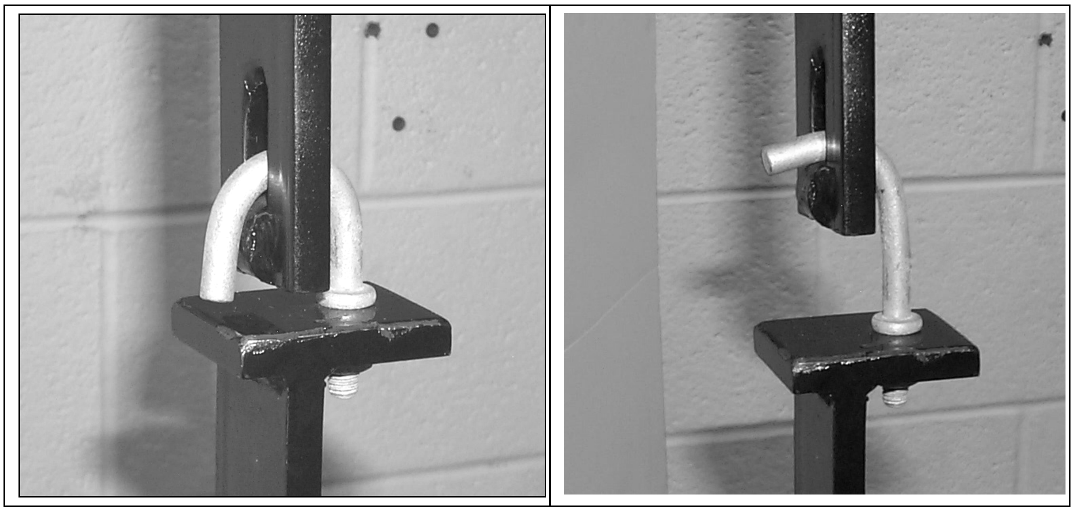
Horizontal Test Results

Results from horizontal testing are presented in Table 1 and Figure 3. The force-deflection relationship for the 0.20 mm/sec horizontal testing showed a nearly identical initial modulus of elasticity. However, the initial yield point varied between 2.3 and 3.0-kN. Also, the force-deflection relationship for the 185 mm/sec horizontal testing showed a nearly identical initial modulus of elasticity, although different than the static test result. But unlike the static tests, the initial yield force for the dynamic cases was very consistent at 3.2-kN.

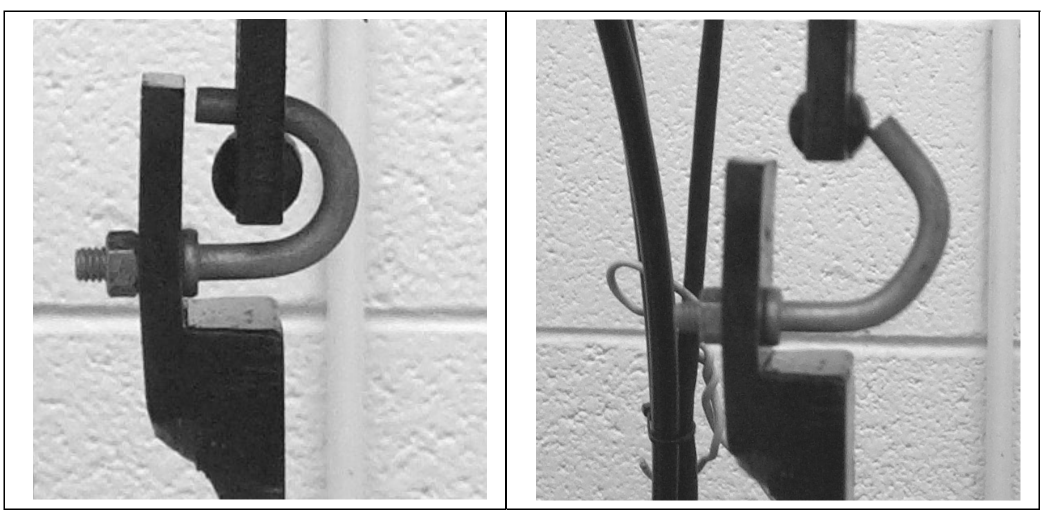
A slight variation between static and dynamic testing for the horizontal testing was noted, as evident in Figure 3. The initial stiffness for dynamic testing was higher than that for static testing. Additionally, the dynamic loads were consistently about 8% higher than the static loads.

Vertical Test Results

Results from vertical testing are presented in Table 2 and Figure 4. There was essentially no difference between static and dynamic results for vertical hook bolt pullout. The bolts began to yield (i.e., bend) when loads reached about 2-kN. Peak loads were reached near 2.9-kN at around 5-mm of deflection. After peak loads, the hooks continued to bend with decreasing loads until the loading device lost contact with the bent hook, generally around 25-mm of deflection.



Horizontal Testing



Vertical Testing

Figure 2. Hook Bolt Test Configurations

Table 1. Horizontal Hook Bolt Test Results

Test ID	At Peak Load		Load Rate (mm/sec)	Energy Absorbed (N-m)	
	Load (kN)	Displacement (mm)		at 15 mm	at 25 mm
A-1	3.76	6.38	184.55	45.5	79.0
A-2	3.71	19.22	184.55	44.9	80.0
A-3	3.67	5.64	184.55	44.6	77.5
Average	*3.71*	*10.41*	*184.55*	*45.0*	*78.8*
B-2	3.06	19.35	0.20	38.3	68.8
B-3	3.49	12.79	0.20	40.6	74.4
B-4	3.48	18.33	0.20	43.1	77.2
B-5	3.06	19.30	0.20	38.2	68.0
B-6	3.39	19.15	0.20	42.0	75.7
Average	*3.20*	*18.55*	*0.20*	*40.4*	*72.8*

Note: Test B-1 was experimental, being the first test, and thus, dropped from consideration.

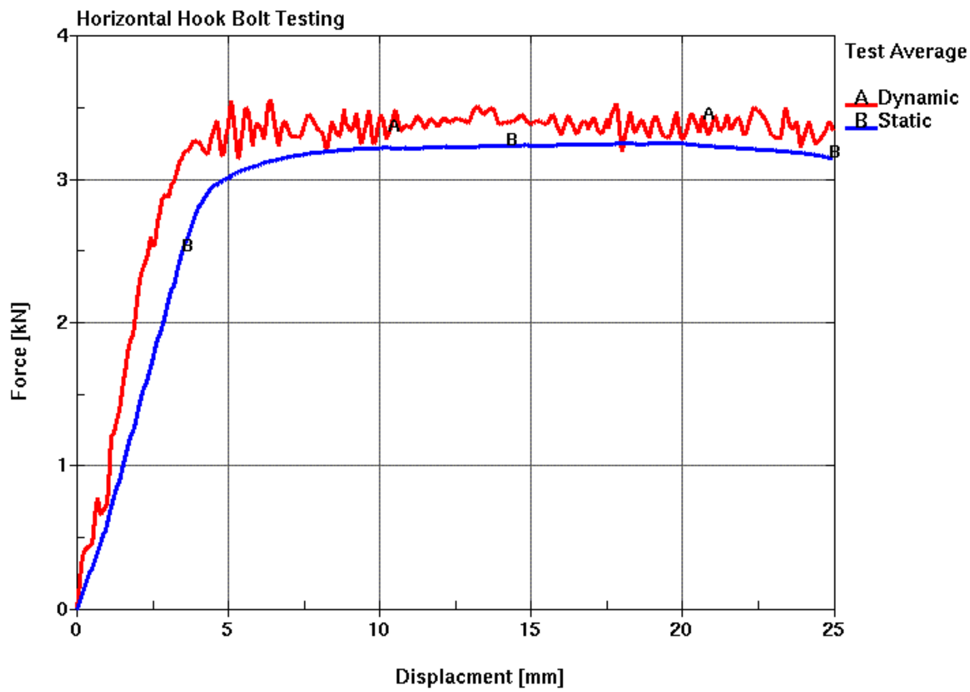


Figure 3. Horizontal Hook Bolt Force-Deflection Results

Table 2. Vertical Hook Bolt Test Results

Test ID	At Peak Load		Load Rate (mm/sec)	Energy Absorbed (N-m)	
	Load (kN)	Displacement (mm)		at 15 mm	at 25 mm
C-1	2.99	5.73	0.20	37.8	50.7
C-2	3.26	5.08	0.20	39.8	52.4
C-3	2.96	4.57	0.20	37.9	50.8
C-4	2.72	5.36	0.20	36.9	47.8
C-5	2.74	4.95	0.20	35.5	45.3
C-6	2.78	5.47	0.20	36.1	48.0
C-7	2.48	5.48	0.20	31.4	N/A
C-8	3.36	2.79	0.20	42.3	57.0
C-9	2.83	3.09	0.20	36.3	46.7
C-10	2.17	4.96	0.20	29.2	N/A
Average	*2.83*	*4.75*	*0.20*	*36.3*	*49.8*
D-1	3.35	3.79	160.35	38.4	50.5
D-2	3.13	6.14	160.35	32.8	N/A
D-4	3.29	4.31	160.35	36.4	47.2
Average	*3.01*	*4.39*	*160.35*	*35.9*	*48.9*

Note: Test D-3 was dropped due to inconsistencies in the data.

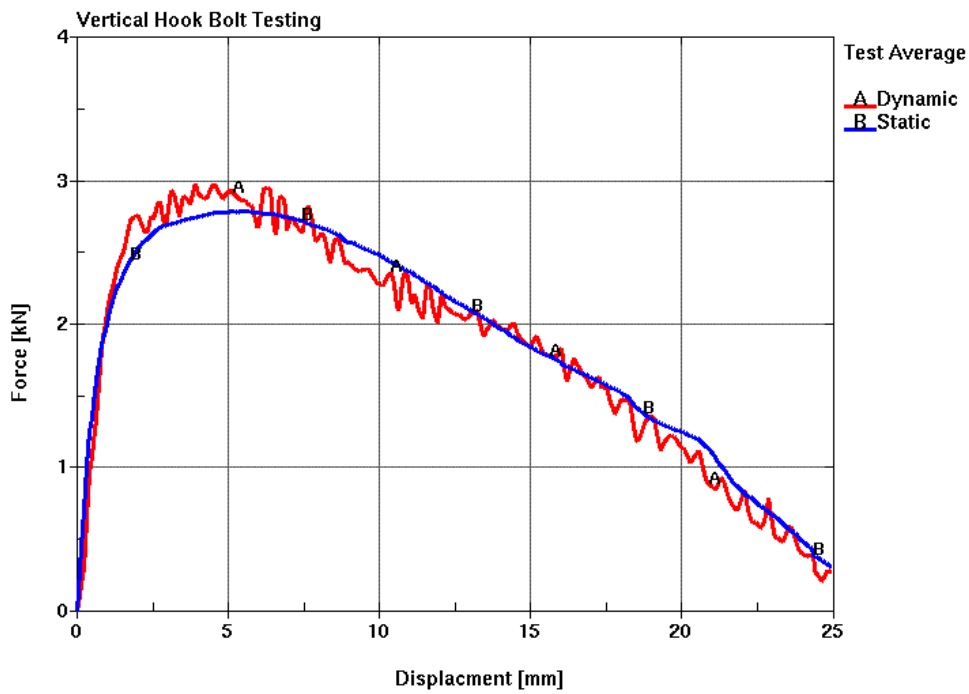


Figure 4. Vertical Hook Bolt Force-Deflection Results

Comparison to Specifications

MMA Laboratories of Newton, PA, performed certification testing of the hook bolt at the request of the Bennett Bolt Works of Jordan, NY, the manufacturer of the bolt. Failure was assumed to occur when "the sample started to bend unless otherwise noted." This was assumed to imply plastic deformation and the loads used for comparison were taken as the value when the force-deflection curve became nonlinear. Results from MMA and MwRSF testing are provided in Table 3 for comparison.

The State of New York Department of Transportation Design and Construction Division specifies hook bolts must "develop an ultimate pull open strength of from 2.225-kN to 4.45-kN (500 lbs to 1000 lbs) applied in a direction normal to the longitudinal axis" of the post. This wide range of allowable strengths creates difficulties in predicting actual strength values of any untested batch of hook bolts. However, results from the testing performed in this study proved to be rather consistent and within specifications.

Table 3. Comparison to Other Testing

DIRECTION	PULLOUT STRENGTH (kN)*		
	MMA Laboratories	MwRSF Testing**	
		Static	Dynamic
Vertical Up	1.63	2.0±0.22	2.5±0.50
Vertical Down	3.50	Not Performed	
Horizontal Straight	4.10	2.75±0.3	3.0±0.22
Vertical Up When ¾" Diameter Slips Out	2.47	2.75±0.22	3.1±0.50

* Failure was defined as when the sample started to bend plastically

** 95% confidence interval

FINITE ELEMENT MODELING

LS-DYNA, an explicit, nonlinear finite element analysis program from Livermore Software Technology Corporation (LSTC), was used to simulate the hook bolt testing.

The model used for simulation is shown in Figure 5. There are three parts in the model, the back plate, the loading bar and the hook bolt. The back plate is simply used for display and is not part of the calculations. The loading bar is composed of rigid solid elements constrained to move in the direction of loading. A prescribed motion is applied to the loading bar, similar to the physical testing. The hook bolt is composed of fully integrated solid elements. Single point constraints are used to fix the end of the bolt. An automatic single surface contact is defined between the loading bar and hook bolt.

Determining the specific parameters for the various model options proved to be the difficult part of this component modeling endeavor. Primarily, efforts were concentrated on the number of elements in the cross-section of the bolt, the material properties of the bolt and the sliding friction coefficient in the contact between the bolt and the bar.

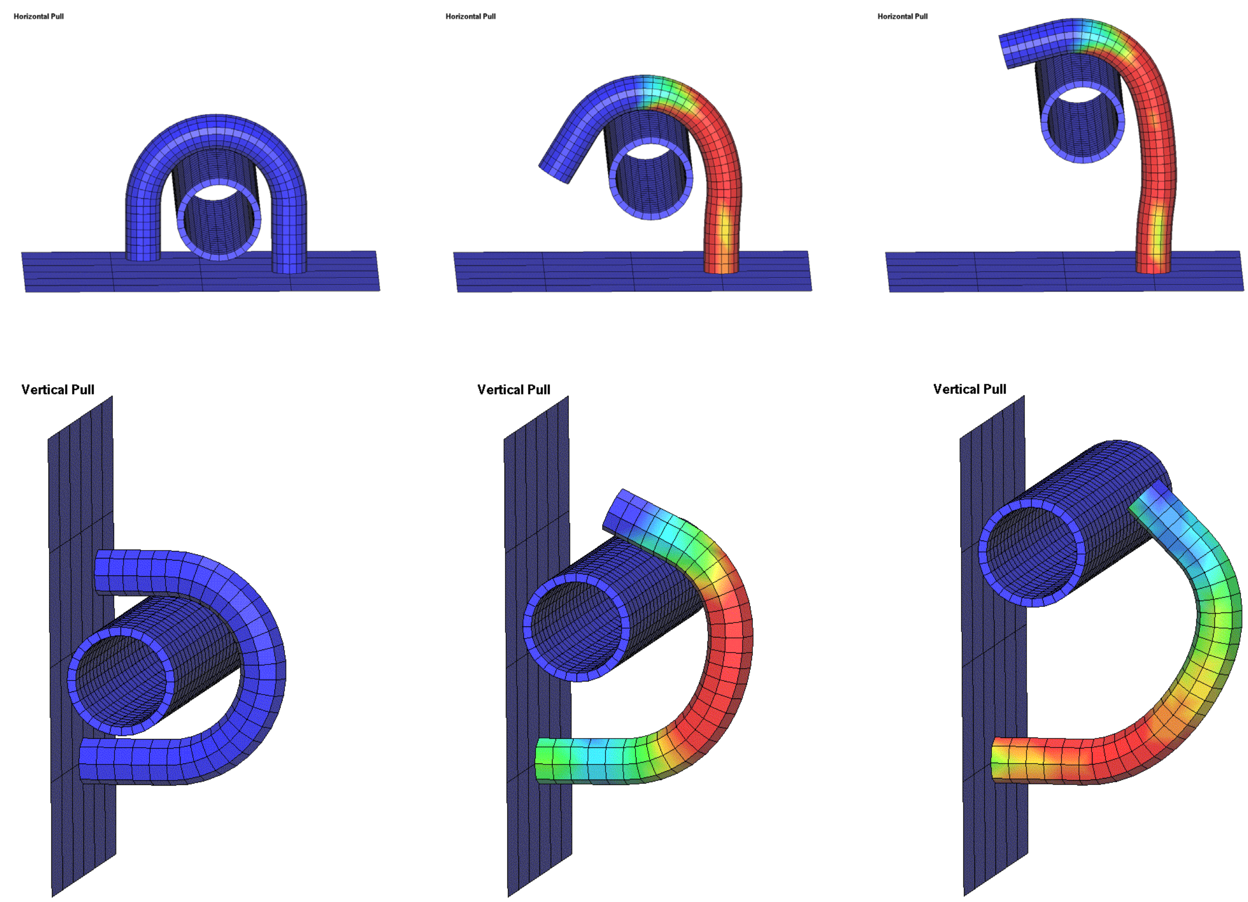


Figure 5. Hook Bolt Pull Simulations – von Mises Stresses

Cross-Section Selection

There is always a compromise between modeling accuracy and the amount of computational power required to perform a simulation. Finding the correct balance between these is essential to efficient computer simulation. The number and size of elements in a finite element model greatly affects the computational costs of the simulation. Minimizing the number of elements and maximizing their size in the cross-section while maintaining reasonable accuracy decreases modeling time and increases efficiency.

At least three integration points through the thickness of a part in the direction of bending must exist to capture plastic bending. As a part begins to bend, plastic deformation begins spreading from the outer fibers of the material inward. Thus more integration points, and thus more elements, are required to capture the variations of the stresses that occur through the thickness.

Six different cross-sections were chosen to examine modeling of the hook bolt. Element densities of 5, 8, 9, 12, 32 and 48 were selected to help determine an optimum cross-section, see Figure 6. Horizontal pull simulation results for different cross-sections are shown in Figure 7; these results fell into four categories: (1) for 5 elements in the cross-section, the load was well below physical testing; (2) for 8 elements, the results appeared strange to the authors and thus neglected; (3) for 9 and 12 elements, the bending loads were relatively constant near 3-kN, and (4) for 32 and 48 elements, again the bending loads were relatively constant near 3.3 kN, very similar to physical testing.

In many applications, it has been noted that a refined mesh often leads to a softer response. A coarser mesh is inherently stiffer than a finer mesh. However, in the hook bolt simulations this general tendency has not been followed. With finer mesh, the loads have increased. This increase has been attributed to the cross-section area. The finer mesh allows the cross-section to be modeled more accurately, increasing its area. This increase in area, approximately 9%, strengthens the bolt and thus, increases the load required for bending.

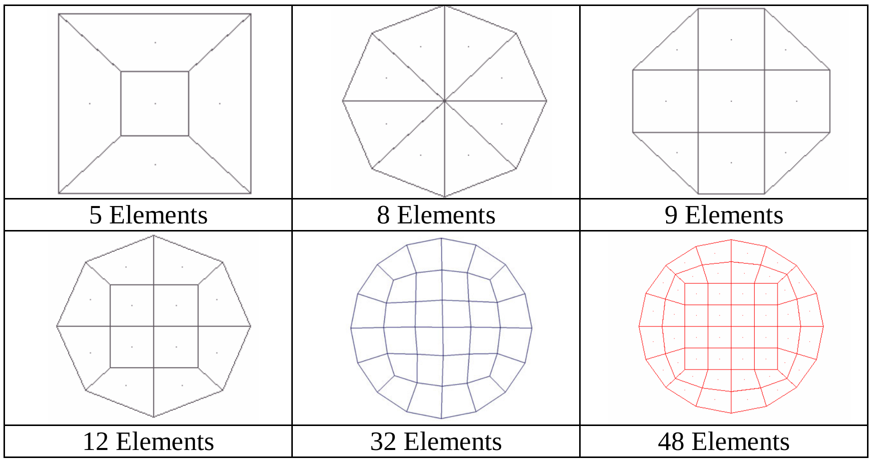


Figure 6. Hook Bolt Cross-Sections

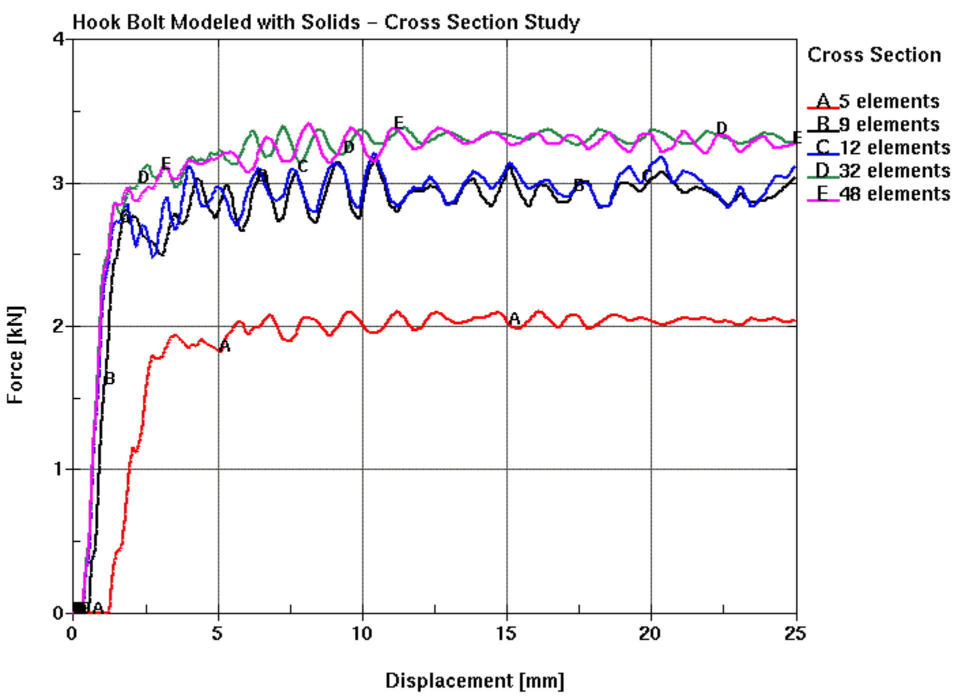


Figure 7. Horizontal Pull Simulation Results

Sliding Friction

Interaction between the loading bar and hook bolt is defined with an automatic single surface contact. As the loading bar bends the bolt, there is sliding between the two parts. The sliding friction coefficient (FC) has a significant influence on the loads required to bend the bolt, as shown in Figure 8 for the horizontal pull simulation. Because there is no practical method for determining the precise friction coefficient, this parameter must be estimated and becomes a tuning parameter for matching simulation to test results.

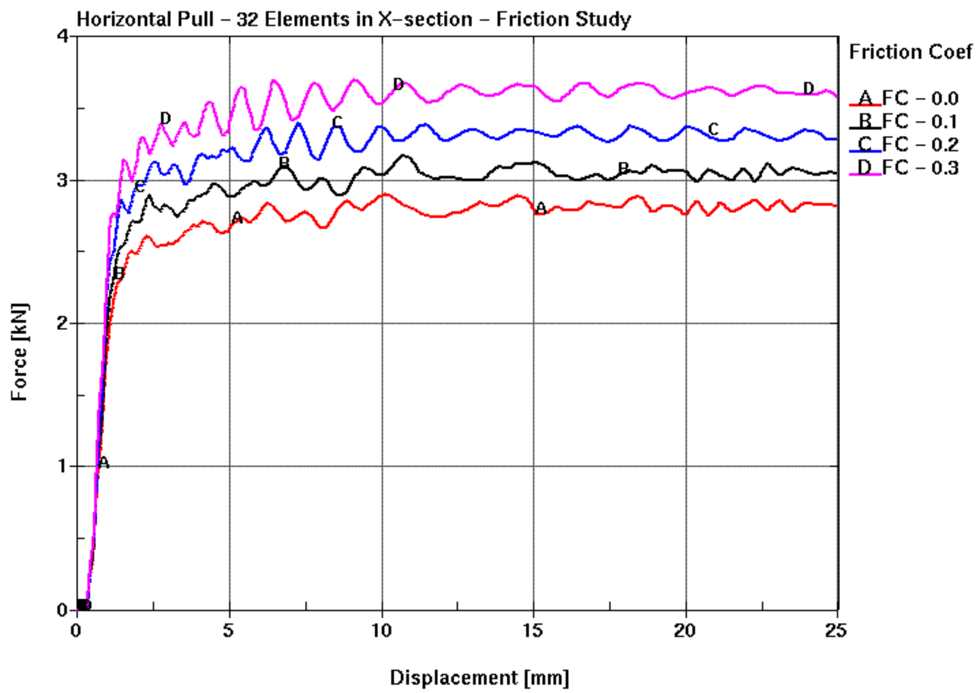


Figure 8. Effects of Sliding Friction Coefficient on Loading

Vertical Loading

Once comfortable with the horizontal pull simulation attention was turned towards the vertical pull. It was found that simulation in the vertical direction was highly dependent upon the positioning of the loading bar (see Figure 9). During testing, the position of the loading bar was measured but its position could vary approximately 1.5-mm on either side of what is labeled as the baseline in Figure 9. Because there is no practical method for determining the precise location of the loading bar, this parameter must be estimated and becomes somewhat of a tuning parameter for matching simulation to test results.

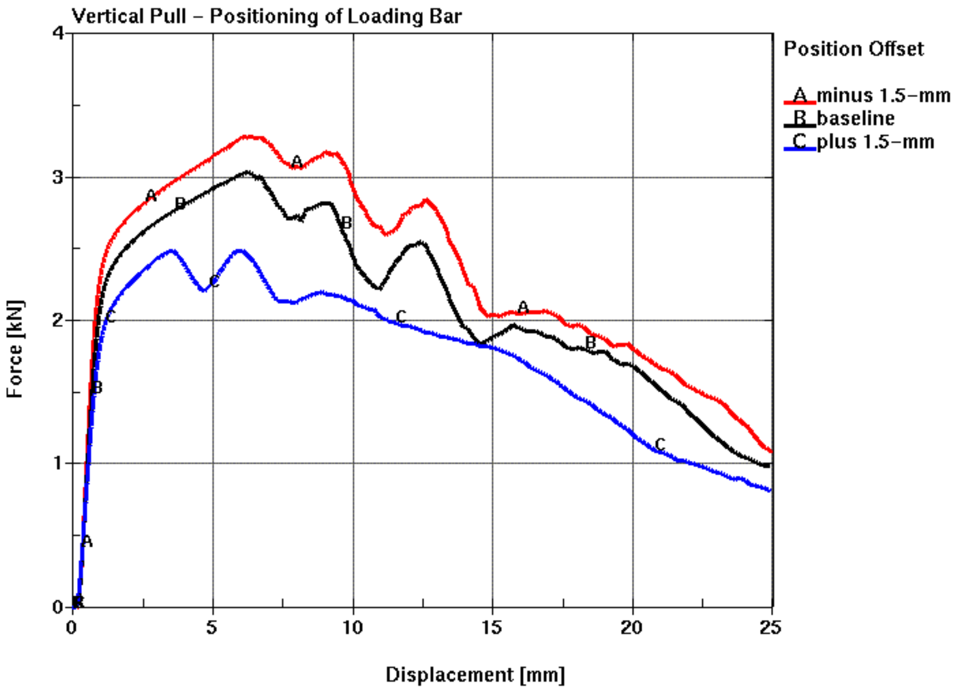


Figure 9. Effects of Positioning of Loading Bar on Vertical Pull

EFFICIENT/REDUCED MODELING

Mass Scaling

Mass scaling was examined to determine the effects of reducing the time step to increase computational efficiency. At relatively small increases in the time step scaling factor, significant increases in mass occurred. In order to achieve a time step of 1.0 micro-second, a reasonable value for roadside safety crashworthiness, the mass is increased by considerable factors, as shown in Table 4. While results were nearly identical in modeling the hook bolt pullout tests, inertial effects due to the large mass increase of the bolts may prove to alter the behavior of the steel posts during full-scale simulation. These effects will have to be investigated during that phase of the project.

Table 4. Mass Scaling

# Elements in Cross-Section	Original Model		Mass scaled to time step of 1.0 micro-second	
	mass [kg]	time step [micro-seconds]	scaled mass [kg]	scale factor increase
9	0.02817	0.2503	0.30449	10.8
12	0.02833	0.1715	0.77314	27.3
32	0.03070	0.1347	1.3584	44.2
48	0.03076	0.0894	2.48026	80.6

Beam Modeling

Another method for efficient modeling would be to use beam elements for the hook bolt. This would decrease the computational time of the hook bolt pullout simulation by factors between 30 and 370, depending on the number of cross-sections in the solid element hook bolt. However, there are some limitations as to the usage of beam elements, and contacts involving beam elements require special handling under many circumstances.

To investigate the potential for improved efficiency, without loss of accuracy, solid and beam elements were examined for their suitability for modeling the hook bolt and the loading bar. Four possible permutations are possible: the loading bar modeled using solid elements with the hook bolt modeled using solid or beam elements, and the loading bar modeled using beam elements with the hook bolt modeled using solid or beam elements.

Based on a limited study of using beams in three of the permutations, it was discovered that modeling the hook bolt with beam elements is extremely dependent upon the modeling of the loading bar, and thus, would also be dependent upon the modeling of the cable in the system model. Therefore, beam element modeling during this component modeling effort was deemed to have very little useful knowledge to be passed along at this time.

SUMMARY

Simulation of cable hook bolts has been shown to be significantly influenced by the number of elements used in the cross-section of the bolt, the sliding friction coefficient between the bolt and the loading bar, and the positioning of the loading bar. Not shown, but also of significance are the properties used for the material model and the modeling of the loading bar itself (deformable or rigid, if deformable, the shape to reduce computational time, and modeling with solid or beam elements). Since the loading bar actually becomes a cable in the system model and the cable modeling has not yet been completed, it is not practical to determine a "final" model for the hook bolt at this time. However, knowledge learned from this component analysis will significantly help determine a good hook bolt model when the system model is built.

Finally, it is always important to compare simulation to test results whenever possible. Even though this component modeling effort can not result in a "final" model, the models under consideration do compare well with testing, as shown in Figure 10. Results shown are from the same model with the difference being the loading direction. The parameters that influence results, as discussed above, were *not* optimized to match test results for Figure 10. They were simply chosen just to show that simulation is definitely in the ballpark of physical testing. Not until full-scale simulation of the 3-cable barrier system begins can a final model for the hook bolt be chosen.

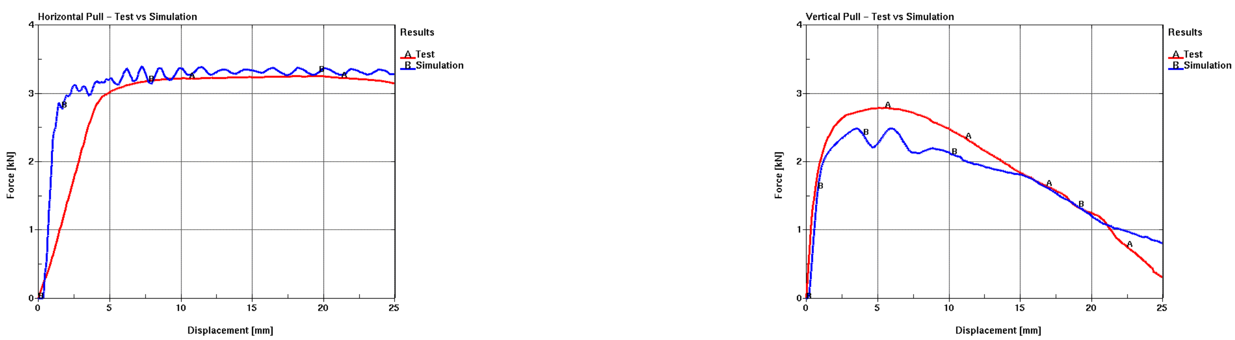


Figure 10. Test versus Simulation

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