TRANSPORT SHOCK ASSESSMENT FOR
A HIGH-RATE TENSILE TEST MACHINE

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TRANSIENT SHOCK ASSESSMENT FOR A HIGH-RATE TENSILE TEST MACHINE

EXECUTIVE SUMMARY

A university engineering laboratory is acquiring a Shimadzu Hydroshot HITS-T10 high-rate tension/compression loading machine for materials testing in a ground-level laboratory space. The test equipment is expected to produce a significant impact force when the material specimen fractures and campus building officials are concerned about the potential for disturbing levels of vibration in the building. The HITS-T10 will be placed on a rubber isolator-supported concrete slab. In-situ vibration tests of the slab are conducted to determine the stiffness and damping characteristics of the rubber isolators. Transient shock analyses are performed to predict the force transmitted to the building foundation and the peak acceleration levels in the vicinity of the HITS-T10 and on the floor above. While the vibration produced by the test equipment will likely be felt by occupants in the building, the levels and frequency of occurrence are considered to be tolerable. After installation, follow-up vibration testing can be performed during HITS-T10 operation to provide a more accurate assessment of the transmitted vibration and to determine if any modifications to the isolation slab are required.
1. INTRODUCTION

A university laboratory is acquiring a high-rate test machine for materials testing research. The Shimadzu Hydroshot HITS-T10 is capable of performing tension and compression tests on materials specimens at speeds of up to 70 ft/sec. The HITS-T10 will be installed on the ground level and the university is concerned that the large shock event that occurs when a test specimen fractures will propagate through the building and disturb others or disrupt other ongoing vibration-sensitive research. The university’s structural engineer requested an assessment of the structural dynamics aspects of the machine operation and the transmission of vibration into the building.

The preferred location for the equipment is shown in Figure 1, where the testing machine will be mounted on an elastically-supported 8-in.-thick concrete slab. The isolation slab, which is bordered by steel C8 channel sections, is supported at its four corners on four rubber isolators. The isolation slab sits on a raised 8.5-in.-thick concrete slab placed on the original finished floor slab. The stiffness and damping properties of the rubber supports are critical parameters that govern the transmission of vibration to the supporting structure, but are not known. Furthermore, no documentation is available that defines the reinforcing of the two concrete slabs or the ultimate compression strength of the concrete ($f_c$).

![Figure 1 Proposed Installation Location for the Shimadzu HITS-T10](image)

In-situ vibration testing of the isolation slab is required to determine the stiffness and damping characteristics of the rubber isolators. The testing also identifies vibration modes of the isolation slab itself, which may provide some insight into the concrete strength. Structural dynamics models of the isolation slab and the test machine mounted on the isolation slab are developed and used to predict the forces transmitted to the building. Finally, a simplified structural dynamics model of a portion of the building structural frame is used to obtain conservative estimates of the vibration transmitted throughout the building in the immediate aftermath of a test. The analyses rely on information provided in formal and informal Shimadzu documentation describing the dynamic performance of their test equipment.
2. ISOLATION SLAB CHARACTERISTICS

The critical characteristics of the isolation slab that determine the shock transmission performance of the isolation slab are its mass and the stiffness and damping provided by the rubber isolators. The slab mass is the only parameter that can be estimated from the known dimensions of the slab. The 6 ft by 7 ft slab has an overall estimated mass (including the perimeter C8 sections) of 4420 lb (137.3 lbf\(\cdot\)s\(^2\)/ft). The vertical stiffness of the rubber isolators can be estimated from \(k_r = E_r A_r / L_r\), where \(A_r\) is the area of rubber in contact with the slab (4.875\(\times\)4.875 in\(^2\)) and \(L_r\) is the height of rubber between the isolation and base slabs (3 in.). The physical dimensions of the rubber are known; however, the Young’s Modulus, \(E_r\), for rubber varies between 1 ksi to 150 ksi, depending upon the specific rubber material. Rather than attempt to determine \(E_r\), the vertical stiffness can be determined directly from in-situ vibration testing. Vibration testing will also identify elastic vibration modes of the slab itself, which may shed some light on the compressive strength of the concrete.

2.1 IN-SITU VIBRATION TESTING

The isolation slab, the isolators, and the base slab are illustrated in Figure 2. The x- and y-axes shown in the figure define a reference frame for the testing and analysis effort. The numbers and small circles at the four corners correspond to the initial accelerometer placement and data channel association. The accelerometers used are identified in Table 1. Acceleration data were acquired using a portable data acquisition (DAQ) system consisting of a Windows-based laptop, a USB-powered four-channel 24-bit data acquisition module (Data Translation DT9837A), and the four single-axis accelerometers identified in Table 1.

This initial test configuration is used to measure the three primary rigid-body modes of the slab, which are used to identify the stiffness of the rubber isolators. The slab was impacted with a rubber-headed mallet at three locations: \((x = 0', y = 0')\), \((x = 3.5', y = 0')\), and \((x = 0', y = 3')\). The first impact location emphasizes the plunge mode (up-down vibration). The second impact location emphasizes the pitch mode vibration, and the third location emphasizes the roll mode vibration. A fourth impact test was performed, \((x = 0', y = 0')\), with accelerometer 3.
relocated to the base slab next to the column. These data provide some insight into the transmission efficiency from the isolation slab to the base slab.

### Table 1 Accelerometers and Channel Assignments

<table>
<thead>
<tr>
<th>Channel</th>
<th>Direction</th>
<th>Accelerometer</th>
<th>S/N</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Z</td>
<td>PCB 393B31</td>
<td>34729</td>
<td>9.88 V/g</td>
</tr>
<tr>
<td>2</td>
<td>Z</td>
<td>PCB 333B52</td>
<td>46983</td>
<td>1.040 V/g</td>
</tr>
<tr>
<td>3</td>
<td>Z</td>
<td>PCB 393B04</td>
<td>32502</td>
<td>1.003 V/g</td>
</tr>
<tr>
<td>4</td>
<td>Z</td>
<td>PCB 393B04</td>
<td>32503</td>
<td>1.009 V/g</td>
</tr>
</tbody>
</table>

The data measured at Accelerometer 4 for the three impact sites is plotted in Figure 3. There are three peaks in the plot that correspond to the plunge, roll, and pitch modes. The lowest mode is plunge mode (18.6 Hz), the higher-frequency modes are very close (30.3 Hz, 30.5 Hz) and correspond to the roll and pitch modes, respectively. The theoretical values for these three modes is used in the following section to determine the axial stiffness of the rubber isolators.

![Figure 3 Vibration Response at Accelerometer 4 for Three Impact Sites](image)

The transmission of vibration from the isolation slab to the base slab (i.e., building) is of primary concern. Accelerometer 3 was moved to the base slab to gain some insight into the transmission characteristics. The data representing the isolation slab (Accelerometer 4) and the data for the base slab (relocated Accelerometer 3) are plotted in Figure 4. There is a 100x reduction in the vibration (power spectral density) measured at the base slab compared with the isolation slab. The vertical scale in the plot is in terms of g^2/Hz, so the actual attenuation in terms of g’s is a 10x reduction. This information is used in Section 3.3 to assess the quality of the shock propagation model.
2.2 RUBBER ISOLATOR AND SLAB CHARACTERISTICS

There are three primary rigid-body modes of the isolation slab that are of interest: the plunge mode, the roll mode, and the pitch mode. Three simple one-degree-of-freedom vibration models can be used to determine the theoretical resonance frequencies associated with each of these modes.

\[
\begin{align*}
    f_{\text{plunge}} &= \frac{1}{2\pi} \sqrt{\frac{4k_r}{m_{\text{Slab}}}}, \\
    f_{\text{roll}} &= \frac{1}{2\pi} \sqrt{\frac{12k_r(B-w)^2}{m_{\text{Slab}}(B^2+h^2)}}, \\
    f_{\text{pitch}} &= \frac{1}{2\pi} \sqrt{\frac{12k_r(L-w)^2}{m_{\text{Slab}}(L^2+h^2)}},
\end{align*}
\]

(1)

where \( w \) is the effective width of the rubber isolators (i.e., the distance from the inside face of the isolator to the center of force generated by the isolator; about 4 in.).

The resonance frequencies in Equations (1) are plotted in Figure 5 for various values of isolator stiffness. The horizontal lines in the plot correspond to the measured vibration identified in Figure 3. The horizontal lines should (and do) cross the theoretical curves at the one value of isolator stiffness that provides the best agreement between the measured resonance frequencies and the theoretical resonance frequencies. In this case, the best agreement is obtained with \( k_r = 39 \) kip/in., which falls well within the expected range determined from the variation of \( E_r \).

The energy dissipation characteristics of the rubber are also critical in the current application. Each impact on the slab with the rubber mallet excites vibration which decays over time. An example of one post-impact decay response is plotted in Figure 6. In this case the amplitude of the data is scaled by the maximum acceleration. The smooth red curve in the figure is the theoretical exponential decay envelope for viscous damping. The frequency of the motion (\( \omega = 2\pi f = 18.6 \) Hz) is used in combination with the critical damping factor, \( \xi_r \), in the exponential decay.

Figure 4 Comparison of Impact Response at the Isolation Slab and Base Slab
A trial and error procedure is used to converge on a reasonable value for the damping factor as $\xi = 0.4$, or $4\%$ of the critical level of damping. This is relatively low for rubber and not ideal for its intended role in the isolation slab application envisioned here. The damping factor, $c_r$, for each isolator is obtained from the plunge mode model as $c_r = \xi \sqrt{k_r m_{slab}} = 0.027 \text{ kip-sec/in.}$
3. SHOCK ANALYSIS

The in-situ test effort successfully identified the stiffness and damping characteristics of the rubber, which are essential parameters for the shock analysis discussed in this section. The HITS-T10 weighs 3300 lbf and is supported on its own rubber isolators. The additional mass of the equipment and the characteristics of its elastic connection to the isolation slab have a significant effect on the shock transmitted to the base slab. Formal and informal Shimadzu documentation provide some definition of the magnitude of the shock generated by the equipment in the immediate aftermath of the material test specimen failure.

3.1 SHOCK CHARACTERISTICS OF THE HITS-T10

The formal HITS-T10 specification document\(^1\) provides the equipment weight and dimensions as well as an impact force of 10 kN (2.25 kips). A separate more informal document\(^2\) provides more information on the post-fracture acceleration response. The data shown in the document is reproduced here in Figure 7 with the red text added to the figure by this author. The author of the document state that the total mass of the equipment achieves a 5-g acceleration in the immediate aftermath of a test, which translates into an impact load transmitted to the supporting floor (the isolation slab in the case of this installation) of 16.5 kips.

![Figure 7 Post-Fracture Vibration of the HITS-T10 (from document\(^2\))] (image)

The two documents provide very different values for the peak impact force: 2.25 kips versus 16.5 kips. In addition, a peak impact force is not very useful without a curve showing how that force is delivered over time. On one hand, if the impact force is applied over a period of time that is much longer than the natural period (inverse of resonance frequency) of the supporting structure, the force is “static” and is not magnified nor attenuated. On the other hand, if the force is applied over a very short period of time relative to the supporting structure’s natural period, then the net impulse (area under the force VS time curve) is all that matters. Unfortunately, no time information is provided in either of the documents.

The acceleration plot shown in Figure 7 is useful in spite of the fact that the time scale is omitted from the plot. The claim that the total equipment mass accelerates at 5g seems unrealistically high based on the plot. The initial period of “complex machine dynamics” involves the base of the machine and the crosshead accelerating and decelerating in opposite directions at slightly different times. It appears that a portion of the overall mass does reach 10g in each direction, but there is no way to determine the effective mass. The period following the high frequency vibration reaches about 1g and certainly represents total equipment mass bouncing up and down.

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2 Takeda, Akira, “Vibration or Impact of HITS-T10,” October 2 [2013].
on its supports. In this case, the 1g acceleration corresponds with a force of about 3.3 kips, which is much closer to the impact force documented in HITS-T10 specifications (2.25 kips).

3.2 TRANSIENT SHOCK ANALYSIS

The HITS-T10 is illustrated on the isolation slab in Figure 8. No technical information is provided regarding the HITS-T10 isolator stiffness and damping characteristics \((k_e \text{ and } c_e)\). The net stiffness, \(k_e\), of the isolation system could have been determined had the time scale information had been provided in the acceleration plot shown in Figure 7. The combined motion of the test equipment and the isolation slab immediately following material specimen fracture is evaluated in this section.

![Figure 8 HITS-T10 Installed on Isolation Slab](image)

Two representative dynamics models are shown in Figure 9. Both models represent the up-down motion of the equipment/slab system. Model 1 on the left-hand side of Figure 9 is used to evaluate the scenario where the slab and test equipment are fully coupled and a known impact force is applied to the coupled system. In this case, the impact force is modeled as a half-sine pulse with total duration of \(\Delta t\) and a maximum force of 2.25 kips per Shimadzu’s specifications. This analysis is repeated for different values of \(\Delta t\) to minimize any risk of deriving conclusions based on an erroneous assumption.

The second model, Model 2, shown in Figure 9 is used to address the more realistic dynamics where the test equipment can move relative to the isolation slab as it moves. In this case, the actual form of the impact force-VS-time curve is not modeled explicitly; rather, the impact event is assumed to take place over a very short period of time. The total impact impulse is determined from the assumed peak acceleration of the equipment mass (on a rigid foundation). If the impact force is delivered over a very short period of time, the net effect is to apply an initial velocity, \(v_0\), to the test equipment mass. The informal Shimadzu documentation suggested a (conservative) acceleration of 5g; hence, the required initial velocity for this analysis is the velocity that causes the
test equipment mass to achieve 5 g when the isolation slab is restrained from moving. The isolation slab restraint is then eliminated and the analysis is repeated to assess the beneficial or detrimental contribution of the combined-system dynamics.

Figure 9 Idealized Shock Dynamics Analysis Models

A summary of analysis results obtained from Model 1 is shown in Figure 10. Four different values for the impact force pulse duration are investigated. The corresponding peak force transmitted to the base slab (building foundation) is listed in the table on the left-hand side of Figure 10. For impact durations longer than about 1 sec, the applied force is essentially a static load of 2.25 kips. The maximum force transmitted to the building is 3.8 kips, which occurs in the special circumstance when the period of the impact event just happens to coincide with the period of slab/equipment resonance. The time series plot on the right-hand side of the figure is the transmitted force time history for this worst-case scenario and shows that the isolation slab could actually magnify the force produced by the HITS-T10. It is much more likely that the impact event will be short-lived and that the isolation slab will reduce the dynamic force transmitted to the foundation as evidenced by a decreasing peak force with decreasing pulse duration (i.e., decreasing net impulse).

<table>
<thead>
<tr>
<th>$\Delta t$</th>
<th>Peak Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 s</td>
<td>122 lbf</td>
</tr>
<tr>
<td>0.01 s</td>
<td>1190 lbf</td>
</tr>
<tr>
<td>0.06 s</td>
<td>3810 lbf</td>
</tr>
<tr>
<td>&gt; 1.0 s</td>
<td>2250 lbf</td>
</tr>
</tbody>
</table>

Figure 10 Summary of Model 1 Analysis Results

A summary of the impact analysis results obtained with Model 2 is provided in Figure 11. The acceleration time history response of the HITS-T10 body and isolation slab are plotted in the left-hand side of Figure
11. The peak 5-g acceleration of the equipment mass drops to about 3.5 g when the isolation slab is allowed to move. The corresponding peak acceleration of the isolation slab is about 1 g. The total force transmitted to the base slab is plotted on the right-hand side of the figure as a function of time. The peak force is 16.2 kips, which is only slightly less than the worst-case number provided by Shimadzu in their informal document (16.7 kips).

![Figure 11 Summary of Model 2 Analysis Results: Acceleration (Left), Transmitted Force (Right)](image)

The shock analyses presented in this section suggest the worst-case transmitted force may fall somewhere between 3.8 kips and 16.2 kips. The latter force is almost certainly overly conservative by a factor of 2 to 3; however, there is too little information about the impact event to confidently reduce the indicated range. The total force (static plus dynamic) applied by each of the four rubber isolators to the base slab can be as high as about 6 kips.

3.3 SHOCK PROPAGATION ANALYSIS

The shock analysis results obtained from Model 1 and Model 2 suggest that a shock propagation analysis is required to determine if the acceleration transmitted throughout the building may be a problem. There are a number of challenges associated with a shock propagation analysis. First, there are no firm criteria to define what a problematic level of vibration is for this particular case. There are no locations in the building where vibration-sensitive equipment is in use. People working in an office environment become annoyed when the amplitude of vibration exceeds about 0.005 g below about 10 Hz. This annoyance level, however, is most reasonably associated with prolonged vibration rather than an occasional and very short duration disturbance that the HITS-T10 will cause.

A second challenge is the complexity of the structure. A shock event in a building will propagate along primary structural members (beams and columns), secondary structural members (slabs and walls), and be damped by non-structural elements such as mechanical systems (ducts, pipes, etc.), partitions, and furniture.

Finally, the laboratory building was constructed at a time that preceded the practice of placing grade beams and slabs on carton forms to separate the structure from expansive soils. Hence, a portion of the vibration transmitted to the ground floor will be transmitted directly into the soil and propagate away from the structure.

A finite element model of a structural frame representing a portion of the Woolf Hall is created for this propagation analysis as shown. The shaded members shown in Figure 12 are included in the finite element model. No attempt is made to include secondary structural and non-structural elements. Furthermore, by limiting the extent of the primary structural elements, the vibration cannot dissipate in the model to the extent that it will
in the real building. This level of conservatism will lead to an over-prediction of the vibration throughout the building but should provide valuable insight.

A two-degree-of-freedom model (Model 2) of the HITS-T10 and isolation slab is incorporated into the finite element model of the frame. The analysis described in the previous section for Model 2 is repeated in this analysis except that the floor structure can respond dynamically with the applied forces. Representative acceleration time-histories for different locations in the building are plotted in Figure 13 for three locations on the ground floor (where the HITS-T10 is installed) and on the floor above.
The maximum vibration occurs, not surprisingly at the base of the column next to the HITS-T10. The peak acceleration at that location is about 0.09 g, which about 1/10th the vibration level observed on the isolation slab (left-hand side of Figure 11). Recall that the in-situ testing measured a similar response ratio for the isolation and base slabs (Figure 4). The agreement between the measured response and the finite element model provides some modest level of validation for the model.

The vibration elsewhere on the ground floor drops to around 0.04 to 0.05 g in this conservative, worst-case analysis. The vibration on the level above drops to between 0.02 and 0.03 g. These levels persist for only about 0.5 seconds and then will fall below the annoyance level.

4. CONCLUSIONS AND RECOMMENDATIONS

The HITS-T10 will very likely cause short-term vibration for about 0.5 seconds that will be felt within the laboratory and on one or more floors above. There are no known vibration sensitive equipment or vibration sensitive experiments located nearby, so the primary vibration concern is related to human comfort. The nature of the testing responsible for the vibration requires setup and breakdown time; hence, the transient vibration effects associated with each test will be intermittent rather than a persistent source of vibration.

The level of vibration cannot be determined with precision because (1) the magnitude and temporal definition of the impact force produced by the HITS-T10 are not well defined and (2) the complexity and uncertainty associated with the structural dynamics of the building structure. Estimated worst-case vibration levels are expected to be less than about 0.05 g, which is ten times the magnitude of noticeable, persistent vibration that people in a typical office environment may consider to be annoying.

Shock analyses performed for this study indicate that the isolation slab may actually slightly amplify the shock rather than mitigate it. If the shock pulse occurs in less than about 0.04 seconds, the isolation slab will provide some level of mitigation. However, the university has the option to place the HITS-T10 on the isolation slab (as planned) or to remove the isolation slab and mount the HITS-T10 directly on the base slab. It is recommended that the university mount the equipment on the isolation slab as planned. At the university’s request, measurements of the vibration on the isolation slab, the base slab, and the floor above can be obtained during a typical materials test. If the data show that the isolation slab is magnifying the impact event, the region between the isolation slab and base slab can be easily filled to rigidly couple the two slabs.