Development of shock-absorbing insert for honeycomb sandwich panel

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A B S T R A C T
Pyrotechnic separation devices have been widely used in various missions of spacecraft in order to separate the structural parts with high reliability. Although they afford advantages of cost-effectiveness and high reliability, pyrotechnic separation devices generate an intensive dynamic response called pyroshock, which can lead to fatal damage to the mounted electronic equipment. Previous studies have attempted to resolve these issues with a shock isolator. However, these studies have limitations such as possible dynamic instability in low frequency and complexity in design. In the present study, a novel design of the sandwich insert is proposed to achieve enhanced shock attenuation without a shock isolator. Static-load tests were conducted to validate the structural performance of the shock-absorbing insert. In order to observe the attenuation performance, shock propagation and response experiments were carried out with consideration that the inserts were utilized to connect parts and to mount devices on the panel. In addition, swept sine vibration tests were carried out to investigate the dynamic response in low frequency. The shock-absorbing insert reduced propagating shock for the joint structure, and the shock response of the mounted equipment was significantly attenuated. The novel shock-absorbing insert saves space and is dynamically stable, and furthermore has the ability to protect the small electronic equipment, which is mounted on the honeycomb sandwich panel, from severe shock. These advantages make it a suitable insert for space structure application for connecting parts or mounting equipment.

1. Introduction
Pyrotechnic separation devices have been used in the aerospace industry to conduct missions such as stage separation, satellite separation, clamp band release, and more. The advantages of pyrotechnic devices include a high-power-to-weight ratio, high reliability, and cost-effectiveness. Despite successful adaptation of pyrotechnic separation devices, pyroshock is of a critical concern due to the possible damage to electronic equipment mounted on space structures. Pyroshock is generated by the loading with high frequency and magnitude induced by the attached separation devices. This transient response of the structures rarely causes structural deformation, but there is a risk of small electronic equipment failure such as relay chatter, failure of circuit components, and short circuits [1–3]. In order to resolve these issues, many researchers have studied methods to reduce the shock response of the electronic equipment. The first approach is to design low-shock separation devices. To accomplish this, the release mechanism of the device should be investigated through a numerical analysis based on the finite element method (FEM). Lee et al. [4,5] identified the separation characteristics of ridge-cut explosive bolts and induced pyroshock using ANSYS AUTODYN based on hydrocodes. From the verified analysis tool, the pyroshock response was predicted and the understanding of release mechanism was improved. In addition to previous studies, Hwang et al. [6,7] established a mathematical model for the separation behavior of split type low-shock separation bolts containing a pressure cartridge. To validate the established model, experiments were carried out and the results were compared. The study helped to design and optimize a split type low-shock separation bolts considering the amount of charge and initial volume. Woo et al. [8] conducted a similar study for pyroshock-reduced separation. From their study, behaviors of internal parts were derived mathematically and established equations were compared with experimental results. Wang et al. [9] studied the pyroshock response prediction of a separation nut using ANSYS AUTODYN and sensitive parameters for the shock response were investigated. In addition to these studies, many researchers and companies have developed non-explosive separation actuators (NEAs) such as an electrical spool and separation nut, a paraffin actuator, shape memory alloy (SMA) devices, and a thermal knife [10,11]. Although NEAs can reduce shock effectively, their lower separation reliability compared to the conventional pyrotechnic de-
The installation of shock isolators is a widely used method to reduce the shock response of electronic equipment. Shock isolators, which are installed between electronic equipment and a structure, can isolate high-frequency vibration effectively by energy harvesting of the isolator system. Generally, elastomeric materials, which have relatively low stiffness, are employed to attenuate high-frequency vibration. Despite the strengths of powerful attenuation performance, precise design and safety tests, e.g. swept sine vibration tests, are required due to the amplification of low-frequency vibration near the natural frequency of the system. Under harsh conditions, the isolator itself is at risk of being destroyed [12-14]. To prevent this problem, Jeong et al. developed frequency tunable mesh washer isolators using shape memory alloy actuators [15,16]. The isolation material was a compressed mesh washer that exploits the pseudoelasticity of the SMA. There are two modes operated by SMA wires: one is for preventing amplification of low-frequency vibration and the other is for pyroshock isolation.

As pyroshock propagates in an elastic wave form, its magnitude can be reduced in a discontinuous region of the structure, and this is called impedance breakdown [1,17]. Material, density, and contact area are the main factors of impedance breakdown, which occurs in the joint and the contact region between inner parts. In order to understand the shock propagation path and characteristics, a finite element analysis or pyroshock experiment can be used. In the phase of space structure system design, it is important to understand pyroshock propagation characteristics and to apply an appropriate shock absorber on the propagation path to avoid malfunction of electronic equipment and mission failure. National Aeronautics and Space Administration (NASA) conducted pyroshock propagation tests for various space structures, such as a honeycomb structure, a longeron, a cylindrical shell, and more [18,19]. From experimental results, the damping performance of the structure was investigated and has been used as the standard for pyroshock analyses. Also, the attenuation factor of various joints evaluated by pyroshock tests has been used to predict the shock response of equipment of interest [17,20]. Due to safety concerns of tests using pyrotechnic separation devices, many researchers have developed pyroshock simulators, which generate mechanical shock. Lee et al. [21] and Jeong et al. [22] developed point source pyroshock simulators that can generate mechanical shock similar with pyroshock. These easy-to-use devices help to conduct shock propagation tests repeatedly and have the advantage of applicability to various structures without constraints. Numerical analyses also can be used for the prediction of pyroshock propagation. Lee et al. [23] proposed a numerical method to predict pyroshock propagation characteristics using ANSYS AUTODYN and studied pyroshock propagation through plates with joints and washers. The method was validated through comparison with pyroshock experimental results. From established techniques, the effects of the shock attenuation by the joints and washers were investigated. Zhao et al. [24] provided a Finite Element-Statistical Energy Analysis (FE-SEA) hybrid modeling technique to predict the shock response of spacecraft. Furthermore, researchers studied visualization of pyroshock through the development of laser scanning measurement technology [25]. Recently, analytic methods for pyroshock prediction have been well established and have helped to resolve the problem of electronic device failure.

However, previous studies only deal with simple plate structures, as they are easy to design and construct. Although honeycomb sandwich panels are widely used in spacecraft due to their high stiffness-weight ratio, studies on shock reduction for the sandwich panels have not been thoroughly carried out. From the studies conducted by NASA, the honeycomb structure shows the lowest damping performance [19,26]. This means that enough distance is required to reduce the magnitude of pyroshock. Accordingly, appropriate methods are needed to ensure safety upon shock on the honeycomb sandwich panel. The general method is to use shock isolators, as shown in Fig. 1. However, this has limitations including possible dynamic instability in low frequency and complexity in design. Also, the shock isolator takes space and requires the installation of numerous inserts. The insert, which is a small part with bolt thread, is used to make joints between panels and to install devices on the panel. In this paper, a novel design of a sandwich insert for shock attenuation is proposed to avoid the problems of the shock isolator. The proposed insert is not only used as a structural joint, but also as a shock absorber. From the impedance breakdown in the inner structure of the shock-absorbing insert, shock attenuation performance is enhanced compared to the conventional insert. As the main roles of inserts are structural connection and conveying load, static-load tests were conducted on the conventional inserts and shock-absorbing inserts. From the results, the structural performance of the shock-absorbing insert was investigated. In order to verify the shock attenuation performance of the shock-absorbing insert, shock propagation and response experiments were carried out. Comparing the results with conventional inserts, the shock attenuation performance of shock-absorbing inserts and applicability without the shock isolator were identified. In addition, a swept sine vibration test was conducted and the dynamic response in low frequency was discussed. For shock-sensitive devices, the shock-absorbing insert can be used instead of the shock isolator. This method has advantages of space-savings, dynamic stability, and enhanced shock attenuation. From various experiments with the shock-absorbing insert, its applicability to space structures was identified.

2. Design of the shock-absorbing insert & static-load tests

2.1. Conventional insert

The honeycomb sandwich panel is widely used in the aerospace industry due to its high stiffness-weight ratio. To construct a space structure and mount equipment on the panel, sandwich inserts are used. The general shape of the insert is a cylindrical structure with two flanges at the bottom and top, as presented in Fig. 2. Based on the Insert Design Handbook [27] published by the European Space Agency (ESA), we made a conventional insert for a M5 bolt connection. Its outer diameter, inner diameter, and height were 17 mm, 9 mm, and 12 mm, respectively. The thickness of the flanges was 1.5 mm. Stainless steel, 304 SS, was employed for the material of the insert. The basic method to install inserts on the honeycomb sandwich panel is to use epoxy resin. There were two holes in the upper flange to inject the epoxy resin.
2.2. Shock-absorbing insert

A schematic diagram of the shock-absorbing insert is shown in Fig. 3. There are four parts to be assembled: the housing, insert core, elastomer washer, and cap. The housing is the main part in contact with epoxy resin. Also, it has a thread to connect with the cap and a space for the insert core with elastomer washers. It was manufactured with an outer diameter of 22 mm and a height of 16 mm. The diameter and the depth of the inner space were 14 mm.

The insert core has bolt thread for M5 bolt connection and it was positioned in the housing with elastomer washers. Two elastomer washers were positioned above and below the insert core’s center. The outer diameter of insert core was 13 mm and the height was 14 mm. Ethylene Propylene Diene Monomer (EPDM), widely used as shock-absorbing material in the aerospace field, was employed for the elastomer in this study. Its outer diameter, inner diameter, and height were 14 mm, 9 mm, and 3 mm, respectively.

The cap has a thread in the radial direction to connect with the housing. Torque was applied to the gaps in the cap by using a customized ratchet wrench. The cap has outer diameter of 14 mm, inner diameter of 10 mm, and height of 4 mm. The assembly procedure is shown in Fig. 4 and is as follows: (1) Put the elastomer washers on the insert core; (2) Input the insert core with washers into the housing; (3) Apply torque to the cap using a ratchet wrench. The role of the cap is to limit the vertical movement of the insert core. The material for the elastomer washers can be replaced according to the required performance or operating environment by opening the cap.

The proposed structure is easy to assemble and the installation procedure is the same as that for the conventional insert. All parts except the washers are made of 304 SS. Due to the impedance breakdown between 304 SS and EPDM in the inner structure, effec-
2.3. Static-load test

First, a series of static-load tests were carried out considering that the main role of the sandwich panel insert is to bear load, especially tensile and shear loads. To identify the structural performance of the proposed insert, both the conventional insert and the shock-absorbing insert were installed in an aluminum honeycomb sandwich panel (100 mm × 100 mm × 20 mm, 1 mm skin thickness) using epoxy resin (CEMEDINE 1500), as shown in Fig. 5. We manufactured the conventional insert to have the same size as the shock-absorbing insert, thereby creating the same contact area between the epoxy resin and the insert’s surface for both cases. For load application, a universal testing machine (Instron 4482) was applied with 1 mm/min load speed. This speed is widely applied for static-load tests. The insert design handbook and other papers [27–29] were referenced to design test fixtures and structural steel, 400 SS, was employed for the material of the fixtures.

2.3.1. Pull-out test

Figure 6 shows the test setup for the pull-out. The honeycomb sandwich panel with the insert was positioned in the fixture and a load carrying bar was connected with the insert using a steel chrome molybdenum (SCM435) bolt perpendicular to the sandwich panel skin. There were two jigs in the Instron 4482 where the bottom jig clamps to the fixture and the top jig clamps to the load-carrying bar. Pull-out tests were carried out for both inserts and the results are shown in Fig. 7. From the results, the maximum tensile load before failure was 3.82 kN for the conventional insert and 3.95 kN for the shock-absorbing insert. The magnitude was quite similar and this indicates that shock-absorbing insert, which is an assembly type and contains an elastomer in the inner space, shows the same structural performance compared to the conventional shape insert made of one material. From the graph,
the behavior of the shock-absorbing insert is different from that of the conventional insert case because during the load application, the upper elastomer washer was compressed first. From the section view of the test specimen shown in Fig. 8, the failure modes were core shear failure and epoxy resin debonding, which are the general modes of a pull-out test [30]. The structural performance results based on tensile loading showed no failure or critical deformation in the inner structure of the shock-absorbing insert.

2.3.2. Shear-out test

Figure 9 presents the test setup for the shear-out. The honeycomb sandwich panel with the insert was positioned in the fixture and a load-carrying bar was connected parallel to the sandwich panel skin. As in the pull-out test, the bottom jig was used to clamp the fixture and top jig for the load carrying bar. A M7 bolt was used to prevent bolt destruction. Results of the shear-out tests are shown in Fig. 10 and the maximum shear load was 10.5 kN and 10.0 kN for the conventional and shock-absorbing insert, respectively. These test results also show that the shock-absorbing insert has similar structural performance to that of the conventional insert. From the section views of the test specimens shown in Fig. 11, the epoxy resin debonding mode appeared for both cases. The collapse of the sandwich panel skin appeared on only the conventional insert case while the shock-absorbing insert penetrated the honeycomb core. The measured load of the conventional insert after epoxy resin debonding was above that of the shock-absorbing insert because more load was needed to push the collapsed honeycomb skin than its core. The behavior of the inserts was different, but the maximum shear load was quite similar and there was no noticeable deformation of the inserts. From the shear-out test, it was identified that the shock-absorbing insert showed similar structural performance to that of the conventional shape insert.

3. Shock propagation experiment

3.1. Experimental setup

For the shock propagation experiment, two aluminum honeycomb sandwich panels (600 mm × 400 mm × 20 mm) and a simple plate (600 mm × 400 mm × 5 mm) made from aluminum-6061 were prepared. There were eight holes at 50 mm intervals on each panel to install inserts, as shown in Fig. 12. Conventional inserts were installed on one panel and shock-absorbing inserts were installed on the other. In order to investigate the shock attenuation performance according to the type of elastomer material, EPDM and polyurethane (PU) washers were prepared. PU is relatively stiffer than EPDM. The elastomer was easily changed by opening the cap of the shock-absorbing insert. The honeycomb sandwich panel and the plate were connected by a bolted joint. This model was suspended in the air using four cables, as shown in Fig. 13, and a free boundary condition was achieved.

For non-contact velocity measurement, a LDV (Laser Doppler Vibrometer) was employed. There were two measurement points, as shown in Fig. 13, and they were 100 mm apart from the joint region. Velocity measurements were performed at a sampling frequency of 1 MHz using a National Instruments PXIe-6366 analog input DAQ board for 20 ms. After the LDV measurements, a band-pass filter for 100 to 100,000 Hz was applied and acceleration in
the time domain was obtained by differentiating the velocity. In order to quantify the measured shock, the Shock Response Spectrum (SRS) was calculated. The SRS indicates the maximum acceleration value obtained by applying time domain acceleration on the Single Degree of Freedom (SDOF) system corresponding to each natural frequency [31]. Generally, the damping ratio of a SDOF sys-
tem is 0.05 and this means that the Q factor is 10. The SRS is the most commonly used method to analyze the shock because it is easy to identify the possibility of damage due to shock in each frequency band. By comparing the SRS of two points, the shock attenuation performance of the inserts could be investigated.

A pyroshock simulator was attached to the simple aluminum plate with M8 thread. The simulator contains a resonator and a gun-type launch device that launches a metal-ball projectile of 6 mm diameter to the resonator with a high velocity of 60 m/s when the loading distance of the spring is 20 mm (see Fig. 14). To validate the capabilities of simulating pyroshock, pre-tests were conducted. From the document for pyroshock criteria [26], the main factors of pyroshock are slope, knee frequency, and maximum acceleration response in the SRS. The slope of the SRS should be ±9 to ±12 dB/octave in the growing region and the maximum acceleration response should be above 1000 G. The knee frequency indicates the frequency at which the slope of the SRS becomes approximately horizontal, i.e., the frequency with maximum acceleration. Typical knee frequency of pyroshock is over 3 kHz and the simulator can control the knee frequency by changing the resonator shape, which has its own natural frequency. The selected resonator shown in Fig. 15 is made of stainless steel, 304 SS.

3.2. Results

The SRS results shown in Fig. 17 compare the three selected cases: the conventional insert, shock-absorbing inserts with EPDM, and PU (see Figs. 16 and 17). Similar observations were made for all the before-joint results, which indicate that the pyroshock simulator has excellent repeatability for shock generation. Also, the knee frequency is about 7200 Hz, the slope of the growing region is 9.7 dB/octave on average, and the maximum acceleration is about 15,000 G. This indicates that the shock, which the pyroshock simulator generates, meets the pyroshock criteria. From the after-joint results, the shock-absorbing insert showed better attenuation performance than the conventional insert, and EPDM was better than PU for shock absorption due to its lower stiffness than PU. To quantify the attenuation performance of the inserts, SRS variance between before-joint and after-joint was calculated in dB unit and shown in Fig. 18. SRS variance of −15 dB indicates that the shock of after-joint was attenuated by 83% compared to the SRS of before-joint. The shock response in the high frequency range (above 2 kHz) was reduced by more than 83% when shock-absorbing inserts with EPDM were installed. This range of frequency is a risk factor to the mounted electronic equipment, and the applicability of the shock-absorbing insert was identified to play a key role of shock attenuation during the propagation.

3.3. Impedance breakdown

In general, especially for high frequencies, shock attenuation comes from elastic wave propagation. The attenuation is achieved by the local stiffness difference between the mechanical structure and the relatively soft structure. This phenomenon is called “impedance breakdown”. It can be illustrated with a simple bar, which has a region of local property discontinuities as shown in Fig. 19. Each discontinuity of local stiffness or density leads to reflected and transmitted shock waves. When the incident wave, which starts from relatively high-impedance material, passes relatively low-impedance material, the transmission ratio is higher than the reflection ratio. In the opposite case, the reflection ratio is higher than the transmission ratio [1]. When the low-impedance structure is positioned between the high-impedance structures, the shock seems to be absorbed into the low-impedance structure. This effect makes shock attenuation in the proposed insert. In the shock-absorbing insert, elastomer washers were positioned between 304 SS structures as shown in Fig. 3. From Table 1, EPDM and PU have quite lower stiffness and density than 304 SS.

In the previous experiment, the EPDM showed better performance in shock attenuation than the PU because the quantity
Fig. 16. Time domain acceleration results of shock propagation experiment: (a) Conventional insert (b) Shock-absorbing insert with EPDM (c) Shock-absorbing insert with PU.
of the attenuation depends on the difference of local impedance value. As the wave velocity is proportional to the square of stiffness and density, the impedance of EPDM is lower than PU and the difference with 304 SS is higher. For a better understanding, additional-torque tests were conducted to investigate the effect of stiffness. The elastomeric material has a feature that the stiffness increases when a compressive load is applied. In the shock-absorbing insert, an additional torque can be applied to the cap and the elastomer washer is compressed like Fig. 20. For the quantitative application, a torque wrench was used for revolving the cap. The additional torques were 0, 11, 20 and 30 Nm. After the revolving cap, the shock propagation experiments for EPDM and PU were conducted with the same procedure. Results of time-domain acceleration and SRS are presented in Figs. 21 and 22. The afterjoint result of the conventional insert was added to the SRS results for attenuation performance comparison. It is observed that the attenuation performance of the insert performance increased when the stiffness of elastomer increases. The performance became similar to the conventional insert when over 20 Nm torque was applied for both EPDM and PU. From this study, it is concluded that the difference in impedance value is a key factor of shock attenuation.

4. Shock response experiment

4.1. Experimental setup

Inserts were also used to mount devices on the sandwich panel, as shown in the left side of Fig. 23. The main concern in the phase of system design of a space structure is to ensure the shock safety of the electronic equipment. Therefore, a shock response experiment was carried out. To identify the shock response of the equipment, the honeycomb sandwich panels were prepared to install inserts, and a schematic diagram of the experiment setup is shown in Fig. 23. A dummy mass made of aluminum-6061 with 1.2 kg was mounted on the panel using four inserts. Figure 24 shows the three cases that were considered: (a) the conventional insert (b) the conventional insert with 6 mm thickness rubber mount (EPDM), and (c) the shock-absorbing insert. For the elastomer washer, only EPDM was considered due to its good attenuation performance, as discussed earlier in this study. As depicted in Fig. 25, the dummy mass was mounted on the panel with four bolts, and the structure was suspended in the air using four cables.

The pyroshock simulator was employed to excite the shock on the sandwich panel. An additional conventional insert with M8 bolt thread was installed to attach the resonator. Four measurement points were selected, as shown in Figs. 23 and 25. The reference point, located 100 mm from the shock source, was measured by the LDV and the other points were measured by accelerometers (PCB 350B03). The LDV measured the velocity of the reference point on the sandwich panel, and the accelerometers measured the acceleration of the three points on the dummy mass. Points were measured with a sampling frequency of 1 MHz using a National Instruments PXIe-6366 analog input DAQ board for 20 ms. After the measurement, a band-pass filter of 100 to 100,000 Hz was applied.

**Fig. 18.** Quantified attenuation performance of inserts.

**Fig. 19.** Impedance breakdown in the simple bar with discontinuity.

**Table 1**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Bulk Modulus (GPa)</th>
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<tr>
<td>304 SS</td>
<td>7900</td>
<td>134</td>
</tr>
<tr>
<td>EPDM</td>
<td>1000</td>
<td>0.4</td>
</tr>
<tr>
<td>PU</td>
<td>1265</td>
<td>2</td>
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</table>
and acceleration in the time domain was obtained by differentiating the velocity of the reference point. SRS values were calculated to quantify the shock. The shock attenuation performance of the inserts was investigated by comparing the SRS of the reference point with that of points on the mass.

4.2. Results

Figures 26 and 27 present experimental results for each case. The results show that the attenuation in the inserts is not enough for cases (a) and (b), which used conventional inserts. However, SRS in the high frequency range was attenuated effectively in the case of using the shock-absorbing insert. In addition, the results indicate that the effect of the contact characteristic between the panel and the dummy mass was not significant. For a precise analysis, results corresponding to each measurement point are shown in Fig. 28. The SRS of the reference point was quite similar for each case, and the repeatability of the simulator was confirmed. Also, it met the pyroshock criteria as the knee frequency, maximum acceleration, and the slope of the growing region were 5080 Hz, 3250 G, and 10 dB/octave respectively. For every accelerometer point on the dummy mass, the shock-absorbing inserts attenuated the high-
frequency shock, and it appears that the impedance breakdown effect was a key factor for the shock attenuation. Figure 29 shows the attenuation performance calculated from the SRS variance between the reference point and the accelerometer measurement point. The attenuation performance of the conventional insert was $-8$ dB on average, and the shock-absorbing insert showed a value of about $-20$ dB, which means that 90% of the shock was reduced, for the high frequency range. From the shock response experiment, it was found that the shock-absorbing insert can reduce the high-frequency shock, which is transmitted to mounted equipment, and
Fig. 26. Time domain acceleration results of shock response experiment: (a) Conventional insert (b) Conventional insert with rubber mount (c) Shock-absorbing insert.
the shock safety can be ensured when using shock-absorbing inserts.

5. Swept sine vibration test

During a space mission, especially in the lift-off phase, the space structure experiences low-frequency vibration due to the engine vibration, aerodynamic load, etc. This low-frequency vibration may affect the structural integrity of the mounting parts of payloads. When shock attenuation devices such as shock isolator are used, the resonant frequency of the system is reduced due to the low-stiffness material. Amplification of low-frequency vibration near the resonant frequency can destruct devices, especially when the vibration is below 100 Hz, which is fatal to the structure because it involves large displacement. Therefore, the resonant frequency of the system is generally required to be above 100 Hz to ensure the stability of the payload. In this section of the study, the swept sine test was conducted for the conventional insert with rubber mount and the present shock-absorbing insert as shown in Fig. 30. A simple plate made of aluminum-6061 (140 mm × 140 mm × 24 mm) with weight of 1.2 kg was prepared as a dummy mass, which is the same as the dummy mass for the shock response experiment. The investigation of the low-frequency vibration response of the mounted mass could help identify the applicability of the shock-absorbing insert for space structures.

The swept sine test was conducted using a shaker (LING 1216VH). Axial (Z-axis) and lateral (X-axis) excitations were considered and the locations of accelerometers are shown in Figs. 31 and 32. Due to technical limitations for mounting the honeycomb sandwich panel on the shaker base, only inserts were mounted on the shaker base. M10 bolt thread on the bottom surface of the insert provides direct connection. After mounting the inserts on the
Fig. 29. Attenuation performance corresponding to accelerometer measurement point: (a) Acc#1 (b) Acc#2 (c) Acc#3.

Fig. 30. Considered cases for swept sine test.

Fig. 31. Location of accelerometers for Z-axis vibration.
shaker base, the dummy mass was connected with inserts using M5 bolts. The swept sine vibration was excited for 1 minute with 0.4 g acceleration and the frequency range was 5 to 2000 Hz. The sampling frequency of the swept sine test was 50 kHz.

The transmissibility of the inserts was evaluated through a comparison of the reference and response accelerations. Figure 33 presents the transmissibility of inserts for the Z-axis and X-axis, and the resonant frequency of the system is presented in Table 2. For the Z-axis case, the resonant frequency of the shock-absorbing insert was lower than that of the conventional insert. Despite the lower resonant frequency, the amplification was very small compared to the conventional insert with rubber mount. The resonant frequency was above 100 Hz with 1.2 kg dummy mass (0.3 kg/unit). These results indicate that the shock-absorbing insert has better attenuation performance in high-frequency vibration without safety in the low-frequency vibration. For the X-axis case, the resonant frequency of the shock-absorbing insert was higher than that of the conventional insert. As explained before, the space between the base structure and the dummy mass is a critical factor for the lateral vibration. The space was 0.5 mm for shock-absorbing insert and 6 mm for rubber mount. As impedance-breakdown system is positioned in the inner-structure of the insert, the shock-absorbing insert has a merit in lateral vibration compared to the rubber mount. Furthermore, the resonant frequency of the rubber mount was near 100 Hz, which is dangerous for the safety of the structure. It means that the increased payload reduces the resonant frequency, making it more dangerous. So, the maximum payload can be determined by the results of the X-axis vibration test. The system is considered as a simple mass-spring system, which resonant frequency is determined by the mass and the stiffness as shown in Fig. 34. Assuming that the dynamic stiffness of the system is constant, the maximum payload, which makes the resonant frequency near 100 Hz, can be determined. From the test results of the X-axis vibration, the maximum payload for the shock-absorbing insert was determined as shown in Table 3. The stability in low-frequency vibration of the shock-absorbing insert and the maximum payload for safety were investigated using EPDM. However, the elastomer washers of the proposed insert can

Table 2
Resonant frequency and transmissibility of inserts.

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<thead>
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<th>Z-axis</th>
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<th>X-axis</th>
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<tr>
<td></td>
<td>Resonant frequency</td>
<td>Transmissibility at R.F</td>
<td>Resonant frequency</td>
<td>Transmissibility at R.F</td>
</tr>
<tr>
<td>Shock-absorbing insert</td>
<td>422 Hz</td>
<td>2.9</td>
<td>297 Hz</td>
<td>3.4</td>
</tr>
<tr>
<td>Conventional insert with rubber mount</td>
<td>1067 Hz</td>
<td>13.2</td>
<td>149 Hz</td>
<td>5.4</td>
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</table>

Fig. 32. Location of accelerometers for X-axis vibration.

Fig. 33. Transmissibility of inserts.
be specified without any constraints. In other words, the proposed insert provides operational safety in a more flexible manner according to the mission environment.

6. Conclusion

In this study, a novel design of a sandwich panel insert for shock attenuation was proposed, and its applicability to a space structure was investigated. The shock-absorbing insert was designed to induce impedance breakdown in its inner structure. Elastomer washers played the key role as the shock attenuator due to their low stiffness. The structural performance of the conventional and shock-absorbing inserts was investigated through static-load tests for pull-out and shear-out. The shock attenuation performance for both inserts was also evaluated by conducting shock propagation and response experiments. In addition, swept sine vibration tests were carried out to investigate the dynamic stability of both inserts at relatively low frequency.

This study found that the shock-absorbing insert had similar structural strength to conventional insert with no significant deformation of parts. The shock-absorbing insert reduced the high-frequency shock during propagation through the honeycomb structure. It also significantly reduced the shock response of mounted equipment without shock isolators. The novel shock-absorbing insert saves space and is dynamically stable, and it has the ability to protect the small electronic equipment, which is mounted on the honeycomb sandwich panel, from severe shock. These advantages make it the most suitable insert for space structure application as a part for constructing joint or mounting equipment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 3

<table>
<thead>
<tr>
<th>Test result (X-axis)</th>
<th>Mass-spring system</th>
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<tr>
<td>Shock-absorbing insert</td>
<td>Maximum payload</td>
</tr>
<tr>
<td>0.3 kg/unit</td>
<td>2.4 kg/unit</td>
</tr>
<tr>
<td>Conventional insert with rubber mount</td>
<td>0.6 kg/unit</td>
</tr>
<tr>
<td>297 Hz</td>
<td>149 Hz</td>
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References


