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Araştırma Makalesi / Research Article

Effect of Cut-outs on the Free Vibration Response of Basalt/Carbon Hybrid Composites

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Cut-out;
Hybrid composite;
Damping;
Vibration,
Stacking sequences

Abstract

The current work deals with an experimental investigation about the influence of cut-outs on dynamic characteristics of basalt/carbon hybrid fiber reinforced composite laminates. The composite samples have been fabricated via vacuum assisted resin transfer molding technique and cut-outs in the form of triangular, square and circular shapes with equal areas have been processed on them to systematically analyze the influences of cut-outs. The dynamic characteristics of the samples have been examined by conducting free vibration-damping tests and expressed in terms of natural frequency and damping ratio using the frequency response and time-acceleration response. The results show that the damping characteristics of the composite samples can be remarkably improved with the help of cut-outs which provide improvements approximately between 2.41% and 16.65% in damping ratio values. The maximum and minimum variations in damping ratio have observed for non-hybrid carbon fiber reinforced composite samples with triangular cut-out (T-C6) and hybrid basalt/carbon fiber reinforced composite samples with circular cut-out (C-B6), respectively. On the other hand, the presence of cut-outs have led to decreases in natural frequency values as a result of reduction in stiffness caused by the cut-outs. This point out that employment of cut-outs can be a promising application to meet the natural frequency requirements of engineering systems constructed with hybrid fiber reinforced composite laminates.

Kesiklerin Bazalt / Karbon Hibrit Kompozitlerin Serbest Titreşim Tepkisine Etkileri

Anahtar kelimeler
Kesik;
Hibrit kompozit;
Sönümleme;
Titreşim,
İstifleme sırası

Öz

Mevcut çalışma, kesiklerin bazalt / karbon melez fiber takviyeli lamine kompozitlerin dinamik özellikleri üzerindeki etkisi hakkında deneysel bir araştırma ile ilgilidir. Kompozit numuneler, vakum destekli reçine transfer kalıplama tekniği ile imal edilmiş ve kesiklerin etkilerini sistematik olarak analiz etmek için üzerlerinde eşit alanlara sahip üçgen, kare ve dairesel şekiller şeklinde delikler açılmıştır. Numunelerin dinamik özellikleri, serbest titreşim sönümleme testleri yapılarak incelenmiş ve frekans tepkisi ve zaman-ivme tepkisi kullanılarak doğal frekans ve sönümleme oranı cinsinden ifade edilmiştir. Sonuçlar, kompozit numunelerin sönümleme özelliklerinin, sönümleme oranı değerlerinde yaklaşık %2,41 ile %16,65 arasında artışlar sağlayan kesikler yardımıyla önemli ölçüde iyileştirilebileceğini göstermektedir. Sönümleme oranındaki maksimum ve minimum varyasyonlar, sırasıyla üçgen kesikli hibrit olmayan karbon fiber takviyeli kompozit numuneler (T-C6) ve dairesel kesikli hibrit olmayan bazalt fiber takviyeli kompozit numuneler (C-B6) için gözlemlenmiştir. Öte yandan, kesiklerin varlığı, deliklerin neden olduğu sertlikte azalmanın bir sonucu olarak doğal frekans değerlerinde düşüşlere yol açmıştır. Bu, kesiklerin kullanılmasının, hibrit fiber takviyeli kompozit laminatlarla inşa edilen mühendislik sistemlerinin doğal frekans gereksinimlerini karşılamak için umut verici bir uygulama olabileceğini göstermektedir.

1. Introduction

Over the past few decades, compared to traditional monolithic materials, polymer-based composite materials have been attracted attentions in many engineering fields with their superior properties such as higher specific strength/stiffness (Madenci *et al*. 2020, Bozkurt 2017, Oğuz *et al*. 2020, Gemi *et al*. 2020, Özütok and Madenci 2017), fatigue life (Roundi *et al*. 2017), resistance to corrosion (Kumar *et al*. 2019, Özkılıç *et al*. 2020, Madenci *et al*. 2020) and good thermal insulation (Yasir *et al*. 2018), and have been extensively used in a wide range of lightweight members with high load-carrying capacity for various engineering applications like construction, aerospace and automotive in recent years (Khosravi and Eslami-Farsani 2016, Uslu *et al*. 2021, Özbek 2020, Bulut *et al*. 2017, Aksoylu *et al*. 2020, Madenci and Özütok 2020, Özkılıç *et al*. 2021, Madenci *et al*. 2020). Moreover, the superior dynamic performance of polymer-based composites widen their popularity for the structural applications such as space shuttles, aircrafts, marine vessels, vehicles, etc (Draiche *et al*. 2014, Qatu *et al*. 2010) that subjected to vibratory loads in service conditions. Although the plenty of researches related with mechanical and thermal properties of composite materials, comparatively limited studies devoted to their dynamic mechanical properties are found in the literature (Noor and Burton 1989, Bozkurt *et al*. 2018, Bulut *et al*. 2020, Huang and Tsai 2015, Murugan *et al*. 2016, Bedon 2019, Duc *et al*. 2017, Bhudolia *et al*. 2017, Wang *et al*. 2019, Özütok and Madenci 2013, Özütok *et al*. 2014). Additionally, the different design parameters such as hybridization, stacking sequences of the composite materials has recently attracted the attention due to the their direct influences on mechanical properties of composite materials (Gemi 2018, Özbek and Bozkurt 2019, Doğan *et al*. 2019, Gemi *et al*. 2020). Furthermore, only a few studies devoted to free vibration characteristics of basalt or carbon fiber reinforced composites are seen in the literature. Bozkurt and Gökdemir (2018) examined the influences of basalt hybridization on the tensile and dynamic characteristics of carbon fiber reinforced composite laminates. It was demonstrated that the inclusion of basalt fiber resulted with an enhancement in damping properties and decrease in tensile characteristics of carbon fiber reinforced composite laminates. Ramakrishna *et al*. (2021) investigated the vibration-damping characteristics of carbon/basalt hybrid fiber reinforced composite laminates that modified with graphite powders. The samples with three different graphite content (1 wt.%, 2 wt.% and 3 wt.%) and stacking sequences were fabricated by hand lay-up technique. They stated that the 3 wt.% graphite powder content was significantly affected the vibration characteristics of basalt/carbon composites. Ilangovan *et al*. (2020) performed the experimental, numerical and analytical studies regarding the free vibration behaviors of basalt/epoxy and E-glass/epoxy composite tubes with silica nanoparticles. They reported that lower amount of silica nanoparticle inclusion (up to 1.5 wt.%) resulted with the increases in natural frequency and damping factor values. Also, they said that BFRP composites showed higher damping properties than GFRP composite samples.

Cut-outs are inevitable geometrical requirements in the structural members for various purposes such as reducing the weight, providing access to different areas, quality control, inspection purposes, ventilation to facilitate heat distribution, to avoid induced acoustic noise (Sinha *et al*. 2021, Mandal *et al*. 2020). The cut-out applications with different geometric shapes are seen in many fields in the aeronautical, mechanical, electrical and civil structures (Hashemi and Hamza-Cherif 2020). The dynamic response of a structural member can be influenced at a certain level due to the application of cut-outs. This leads to increase the possibility of resonance which means the maximum damage. So, the investigation of the dynamic characteristics of a member with cut-outs is a very crucial issue for the structural designs to prevent possible unpredictable scenarios. Several studies devoted to vibration-damping behaviors of polymer-based composites with cut-outs are seen in the literature (Sivakumar *et al*. 1999, Poore *et al*. 2008, Erkliğ *et al*. 2013, Bicos and Springer 1989). Sinha *et al*. (2021) performed the experimental and numerical studies on the free vibration response of glass fiber reinforced composite laminates with cut-outs. The samples having different size and position of cut-outs have been examined at various boundary conditions. No significant effects in frequency were obtained from the cut-out position except eccentric and concentric cut-outs. Erkliğ *et al*. (2014) examined the natural frequency responses of hybrid composites with or without cut-outs. The reinforcement fibers of Kevlar, glass, and carbon were used for the hybridization of composite laminates. The increment in cut-out size ratio (D/W) resulted with decreases in the natural frequency of the samples. Mondal *et al*. (2015) investigated the experimental and numerical studies on the dynamic characteristics of sandwich composite plates with cut-outs at various locations. They expressed that frequency reduces towards the minimum as the hole moves off-center towards the larger side of the plate.

To the best knowledge of authors to date, there is no published study in the open literature about the effect of cut-outs on dynamic properties of basalt/carbon hybrid fiber reinforced composites. Hence, the motivation of the current study is to experimentally evaluate the effect of cut-outs on the dynamic properties of basalt/carbon fiber reinforced composite laminates in terms of natural frequency and damping ratio using the frequency response and time-acceleration response. In order to gain a better insight into the effect of cut-out application, the composite samples (three hybrid and two non-hybrid) fabricated by vacuum-assisted resin transfer molding were prepared and subjected to free vibration tests. Three different cut-out shapes (triangular, square and circular) with the equal area were processed to the center of the beam type samples.

2. Materials and Method

2.1 Materials

In order to evaluate the dynamic responses of composite laminates, basalt plain woven fabric (supplied from Tila Kompozit Ltd. Şti., Turkey) and carbon plain woven fabric (provided by Dost Kimya A.Ş., Turkey) were used as reinforcements in fabrication of composite laminates. For the matrix phase of composites, an epoxy (MOMENTIVE-MGS L160) and a hardener (MOMENTIVE-MGS H160) procured from Dost Kimya A.Ş., Turkey, were mixed in the stoichiometric weight ratio of 100:25, respectively. The mixture was prepared at 8000 rpm for 30 minutes with a mechanical stirrer. The mechanical and physical properties of fabrics and resin were presented in Table 1.

Table 1. The mechanical and physical properties of fabrics and resin materials.

Material	Density	Tensile strength (MPa)	Tensile modulus (GPa)	Fabric thickness (mm)
Basalt fabric	202 g/cm^2	2000-2300	90-92	0.28
Carbon fabric	204 g/cm^2	2500-3000	200-700	0.25
Epoxy (neat)	1.18-1.20 g/cm^3	70-80	3.2-3.5	-

2.2 Preparation of Samples

The vacuum-assisted resin transfer molding process, illustrated in Figure 1, was implemented for the manufacturing of both hybrid and non-hybrid composite samples. A rigid-flat aluminum platform equipped with resistance heating elements was utilized as a bottom mold. The fabrics (40 cm x 50 cm) with twelve layers were cut and placed on the rigid platform. Then, a peel ply and a resin distribution media, respectively, were stacked over fabric preform to provide a uniform distribution of resin and easy removal of the composite laminates from the mold structure. After that, the fabric stack, peel ply and resin distribution media were covered with a vacuum bagging film to create a closed media as the mold. Lastly, the prepared resin mixture was injected into the mold system with the help of 680 mmHg vacuum pressure. After the whole laminates were wet, the initial curing process was started by turning off the resin inlet valve and leaving the composite laminates at 80^{o}C temperature for 8 hours. Following this, post-curing of composite laminates was performed at 40^{o}C temperature for 2 hours.

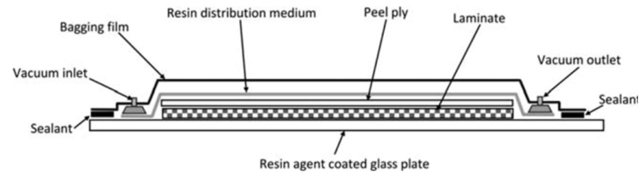

Figure 1. Schematic illustration of vacuum-assisted resin transfer molding (Bozkurt 2017)

The different stacking sequences, as shown in Figure 2, were used in each 12 layered composite laminates. The hybridization process was started with totally basalt/epoxy fiber reinforced composites and were ended with totally carbon/epoxy fiber reinforced composites by replacing twos of inner basalt fabric layers symmetrically with carbon fabrics (2, 6, 10 number of layers).

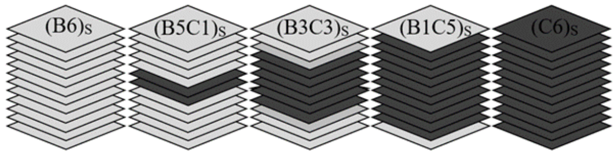

Figure 2. Stacking sequences of basalt (B) and carbon (C) fabric layers

After the production process, vibration test samples with 20 mm wide and 200 mm length were prepared by using a 3-axis CNC router. The tests were repeated for at least five samples of each composite configuration and the values were averaged. The naming and thickness information of each configuration were given in Table 2.

Table 2. Naming and thickness information of composite laminates

Configuration	Naming	Thickness (mm)
$(B6)_s$	B6	2.18
$(B5C1)_s$	H1	2.22
$(B3C3)_s$	H2	2.43
$(B1C5)_s$	H3	2.63
$(C6)_s$	C6	2.86

The cut-outs in the form of triangular, square and circular shapes with the same areas were used to evaluate the effects of cut-outs on the free vibration response of composite laminates as shown in Figure 3. An equal area, 43.3 mm, was considered for all cut-outs and each of them was compared with the samples without cut-outs. The diameter and edge values of cut-outs were 7.42 mm, 6.58 mm and 10 mm for circular, square and triangular cut-outs, respectively. After this section, the prefix U, T, C and S notations were used for expressing of without cut-out, triangular cut-out, circular cut-out and square cut-out, respectively.

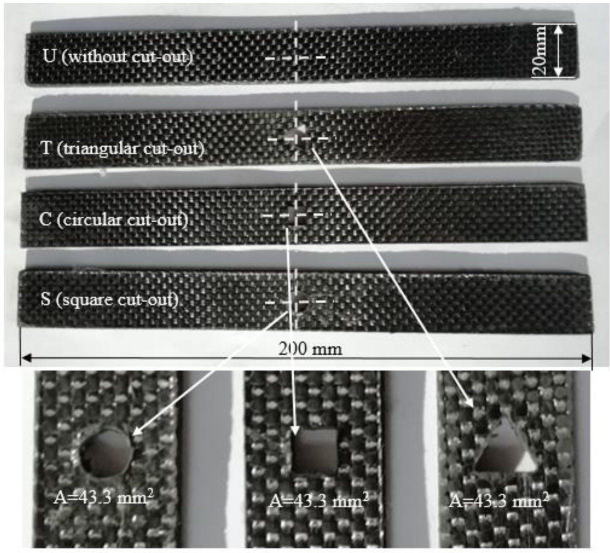

Figure 3. Test samples with different cut-out shapes

2.3 Free Vibration Experiments

An experimental set-up composed of an accelerometer, impact hammer and Signal Express software, was used to determine modal vibration properties of the fabricated test samples. A general-purpose PCB 086C03 modal impact hammer to impulse a force on composite sample and a general-purpose PCB 352C03 ceramic shear ICP accelerometer to measure time-dependent acceleration response were utilized. The 50 mm portion of composite beam samples were clamped to provide cantilever beam behavior. The accelerometer was placed near the cut-out region which was approximately 40 mm away from the clamped side towards the free end of the sample. The tests were performed by exciting each sample at least five times from the same identical point which was near to the cut-outs (opposite side of the accelerometer). A photographic view and the excitation point were seen in Figure 4.

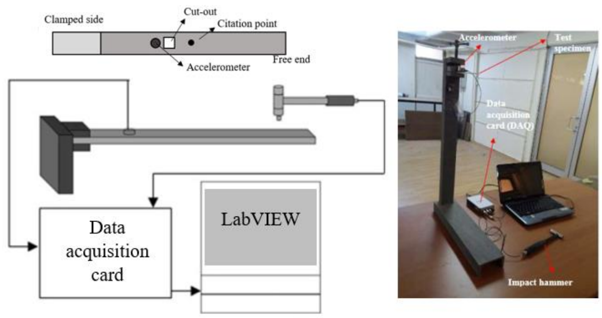

Figure 4. Free vibration experiments

Using fast Fourier transformation, time-dependent acceleration response taken from LabVIEW software after impact excitation was transformed into the frequency domain to generate the frequency response functions (FRFs). The values of natural frequency were obtained from the amplitude information in the first peak of FRF curves. Then, the damping ratio (ξ) was calculated through half-power bandwidth method as follows (Kabir and Hoa 2011);

$$\xi = \Delta\omega / 2\omega_1 \quad (1)$$

where $\Delta\omega$ and ω_1 are the bandwidth and first mode natural frequency, respectively.

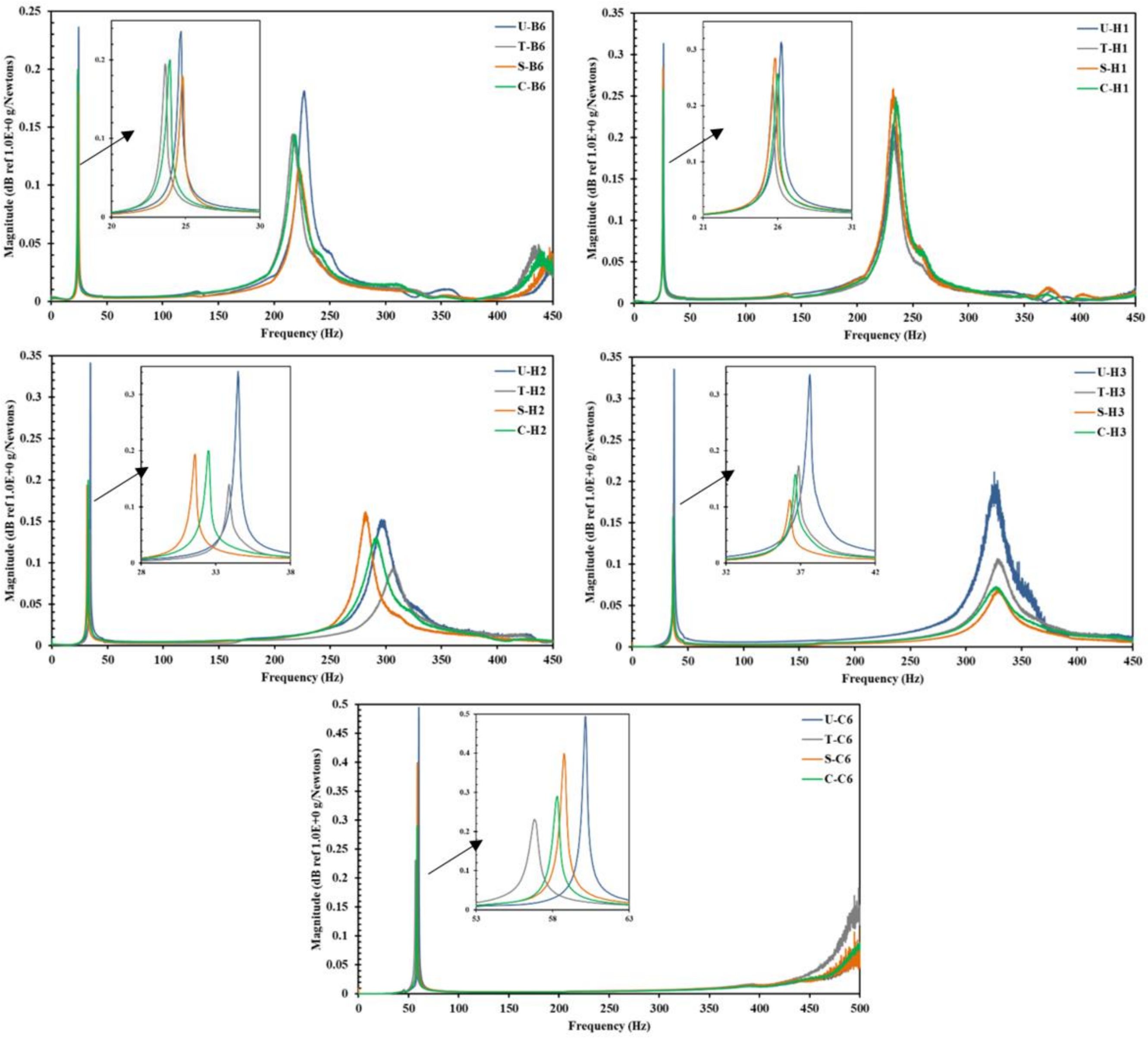

Figure 5. Frequency response curves of the hybrid/non-hybrid samples with different cut-outs

3. Results and Discussions

The curves of frequency response function (FRF) versus amplitude of the hybrid and non-hybrid samples with different cut-out shapes were given in Figure 5. The first mode which is seen as more dominant was used to determine the dynamic mechanical properties of composite laminates through the half-power bandwidth method. The first mode of natural frequency for all composite laminates were presented in Figure 6 to clearly follow the variations in natural frequency values. It is evident that cut-out shapes directly influence the frequency responses and both the hybrid and non-hybrid composite samples with cut-outs have lower natural frequency than the samples without cut-outs. The maximum reductions in natural frequency values as %6.11 and %4.66 were obtained from triangular samples for C and B non-hybrid samples, respectively. In most of the samples, square cut-outs led to the minimum decreases in natural frequency values compared to samples without cut-outs. The results obtained from the samples with circular cut-out remained the intervals of triangular and square cut-out. This can be attributed to the presence of the cut-outs that leads to reduction in the stiffness of composite laminates. Similar findings can be seen in the literature (Mandal *et al*. 2020, Jadhav and Deshmukh 2016). In a study related with the free vibration characteristics of glass fiber reinforced composites with arbitrary cut-outs, Mandal *et al*. (2020) declared that reduction in stiffness led to the frequency decreases for the small size of cut-outs.

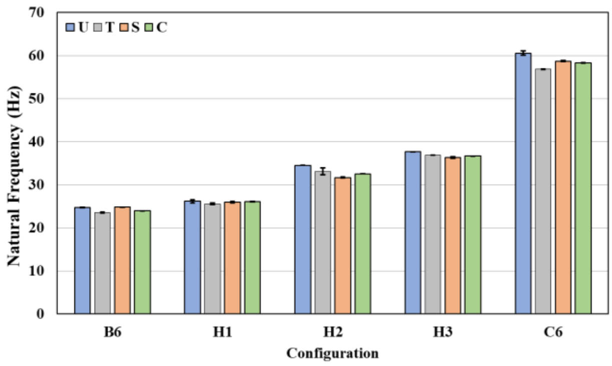

Figure 6. Natural frequencies of the hybrid/non-hybrid samples with different cut-outs

It is also seen that the characteristics of composite samples are significantly dependence on constituent materials. The incorporation of carbon fiber into basalt fiber reinforced laminates was resulted with the increases in frequency values as in (Bozkurt and Gökdemir 2018) and the maximum frequency was obtained from U-C6 samples as 60.55 Hz which was 6.51%, 3.12% and 3.88% higher than those of T-C6, S-C6 and C-C6 samples, respectively. It can be said that all samples with cut-out showed decreases in the natural frequency values. As seen from the literature, many factors such as bending stiffness, extensional stiffness, coupling stiffness, stiffness of the cross-section, and boundary conditions might have significant influences on the natural frequency of composite laminates (Venkateshappa *et al*. 2019, Jones 1998). Furthermore, the inclusion of carbon fiber content led to the significant increases in the natural frequency of basalt fiber reinforced laminates (B6) with or without cut-outs (Bozkurt and Gökdemir 2018). It can be said that the natural frequency of basalt fiber reinforced composites (B6) was increased with the carbon fiber hybridization. Compared to those of C-B6 samples, the increases in natural frequency of C-H1, C-H2 and C-H3 samples are 8.9%, 35.8% and 53.2%, respectively.

Damping ratio values of composite samples were presented in Figure 7. It was clearly seen that the presence of cut-outs was resulted with the increase in the damping characteristics of composite laminates for those of hybrid and non-hybrid samples. The composite samples with triangular cut-outs were exhibited the maximum damping ratios. T-B6, T-H1, T-H2, T-H3 and T-C6 samples had the damping ratio values of 0.006465, 0.006175, 0.005077, 0.004445 and 0.004106, respectively. The maximum damping ratio was obtained from the T-B6 samples and is 5.98% higher than those of U-B6 samples. Furthermore, all samples with cut-out showed the better damping ratio than samples without cut-out. This can be attributed to the decrease in stiffness of the material as a result of cut-out application. Thus, it is known that stiffness and damping are opponent properties and if there was an increase in one of them can be accompanied by a reduction in another (Lakes 2002). Due to the less stiff nature of basalt fiber, the increase in basalt fiber content of hybrid laminates provided the enhancement in damping characteristics. Bozkurt and Gökdemir (2018) stated that the poor interfacial adhesion between basalt fiber and epoxy matrix led to an additional energy dissipation mechanism can be viewed as another source of increase in damping ratio. In comparison of cut-out shapes, minimum damping values were obtained from the samples with circular cut-outs. When compared to cut-out shapes with each other, the maximum reductions in damping ratio were determined as 3.37%, 5.02%, 10.28%, 8.26% and 11.47% for C-B6, C-H1, C-H2, C-H3 and C-C6 samples, respectively.

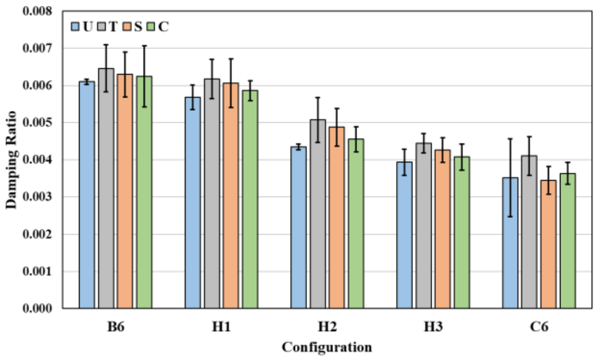

Figure 7. The damping ratio of the hybrid/non-hybrid samples with different cut-outs

For a better understanding for the effect of cut-out applications on the free vibration characteristics of the composites, the time-acceleration responses of the carbon fiber reinforced composite samples with or without cut-outs were presented in Figure 8. Amplitude-time decaying curves were recorded within the same time intervals (5 seconds) to make reliable comments on damping behaviors of the samples. The amplitude of oscillations for the samples without cut-out was occurred around 4s interval while the samples with triangular cut-outs showed the stabilization approximately 3s interval. This may be explained by a decrease in vibration energy dissipation along the longitudinal direction (Bozkurt *et al*. 2016) because the samples with triangular cut-out had the maximum reduction in cross-sectional area. Liang *et al*. (Liang *et al*. 2011) reported that the increase of effective damping could be led to decrease in dissipated energy employing amplitudes. Furthermore, the samples with square or circular cut-outs showed shorter oscillation periods compared to the samples without cut-outs due to decrease in cross-sectional stiffness which resulted with increases in damping characteristics.

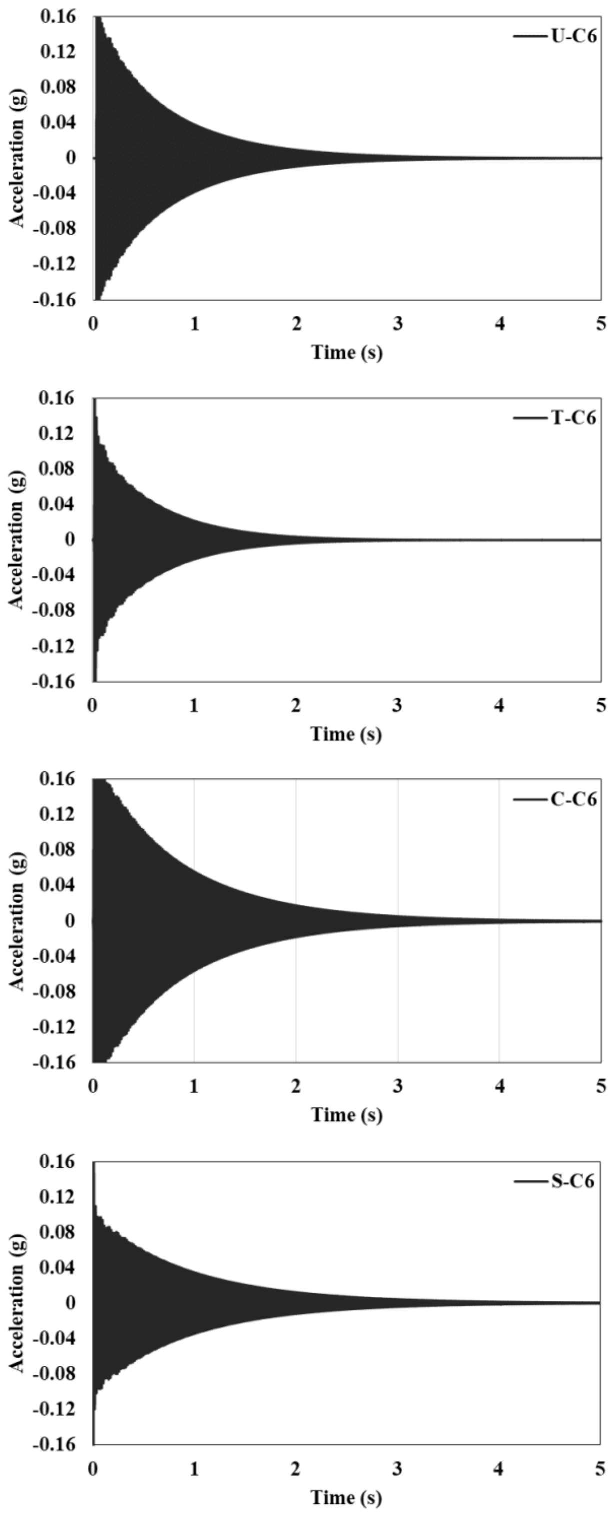

Figure 8. Time-acceleration response of carbon fiber reinforced composite laminates

4. Conclusions

In this study, the effects of cut-outs on the free vibration characteristics of basalt/carbon hybrid fiber composites were experimentally investigated. The results showed that cut-outs in the form of triangular, square and circular shapes have contribution on the improvement of damping characteristics of composite laminates.

- The maximum improvement in damping ratio was obtained from the triangular cut-outs. Even though the increase in damping values, the cut-outs led to decreases in natural frequency of the samples.
- It was also seen that fiber hybridization had remarkable impacts on vibration-damping response of composite laminates.
- The hybridization with basalt fiber were improved the damping capability of the carbon fiber reinforced laminates.

In conclusion, the employment of cut-outs can be a promising application to meet the vibration-damping requirements of an engineering system constructed with hybrid and non-hybrid fiber reinforced composite laminates.

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