“Crash Pendulum” Energy Absorption Test System

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Abstract
In this study, a novel “crash pendulum” test system which enables the observation of energy absorption capabilities of the materials/structures was developed. The system works with two simple pendulum principles and allows free mass collision axially. On the system, each mass block fixed to pendulum arm has an energy capacity of 4 kJ and moves at a velocity of 8 m/s. The data for the velocity of the mass block versus time were derived from the data for the angular displacement versus time. Kinetic energy was calculated by processing the velocity–time data with momentum equations. Restitution coefficient ($e$) of materials/structures on the contact region and mean impulsive force can also be calculated. In this study, steel and foam materials, whose restitution coefficient had already been known, were tested to validate the system. Finally, characteristics of a cylindrical aluminum tube were measured and then compared with the values which are available in the literature.

Introduction
Determination of the energy absorption characteristics of a part/system which is subjected to crushing force is very crucial for crash energy management such as design studies of crashworthy vehicles. For this reason, a number of test techniques with different principles were developed.

In the literature, drop hammer test is mostly used for measuring response of laminates.1,2 Drop tower facilities are suitable for axial and off-axis crashing test for tubular geometries.3 Rigid wall crash tests can be realized by means of striking the mass blocks to a rigid stationary surface by a pneumatic or hydraulic thruster for several types of crush applications.4–6 Moreover, there are specific applications for determining the crashing responses of the structures. Such additional apparatus may be mounted into the classical systems to increase the deformation speed with high strain rate effects.7 Another one is the single arm pendulum developed for motorcycle tire assembly.8

In this study, “Crash Pendulum” test facility was established in order to carry out the dynamically loaded crash experiments. The system has several advantages compared to drop-weight tower test systems. Vertical falling of the rigid mass under gravity, such as in drop towers, can result in high inertial force which is not truly in real-world crashes. Inertia can also cause the spring back effect particularly during collision if the mass is heavy. On the contrary, pendulum system minimizes these disadvantages since each arm can travel freely around on their path after it reached its limit before collision phase. In crash pendulum system, basic energy absorption characteristics such as absorbed energy, mean crushing force (impulsive force), and restitution coefficient can be easily defined by momentum equations.

Configuration of the Test System
The system was designed to produce an axially impact loading without gravity effect during impact. Thus, the system has double simple pendulum illustrated schematically in Fig. 1. Each arm of the system can carry adjustable mass block between 0 and 250 kg and move them with a velocity up to 8 m/s. As shown in Fig. 1, the startup potential energy can be adjusted with mass value ($m$) of blocks and initial height ($h$) of them. Therefore, the system has a wide range of potential energy which is completely converted into kinetic energy just before impact.
mass blocks, box profile (40 × 60 mm, thickness of 2 mm and mass of 2.91 kg/m), two mounting plates (500 × 100 × 10 mm) that connect box profile to the rotation axle, four aluminum cylindrical parts, and a number of several type bolt and nuts. The kinetic energy of the arms and auxiliary parts were neglected in the calculation, since their effect is considerably weaker than the blocks’ effect in the crash, and the linear velocity of their gravity center is about three times lower than that of the mass blocks.

The length of the arm between the gravity center of the mass blocks (loading axis) and rotation axis is 2850 mm. As shown in Fig. 3, distance between rotation axes of the arms can be adjusted by a change of mounting holes.

Test specimens can be fixed to mass blocks by a special apparatus or pasting by adhesive. Thus, they become coaxial with the loading axis.

Data acquisition system
The velocities of mass blocks have been derived from data of instant position. To collect position data, two Haidenhain rotary encoders with 3600 pulse/rev were attached to rotation axis of the arms having 6/1 gear ratio. Twenty-one thousand six hundred (3600 × 6) pulses have been generated from a revolution of the arm which has a length of 2850 mm. Thus, linear mass displacement along the path can be measured with a precision of 0.829 mm.

A load cell with 200 kN was axially located in front of the active mass in order to measure the impact forces which occurred during collision. Data acquisition has been performed by using both Haidenhain IK220 counter card and National Instruments NI-USB6009 DAQ card on LABVIEW8.0 user interface platform.
Analysis of Crash Data

Experimental data were analyzed by Microsoft Office Excel. Figure 4(a) shows an analysis of a sample test data obtained from crashing of an aluminum tube (diameter of 75 mm, length of 150 mm, and thickness of 2 mm). The raw data collected with DAQ system is in the format of position versus time and contain all crashing stages such as before, during, and after. Since the slope of position–time data corresponds to velocities of the arms, before- and after-impact stages were analyzed separately at different graphics as shown in Fig. 4(b and c). The slope of the position–time data can be obtained from the derivation of the linear equations fitted to the data at the short time.

From Fig. 4(b and c), it is understood that change of position versus time is linear. Thus, it is assumed that arm velocities have a constant value for a short crash time. These values were used for calculating kinetic energy of the mass blocks ($E_k = 0.5 \cdot m \cdot v^2$). For the crash energy management, absorbed energy ($E_A$) is calculated as a difference of the kinetic energies of the mass blocks before and after crushing, as follows:

$$\sum_{i=1}^{n} \frac{1}{2} m_i v_i^2 = \sum_{i=1}^{n} \frac{1}{2} m_i v'_i^2 + E_A, \quad (1)$$

where $m_i$ is the mass, $v_i$ and $v'_i$ are before- and after-impact velocities of the block for each arm, respectively. Impulsive force ($F$), which may be determined as mean crashing force, can be calculated by momentum and impulse equilibrium in Eq. 2, as follows:

$$m_1 v_1 + \sum F \Delta t = m_1 v'_1, \quad (2)$$

where $\Delta t$ is the acting time of impulsive force during impact which is obtained from position–time graphic analysis. Because of the mechanical characterization of a material or a system, absorbed energy value for unit mass of them should be defined as specific energy absorption (SEA) ratio with Eq. 3, as follows:

$$SEA = \frac{E_A}{m}. \quad (3)$$

Finally, restitution coefficient ($e$), which is expressed as the energy transferring efficiency of energy absorbers in the free mass collisions, can be defined by Eq. 4, as follows:

$$e = \frac{v'_2 - v'_1}{v_1 - v_2}. \quad (4)$$

Experimental Study

In order to confirm the double-arm pendulum energy absorption testing system, three different types of structures such as polystyrene foam, steel block, and aluminum tube were selected, then tested on different startup conditions for three times. Test data were analyzed by graphic and analytic analysis. The results obtained from this study were presented and compared with earlier studies (Table 1).

Crash test data for polystyrene foam material were presented in Fig. 5(a and b) as position versus time and velocity versus time, respectively. For this study, velocity data were computed from derivative of position versus time data, as a different way of investigation.
Table 1 Experimental and analytical results of studied samples

<table>
<thead>
<tr>
<th>Material types</th>
<th>Foam material</th>
<th>Metallic material</th>
<th>Aluminum tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of block [kg]</td>
<td>85</td>
<td>85</td>
<td>115</td>
</tr>
<tr>
<td>(v_1) [m/s]</td>
<td>2.8</td>
<td>1.38</td>
<td>7.38</td>
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<tr>
<td>(v'_1) [m/s]</td>
<td>0.2</td>
<td>0.25</td>
<td>4.2</td>
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<tr>
<td>(v'_2) [m/s]</td>
<td>2.6</td>
<td>1.12</td>
<td>3.13</td>
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<tr>
<td>(t) [s]</td>
<td>0.056</td>
<td>0.018</td>
<td>0.019</td>
</tr>
<tr>
<td>(E_k) [J]</td>
<td>364</td>
<td>81</td>
<td>3089</td>
</tr>
<tr>
<td>(E_A) [J]</td>
<td>47</td>
<td>24.9</td>
<td>1512</td>
</tr>
<tr>
<td>(F_{av}) [N]</td>
<td>4250</td>
<td>5336</td>
<td>26,800</td>
</tr>
<tr>
<td>(e) (obtained)</td>
<td>0.92</td>
<td>0.63</td>
<td>0.146</td>
</tr>
<tr>
<td>(e) (literature value)</td>
<td>0.96(^9)</td>
<td>0.6(^{10})</td>
<td>—</td>
</tr>
<tr>
<td>SEA (obtained) [j/g]</td>
<td>—</td>
<td>—</td>
<td>36.52</td>
</tr>
<tr>
<td>SEA (literature value) [j/g]</td>
<td>—</td>
<td>—</td>
<td>37(^{11})</td>
</tr>
</tbody>
</table>

Figure 5 Crash test data of polystyrene foam material. (a) Position versus time data; (b) derived velocity versus time data.

Polystyrene foam material is highly compressible without being subjected to plastic deformation. Thus, it can almost completely transfer the first arm’s kinetic energy to the second one during the crash. Since it behaves as a spring, absorption of energy does not occur, except for a small loss of energy caused by internal friction forces.

At the startup, each arm was loaded by a mass of 85 kg. From Fig. 5(b), former and subsequent velocities of the arms and crash time were defined as \(v_1 = 2.8\) m/s, \(v'_1 = 0.2\) m/s, \(v'_2 = 2.6\) m/s, and \(t = 0.056\) s, respectively. Thus, initial kinetic energy, \(E_k = 364\) J, absorbed energy, \(E_A = 47\) J, average crash force, \(F_{av} = 4250\) N, and restitution coefficient of material, \(e = 0.92\), have been determined. For this material, the \(e\) value of 0.92 is compatible with 0.96, which was defined in an earlier study.\(^9\)

For the metallic material crash test, 4140 alloy steel specimens were prepared in cylindrical form (with diameter of 40 mm and length of 50 mm) with 15 mm fillet radius in the front side of the specimen. Energy absorption can be performed by elastic shock wave propagation and/or locally plastic deformation according to contact surface area of the rigid block structures. In the rigid block impacts, highly impulsive force may occur even when tough kinetic energy is low. Startup velocity of the first arm was kept low since test system may be damaged from these types of forces caused by metal–metal rigid impact. Figure 6 shows the test data for metal block impact. Velocity data were calculated by processing the data of position before and after crash, separately. So velocity data

Figure 6 Metallic material impact test data. (a) Position versus time data; (b) analyzed test data.
have been derived from the linear models of the position data.

At the startup of testing, each arm was loaded with a mass of 85 kg. From Fig. 6(a and b), former and subsequent velocities of the arms and crash time were defined as \( v_1 = 1.38 \text{ m/s}, \) \( v'_1 = 0.25 \text{ m/s}, \) \( v_2 = 1.12 \text{ m/s}, \) and \( t = 0.018 \text{ s}, \) respectively. Thus, initial kinetic energy, \( E_k = 81 \text{ J}, \) absorbed energy, \( E_A = 24.9 \text{ J}, \) average crash force, \( F_{av} = 5336 \text{ N}, \) and restitution coefficient of material, \( e = 0.63 \) have been determined.

Another tested material is aluminum tube (with diameter of 75 mm, length of 150 mm, and thickness of 2 mm). Aluminum tubes are widely used for crash applications because of their plastic deformation capacities which are directly related to energy absorption capacities. Crash data of the tube were also presented in data-analyzing part of this paper (Fig. 4). The deformed shape of the aluminum tube after crash was presented in Fig. 7.

At startup, each arm was loaded with a mass of 115 kg. From Fig. 4(a and b), former and subsequent velocities of the arms and crash time were defined as \( v_1 = 7.38 \text{ m/s}, \) \( v'_1 = 4.2 \text{ m/s}, \) \( v_2 = 3.13 \text{ m/s}, \) and \( t = 0.019 \text{ s}, \) respectively. Thus, initial kinetic energy, \( E_k = 3089 \text{ J}, \) absorbed energy, \( E_A = 1512 \text{ J}, \) average crash force, \( F_{av} = 26.8 \text{ kN}, \) and restitution coefficient of material \( e = 0.146 \) have been determined. Tube mass is 0.194 kg for deformed length of \( s = 32 \text{ mm}. \)

So, SEA of aluminum tube (SEA\text{AL}) can be calculated as 36.52 kJ/kg by Eq. 3. For aluminum tube SEA\text{AL} value of 36.52 kJ/kg is compatible with 37 j/g, which was defined in an earlier study.\(^{11}\)

Conclusions

In order to obtain crushing responses of different types of materials/structures, such as bumper, crash box, shock absorbers, etc., a novel “Crush Pendulum” test facility with two simple pendulum principles was developed. Crash applications require definition of the kinetic energy-transferring characteristics of a part/system. This testing system allows axial impact for free body collisions to realize real-world crash conditions and determines SEA characteristic of materials/structures. The system has wide range of kinetic energy capacity in terms of mass blocks which is loaded to each pendulum arm and initial angular position of arms.

In the study, three different conventional types of materials were tested for the verification of the system. Experimental results and calculations validate that the system can define energy absorption behaviors of different types of materials, easily and correctly. Thus, crash-pendulum-type test system is able to perform several crash applications effectively. Furthermore, using this method, the momentum and kinetic energy conservation equations can experimentally be taken into effect.

Experimental analyses show that this crash-pendulum-type test system has a high accuracy in determining the SEA ratio, mean crashing forces, and restitution coefficient, which are the most important energy absorption characteristics of material/structures.

However, the system still has some following constraints:

- Because rotational movement of the arms causes the relative rising movement between block axis, very long specimens are not suitable for crash applications.
- Crashing velocity depends on the arm length of 2850 mm. Thus, an additional acceleration unit should be added to the system in order to acquire high impact velocity.

This novel crash pendulum energy absorption test system can effectively be used not only for scientific research but also for industrial applications. Hence, manufacturers of the energy absorbers, especially automotive chassis manufacturers, can easily set up this kind of test facility in their laboratory and take its advantages.

Acknowledgment

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References

2. Han, H., Tahberi, F., Pegg, N., and Lu, Y., “A Numerical Study on the Axial Crushing Response of...


