SMALL-SCALE EXPERIMENTAL STUDY OF THE EFFECT OF NONSTRUCTURAL MASS ON DEBRIS IMPACT FORCES

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Abstract

Small-scale experimental tests have been carried out to investigate impact forces when flexible debris hit a relatively rigid structure. The tests involved HSS2x2x1/8 steel tubes of two and three meters in length impacting a load cell. The tests herein are an extension of work by Paczkowski et al. (2012). As compared to those tests, the tests herein included a more detailed measurement of strains in the projectile, as well as ‘nonstructural’ mass added to the steel tube. The purpose of this additional mass was to gain an initial understanding of how the mass of contents inside a shipping container might affect impact.

Analysis of the new tests supported the findings presented in Paczkowski et al. (2012). Based on the more detailed strain measurements herein, the stress wave propagation in the specimens was reanalyzed. Due to an uneven contact surface, bending caused the stress wave to propagate unevenly in the cross section along the specimen length. A step force with a finite rise time is used to possibly explain the load cell response. The analysis of the periods of the oscillations during impact may explain the load cell force-time history and its sudden changes in magnitude. The strain gages provided consistent results when analyzing the forces in the specimen. The force calculated from these strains was determined to be about 70% to 80% of the one-dimensional theoretical solution. The decreased response may be explained by the uneven contact surface causing a problem that is not one-dimensional and/or the ability of the experimental setup to model the necessary boundary condition of zero displacement.

After a thorough investigation of the original test setup, the nonstructural mass effect was investigated. Nonstructural mass can have a small additive effect in force during the impact of up to 20%. As the stress wave returned to end the impact, the specimen temporarily remains in contact with the load cell. This contact allows the nonstructural mass to transfer its own effect to the load cell before rebounding. This effect is greatest when considering heavier masses. Analysis of the strains in the specimen indicates that the nonstructural mass acts as its own body, separate from the specimen. The results indicate that the nonstructural mass effects should not be ignored for impact.
design. Additional testing is needed to fully evaluate this effect due to the experimental limitation of how much weight was added during testing and the impact velocities that were achieved.
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1. **Introduction**

1.1. **Background**

Recent tsunamis, such as the incidents in Chile 2010 and Japan 2011, have shown that damage to life and to property can be significant in these events as seen in Figure 1.1. In addition to the hydrodynamic forces, objects in coastal areas, such as telephone poles and shipping containers, can pose a serious threat if they become floating debris. Code provisions for tsunami-related design are scarce, and the codes that do provide guidance on evaluating debris forces are based on the theory of rigid body impacts. No consensus can be made between codes on certain design parameters such as the impact duration.

![Figure 1.1: Shipping Containers after the Chile Earthquake/Tsunami in Talcahuano](Garcia, 2010)

This report focuses on shipping containers with an emphasis on the amount of mass they carry. A standard 20-foot (6.1m) shipping container has an empty
weight of about 5,000 lb (2,200 kg). When loaded, the container can have a weight of up to 53,000 lb (24,000 kg), up to 10 times the empty weight of the container. With 40-foot (12.2m) shipping containers, the empty weight would be about 8,000 lb (3,700 kg) and a full weight of 67,000 lb (30,500 kg), about eight times the empty weight. A reasonable flow velocity for a loaded shipping container can be estimated at 10 to 20 mph (Paczkowski et al., 2012). Considering the significant difference in mass between a loaded container and an empty container, the need to evaluate the effects of nonstructural mass on impact forces is emphasized in this report.

Testing considered the design condition of a flexible projectile impacting a rigid supporting element such as a column or a wall. Studies have shown that a concrete or steel column when struck by a flexible projectile, such as a shipping container, is essentially rigid when compared to the projectile (Mikhaylov, 2009). In order to design the structure to withstand tsunami and tsunami-debris forces, theoretical modeling and experimentation need to be carried out. Shipping container impacts have been noticed in the recent Chile 2010 and Japan 2011 tsunamis, and these impact studies are gaining popularity due to past research done on woody debris. The goals of this report were to supplement test procedures and results and to provide an insight on how to evaluate the impact forces. The ultimate goal of testing was to gain results that could relate to the mass effect of the cargo that shipping container hold during a tsunami impact.

1.2. Objective

The initial objective of the author was to investigate the effects of nonstructural mass on the existing test setup. In order to understand these effects, the structural response without nonstructural mass first needed to be evaluated. Paczkowski et al. (2012) investigated the structural response without nonstructural mass. Their load cell force varied up to 27% from the theoretical force due to oscillations, and there were insufficient strain gages on the specimen to calculate a force. This study utilized more strain gages to analyze
the more detailed stress wave propagation and to calculate a force in the specimen. Through more tests, the theoretical force was correlated with the load cell force and the force calculated from the strain gages on the specimen. By adding weights to the specimens and testing them in the same manner, the effects of nonstructural mass can be evaluated by the change in the original structural response without nonstructural mass compared to the new tests with the addition of nonstructural mass.

1.3. **Literature Review**

1.3.1. **Theory**

For its practical use, the results of a one-dimensional model of impact were compared to the experimental results. Basic assumptions were made to simplify the model. Flexible projectiles were homogeneous, isotropic, and linearly elastic with a uniform density. The equation of motion no longer modeled a lumped mass system because an infinite number of particles must be considered. To evaluate the model, a partial differential equation involving space ($x$) and time ($t$) must be used. All degrees of freedom were ignored except the projectile’s displacement ($u$) in the longitudinal direction. An analysis of the one-dimensional forces over a segmental increment of the projectile yields the wave equation:

$$\frac{d^2 u}{dt^2} = c^2 \frac{d^2 u}{dx^2}, \quad c = \frac{E}{\sqrt{\rho}}$$

in which $c$ is the speed of sound in a medium, $E$ is the elastic modulus, and $\rho$ is the mass density.

This report will consider a flexible projectile impacting a rigid wall. Upon impact, two boundary conditions exist. The displacement at the contact surface is zero, and the force at the opposite end is zero. The initial condition is that the velocity everywhere is $v$. A stress wave is generated that will travel down the flexible projectile as a function of position and time.
The wave solution for the projectile hitting a rigid wall results in a stress wave of magnitude, $\sigma$:

$$\sigma = \frac{Ev}{c} = \rho vc.$$

This solution represents the structural response of the projectile. As considered, this response does not reflect the effects of any added nonstructural mass. However, this solution gives a numerical approximation of the stresses upon impact. Since this solution is based on a planar contact surface hitting a rigid wall, it can be taken as a unique upper bound.

1.3.2. **Initial Investigation**

The experimental setup used for this report was designed by Paczkowski et al. (2012) to investigate impact forces. The tolerances to certain design elements were relaxed compared to similar impact testing that has been published previously. The relaxed tolerances were acceptable to consider accurately the realistic impacts that can occur. Definite conclusions can be made on the impact duration and wave propagation speed. Results indicated that the impact duration is slightly longer than theory. The propagation speed matched acceptable values for structural steel. The load cell outputs exhibited high frequency oscillations during impact. Load cell force readings varied up to 27% from the theoretical force. Four different length specimens were used in the tests: 1m, 2m, 3m, and 4m. These different lengths will have different impact durations, and the dynamic effects of the oscillations will have varying effects. Forces calculated from strain gage data did not always match load cell forces. This discrepancy can be explained by an insufficient number of strain gages to evaluate force. Paczkowski et al. (2012) provides a more detailed explanation including the finite element model and the theoretical background used as the basis for their study.

1.3.3. **Past Experimentation**

Conway and Jakubowski (1969) investigated wave propagation on short cylindrical bars using a modified Hopkinson-bar apparatus. As stated in their article, a planar contact surface would be easier to analyze compared to the end
effects created using a rounded end. Strain time histories were collected, and an agreement with the linearly elastic theory can be made from results located further away from the impacted face. The tests utilized two identical bars that impacted each other at the same velocity. Considerable care was taken to ensure a perfectly planar impact including the use of optical techniques to create a planar contact surface on the specimen and carbon paper to inspect a uniformly dense imprint of the contact surfaces. Audio techniques were used to check the presence of bending modes, and the strain gage readings should be identical unless there is misalignment.

Their findings were similar to results gathered by the author and past researchers. The duration of impact was larger than the classical theory. Higher accuracy was achieved by increasing the impact velocity to avoid the cushioning effects of air. However, Conway and Jakubowski (1969) also considered Love’s theory, which takes a one-dimensional energy approach. Considering the cushioning effects of air, they rationalized the use of ramp loading as their end effects. With ramp loading, the agreement between experimental results and theoretical results was greatly improved.
2. Experimental Setup

Figure 2.1 illustrates the impact set up. The projectile is guided down the rail and impacts a horizontally mounted load cell. A high speed camera and data acquisition system (not shown in Figure 2.1) is used to collect data from the tests. In this section, the instrumentation and test specimen are described. The nonstructural mass setup (not shown on the projectile in Figure 2.1) will also be described through the use of fabricated mounts and free weights.

2.1. Instrumentation

2.1.1. Load Cell

The MTS Fatigue Resistant Load Cell, Model 661.23A-01 (Figure 2.2) was used to measure the impact force. It has a diameter of 6 inches (152.4 mm) and a length of 7 inches (177.8 mm). Its static capacity was 55 kips (244 kN) with a spring constant of 17 million pounds per inch \( (3.0 \times 10^3 \text{ kN/mm}) \). The total weight of the load cell was 32.9 lb (14.916 kg).
The load cell was mounted horizontally onto a stiffened angle bracket fabricated with steel plates welded together. Details of this steel back support are given in Figure 2.3. Six 3/4" diameter bolts arranged in a 3.5" diameter bolt circle were used to mount the load cell onto the angle bracket. The angle bracket rested on 3 square steel shims and was secured to the laboratory floor using a 1” threaded rod and nut. The nut was torqued using a pneumatic impact wrench to provide the necessary pressure to secure the setup to the ground. A steel plate was secured to the front of the load cell to protect the load cell from damage.
2.1.2. **Strain Gages**

SR-4 strain gages (Figure 2.4), model CEA-06-250UN-350/P2 from the Vishay Precision Group were used. The electrical resistance strain gages were attached to the steel projectile at various locations to measure longitudinal strain. The grid resistance was 350 ohms with a gage factor of 2.12.
2.1.3. **Data Acquisition System**

The data acquisition system (Figure 2.5) consisted of a National Instruments SCXI-1000 mainframe. The SCXI-1000 chassis supported up to four SCXI modules. The SCXI-1600 was a USB data acquisition and control module. It was used to obtain data from the load cell and strain gages. The coaxial input connector was used as a trigger to begin data collection. Two SCXI-1520 modules were needed to input the load cell and strain gage data.
2.1.4. High Speed Camera

The MegaSpeed MS30K high-speed camera (Figure 2.6) has a capture rate of up to 1000 frames per second. It has a picture resolution of up to 1280x800, but 960x600 was used in the experimentation to ensure a successful dump from the camera’s onboard RAM to the computer’s hard drive.
2.2. **Test Specimens**

A structural steel HSS2”x2”x1/8” section was used for the experimental testing. No structural modifications were made to these specimens except cutting them to length with both ends open. Table 2-1 provides important section and material properties that were used in calculations.

<table>
<thead>
<tr>
<th>Table 2-1: Assumed Properties of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, Area</td>
</tr>
<tr>
<td>ρ, Density</td>
</tr>
<tr>
<td>(c_p), Speed of Sound in Steel</td>
</tr>
<tr>
<td>(E), Elastic Modulus</td>
</tr>
<tr>
<td>2m Specimen</td>
</tr>
<tr>
<td>3m Specimen</td>
</tr>
</tbody>
</table>

2.2.1. **2m Length**

The steel section was cut to a two meter length. Strain gages were placed at the following three sections of the HSS tube for this length.

-2 inches away from the impact face
-18 inches away from the impact face
-1 meter away from the impact face (at the middle of the tube)

Figure 2.7 provides an illustration of the location of these sections and the location of each strain gage on the section face.
2.2.2. **3m Length**

The steel section was cut to a three meter length. Strain gages were placed at the following three sections of the HSS tube for this length.
- 2 inches away from the impact face
- 27 inches away from the impact face
- 1.5 meter away from the impact face (at the middle of the tube)

Figure 2.8 provides an illustration of the location of these sections and the location of each strain gage on the section face.
2.2.3. Comments/Remarks

Prolonged storage in the laboratory resulted in noticeable surface rust to the test specimens. Additional strain gages were attached to the test specimens due to prior testing conducted by Paczkowski et al. (2012). To avoid the effects of rusting, all pertinent strain gages were replaced and used within a year’s time. Due to their delicacy, strain gages were vulnerable to damage during storage in the laboratory and during testing. Strain gages were replaced when needed.

2.3. Nonstructural Mass Setup

Free weights were used to add nonstructural mass to the specimen. Mounts were designed and fabricated for the temporary application of these weights for testing.

2.3.1. Mounts

Mounts were fabricated using a 2.5” length, ¾” diameter threaded rod welded at the base to a steel plate (PL3”x1.5“x1/8”) as shown in Figure 2.9. Washers and nuts were used to secure the weights during testing.

Figure 2.9: A Typical Mount Used to Add Free Weights onto the Specimen

Two mounts were placed on each specimen in the configuration shown in Figure 2.10. The mounts were placed a distance of 10% of the length away from the center of the specimen, center-to-center, in front and behind. JB-Weld, a two-part steel-reinforced epoxy, was used to attach the mounts.
Table 2-2 provides mass details for the tests being considered. The label ‘X.Y’ indicates the ‘X’ specimen length and the ‘Y’ indicates the nth mount from the impact face. Two sets of mounts were used because the epoxy failed during testing of the 10 lb weights described in section 2.3.2. Specimen ‘before’ weights include all strain gages that were attached to them. Specimen ‘after’ weights include the ‘before’ weights plus all mounts, washers, nuts, and epoxy. Mounts were similar in weight for the two sets. The addition of the mounts increased the weight of the specimens by 1.3 lb, but testing revealed that the effects of these mounts were insignificant. Generally, the first set of mounts was used for nonstructural mass tests of up to 5 lb per mount. The second set of mounts was used for the nonstructural mass tests of 10 lb per mount.

<table>
<thead>
<tr>
<th></th>
<th>Set 1</th>
<th>Set 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Mount</td>
<td>0.4225</td>
<td>0.4190</td>
</tr>
<tr>
<td>Washer</td>
<td>0.0860</td>
<td>0.0800</td>
</tr>
<tr>
<td>Nut</td>
<td>0.1120</td>
<td>0.1145</td>
</tr>
<tr>
<td>SPECIMEN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>19.5</td>
<td>28.9</td>
</tr>
<tr>
<td>After</td>
<td>20.8</td>
<td>30.2</td>
</tr>
</tbody>
</table>
2.3.2. **Weights**

Solid cast-iron weighted plates shaped in a circular disc raised at the center and at the edges were used to add mass to the specimens. They are presented in Figure 2.11. These are standard free weights commonly used in weight lifting.

Three different weight plates were used: 2.5 lb, 5 lb, and 10 lb. The specification of each plate is given in Table 2-3.

![Figure 2.11: Typical Free Weights](image)

**Table 2-3: Free Weights Specifications**

<table>
<thead>
<tr>
<th>Weight</th>
<th>Sample</th>
<th>Actual Weight</th>
<th>Inner Diameter</th>
<th>Outer Diameter</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1</td>
<td>2.4245</td>
<td>1.125</td>
<td>5.375</td>
<td>0.6875</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.3350</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5.0860</td>
<td>1.125</td>
<td>6.625</td>
<td>0.9375</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5.1100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>10.3670</td>
<td>1.125</td>
<td>8.75</td>
<td>1.3125</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9.9215</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. **Procedure**

3.1. **Testing**

The specimen was placed on the fabricated steel rail. The rail was designed to guide the specimen to the load cell. The impact was designed to be at its worst case: a head-on longitudinal impact of the specimen hitting the load cell squarely at its center. The strain gages were connected to the data acquisition through the use of a strain board according to the strain configuration being considered. Strain configurations will be explained in the “Results” section of this report. The load cell was connected to the data acquisition. The high speed camera was placed in an optimal position to capture the impact. A flood lamp was used to improve the picture quality of the video. If weights were used, the weights were placed on their respective mounts and secured by hand using a washer and nut. If no weights were used, the washer and nut were not used. An illustration of the rail and impact surface is provided in Figure 2.1

To propel the specimen, it was manually pushed from behind using the rail as a guide. The specimen was allowed to glide a distance before impacting the load cell. As weights were added to the specimen, the increased friction from the rail made it difficult for the specimen to glide on its own. When 10 lb were placed on each mount, it was impossible for the specimen to glide on its own. Therefore, Tri-Flow superior lubricant aerosol was used on the rail before the placement of the specimen for the tests involving the 10 lb weights. The Tri-Flow lubricant significantly decreased the friction along the rail. No significant effort was required to push the specimen with the 10 lb weights mounted onto it.

3.2. **Analysis**

Impact velocity was determined using the high speed camera and a tape measure. Velocity was measured using the time stamps from the high speed camera that collected 1000 frames per second of the specimen’s front end reaching the 3.0 cm distance and 1.0 cm distance away from the impact face.
The data acquisition system collected the time histories of the load cell and six strain gages at a sampling rate of 25,000 Hz (i.e. every 0.00004s).

To evaluate the effects of nonstructural mass, six trials were conducted for each different test combination involving weights, specimen lengths, and strain gage configurations. Details of these different test combinations will be explained in the “Results” section of this report if needed. A total of 120 trials were expected, but only 117 trials were carried out due to an additional failure of the epoxy securing the mounts.
4. Results

4.1. Overview

The following sections will analyze the test data.

Section 4.2 will analyze the test results for the original test setup. Nonstructural mass was not used in the analysis of section 4.2. New data collected herein as well as the load cell data from Paczkowski et al. (2012) will be used to understand the dynamic response of the load cell. With the strain gages shown in Figure 2.7 and Figure 2.8, the stress wave propagation will be analyzed for the front half of the specimens. A comparison will be made between the load cell force and the strains in the specimen.

Section 4.3 and section 4.4 will analyze the nonstructural mass effects for the two specimens. Two specimens were chosen to ensure conclusions can be made based on more than one specimen length. Testing of the nonstructural mass was divided into sets of trials with each set consisting of six trials. These sets were determined by the various combinations of specimen length, strain gage configuration, and weights that were being used. Strain gage configuration will be explained when needed.

Comparisons between the trials were difficult to compare because the calculated impact velocities varied. Nondimensionalization of force, strain, and time were used to compare the results:

\[
\text{Nondimensional Force} = \frac{\text{Force}}{EA\frac{v}{c}}
\]

\[
\text{Nondimensional Time} = \frac{\text{Time}}{L/c}
\]
\[ \text{Nondimensional Strain} = \frac{\text{Strain}}{v/c} \]

in which \( L \) is the specimen length. These nondimensional values are based on the one-dimensional theory. A nondimensional force of one represents 100% of the one dimensional theoretical force. A nondimensional time of one represents the time needed for the stress wave to travel the length of the specimen. Therefore, a nondimensional time of two represents the impact duration. The strain was nondimensionalized by the one-dimensional theory for strain.

Comparisons between trials can be made if the impact velocities are approximately equal. Otherwise, comparisons must be made through nondimensionalization.

### 4.2. Original Test Setup

To investigate the effects of nonstructural mass on debris impact, the structural mass effects needed to be understood. Paczkowski et al. (2012) investigated these effects. The tests were conducted again with the exact experimental setup and the same 2m specimen and 3m specimen. Their findings were confirmed. The following sections reanalyzed existing data as well as the new data to understand the dynamics of the load cell and the stress wave propagation.

#### 4.2.1. Reassembly of Load Cell and Its Response to Impact

Paczkowski et al. (2012) conducted their tests using two different assemblies. In November 2010, the 1m, 2m, and 3m specimens were tested using the experimental setup described in this report. Afterwards, a cubic meter block of concrete was tested as the back support and the load cell was detached. However, it was reattached because the steel back support provided a better rigid support. Paczkowski et al. (2012) tested the 4m specimen in March 2011 after reattachment. The tests were repeated using the 2m specimen and the 3m specimen. The results are shown in Figure 4.1 and Figure 4.2. The nondimensional time was calculated based on a 1m specimen to compare
specimens of different length along the same time frame. Therefore, an impact duration of 2 was expected for a 1m specimen, a duration of 4 for the 2m specimen, a duration of 6 for the 3m specimen, and a duration of 8 for the 4m specimen. With this exception to nondimensional time for section 4.2.1, all other analysis involving nondimensional time follows the convention presented in section 4.1 with an impact duration of 2. Assembly 1 represents the time history of the trials that were achieved during the testing of November 2010. Assembly 2 represents the time history of the trials that were achieved after March 2011. Because of reattachment, the time history of the load cell changed. For the new tests carried out herein, the load cell setup was unbolted from the ground and re-bolted to the ground. However, the load cell was not detached from the steel back support. This change is significant for further testing. The load cell force-time history was similar. However, the impact face of the load cell can never be aligned exactly like assembly 2. This has a great effect on the stress wave propagation as the change would be evident in the strains closest to the impact face. For the nonstructural mass testing, these tests were repeated.

Figure 4.1: Nondimensional Load Cell Force for Trials with an Impact Velocity of 3.2 mph under Assembly 1 (Paczkowski et al., 2012)
Figure 4.2: Nondimensional Load Cell Force for Trials with an Impact Velocity around 3.0 mph under Assembly 2 (Paczkowski et al., 2012)

Figure 4.1 and Figure 4.2 also illustrate the load cell response to the impact. The load cell response to the impact of the HSS section was similar despite the length and total mass. Having the same response can be explained by having the same section and material properties which is supported by the one-dimensional solution. However, having that solution stay constant over the duration of the impact is not represented in Figure 4.1 and Figure 4.2. An analysis of the dynamic response of the load cell was needed.

4.2.2. Step Force with Finite Rise Time

The one-dimensional solution is a finite step force with no rise time. However, an instantaneous increase in force is unrealistic. The use of a ramped step force is supported when considering the stiffness of the load cell and specimen. Conway and Jakubowski (1969) also considered a ramp step force when they conducted their modified Hopkinson-bar apparatus test. They rationalized the step force
due to a cushioning effect from air. However, the effect of air was minimized with an increase in impact velocity. The step force with rise time did improve their theoretical model to match their experimental data. Figure 4.3 illustrates the dynamic response of an undamped single degree-of-freedom system to a step force with a finite rise time \( t_r \) less than the natural period, \( T_n \). This condition is similar to the dynamic response in the load cell during impact.

![Figure 4.3: Dynamic Response of Undamped SDF System to Step Force with Finite Rise Time (Chopra, 2007)](image)

### 4.2.3. Periods of the Forced Oscillations

Impact forces exhibit high frequency oscillations that are not harmonic in nature. Figure 4.4 and Figure 4.5 represent a trial from each assembly. They are analyzed in Table 4-1 and Table 4-2. Peaks were considered to be the local minimums and local maximums of the figures. Full response periods were calculated based on successive half-periods with a ‘response period’ equal to twice the difference of time between a maximum peak and a minimum peak. The tables suggest that the initial oscillations with a response period of 0.1 ms do not vary much. However, longer response periods are common afterwards and the load cell response increases. The load cell forces seem to respond greatest when the response period is around 0.36 to 0.46 ms. The accuracy of these values may vary due to the sampling rate of the trial. The 3m trial was sampled at a rate of 30,000 Hz, and the 4m trial was sampled at a rate of 50,000 Hz.
Figure 4.4: 3m Specimen from Assembly 1 (Paczkowski et al., 2012)

Table 4-1: High Frequency Analysis of Impact for Figure 4.4

<table>
<thead>
<tr>
<th>Time at Local Peak (s)</th>
<th>Time at Local Peak (s)</th>
<th>Response Period (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00013</td>
<td>0.00020</td>
<td>0.133</td>
</tr>
<tr>
<td>0.00020</td>
<td>0.00027</td>
<td>0.133</td>
</tr>
<tr>
<td>0.00027</td>
<td>0.00040</td>
<td>0.266</td>
</tr>
<tr>
<td>0.00040</td>
<td>0.00050</td>
<td>0.200</td>
</tr>
<tr>
<td>0.00050</td>
<td>0.00063</td>
<td>0.266</td>
</tr>
<tr>
<td>0.00063</td>
<td>0.00087</td>
<td>0.466</td>
</tr>
</tbody>
</table>
Paczkowski et al. (2012) determined the natural period using a fast Fourier transform on the free vibration of the load cell after impact. They estimated the natural period of the load cell setup to be about 4 ms, which is at least 10 times as long as any response period during the forced oscillations. However, this natural period may represent how the load cell was setup. Because the load cell was not restrained laterally, it could oscillate laterally as seen in the high speed video.
Impact means to apply a sudden force. When a load cell is subjected to a sudden force, it behaves like a spring. If the load cell was modeled as a lumped mass, single degree of freedom system, its natural frequency, $\omega_n$, can be estimated as

$$\omega_n = \sqrt{\frac{k}{m}} \quad \text{and} \quad \omega_n = \frac{2\pi}{T_n}$$

in which $k$ is the axial stiffness, $m$ is the effective mass, and $T_n$ is the natural period.

With an axial stiffness of 17 million pounds per inch and a total weight of 32.9 lb, the fundamental period of the load cell was calculated as 0.44 ms. However, the effective mass is less than the total mass. Therefore, the natural period of 0.44 ms would be an over approximation. As previously stated, the load cell oscillations varied greatest when the response periods were around 0.36 to 0.46 ms. These large oscillations can be a result of the load cell's natural frequency. Although the manufacturer did not state the natural frequency of the load cell, the load cell response suggested that it is susceptible to oscillations.

**4.2.4. Stress Wave Propagation (Bending)**

Figure 4.6 shows an illustration of the strain gages on the specimen at each section as drawn in Figure 2.7 and Figure 2.8. Although a total of 10 strain gages are located at the three sections, only six are needed to measure stress wave propagation. In the analysis, strainA1, strainA2, strainB1, strainB2, strainC1, and strainC2 are represented in Figure 4.6. Because the contact surface is not perfectly planar, bending will occur in the specimen. To eliminate bending effects, the two strains at each section were averaged to strainA, strainB, and strainC as shown.

$$\text{strainA} = \frac{\text{strainA1} + \text{strainA2}}{2}$$

$$\text{strainB} = \frac{\text{strainB1} + \text{strainB2}}{2}$$
As seen in Figure 4.7 and Figure 4.8, the stress wave propagations in the two specimens are very similar. Because the contact surface was not planar, bending would have the most effect on strains measured closest to the impact as seen in strainA1 and strainA2. StrainB1 and strainB2 exhibited some oscillation because of the bending, but they oscillated about a constant average. Minimal effects of bending are seen in strainC1 and strainC2. StrainC1 and strainC2 are equal as the stress wave first reaches them but diverges as soon as the stress wave is reflected. When comparing the average strains, strainA and strainC indicated that the stress wave maintained its magnitude from the two points. However, strainB indicates a decrease between these two points as relevant in both specimens. A more detailed analysis of the cross section is needed to evaluate the stress response of strainB. This is done in the next section.
Figure 4.7: Typical Strain Outputs/Results for 2m Specimen (V=3.61 mph)

Figure 4.8: Typical Strain Outputs/Results for 3m Specimen (V=3.61 mph)
4.2.5. Stress Wave Propagation (Magnitude)

Figure 4.9 shows an illustration of the strain gages on the specimen at each section as drawn in Figure 2.7 and Figure 2.8. Although a total of 10 strain gages are located at the three sections, only six are needed to measure strain around the cross section. In the analysis, strain0, strain1, strain2, strain3, strain4, and strain5 are represented in Figure 4.9 by their numeral. Because the contact surface is not perfectly planar, bending will occur in the specimen. To eliminate bending effects, the strains at each section were averaged to strain02 and strain1345 as shown.

\[
\begin{align*}
\text{strain02} &= \frac{\text{strain0} + \text{strain2}}{2} \\
\text{strain1345} &= \frac{\text{strain1} + \text{strain3} + \text{strain4} + \text{strain5}}{3} \\
\end{align*}
\]

Figure 4.9: ‘C’ Strain Gage Configuration Used to Evaluate the Force Magnitude

In this analysis, strain averages from two different strain gage configurations were used. Because more strain data was needed to explain the decrease in stress for strainB in Figure 4.7 and Figure 4.8, another trial was used to incorporate the average strains of strain02 and strain1345. For the two different trials, the strain gages for strainB and strain02 are the same. Because two different trials were compared, the strains needed to be nondimensionalized by their different impact velocities.
Figure 4.10 compares the strain averages of the two different strain gage configurations. Strain1345 corresponds well with strainA and strainC. StrainB and strain02 also corresponds well since they are the same. The same response is present in both specimens. Figure 4.10 indicates that the stress wave propagation for the HSS section is uneven across each face. In order for the specimen to deform and keep plane sections plane, the stress wave magnitudes can vary across the cross section at any length. However, Figure 4.10 represents stress propagation for the front half of the specimen only.

4.2.6. Low Impact Velocities

Testing of the specimen without mounts often resulted with an impact velocity of at least 2.0 mph. Lower velocities were less likely achieved because the specimens are very light and they were manually pushed. Nondimensional analysis of the force time history revealed that all trials responded similarly as seen in Figure 4.11.
However, testing of the specimens with mounts resulted in a few trials with impact velocity less than 2.0 mph. As seen in Figure 4.12, the lower velocity trials resulted in a decreased force response compared to the other trials. A factor that can influence these values can be the instrumental error. Because the calculated value for impact velocity was low, the instrumental error would introduce a larger uncertainty. Also, Conway and Jakubowski (1969) suggested that air can act as a cushion if the impact velocity was low. With open-ended hollow sections, these specimens were most likely not affected by the air. Most likely, the calculated impact velocity could be an over approximation. The experimental evaluation of the impact velocity allows for a loss of velocity over the one cm distance it has to travel before impacting the load cell. For low impact velocities, the specimen is more susceptible to losing velocity because it takes longer to travel the one cm distance. For the remaining analysis of this report, trials with an impact velocity much less than 2.5 mph were excluded, including the trials with nonstructural mass.
4.2.7. Impact Forces

For this analysis, the load cell force will be matched with the force calculated from strains in the specimen. Strain force will be calculated based on averaged strains at the cross-section shown in Figure 4.9.

\[
\text{strain force} = \frac{EA \cdot (\text{strain}02 + \text{strain}1345)}{2}
\]

\[
\text{Nondimensional Strain Force} = \frac{\text{strain force}}{EA \cdot \frac{V}{c}}
\]

The comparison between load cell force and strain force is shown in Figure 4.13 for the 2m specimen. These tests involved a specimen without nonstructural mass. The effects of the mounts were investigated, and Figure 4.13 shows no effect to the load cell force or the strain force due to its light mass. The mounts only added 0.8 lb to the specimen. When analyzing the strain force, an impact force of about 70% to 80% of the theoretical force was achieved. This result is representative of the load cell force at its first, immediate peak. As time progressed during impact, the load cell responds dynamically through oscillations similar to Figure 4.5.
Similar tests involving the 3m specimen are shown in Figure 4.14. The strain force is estimated at about 70% to 80% of the theoretical force. The load cell force immediately peaks to 70% of the theoretical force, but the load cell responds dynamically thereafter. The conclusions made for the 2m specimen is supported by the testing of the 3m specimen.
No definite conclusions can be made on why 70% of the theoretical force is achieved, but the strain force calculated in the specimen support it. The boundary condition of zero displacement may be a possible reason. Because the load cell deflects to calculate load, this boundary condition is not met. However, the displacement is minimal. Also, the imperfect contact surface caused bending due to a non-planar impact. Therefore, the problem needs to be modeled in three dimensions. If the theoretical force was produced, the force would be sent out as a longitudinal wave and shear wave. It is unclear how much of this force is represented in these tests. However, the results of these tests will be used as a comparison with the results of the nonstructural mass tests for both specimens.
4.3. **Nonstructural Mass Effect (2m Specimen)**

For the nonstructural mass tests, free weight plates were placed on the mounts. Each mount had the same weight placed on it during each trial. The weights used were 2.5 lb, 5 lb, and 10 lb plates described in Table 2-3. During the analysis, it was discovered that the 2.5 lb weights did not add much of an effect to the load cell force as seen in Figure 4.15. As mentioned, the mounts alone added 1.2 lb to the specimen. With the 2.5 lb weights, the added weight was about 6.2 lb per specimen. The data presented in Figure 4.16 and Figure 4.17 is the results of the tests involving the 5 lb weights and 10 lb weights. These tests produced a more noticeable response in the load cell. Table 4-3 details the masses to be considered.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Structural Mass (lb)</th>
<th>Nonstructural Mass (lb)</th>
<th>% Added Nonstructural Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Only</td>
<td>19.5</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Specimen with 2.5 lb Weights</td>
<td>19.5</td>
<td>6.2</td>
<td>31.8</td>
</tr>
<tr>
<td>Specimen with 5 lb Weights</td>
<td>19.5</td>
<td>11.2</td>
<td>57.4</td>
</tr>
<tr>
<td>Specimen with 10 lb Weights</td>
<td>19.5</td>
<td>21.2</td>
<td>108.7</td>
</tr>
</tbody>
</table>
Figure 4.15: Nondimensional Load Cell Force for 2m Specimen with 2.5 lb Weights

Figure 4.16: Nondimensional Load Cell Force for 2m Specimen with 5 lb Weights
As seen in Figure 4.18 and Figure 4.19, the effect of the nonstructural mass has an additive response during and after the impact. Because the tests involved manually pushing the specimen, the impact velocity varied randomly. Trials with an impact velocity of 2.35 mph were selected in this analysis because these velocities were achieved for different test scenarios. The structural response occurred from time 0 to about 0.0009 second, and the nonstructural mass began acting onto the load cell at about 0.0005 second. During the structural response time, the peak difference of about 20% to 25% in force was achieved between the trial with no weights and the weighted tests. The nonstructural mass effects after the impact for times after 0.0009 second were also significant. This time represents the return of the stress wave from the initial impact. Since the nonstructural mass had a response after this time, it suggested that the contact surface between the load cell and the specimen was still intact. Based on the weights used, heavier nonstructural mass would have a greater response after impact if the contact surface is still intact. However, Figure 4.19 suggested that
these weights do not act consistently compared to the structural response without weights. It is also unclear how much more of an effect these weights would have because the specimen rebounds after impact.

![Load Cell Force for 2m Specimen: V=2.35 mph](image_url)

Figure 4.18: Comparison of Nonstructural Mass (up to 5 lb per Mount) Tests for 2m Specimen with an Impact Velocity of 2.35 mph.
4.4. **Nonstructural Mass Effect (3m Specimen)**

Figure 4.20, Figure 4.21, Figure 4.22, and Figure 4.23 are analogous to Figure 4.15, Figure 4.16, Figure 4.17, Figure 4.18, and Figure 4.19 done for the 2m specimen. The same conclusions can be made for the 3m specimen. The nonstructural mass response can occur during the structural response and have an additive effect of up to 25%. As seen in Figure 4.23, the 5 lb weights did not add to the structural response. This could be the result of how the weights were secured to the mounts. After every trial, the weights tend to loosen the nuts. The nonstructural mass effect after the return of the stress wave is also evident. The results suggest that the contact surface is still intact. Also, heavier weights would produce a greater response at this time. This response is variable and is not as consistent as the structural response. Table 4-4 details the masses to be considered.
Table 4-4: Mass Detailing of 3m Specimen during Testing

<table>
<thead>
<tr>
<th>Setup</th>
<th>Structural Mass (lb)</th>
<th>Nonstructural Mass (lb)</th>
<th>% Added Nonstructural Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Only</td>
<td>28.9</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Specimen with 2.5 lb Weights</td>
<td>28.9</td>
<td>6.2</td>
<td>21.5</td>
</tr>
<tr>
<td>Specimen with 5 lb Weights</td>
<td>28.9</td>
<td>11.2</td>
<td>38.8</td>
</tr>
<tr>
<td>Specimen with 10 lb Weights</td>
<td>28.9</td>
<td>21.2</td>
<td>73.4</td>
</tr>
</tbody>
</table>

Figure 4.20: Nondimensional Load Cell Force for 3m Specimen with 2.5 lb Weights
Figure 4.21: Nondimensional Load Cell Force for 3m Specimen with 5 lb Weights

Figure 4.22: Nondimensional Load Cell Force for 3m Specimen with 10 lb Weights
4.5. **Nonstructural Mass Effect on the Specimen**

It was important to evaluate the effects of the nonstructural mass on the load cell because the load cell represented the structural design element for debris impact. However, the response of the weights can be evaluated by the strains in the specimens. In Figure 4.24, the trials with the 10 lb weights were considered due to their more pronounced effect. The strain force calculation was chosen because it represented a cross section and behaved consistently in most of the trials. In both specimens, the structural response was evident in the beginning of the impact. Despite their close proximity to each other (the strain gages and the first weight), the time for the weights to act was delayed. As a result, the weights and the specimen act as two different bodies. These increases in compressive strain indicate the weights will continually move forward despite the specimen rebounding off the load cell.
Figure 4.24: Nondimensional Strain Force for Trials with 10 lb Weights
2m Specimen (left) and 3m Specimen (right)
5. Conclusion

5.1. Experimentation

Due to the findings of this report, refinement to the existing experimental setup and testing may need to be done for any party wishing to duplicate these tests. Due to the nature of impact studies, a load cell should be carefully selected to avoid dynamic complications. If the same structural steel section was being used, short specimens can be avoided because a long specimen can replicate the same response for longer impact durations. Short specimens had the benefit of better handling during testing. Strain gages should be avoided near the back end of the specimen due to the gage’s inability to develop the full strain before the stress wave is reflected. Without strict preparation to ensure a perfectly planar contact surface, bending must be assumed, and the placement for the strain gages must be considered for this purpose. To properly evaluate the forces in the specimen, a strain gage on each face of the specimen needs to be used. Methods to deliver higher impact velocities should be considered in order to relate test results to a real-world application. Care needs to be taken when selecting measuring devices and determining parameters such as sampling rate in order to minimize instrument error.

5.2. Impact Forces

Due to bending, the simplified one dimensional model may not be accurate for this study. However, the tolerances in the contact surface were able to create a stress wave of up to 80% of its theoretical value. When nonstructural mass was added, it was shown that these masses were able to help maintain the specimen’s contact on the load cell and transfer the mass effects to the load cell. The nonstructural mass can have a small additive effect on the structural response of the specimen during impact.
5.3. **Extension to Real-World Application**

The goal of this report was to relate a small scale model of the nonstructural mass effects on tsunami debris forces to a full-scale tsunami shipping container impact. For design load purposes, the force results of this report can be related. Although the experimental testing was designed to have the specimen impact at the worst condition, the one dimensional model may be too conservative and unlikely. However, a maximum of 80% of the structural response should be considered based on the findings of this report. Also, the testing that was done simulated in-air impacts. During a tsunami, there could be other factors that can help keep the container in contact with the design structural element. The intact contact surface will aid in transferring the nonstructural mass forces into the object and a greater force may be expected. However, the testing only considered at most 100% of the structural mass be added to the specimen as nonstructural mass. In reality, shipping containers can weigh up to 10x their structural mass. In this case, the testing implied that the nonstructural mass may be a significant factor in determining the design load for a shipping container impact.
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Paczkowski et al. (2012) is recognized for preparing the experimental setup and recognized for the use of their data and findings. The author would like to thank them for their input and advice on developing the nonstructural mass setup.

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List of References


