Long Duration Shock Pulse Shaping Using Nylon Webbing

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ABSTRACT

Typical shock testing requirements specify shock pulses of several hundred to several thousand g's, with pulse duration usually less than a few milliseconds. A requirement to qualify a shipping container to a head-on tractor-trailer crash environment, led to the development of a new test technique capable of low-g (< 50 g), long-duration (> 100 ms) shock pulses. This technique utilizes nylon webbing engaged in tension to shape the pulse produced by the interaction of two sleds on an indoor track. A combination of experimental and computational methodology was used to successfully develop the test technique to solve a specific testing requirement. The process used to develop the test technique is emphasized, where a prudent balance between experiment and modeling resulted in a cost effective solution. The results show that the quasi-static load-elongation behavior of the nylon webbing can be used to adequately model the dynamic behavior of the webbing, allowing design of the experimental setup with a simple computational model. The quasi-static load-elongation measurements are described along with the development of the computational model. Results of a full-scale experiment are presented, showing that the required shock pulse could be achieved with this test technique.

INTRODUCTION

The Area III Mechanical Shock Lab at Sandia provides shock testing of large components and subsystems for various Sandia National Labs programs. Most environments are simulated with a haversine or other shock pulse shape having amplitude over 1000 g's and duration less than 5 milliseconds. At this facility, a high-speed pneumatic piston (actuator) is used to propel a sled along an indoor track. After traveling a few feet, the sled strikes a stationary sled which contains the test item. Both sleds then continue along the track where they gradually slow to a stop using pneumatic brakes. The impact between the two sleds is the action that produces the desired shock input to the test item. The shock pulse shape, amplitude, and duration are controlled as a function of the weight of each sled, the impact speed, and by various pulse-shaping materials placed on the impact surfaces. The elastic or crush properties these materials, which include felt pads, plastic or rubber slabs, and aluminum honeycomb, are used to control pulse shape. Two actuators are available at the facility. A 12" bore actuator is capable of propelling a 300 lb sled to 300 ft/sec, and an 18" bore actuator is capable of propelling a 1000 lb sled to 200 ft/sec. These launch speed capabilities allow shock pulses with high velocity changes, up to 300 ft/second.

A recent request to simulate the shock environment produced by a high-speed tractor-trailer crash was radically different from the typical high-g (>1000 g), short-duration (< 5 ms) shocks produced by actuator tests. In general, this environment produces a low-g (< 50 g), long-duration (> 100 ms) shock, with an associated velocity change up to 100 ft/sec (69 MPH). The specific test request for several large shipping containers was based on trailer deck acceleration measured during a 69 MPH head-on crash into an essentially immovable buttress. Although the measured acceleration shape was more complex, an "equivalent" haversine test pulse was developed using shock response spectrum (SRS) enveloping techniques. The resulting idealized test pulse requirement for one of the containers was a 33 g, 170 ms (baseline duration) haversine pulse, having a velocity change of about 90 ft/sec. The objectives of the test were qualification of the container and restraint system (chains), and validation of analytical models.

The test requirements provided a number of technical challenges. The cargo weight (up to 1200 lb) and size of the restraint system, which covers a 6' x 9' area, required a unique sled that nearly filled the available space surrounding the 18" actuator track. Even more challenging was developing a technique to produce such a long duration shock pulse. For a two mass collision the required pulse would result in a relative displacement of 4' to

7’ depending on the weights of each sled and on the coefficient of restitution of the material used to shape the pulse. Typical pulse-shaping materials such as Delrin have a maximum useable strain of about 4%, so a column of Delrin would need to be 100’ to 175’ long in order to allow the relative displacement required. Clearly, Delrin and other plastics were not acceptable. Even for materials such as rubber, where strains up to 50% are possible, a column about 10’ long would be needed. At this length, the column of rubber would buckle well before the required loads would be attained. Pneumatic cylinders were considered and determined to be technically feasible by placing one or more in series and/or in parallel between the two sleds, essentially acting as an undamped shock absorber. The peak forces required for the test (up to 150,000 lb) dictated a large total piston area. This along with the long stroke required meant very large and expensive cylinders, which proved cost prohibitive. In addition, the lead time to acquire the cylinders was unacceptable for the required test schedule. Ultimately, a low-cost test technique was implemented using nylon webbing engaged in tension to shape the required shock pulse. The development of this technique is described in the following sections.

SHOCK PULSE SHAPING CONCEPT

Figure 1 depicts the concept used to produce low-g, long-duration shock pulses using nylon webbing as the pulse-shaping material. The nylon webbing is engaged in tension by propelling the *impact sled* into looped nylon webbing as shown. The ends of the webbing are attached to the *test item sled,* which is initially at rest. When the impact sled engages the webbing, the test item sled begins to accelerate as the nylon is stretched. The nylon essentially acts as the spring in a two-mass single degree of freedom system. The natural frequency (or pulse duration) is determined by the weights of the two sleds and the stiffness of the spring (webbing). The stiffness can be changed as a function of the web length as well as the number of webs engaged in parallel. The impact sled was propelled by the 18” actuator indicated in the left side of figure 1. Since the test item sled was positioned between the actuator and the impact sled, the impact sled was fitted with a long column that extended beneath the test item sled to make contact with the actuator thrust column (piston rod). The test item sled was elevated above the track just enough to allow clearance of the actuator thrust column and the column attached to the impact sled. When the actuator was fired it pushed on the column, propelling the impact sled to the right in figure 1. Near the end of the actuator stroke (~3’) the impact sled separated from the thrust column and continued along the track.

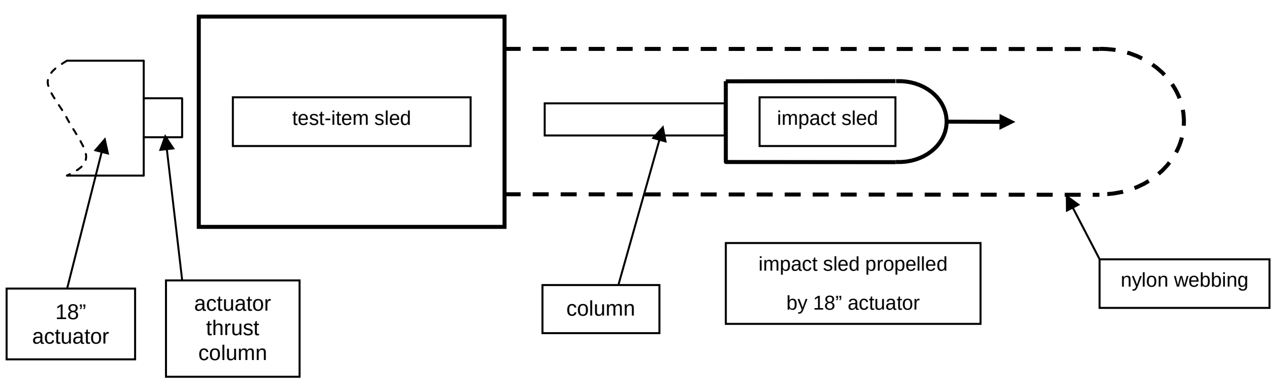

Figure 1. Shock test concept. At launch, the column of the impact sled extends beneath the test-item sled and is in contact with the actuator thrust column, which propels the impact sled to the right.

Load-elongation data is not readily available from most manufacturers of nylon webbing, however, failure load ratings and elongation at failure were more commonly available. One rope manufacturer[1] had products that typically exhibited 20% to 30% elongation at failure. Based on this information, it was estimated that strains of 10% to 15% could be utilized without failure of the webbing. For the relative displacement required (4’ to 7’), webbing 30’ to 50’ long (length L in figure 1) would be required to produce the required shock pulse, with enough webs in parallel to accommodate the peak loads produced by the 33 g pulse. At this conceptual stage of the project, there was considerable uncertainty with regard to the dynamic behavior of the nylon webbing. However, for the lengths required (~50’), and the time to peak strain (~.085 ms), the average strain rate is about 1.8/sec, which we viewed as low enough that quasi-static and dynamic behavior should be similar. After this conceptual development, the following project plan was outlined:

1. Pugeot Sound Rope, Anacortes, WA

1. Select nylon webbing and conduct quasi-static load-elongation measurements.
2. Develop a very simple calculation tool that solves the equations of motion of the two-mass and spring system, using the quasi-static load-elongation data to model the nylon webbing behavior.
3. Use this design tool to select webbing length and number of webs, to produce the desired shock pulse.
4. Conduct a few full-scale calibration experiments with selected webbing length/quantity to evaluate the actual nylon performance as compared to the prediction.
5. Adjust the model if required, to allow the selection of the webbing length/quantity needed to produce the required shock pulse.
6. Conduct the required shock test on the shipping container.

This project plan was selected to reach an engineering solution for a specific test requirement, which had significant budget and schedule constraints. In particular, we had no desire to turn this into a research project on the dynamic properties of nylon webbing. The approach relied on experimental methodology, along with simplistic semi-empirical modeling of the nylon material. The quasi-static load-elongation measurements required no more than two days of lab time. The calculation tool required about one day to develop in Microsoft Excel using approximations to the quasi-static data for the webbing behavior. The emphasis here is that resources were expended only to the extent necessary to reach a solution to the test requirement. Considerably more time was spent on sled design and fabrication, and on conducting the full-scale calibration experiments.

QUASI-STATIC LOAD ELONGATION

Two-inch wide nylon webbing manufactured by Southern Weaving[2] was selected for the project. The manufacturer rated this product at about 19,600 lb breaking strength, but was unable to supply load-elongation information. We performed a few simple experiments using a tensile test machine to measure the quasi-static load-elongation of a single web. Figure 2 shows the experimental setup in the test machine. An eye was sewn on each end of the webbing using Kevlar thread with a zigzag stitch. This left approximately 8" of web exposed between the eyes, where an extensometer was attached to measure the elongation. Each end of the of the extensometer was attached to a custom clamp that was intended to remain attached at a fixed point on the web, without significantly affecting the performance of the web as it was stretched. The distance between clamps was approximately 5 inches. Figure 3 shows the construction of the clamp, which had a double row of needles that anchored it to the web by piercing through the yarn. This design allowed minimal clamping pressure to be applied to the web, which otherwise might have damaged the yarn. This design was selected in favor of a frictional clamp, which we thought could slip as the cross-sectional dimensions change during stretching. This clamp performed adequately for the experiments we conducted, although if additional testing is needed, we would make a few modifications. The length of the clamp (parallel to the warp) could be increased to reduce rotation of the clamp, and a non-rigid adhesive could be included to improve connection with the web. As it was, we estimated that the clamp introduced a bias error in the strain measurement of no more than .005 strain, which was quite adequate for the measurements we required. Force measurements were made with a load cell attached to the head of the tensile test machine.

The webbing was first loaded to 7000 lb then unloaded to 100 lb, to provide a pre-stretch cycle. We wanted to measure the load-elongation data for pre-stretched conditions since we intended to use the same webbing for multiple shock tests. After the initial pre-stretch cycle, the webbing was loaded again to 7000 lb followed by unloading. On the next cycle, the loading was taken to 14,000 lb followed by unloading. The loading was essentially quasi-static, with about 200 seconds for the loading cycle and about 240 seconds for the unloading cycle. Figure 4 shows the result of the load elongation measurements. Only one loading curve is shown, since the 0 to 7000 lb portions of both cycles were nearly identical.

2. Southern Weaving Co., Greenville SC

Figure 2. Load elongation measurement setup

Figure 3. Clamp detail (actual picture to be used will show clamp detail)

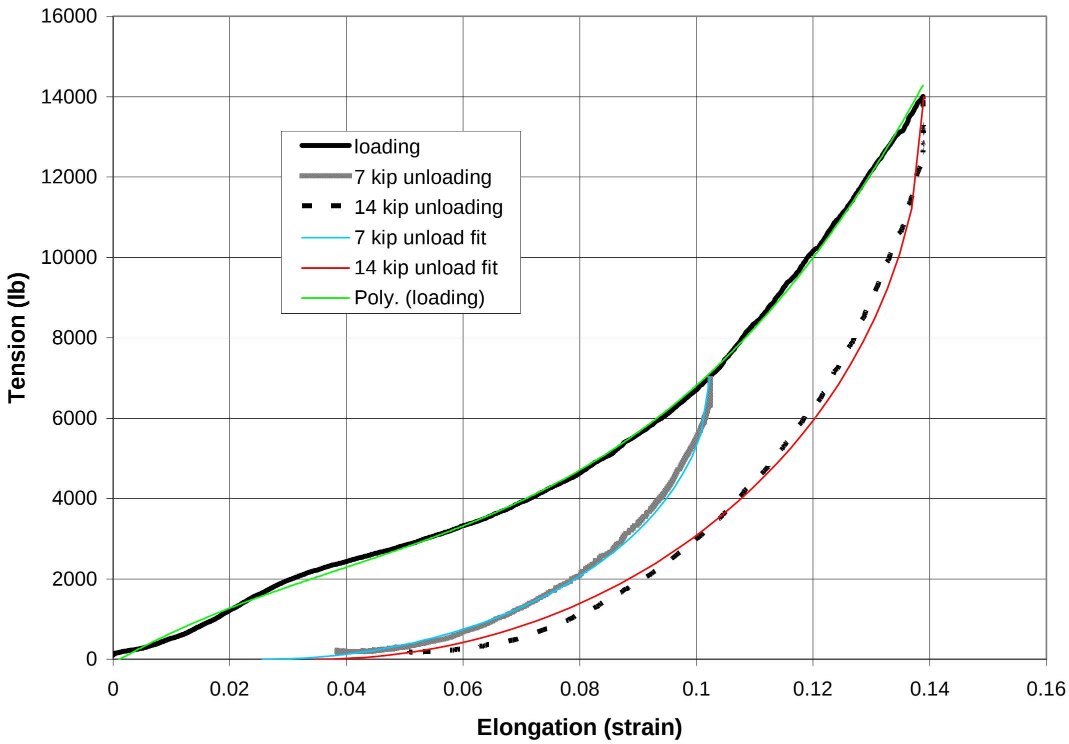

Figure 4. Measured quasi-static load-elongation for the 2" wide nylon webbing, along with analytic curve-fit approximations

MODELING THE WEBBING

Curve fitting techniques were used to approximate the measured load-elongation data with analytical functions. The loading curve was fit with a third order polynomial using least squares. The unloading curves were more difficult, since a family of curves is required to allow unloading from any point along the loading curve, and we had only two measured unloading curves to work with. We found that the unloading curves could be adequately approximated with a circular arc, with center at a point that is a function of the load and elongation at the transition to unloading. The following equations were used to approximate the measured load-elongation data.

Loading:

$$P = k_3\varepsilon^3 + k_2\varepsilon^2 + k_1\varepsilon + k_0 \qquad (1)$$

Where:
P = tension in nylon web during loading
ε = strain in nylon web during loading
Least square constants:
k_0 = 7.379653 x 10^6
k_0 = -8.747806 x10^5
k_0 = 8.276403 x 10^4
k_0 = -93.57704

Unloading:

$$(\varepsilon - c\varepsilon_m)^2 + \left[\frac{\varepsilon_m(1-c)}{P_m}\left(P - P_m\right)\right]^2 = \varepsilon_m^2(1-c)^2 \qquad (2)$$

Solving for P:

$$P = P_m\left(1 - \frac{\sqrt{\varepsilon_m^2(1-c)^2 - (\varepsilon - c\varepsilon_m)^2}}{\varepsilon_m(1-c)}\right) \qquad (3)$$

Where:
P = tension in nylon web during unloading
ε = strain in nylon webbing during unloading
P_m = tension in web at transition from loading to unloading
ε_m = strain in web at transition from loading to unloading
c = .25 (empirical constant for best fit to data)

Figure 4 shows the curves fit to the measured load-elongation data, using the equations above. These analytical functions were then used in the equations of motion of the two-mass system depicted in figure 1. In addition to the tension of the nylon webbing acting between the two sleds, friction forces were included to accommodate the action of the pneumatic sled brakes. The equations of motion were solved using a simple trapezoidal integration algorithm that was programmed in a Microsoft Excel spreadsheet. This simplistic solution technique was easy to implement, and proved quite adequate for the requirements of this project. The algorithm accounted for the transition from loading to unloading by monitoring the elongation of the webbing. When the elongation reached a maximum, the algorithm saved the maximum conditions and transferred calculations to the unloading equation.

RESULTS OF CALIBRATION EXPERIMENTS

The test-item sled, shown in Figure 5 was designed based on the size and weight of the test item and with respect to the maximum loads anticipated. For the calibration shots, the mass of the actual test item was simulated with rigid steel ballast attached to the sled. The platform was designed to simulate the trailer deck and was sized to accommodate the shipping container and its restraint system. The impact sled, shown in Figure 6 took advantage of existing sleds and other hardware. Note the spool-shaped fixture that engages the webbing at impact. The two sleds are shown separated in figures 5 and 6, but at launch, the impact sled is positioned so that the aluminum column extends beneath the test-item sled and rests against the actuator thrust column, as shown in the right side of figure 6. Figure 7 shows the test-item sled with the shipping container installed with the chain restraint system.

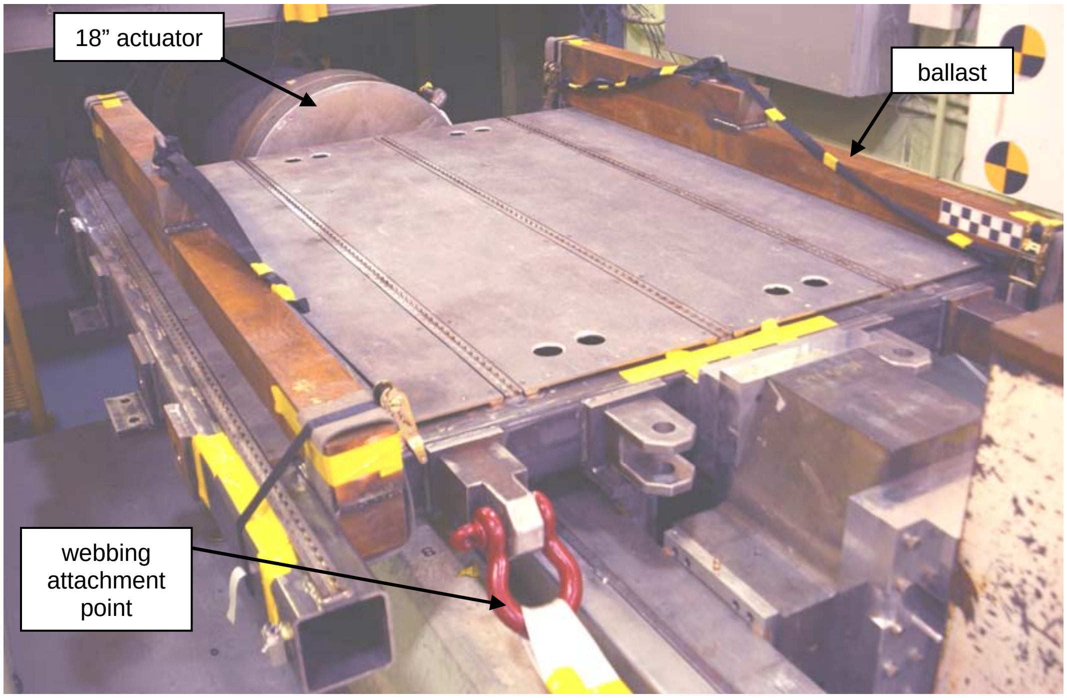

Figure 5. Test –item sled

Figure 6. Left: impact sled. Right: configuration for calibration shot, showing nylon loop crossing track, and impact sled in position with column extending beneath the test-item platform

Figure 7. Shipping installed on test-item sled with restraint tie-down system

Based on calculations from the analytical model above, the length and quantity of webbing was selected to produce the desired shock pulse. Several calibration shots were conducted, starting at about 23 g's and incrementing up to the 33 g amplitude required. For these calibration shots, the impact speed was the only parameter varied. Higher impact speed produced higher amplitude without significantly changing the pulse duration. Table 1 lists relevant parameters for the final calibration shot. It should be noted that the braking forces had to be optimized to allow minimal affect on the motion of the sleds, but also prevent impact between the two sleds as they approached each other following engagement with the nylon.

Figure 8 shows the acceleration pulse for the final calibration shot, along with the predicted pulse and haversine test requirement. The agreement between the measured pulse and the predicted pulse is quite good considering that quasi-static load-elongation data from a single experiment was used to model the behavior of the webbing. We were expecting the dynamic behavior to cause a much greater difference than observed, and we were prepared to experimentally iterate to the final test conditions (nylon length and quantity of webs). However, the agreement with the model was so good, that we did not need to change the nylon at all, but merely adjusted impact speed to achieve the desired pulse amplitude for the actual test on the shipping container.

Measurements from the calibration shot enabled us to calculate dynamic load-elongation for the webbing. Figure 9 shows the dynamic web behavior compared to the quasi-static behavior used in the computational model. Except near the transition from loading to unloading, the dynamic and quasi-static behaviors are very similar. This difference undoubtedly explains the higher peak amplitude predicted by the model. The comparisons shown in figures 8 and 9 were also done for other calibration shots, including configurations intended to produce 45 g, 100 ms haversine test requirements. Similar agreement was obtained for all calibration configurations. In each case, the prediction matched the measured pulse, except near the peak, where the prediction was consistently 12% to 17% higher than the measured pulse.

Table 1. Parameters for Final Calibration Shot

Total weight of test-item sled and ballast	2953 lb
Total weight of impact sled	5733 lb
Length of webbing (length L in figure 1)	51 ft
Quantity of webs acting in parallel	8 (4 in each leg of figure 1)
Constant brake force on test-item sled	9150 lb
Constant brake force on impact sled	1780 lb
speed of impact sled at initial contact with webbing	92.5 ft/sec

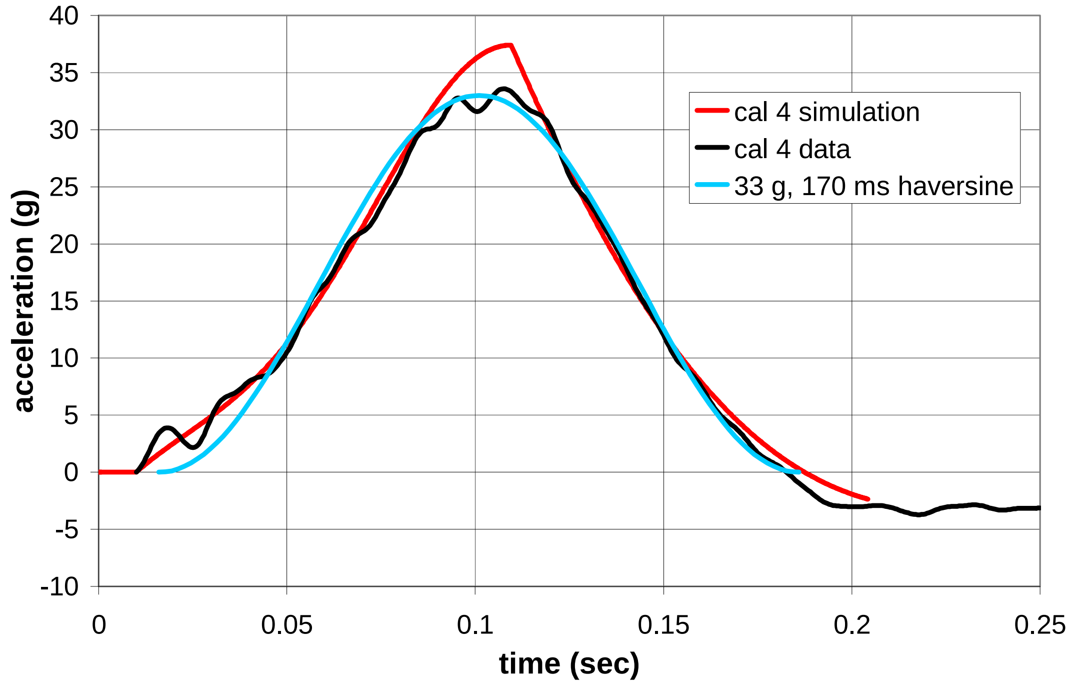

Figure 8. Test-item sled acceleration measured during the final calibration shot, compared to the model prediction and haversine test requirement

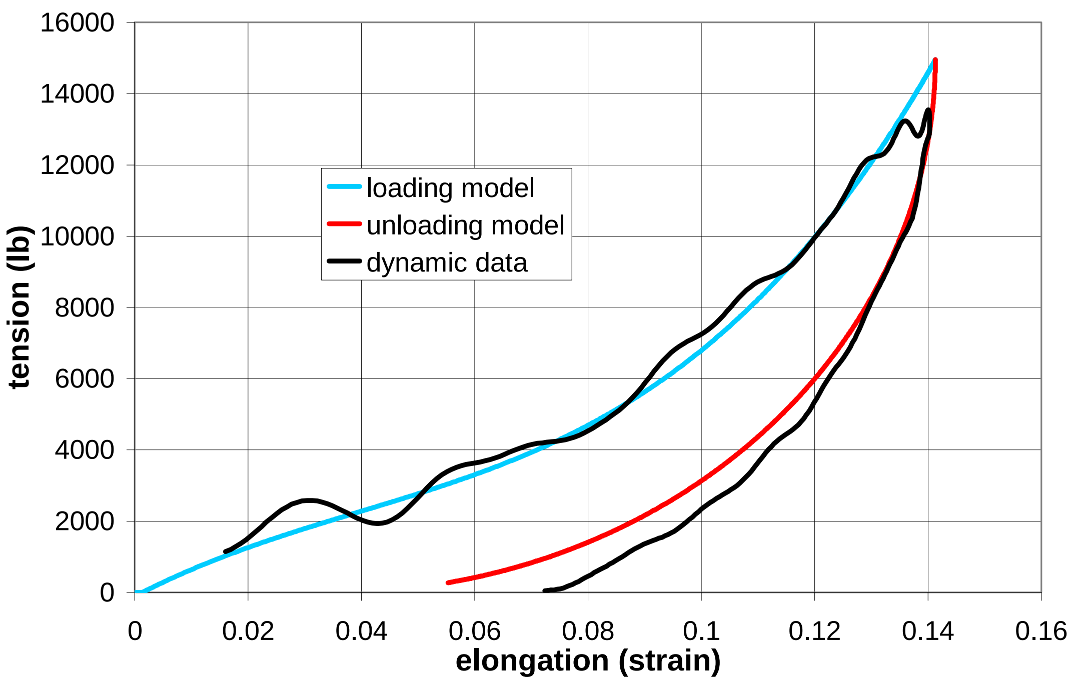

Figure 9. Dynamic load-elongation response of the nylon webbing compared to the quasi-static model

CONCLUSION/SUMMARY

A shock testing technique, capable of producing low-g long-duration shock pulses was developed by utilizing the elastic behavior of nylon webbing connected between two sleds to produce a controlled shock pulse shape on the test-item sled. This technique was developed specifically for qualifying a shipping container and its restrain system to a 33 g, 170 ms shock pulse that simulates a head-on crash environment for a tractor-trailer into an immovable buttress. A simple computational model of the two-sled dynamic system was developed using measured quasi-static load-elongation data for the webbing behavior. Several calibration shots were conducted that showed the model accurate enough to allow selection of test parameters for producing the required shock pulse. Ultimately, this technique was utilized to subject the shipping container and restraint system to the required 33 g, 170 ms shock pulse.

The development of this test technique emphasized a minimalist approach which utilized both experiment and modeling to reach an engineered solution to a specific test requirement, within budget and schedule constraints. Development of a simple computational model virtually eliminated the need for a trial-and-error experimental approach that would have been required if a totally experimental approach had been used. However, we also did not over-invest in modeling, which could have adversely affected the cost and schedule of the project, with only marginal increase in computational fidelity. An example of over-investment in modeling would have been the use of a finite element code to model what is essentially a one-degree-of-freedom system. If this technique were to be developed into a general purpose test platform, requiring a wide variation in shock pulses, it would be worth investing a little more effort to include the dynamic load-elongation behavior of the nylon, which differs slightly from the quasi-static behavior used in the computational model. This could be accomplished with the same simple computational approach, but with a dynamic webbing behavior instead of the quasi-static behavior used for this project.