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Experimentally generated high-g shock loads using Hydraulic Blast Simulator

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ABSTRACT

Reliable and repeatable experimental generation of high-g shock environments is a long-standing problem which faces significant difficulty. The shock levels experienced by various defense-related structural and mechanical components are not always easily obtained in the true environments but are known to span a significant range of peak accelerations and pulse durations. The reproduction of these high-g shock levels in a controlled setting is highly important but also quite complicated. A system which is characterized by substantial energy output, a high level of precision, and adjustability is ideal for producing the varying and intense conditions experienced by structures and components subjected to shock loads.

The Blast Simulator, a complex experimental device which simulates explosive blasts without the use of explosive materials, has proven to be an appropriate tool for this application. The system uses high-precision, computer-controlled hydraulic actuators to fire a piston mounted with various impact materials at high velocities into the specified test article. In the developed experimental series, a cylindrical steel specimen is launched by the Blast Simulator from a set of custom pedestals into a catcher pit. The response of the test article to the impact is acquired and analyzed using the shock response spectrum. The results are used to display the capabilities of the Blast Simulator to induce a wide range of shocks on the test article and display the effectiveness of the device as a shock loading tool.

1. Introduction

The proper function of structures and mechanical components can be suddenly brought to a halt by the presence of a high-energy, short-duration load. This type of threat, known as a shock load, can cause critical damage to a wide range of components which are vital to the operation of various structures and mechanical devices such as buildings, bridges, military craft and vehicles, and aerospace components. Because of the need to properly design such structures to resist shock loading, effective experimental techniques must be designed to recreate the loading environments experienced by the various components found in these systems.

The Blast Simulator [1] has proven to be an effective tool for the application of shock loads. Typically used for the simulation of blast-like pressure pulses upon various structural components such as columns and walls, the Blast Simulator is capable of producing high-intensity loading scenarios [2,3] on specimen ranging from approximately 18 kg (40 lbs) for light-weight concrete panels [4] to 815 kg (1800 lbs) for concrete walls [5] per actuator. Using a set of programmable pressures, hydraulic oil, and an adjustable impacting ram, the device is ideal for applying a series of varying shock loads on a given test article. For the investigation described in this paper, the Air Force Research Laboratory (AFRL) at Eglin Air Force Base, Florida, provided a 190 kg (420 lb) custom steel cylinder for shock testing at the Blast Simulator testing facility. Through modifying various testing parameters such as the impacting medium and velocity at impact, a wide range of peak accelerations and loading durations were induced on the test article. These shocks were examined using the shock response spectrum.

2. Shock response fundamentals and SRS

Mechanical shock is a complex loading event which involves the application of a large force over a duration which is significantly shorter than the natural period of the structure being loaded. A basic definition of mechanical shock was provided at the first Shock

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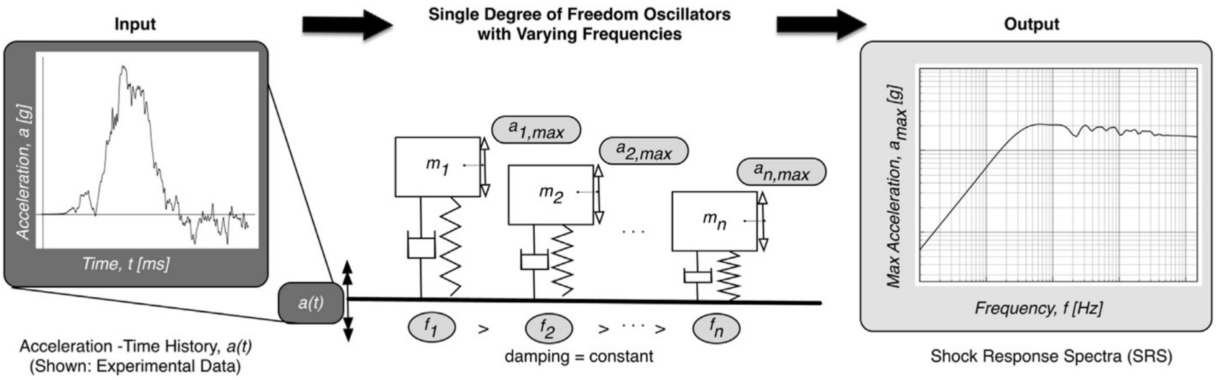

Fig. 1. Schematic of shock response spectrum calculation.

and Vibration Symposium in 1947: “a sudden and violent change in the state of motion of the component parts or particles of a body or medium resulting from the sudden application of a relatively large external force, such as a blow or impact [6].” The study of the effects of shock loading on structures and development of design approaches for resisting such loads is highly important to the defense industry.

Because of the need for specially-designed structures and mechanical devices which can withstand shock loads, experimental techniques are necessary for testing these components. Drop towers, gas guns resonant fixtures, and Hopkinson/Kolsky bars are all typical experimental methods for inducing shock. A drop tower uses gravity and often times tension cables to rapidly accelerate a mass towards a test article [7]. Gas guns utilize the sudden release of a large amount of pressure to accelerate a small projectile towards a specimen [8]. With knowledge of the fundamental frequency of a test article, a resonant fixture uses an impactor to strike a rod or platform which is designed to vibrate at the primary natural frequency of the specimen, thus inducing large accelerations. This approach to shock loading is explained in a pyroshock test procedures report produced by staff at the US Army White Sands Missile Range [9]. Additionally, Hopkinson/Kolsky bar apparatus can induce shock waves through a bar and onto a specimen to measure dynamic stress and strain [10]. The choice of test methodology generally depends on the strains/strain rates of interest, the size of the specimen and the availability of the testing equipment. The Blast Simulator provides a new method for shock generation which uses special hydraulic actuators to impart shock loads on relatively large specimen.

The shock response spectrum (SRS) is an analytical tool often used in shock applications to understand the risks faced by various components in a given structural or mechanical system. When a system is loaded with a short-duration pulse and undergoes transient dynamic stresses, the response will be a candidate for evaluation with the shock response spectrum. George Henderson and Allan Piersol broadly define the shock response spectrum as “the peak response of a simple oscillator (single-degree-of-freedom) to an excitation as a function of the natural frequency of the oscillator [11].” Thus, for a system characterized by a wide range of frequencies and for a component with solely elastic response, the expected peak response at each of the frequencies can be determined using the SRS method.

To calculate the response, a given excitation, $a(t)$, is applied to a set of single-degree-of-freedom oscillators, each with mass, m, spring constant, k, and damping, c, but varying natural frequencies, f_i. The governing equations for these single-degree-of-freedom oscillators, (assuming the base is fixed) are given in eqns. (1) and (2). The damping ratio, ξ, is given by the formula shown in eqn. (3) and is selected based on the dissipation of energy in the system caused by Coulomb friction (between parts), fluid friction (moving through air), internal friction (friction between molecules) and other factors. From this, the equation of motion in eqn. (1) can be rewritten as shown in eqn. (4). Using a convolution integral, the peak acceleration response, $a_{\max}(t)$, of each oscillator is determined. Further details of the approach are provided in Refs. [12,13].

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = 0 \tag{1}$$

$$\omega = \sqrt{\frac{k}{m}}[\mathrm{rad/sec}], \quad f = \frac{\omega}{2\pi}[\mathrm{Hz}] \tag{2}$$

$$\xi = \frac{c}{2\sqrt{km}} \tag{3}$$

$$\ddot{x}(t) + 2\xi\omega_i\dot{x}(t) + \omega_i^2x(t) = 0, \quad f_i = \frac{\omega_i}{2\pi} \tag{4}$$

Using the results from the shock response computation, the threat (in terms of peak acceleration) faced by a component of any given natural frequency in the system can be analyzed. The analyst can determine the range of natural frequencies which are relevant for the given system and specify this set to be used in the calculation. For an accurate response, the sampling frequency of the data acquisition system must be considered when determining the maximum frequency value to use in the results. The IES Handbook for Dynamic Data Acquisition and Analysis [14] provides guidelines for determining cutoff frequencies when performing analysis in either the time or frequency domain. Since the shock response spectrum calculations are performed in the time domain, a sampling rate which is 10 times greater than the maximum frequency response is recommended to produce a magnitude error which is less than 5%. Because the system being used for the test series was characterized by a 1 MHz sampling rate, a maximum frequency value of 100 kHz was used in the results produced in this study. The analytical approach for forming the response spectrums seen in the subsequent section was formulated by David Smallwood [12]. Fig. 1 shows a schematic of the shock response computation process.

As discussed in Ref. [15], specific properties of the input acceleration–time history have noteworthy effects on the resulting shock response spectrum. For example, in the high-frequency region of the plot (>1000 Hz for the purposes of this analysis), the shock response curve will tend towards the peak acceleration found in the input signal when the damping is small. For a given peak acceleration, an increase in pulse duration will increase the response values in the low-frequency region (<100 Hz) of the shock response spectrum. Thus, an increase in area under the pulse curve will naturally raise the values in this region. Concepts which are commonly used in earthquake engineering can be used to explain this phenomenon. Tall structures which have longer periods (smaller natural frequencies) are more prone to be excited to high acceleration levels by ground motions which have a significant amount of low-frequency content than those with mostly high-frequency content. Similarly, a mechanical component with a low natural frequency will generally face greater risk from an input pulse with a long duration than from one characterized by a short duration. Multiple SRS examples which show the response at varying frequencies are provided in the experimental results section.

3. Hydraulic Blast Simulator

The Blast Simulator was initially developed by MTS Corporation for use at the University of California San Diego in 2005 as an alternative experimental approach to blast testing. The typical method for investigating the effects of blast loads on structures is to conduct a field test. This involves the detonation of a column or pile of explosives which is placed at a specified distance from the test article. However, the field testing approach has several limitations/difficulties. First, reproducing the same explosive charge configuration (density of explosive material, shape, etc.) for subsequent tests is difficult and requires precise and expert care to minimize deviations. Second, the fireball and/or dust cloud produced by the explosion will typically disturb any camera view of the specimen during loading. As a result, visual examination of the progression of deformation in the structure being studied is also difficult and requires advanced techniques such as X-ray cinematography. Finally, field tests are typically very costly and conducted in difficult work environments which are offset from civilization. While ultimately being necessary for a full characterization of a structure's ability to withstand blast loads, field tests are clearly limited in these specific areas. In contrast to a standard field test, the Blast Simulator applies a blast-like load in a laboratory environment without the use of explosive materials, described in detail in Refs. [16,17]. Consequently, since no fireball is created, a full qualitative analysis of the loading and test article response can be conducted using video captured with high-speed cameras. Additionally, because the Blast Simulator function is controlled electronically, a high level of repeatability in results between identical test setups is readily obtainable. The device has proven to be an effective tool for a comprehensive examination of the response of various structural components to impulsive loading [5,18,19].

In order to reproduce the types of pressures and impulses created by explosions, the Blast Simulator system uses a combination of pressurized nitrogen and hydraulic oil in conjunction with unique actuator systems known as Blast Generators (BGs). Two types of these devices are typically used at the Blast Simulator facility. The smaller device, known as a BG 25, is capable of producing peak velocities at specimen impact of approximately 82–98 ft/s (25–30 m/s) and is often used for tests involving wall systems. The larger option, the BG 50, can reach peak impact velocities of 164–197 ft/s (50–60 m/s) and is used for articles such as columns, defense-related components, and other structures which require a very high level of loading. The BG 50 was used in the experimental series for this study and is shown in Fig. 2.

The generators operate through interactions between accumulated pressure, hydraulic oil, and a piston assembly which is rapidly forced out of the generator. Pressure transducers and high-precision poppet valves are used to monitor and control the flow of oil and transfer of pressure to produce a very specific motion of the piston. This motion is programmed by specifying various input parameters including pressure levels and the starting position of the piston before the test. A schematic of a BG 50 showing its operational components is provided Fig. 3.

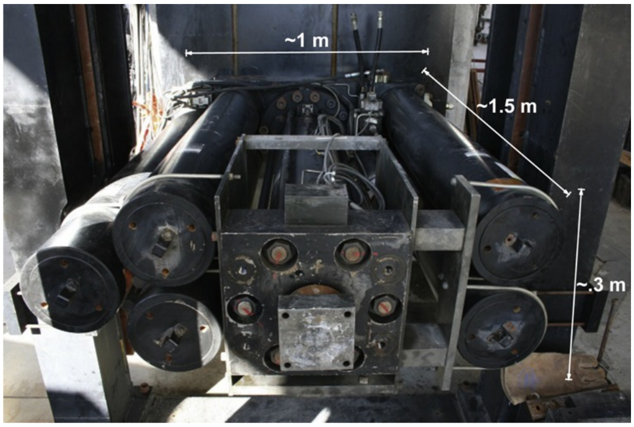

Fig. 2. BG 50.

Mounted to the piston is an aluminum or steel plate known as the "impacting mass." Because the size of this mass can be adjusted, the total weight being applied to the specimen and, thus, the incoming energy can be easily modified to impart different loads. Attached to the mass is a specially-designed urethane pad with a specific pyramidal geometry. The pyramids extending from the front face were designed specifically to reproduce the types of loading durations experienced during far-field and near-field blast events. An examination of the adiprene material which comprises the pad is provided in Ref. [20]. The combination of the metal plate, programmer, and any other attachments will collectively be referred to as the "impacting mass" for the purposes of this study. Also, the velocity at which the impacting mass collides with the test article will be known as the "impact velocity." The desired impact velocity programmed for the test, which is typically not identical to the true impact velocity but very close, will be known as the "target impact velocity" in subsequent sections.

A set of rails and sliders are used to guide the impacting mass along a level path towards the test specimen. The rails are bolted securely to both the Blast Generator and a set of steel support towers and checked with a leveling device between tests. The sliders are composed of a phenolic material and designed to have greater strength in a specific direction such that they resist the unique loads experienced during the blast simulations. Because of the importance of keeping the impacting mass at a specific height for collision, the rails and sliders are vital for maintaining the predictable and repeatable nature of the tests. A display of the impacting mass, rails, and slider is shown in Fig. 4.

The Blast Simulator has the unique capability of applying a specified loading duration to test articles. This is done though the acceleration and deceleration of the impacting mass and piston rod by computer-controlled hydraulics and poppet valves. This so-called "punch" is described as the forward motion of the impacting mass into the test article up to a very specific point followed by a regression back towards the Blast Generator. Unlike other impulsive loading devices such as drop towers and gas guns, which can impart high-energy loads, any return of the impactor towards its origin will be a result of natural rebound rather than a programmable event as with the Blast Simulator. This capability allows for effective modification of the types of loading and duration required for blast simulations and shock generation.

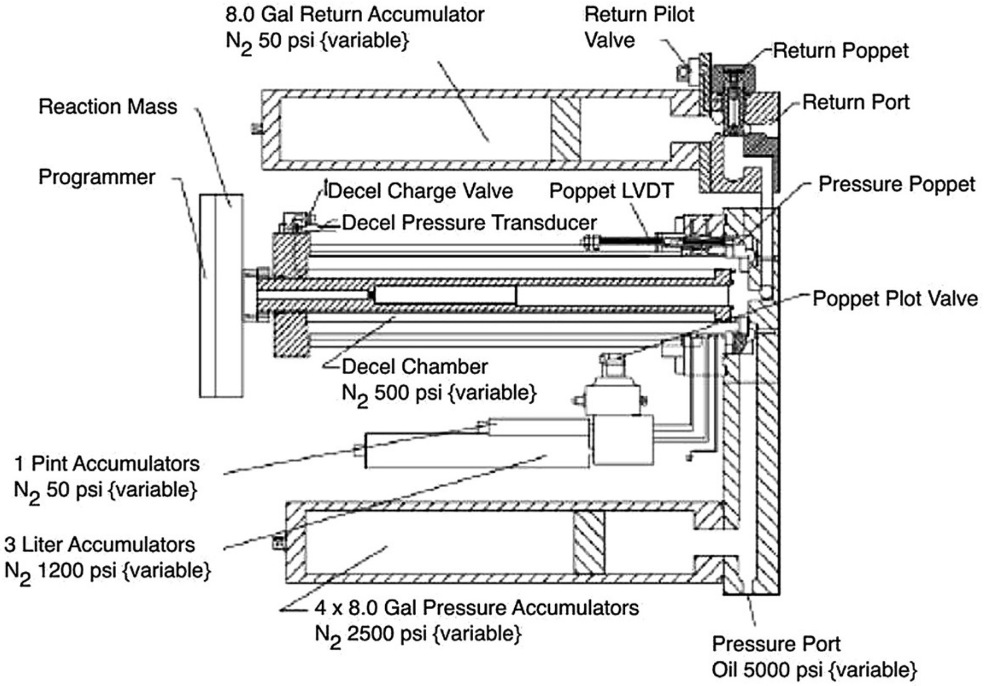

Fig. 3. Schematic of BG 50.

4. Experiment description

4.1. Test specimen

The specimen used in this investigation was a hollow steel cylinder with a 16 × 16 × 1.5 in (40.6 × 40.6 × 3.8 cm) steel plate welded to the impact side (Fig. 5). The back half (non-impact side) of the cylinder had a slight taper with increasing diameter towards the free end. The cylinder weighed 310 lbs (140 kg) and the steel plate weighed 110 lbs (50 kg) for a total specimen weight of 420 lbs (190 kg). Accelerometers were attached to the specimen through a welded threaded coupler at various locations of interest. A protective steel cover was welded to the specimen to prevent damage. Two types of accelerometers and data acquisition systems were used: PCB 350B03 10 kg piezoelectric accelerometers and Endevco model 7270A 60 kg piezoresistive shock accelerometers. The two systems were used to ensure the acceleration response and the anti-aliasing schemes produced consistent results. For this discussion, the results from the PCB accelerometers are shown, exclusively.

4.2. Test design

The experiment was setup as shown in Fig. 4 with a single actuator and an impacting mass. The aluminum impacting mass was 16 in × 16 in × 2.75 in (40.6 × 40.6 × 7.0 cm) and weighed 60 lbs (27 kg). The total weight of the piston rod, collar and mass was 242 lbs (110 kg). Three custom steel pedestals were designed to support the specimen and allow it to fly freely away from its resting position upon impact. Each of these was supported on a custom steel table configured at the desired height. In order to insure that the specimen was located at the same height and resting at the same angle for each test, the pedestals were designed as threaded assemblies which could be finely adjusted to modify the position and rotation of the test article. A catcher pit composed of four large concrete blocks and sand bags was used to stop the specimen during its flight and absorb the high amount of energy being carried away from the collision. The setup with catcher pit, specimen and supporting table is shown in Fig. 6.

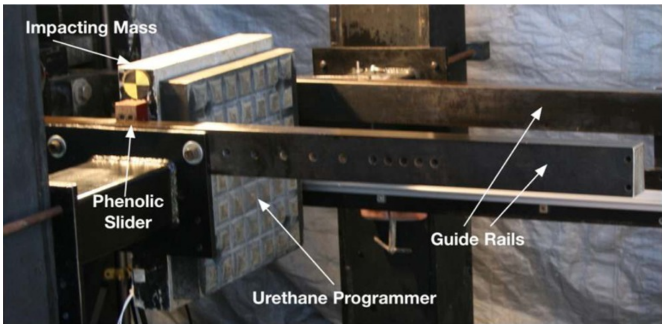

Fig. 4. Impacting mass and guide assembly.

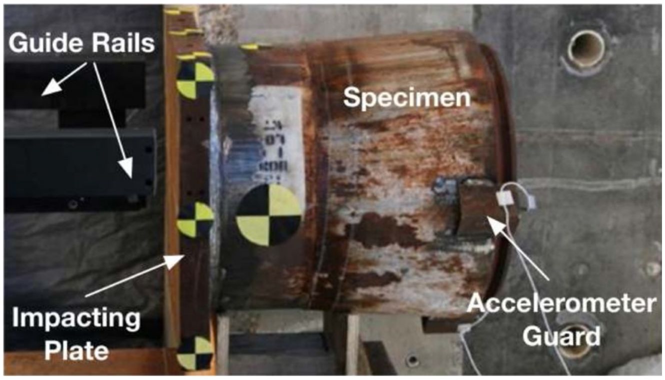

Fig. 5. AFRL test article.

Fig. 6. Test setup with catcher pit.

A thorough examination of the ability of the Blast Simulator to impart a wide range of shock loads was conducted using three specific impact velocities and three impact materials. The velocities for each series were programmed to 49 ft/s, 98 ft/s, and 131 ft/s (15 m/s, 30 m/s, and 40 m/s), which were chosen as representative low, medium and high velocities relative to the capability of the actuators. For each of these cases, urethane (as used for blast tests), leather, and sand confined in a bladder and custom steel box were placed at the end of the Blast Simulator impacting ram. In an attempt to avoid producing high-frequency ringing in the specimen accelerometer response through metal-to-metal contact, tape was often used to secure the materials to the impacting assembly rather than steel brackets or bolts. The application of the leather with tape was conducted in a consistent manner between tests (i.e. layers of tape, location). The tape did not provide any noticeable effect in the acceleration data that was of interest. A display of the impacting material set is shown in Fig. 7.

5. Results

This section provides the results from 15 representative tests from the experimental series. The data from these experiments, which have varying impact velocity and impact material, are used to validate the capability of the Blast Simulator to induce a wide range of shock loads and display the effectiveness of the device as a shock loading tool. In each instance, the data shown is the unfiltered data from each accelerometer. The data was then filtered with a lowpass filter at 1.5 times the maximum analysis frequency (100 kHz) and a highpass filter at 0.001 times the maximum analysis frequency before applying the SRS algorithm. It is likely that additional filtering is necessary; however, the purpose of this paper is to show the range and type of experimentally generated peak accelerations and durations and therefore no other modifications to the data was made. SRS results are shown in the frequency ranges of interest to AFRL. Additional studies are needed as to the methodology and effectiveness of the Blast Simulator data acquisition and filtering procedure for outside this range. A constant damping ratio of 5% was chosen for the system and determined to be representative based on previous data and calculations conducted by AFRL.

5.1. Repeatability of system

Repeatable generation of high-g shock environments is of utmost importance in the capabilities of the experimental tool. Because of this, a test series was initially conducted to examine the reliability of the tool in order to give confidence with the approach of using the Blast Simulator as a shock device. Multiple tests were conducted with the urethane programmer at various impact velocities. Fig. 8 shows the response of the steel specimen to a set of 2 different tests series which had identical inputs. Tests A and B were conducted at 131 ft/s (40 m/s) and Tests C, D and E were conducted at 157 ft/s (48 m/s). 48 m/s was chosen because it is at the very high range of the actuator's capability and represents the most difficult level to control repeatability. It is clear that, in addition to producing a significantly large peak acceleration across a clearly measurable pulse duration, the testing showed an impressive level of repeatability for the shape of the pulse. The results for the peak acceleration repeatability were sufficient for displaying the effectiveness of the device for inducing shock loads in a specimen such as the AFRL test article being examined in this analysis, being consistent with results of other current used testing methods. The double peak in this set of tests was attributed to a combination of the urethane programmer pyramid geometry and the valve command times specified for this initial set of tests. Additional tests were conducted to adjust the pulse shape and duration and are described in the subsequent sections.

5.2. Effect of impact material on specimen response

Shock response spectrum comparisons are provided to display the differences in test results across the specified range of spectrum frequencies for varying impact materials. Because the tests were conducted with very different impact mediums, the plots provide useful comparisons for examining how the loading durations and peak accelerations induced by the various materials affect the response spectrum. For the purposes of this analysis and discussion, the "low-frequency" region spans from 0 to 100 Hz, the "mid-frequency" region from 100 to 1000 Hz, and the "high-frequency" region from 1000 to 100,000 Hz.

Fig. 7. Impact materials from left to right: urethane, leather, confined sand.

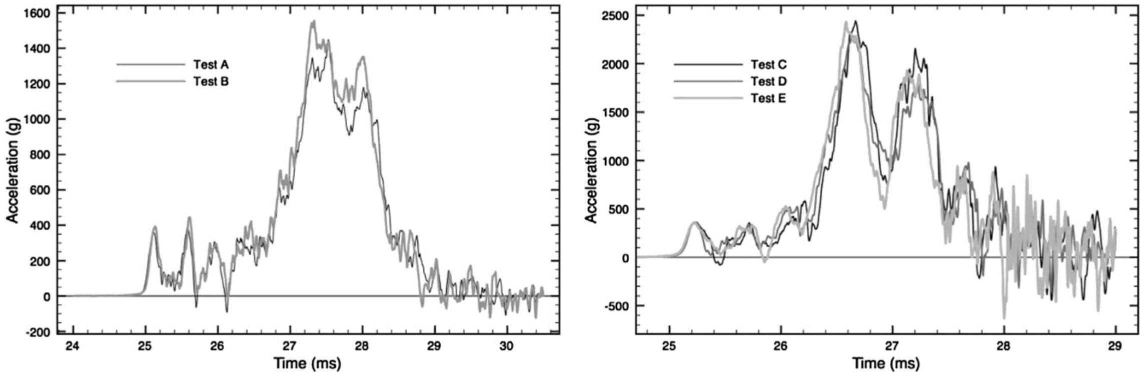

Fig. 8. Results from 40 m/s (left) and 48 m/s (right) test series showing repeatable results.

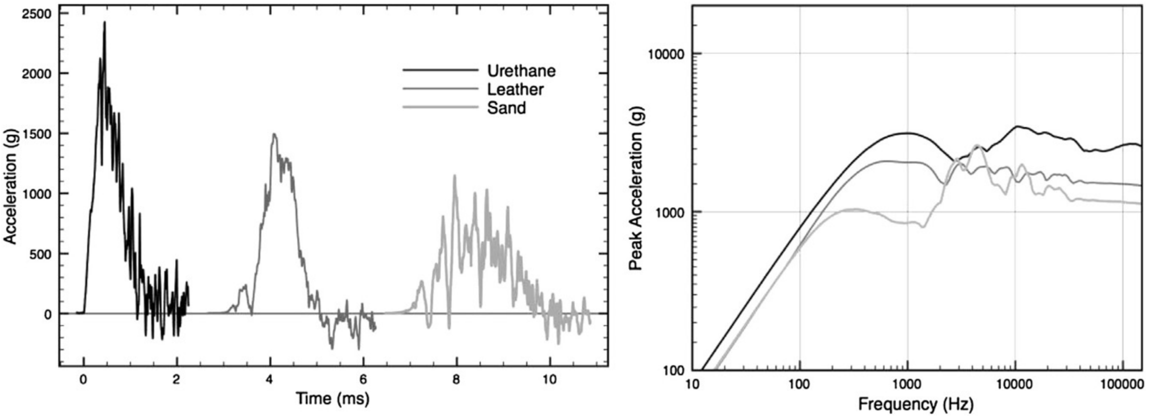

Fig. 9. Specimen acceleration (left) and SRS (right) with impact velocity of 15 m/s.

A comparison of the specimen accelerations and corresponding shock responses for tests which were conducted with a target impact velocity of 49 ft/s (15 m/s) is displayed in Fig. 9. For visualization purposes, the data is plotted at varying initial times, but the time scale remains constant. The test which used a urethane programmer, had the highest peak acceleration of the three tests and, consequently, the highest SRS response in the range of interest. The confined sand test, with a longer duration pulse reached its initial plateau at a lower frequency, as expected since this lower duration pulse would tend to excite oscillators with lower frequencies. At the high-frequency level, the sand exhibited a high level of response similar to the other tests. It was initially unclear if this high-frequency response was a function of the input and loading or attributed to the mounting of the accelerometer. Additional tests were conducted with various accelerometers and mounting fixtures and the results remained consistent.

Fig. 10 shows the results for tests which were conducted at an impact velocity of 98 ft/s (30 m/s). The plot displays the ability of the Blast Simulator to produce a set of shock responses which are consistent in terms of the peak accelerations produced and the duration's effect on the initial plateau. The urethane again produced the highest acceleration and smallest duration while the

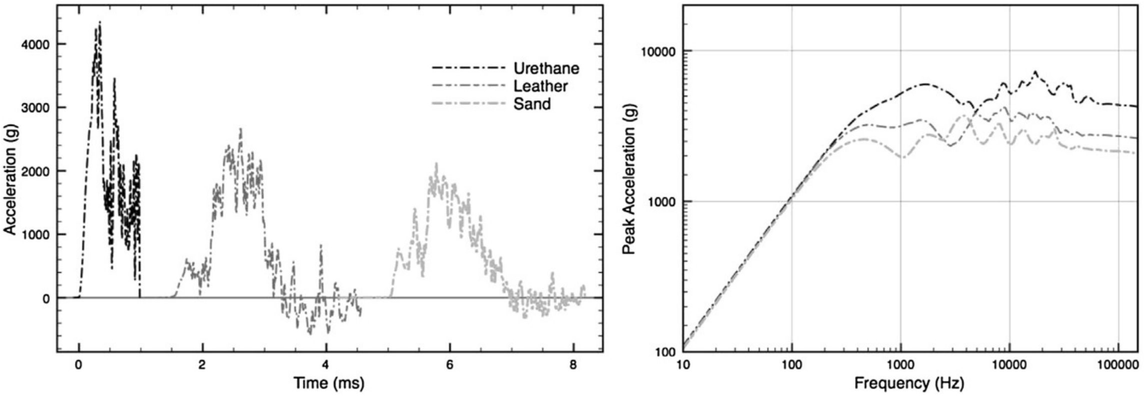

Fig. 10. Specimen acceleration (left) and SRS (right) with impact velocity of 30 m/s.

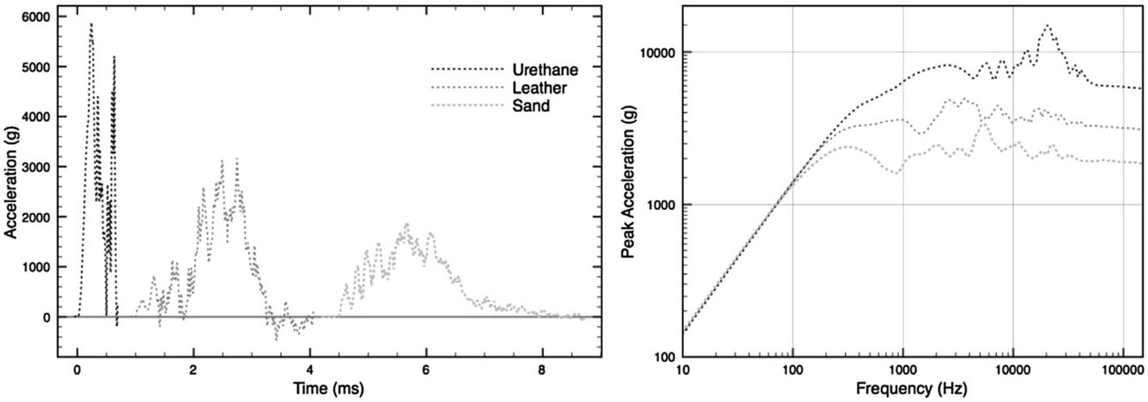

Fig. 11. Specimen acceleration (left) and SRS (right) with impact velocity of 40 m/s.

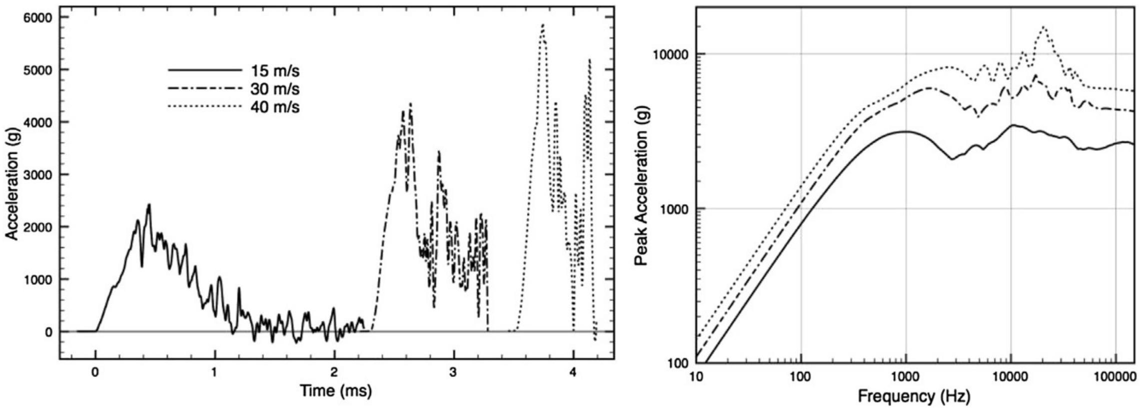

Fig. 12. Specimen acceleration (left) and SRS (right) with urethane impacting material.

sand produced the lowest peak acceleration and the longest duration.

The specimen accelerations for tests conducted with a target impact velocity of 131 ft/s (40 m/s) are shown in Fig. 11. The SRS have trends similar to that of the test set conducted at 98 ft/s (30 m/s). The results for each material in the low-frequency range are very similar since the pulse durations for all materials correspond to a frequency greater than 100 Hz. The response above 100 Hz shows noticeable variation due to the various pulse durations in this range. The increase in impact energy from the tests at 98 ft/s (30 m/s) results in a shift in all of the specimen responses towards higher peak accelerations at each frequency.

5.3. Effect of impact velocity on specimen response

In addition to noting the effectiveness of modifying the impact material to tailor the shock response of the test article, it is also important to note the effect of adjusting the impact velocity for a given impact material. Because the Blast Simulator is characterized by a high level of precision in producing the programmed impact

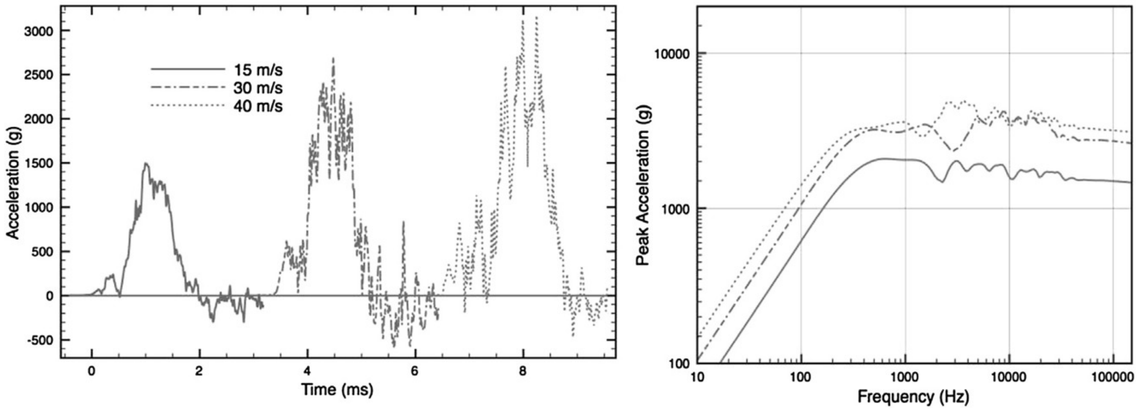

Fig. 13. Specimen acceleration (left) and SRS (right) with leather impacting material.

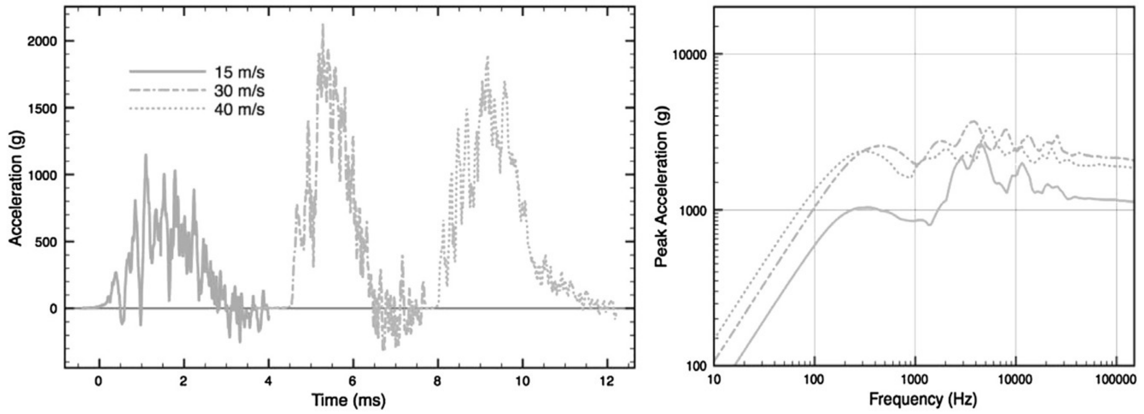

Fig. 14. Specimen acceleration (left) and SRS (right) with sand impacting material.

Table 1
Testing summary.

Impact velocity (m/s)	Loading medium	Peak acceleration (g)	Pulse duration (ms)
15	Urethane	2425	1.03
15	Leather (3 cm)	1644	1.25
15	Sand (18 kg)	1148	1.94
30	Urethane	4865	0.62
30	Leather (6 cm)	2573	1.03
30	Sand (18 kg)	2129	1.80
40	Urethane	5888	0.40
40	Leather (12 cm)	3168	1.34
40	Sand (27 kg)	1944	2.15

velocity during testing, understanding the effect of this parameter across a variety of velocity levels is valuable to test design.

Tests conducted with a urethane programmer as the impact material showed a distinct trend in the acceleration responses of the specimen. As the impact velocity increased, the peak acceleration increased and the loading duration decreased. This trend produces an increase in the shock response of the test article across the entire designated frequency range (Fig. 12). While a decrease in pulse duration given a specific peak acceleration will lead to an earlier plateau in the frequency range.

The urethane programmer's geometry contributes to a double peak in the pulse as the velocity increases. Initially the tip of each pyramid impacts the specimen and creates the initial peak in acceleration. If the velocity is slow enough, the specimen will accelerate outside of contact before the pyramid becomes fully compressed. If the velocity is sufficiently fast, the pyramid will fully compress creating an additional load on the specimen due to the momentum of the impacting mass in it's compressed state. These second pulses are generally shorter duration that the first pulse and may or may not be a desired effect, depending on the nature of the investigation. The effect can be minimized but, in general, not completely eliminated with valve commands of the Blast Simulator.

The leather tests, which had varying leather thicknesses, showed an increase in the peak acceleration response with an increase in impact velocity, as expected, similar to the other materials. Unlike the urethane, the significant decrease in pulse duration was not observed with the increase in velocity. One parameter adjustment which led to this result was the doubling of the layer thickness with each increase in impact velocity. These tests were conducted to show the feasibility of keeping the duration constant while increasing the peak acceleration. These results are shown in Fig. 13.

Testing of confined sand showed that the amount of sand being used as the impact material has a significant effect on both the pulse duration and peak acceleration, as shown in Fig. 14. The tests at 49 ft/s (15 m/s) and 98 ft/s (30 m/s) both used 40 lbs (18 kg) of sand, but the higher velocity test used 60 lbs (27 kg). While the peak acceleration doubles and loading duration decreases with an increase in impact velocity for the two lighter tests, the heavier test shows to have a lower peak acceleration and longer loading duration than the test at 98 ft/s (30 m/s). Because it would be expected that the peak would increase given the same mass of sand, it can be

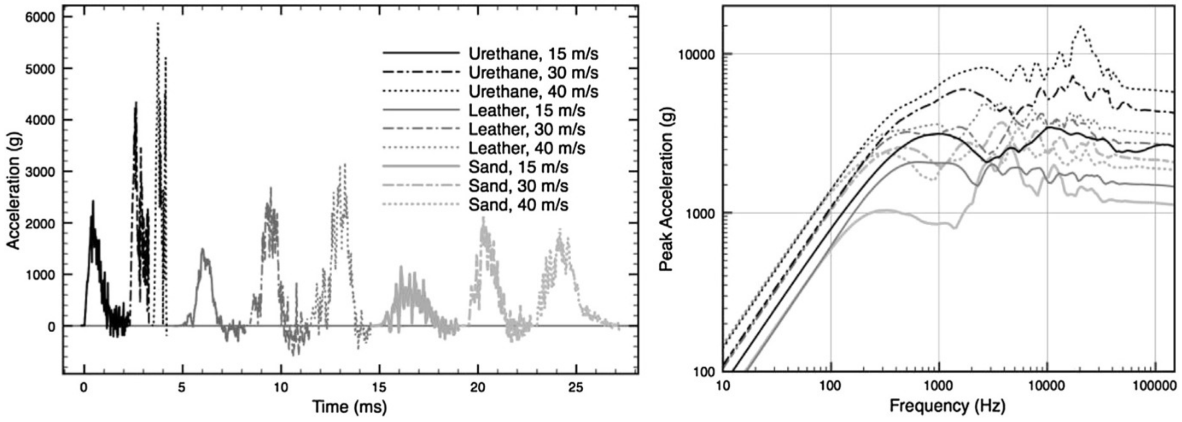

Fig. 15. Summary of specimen acceleration (left) and SRS (right).

concluded that an increase in sand will effectively extend the pulse duration but lower the peak response of the specimen.

5.4. *Summary of results*

A summary of the experimental data is described in Table 1 and shown in Fig. 15. They provide a full summary of the range of specimen acceleration time histories and corresponding shock response spectrums for comparison purposes. It is clear that the urethane material produces the largest peak acceleration and shortest loading duration for any given impact velocity and the sand produces the smallest peak acceleration and longest loading duration. The leather results show that it falls in between the urethane and sand in terms of both its peak response and pulse duration for each impact velocity.

6. Conclusions

The experimental testing results show that the Blast Simulator is capable of inducing a wide range of shocks on a test article. It has been determined that the pulse and shock response of the specimen can be reliably tailored by adjusting the impact material, impact material configuration (i.e. thickness, mass) and velocity at impact. These results, along with the validation of repeatability of the shock generation, suggest the Blast Simulator as a valid method for high-g shock generation.

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