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Natural Cork Agglomerate Employed as an Environmentally Friendly Solution for Quiet Sandwich Composites

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Carbon fiber-synthetic foam core sandwich composites are widely used for many structural applications due to their superior mechanical performance and low weight. Unfortunately these structures typically have very poor acoustic performance. There is increasingly growing demand in mitigating this noise issue in sandwich composite structures. This study shows that marrying carbon fiber composites with natural cork in a sandwich structure provides a synergistic effect yielding a noise-free sandwich composite structure without the sacrifice of mechanical performance or weight. Moreover the cork-core sandwich composites boast a 250% improvement in damping performance, providing increased durability and lifetime operation. Additionally as the world seeks environmentally friendly materials, the harvesting of cork is a natural, renewable process which reduces subsequent carbon footprints. Such a transition from synthetic foam cores to natural cork cores could provide unprecedented improvements in acoustic and vibrational performance in applications such as aircraft cabins or wind turbine blades.

Cork is a natural product obtained from removing the outer bark of the cork tree[1]. As the outer bark replenishes to its full thickness every nine to twelve years, cork can be harvested as a natural, renewable resource. Cork has been well studied and reported for their extraordinary and remarkable mechanical properties[1–8]. They show intriguing properties including nonlinear elasticity, super compressibility without fracture, and unusual dimensional recovery capability, which gives rise to outstanding energy absorbing performance. As a cellular material its unique properties seem to arise from the combination of aligned, prismatic closed cells and their structural arrangement. In addition to the mechanical properties, other attractive features involve better thermal insulation properties[7,9] and impermeability to gases or liquid. With the use of cork in the form of agglomerate, referred to as "cork agglomerate", it has been widely used in a variety of applications ranging from a wine stopper to aerospace structures, which are often exposed to extremely harsh environments.

In many structural applications including aerospace, automotive, marine and renewable wind-turbine blades, there is an increasingly growing interest in the use of sandwich composite materials due to their high stiffness and strength-to-weight ratios. A sandwich composite is typically structured by sandwiching a thick, lightweight core between two thin, stiff face sheets. Most sandwich composites are composed with core materials of either polymer synthetic foam (i.e., Rohacell) or honeycomb cores (i.e., Nomex or Kevlar). However, ironically, a sandwich composite's high specific stiffness and strength offer undesirable vibrational performance including poor acoustic properties by radiating noise beginning at low frequencies. For instance, aircraft cabin noise is radiated from several sources including engine vibration and acoustic excitation of the fuselage, which can cause passengers discomfort. However, it is common to use sandwich composites with honeycomb cores for commercial aircraft structures for their high mechanical properties and light-weight. To reduce the undesirable noise level, additional sound absorbing material is necessary, which thickness must be comparable to the wavelength of the noise[10]. It was reported in earlier studies[11–18] that the properties of the core material including shear modulus can dictate the vibrational and acoustic response of such sandwich composites. Cork agglomerate seems to be an ideal core material for sandwich composites because of the benefit from the blend of its lightweight, low shear modulus, superior energy absorbing properties, and thermal insulation properties. Thermal conductivity values, coefficients of thermal expansion, and specific heat values (C_p) are also similar for cork agglomerate and commonly used foams in sandwich composites. Studies have also showed that cork agglomerate can withstand temperatures up to 200°C with minimal mass loss (up to 6%). Also, negligible changes to the cellular structures and dimensions are observed for heating up to 150°C[8]. In addition to these excellent mechanical and thermal properties, cork is a natural, biodegradable material whereas foam and honeycomb core materials are non-recyclable and non-biodegradable. Surprisingly even with these favorable properties, cork agglomerate is significantly cheaper than synthetic foams; the cork purchased for this study was roughly 10% of the price of the Rohacell foams. Very recently, the use of natural cork agglomerate as a core material was suggested for high energy absorption and damping performance[1-6]. However, it should be noted here that, although applications demand it, hardly any data exists in literature that has unveiled the acoustic properties of natural cork agglomerate core sandwich composites. In this paper, we study the sound and vibrational response sandwich composites with carbon fiber face sheets and a natural cork agglomerate core and, to the best of our knowledge, report for the first time that such sandwich composites exhibit virtually noise-free properties and still remain uncompromised in other mechanical performance.

Results

Morphology Characterization. The morphology and structure of both cork agglomerate and Rohacell foams were first examined and compared before and after a compression test. Figure 1(a) shows the results of the compression test, while subsequent figures show the SEM images of the materials at certain compressive strains. Figures 1(b), (c) and (d) show the SEM images of cork agglomerate prior to compression, at 90% strain, and after testing during relaxation, respectively. Similarly Figures 1(e), (f) and (g) show Rohacell 110 WF at the same aforementioned stations. As Rohacell 110 WF and 110 IG had similar compressive responses, only 110 WF is shown as a representative sample. In analyzing cork and Rohacell at the microscopic level, both materials have a similar microstructure in that they are cellular. However while the Rohacell foams have cell sizes ranging from 309–824 μm, cork has a significantly smaller cell size of approximately 41 μm; also cork boasts a smaller cell wall thickness of 1.04 μm compared to 18.8 μm and 26.3 μm for 110 WF and 110 IG. To test their energy absorption and recovery capacity capabilities, both cork and Rohacell foams were subjected to compression tests (Figure 1(a)). Similar to earlier reports[5,7,19–20], the Rohacell foams and cork agglomerate exhibit non-linear elastic behavior composed of

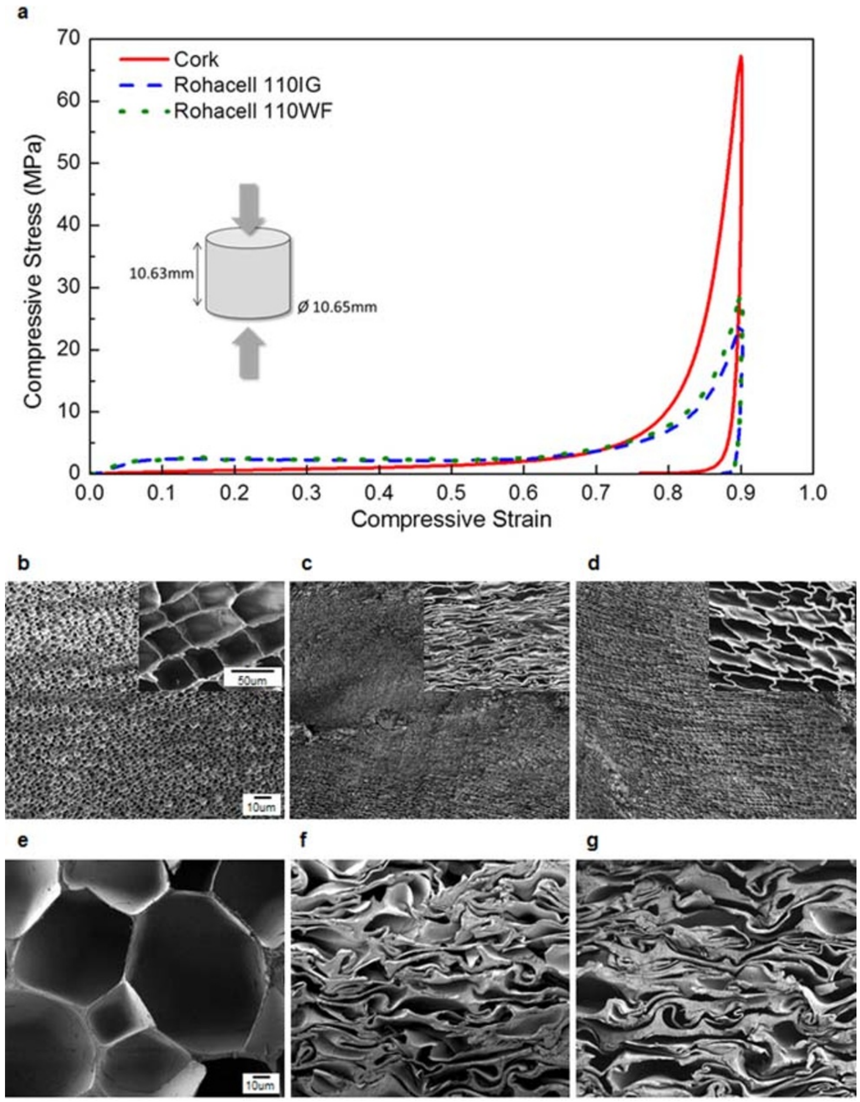

Figure 1 | (a) Compressive stress-strain results for cork agglomerate, Rohacell 110 IG and Rohacell 110 WF. Note how both 110 IG and 110 WF have similar responses. However cork shows substantially greater energy absorption capabilities at strains greater than 0.7, as well as a higher compressive modulus. (b) (c) (d) SEM images of cork agglomerate prior to compression, at 90% strain, and after testing during relaxation time. Note how the cells of the cork agglomerate core recover to almost their original shape and size. All images and insets have the same scale. (e) (f) (g) SEM images of Rohacell 110 WF prior to compression, at 90% strain, and after testing during relaxation time. In contrast to cork agglomerate, the Rohacell 110 WF cells do not recover. Also note that this effect occurred in Rohacell 110 IG; 110 WF is shown as a representative sample. All images have the same scale.

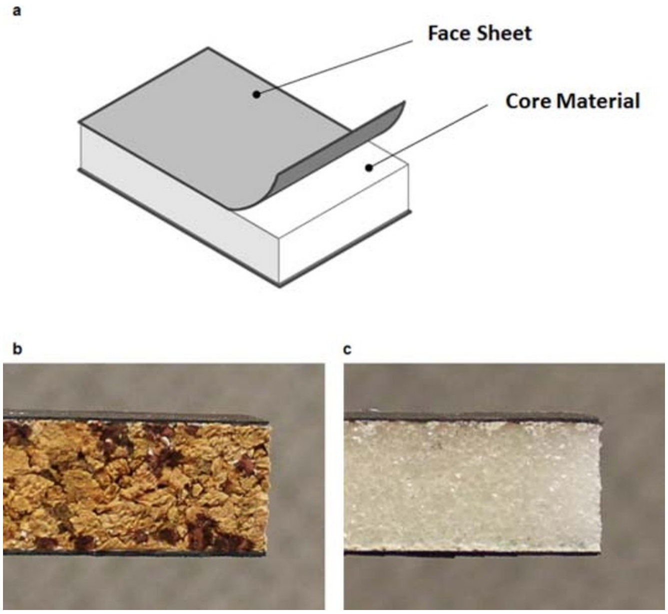

Figure 2 | (a) Sandwich beam schematic. Note the thick core material in between the two, thin face sheets. (b) Photograph of the carbon fiber-epoxy with natural cork agglomerate core sandwich composite beam. (c) Photograph of the carbon fiber-epoxy with Rohacell 110 WF core sandwich composite beam.

distinct moduli regions (low modulus, or initial plateau, and high modulus regimes). In the initial plateau region, where cellular buckling occurs, both materials resist the compressive load with increases of strain. While Rohacell foams display a compressive modulus of 39 MPa, cork's modulus is shown to be 2.8 MPa in the low modulus regime. However as strain increases, the response enters the maximum modulus region, which displays a sharp increase in stress. Figures 1 (c), and (f) show the SEM images of the samples compressed to 90% strain. It is here where cork shows a significantly improved compressive modulus of 870 MPa, compared to Rohacell 110 WF and 110 IG moduli of 310 MPa and 246 MPa, respectively. This indicates that cork has better energy absorption at higher strains, due to the collapse of individual cork cells and densification of the cork agglomerate structure. Figures 1 (d), and (g) show SEM images after the specimens were compressed to 90% and released; in comparison of these figures, it is seen that cork agglomerate has large recoverable strains, almost back to the original thickness, whereas the Rohacell samples stay compressed with the permanent collapse of its individual cells (Figure 1(g)).

Based on the above observations, it is noted that the cork agglomerate exhibits exclusive and intrinsic characteristics including nonlinear elasticity, large deformation, and thereby extraordinary recovery capacity when compared with the high performance synthetic foams. This suggests to us the use of cork agglomerate as a core material in a sandwich composite to overcome the poor acoustic properties with its intrinsic characteristics. Here, it will be extremely interesting to fabricate and investigate the sound and vibrational properties of the natural cork agglomerate core sandwich composites by marrying natural cork agglomerate with carbon fiber face sheet composites, which are the strongest structural materials that humans have made.

Acoustic Performance Characterization. In order to test acoustic performance, sandwich composite beams were fabricated by adhesively bonding cork agglomerate core material with carbon fiber-epoxy face sheets; see Figure 2(a) for a schematic of a sandwich beam. Both Rohacell 110 WF and 110 IG foams were also used as core materials to compare the acoustic performance with one of the carbon fiber-natural cork agglomerate core sandwich composite. Figures 2(b) and (c) show images of the carbon fiber face sheets bonded with cork agglomerate core and Rohacell 110 WF core, respectively. Acoustic properties were characterized through the use of wave number analysis, which is often employed in the field of sound and structural vibration[11,13–16]. Detailed information regarding the wavenumber analysis and experimentation is provided in the methods section. The wave number method provides useful insight into how and when a structure will radiate noise under mechanical and acoustical vibration environments, thus there are two key properties; coincidence frequency and wave number amplitudes. The coincidence frequency is a certain vibrational frequency when the structure will start radiating noise. Therefore a greater coincidence frequency can lead to a reduced frequency range in which the structure will radiate noise, which consequently results in an improvement in acoustic performance. This information can be found in a dispersion curve (Figure 3(a)). The coincidence frequency is the same frequency in which the wave number data points intersect the speed of sound (dashed line); this is shown in Figure 3(a). Thus, any data points which lie in the gray area are at frequencies which the structure will radiate noise. It is observed that carbon fiber beams with Rohacell 110 IG and 110 WF cores have coincidence frequencies in the range of 2.2–2.5 kHz, which is less than the half of the coincidence frequency for an aluminum beam[11,14]. In a sharp contrast to the synthetic core sandwich composites, which are currently the most commonly used materials in aerospace and automobile structures, the coincidence frequency of the carbon fiber-natural cork agglomerate core sandwich composite is not able to be measured in the 10 kHz range. In fact, its amplitudes are shown to be so low at frequencies above 5 kHz that wave number peaks could not be observed (Figure 3(b) and (d)) for the wave number amplitudes. This could imply that the coincidence frequency may not be identified even within audible frequency range from 20 Hz to 20 kHz[21]. As mentioned, of equal important to coincidence frequency are the wave number amplitudes, which correlate to the level (or magnitude) of noise which is radiated from the structure; thus lower amplitudes result in lower noise. It is easily seen in Figures 3(b) through 3(e) that the carbon fiber-natural cork agglomerate core sandwich beam's amplitudes are significantly lower than one for the carbon fiber- Rohacell 110 IG sandwich composite. For frequencies under 1000 Hz, the natural cork agglomerate core beam has amplitudes that are only 25% of that of the Rohacell 110 IG core beam; for frequencies above 1000 Hz, this percentage further drops to 14%. As a consequence, the natural cork agglomerate core sandwich composite will radiate little to no noise in a frequency range of at least up to 10 kHz. Coupled with the fact that there is no observable coincidence frequency in this 10 kHz range, it can be concluded that minimal, if any, noise would be radiated from the carbon fiber-natural cork agglomerate core sandwich composite, which is a combination of natural material and the strongest human-made fiber composite.

Such a solution to this sandwich composites-acoustic problem can be utilized in many applications; one specifically which has taken much interest recently is the noise radiation from wind turbine blades[21,22]. During operation, wind turbine blades emit sound at levels of approximately 100 dB and up to 3600 Hz, which is equivalent to listening to a pneumatic hammer or very loud music and results in discomfort for many of residents who live near wind farms. Thus, large scale turbines must be kept far away from cities and residential areas according to local and federal laws regarding noise radiation limits. Since our study shows that natural cork agglomerate-based sandwich composites can be noise-free structures, utilizing them in wind turbine blades and their nacelles can substantially

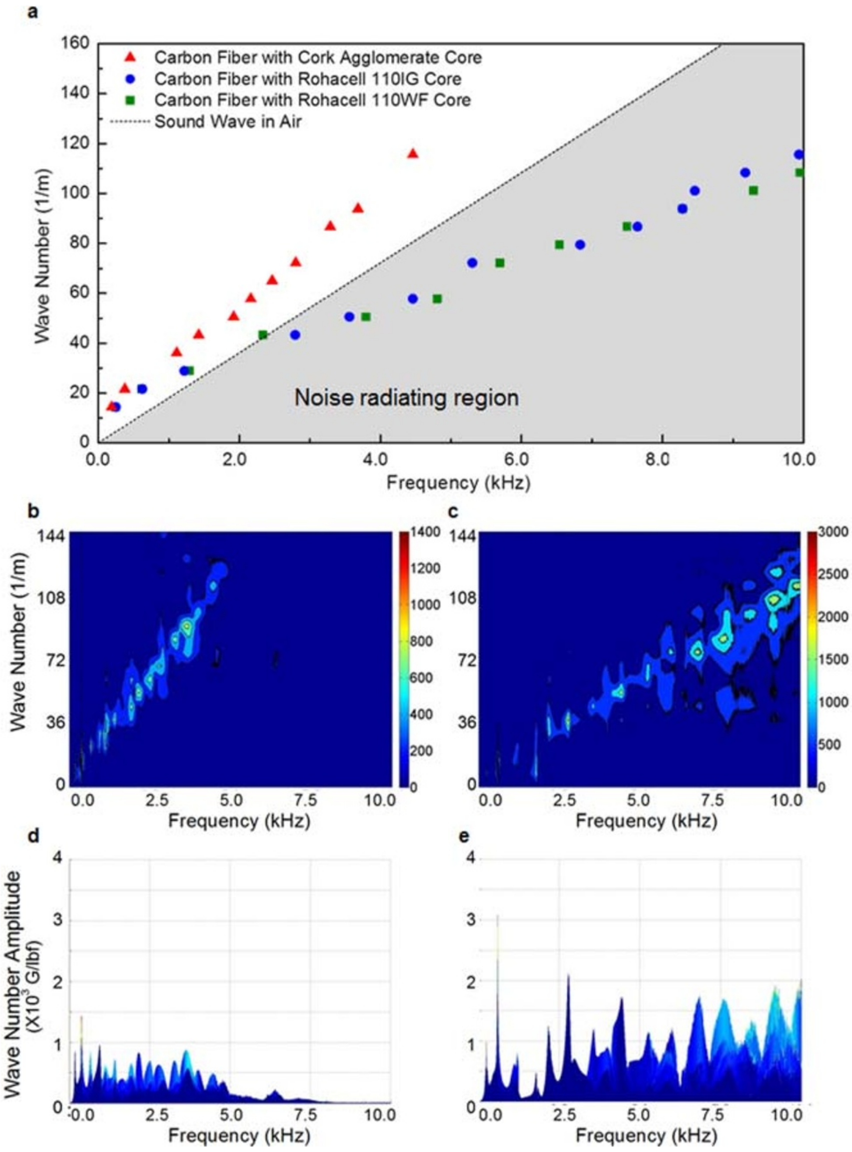

Figure 3 | (a) Dispersion plot of carbon fiber beams with cork agglomerate core, Rohacell 110 IG core and Rohacell 110 WF core. The gray area to the right of the dotted line represents data points which radiate sound from supersonic vibrational waves. Note how the Rohacell 110 IG and 110 WF beams transition to this area at approximately 2.5 kHz, whereas the natural cork agglomerate core beam does not enter this region in this 10 kHz range, and consequently is ''noise-free''. (b) Wave number contour plot for the carbon fiber with natural cork agglomerate beam. Note the correlation between the peaks of the contour and the data points in Figure 3a. Since there are no peaks above 5.0 kHz, it is said that the beam is ''noise free''. (c) Wave number contour plot for the carbon fiber beam with Rohacell 110 IG core. Since both Rohacell 110 IG and 110 WF have similar wave number responses, Rohacell 110 IG is used as a representative sample of both Rohacell cores. Note the scales are different between Figures 3b and 3c, as to show the clearest images possible. (d) Wave number amplitude-frequency projection for carbon fiber with natural cork agglomerate core. This is another view of Figure 3b; note how the peaks of this plot match to peaks seen in Figure 3b. (e) Wave number amplitude-frequency projection for carbon fiber with Rohacell 110 IG core. The amplitudes here are significantly higher than the cork agglomerate core beam in Figures 3(b) and 3(d), and consequently cause the Rohacell 110 IG and 110 WF beams to radiate more noise over the entire 10 kHz frequency range.

improve their acoustic performance, and be brought closer to the areas which they power, which would increase energy efficiency.

While the wave number methodology is a way to characterize acoustic performance based upon vibrations, other methods exist to measure acoustic properties. One method which could be used is a sound attenuation index method, which is commonly referred to in accordance with international standard ISO 140. Such a method is used to measure sound insulation over a similar frequency range used in the wave number study. Only a few studies[23,24] have been reported on the measurement of the sound attenuation index on sandwich composites, mainly because of the required size of the specimens. These sizes range from large panels to wall partitions[25], and along with the required equipment, remain outside the scope of this study. However, this method is something which can be studied in the future. From the results of the wave number analysis, it is hypothesized that the cork-cored sandwich composites would show excellent sound insulation capabilities via the attenuation index method.

Damping Characterization. It is also expected that the carbon fiber-natural cork agglomerate sandwich composite can have much higher damping properties due to significant lower amplitudes over the carbon fiber-Rohacell core sandwich composite (Figure 3(d) and 3(e)). Improved damping in a structure is quite significant, as it

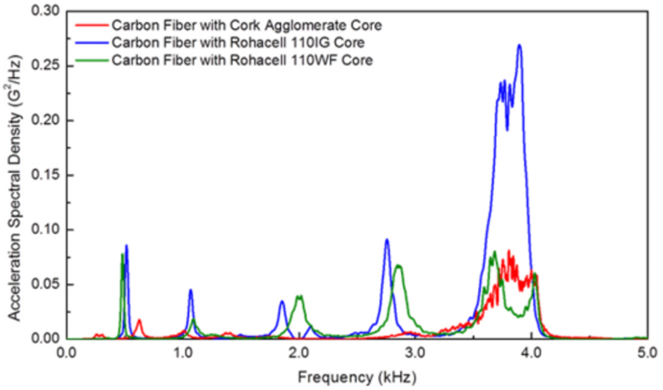

Figure 4 | Frequency response functions for all three beams. Note how the amplitudes of the frequency response function of the cork agglomerate core beam is significantly lower over the 5 kHz frequency range, providing better damping capabilities. Also note that the damping properties are characterized with loss factors (not seen in this figure). It is observed that the cork agglomerate core beam exhibits approximately 250% greater loss factor ranging from 0.095 to 0.12 up to 3.2 kHz than one of the Rohacell core beams ranging from 0.03 to 0.07.

leads to improved fatigue properties and durability, allowing the structure to survive more service time under more severe loads until failure. This will be particularly true in wind-turbine blades whose blade span length becomes greater to more efficiently generate power against wind. As such, the intrinsic damping capability will lead to not only improved fatigue life, but also more power generation. The same sandwich beams used in characterizing the acoustic performance were utilized to measure damping properties. It is observed that the cork agglomerate core beam displays significantly lower amplitudes in the frequency response function than the Rohacell 110 IG and 110 WF core beams (Figure 4), which can imply that the cork core beam has much greater damping capabilities over the synthetic core beams. Damping capabilities of each sandwich beam was quantified by measuring the loss factors according to ASTM E756-05. With the cork agglomerate core beam having loss factor values ranging from 0.095 to 0.12 for frequencies up to 3.2 kHz, they are approximately 250% greater than those of either 110 IG or 110 WF core sandwich composite beams ranging from 0.03 to 0.07 in loss factors. This indicates that such engineered natural cork agglomerate core sandwich composites could offer the suppression of unwanted vibrations. Therefore, it will significantly increase service life time of dynamic structures such as wind-turbine blades or aircraft wings and also improve their energy efficiency.

Bending Stiffness Measurement. In order to be a viable replacement for synthetic core sandwich composites, natural cork agglomerate core sandwich composites must display uncompromised mechanical properties. One of the main design criteria in a structure is bending stiffness, therefore each beam's bending stiffness was measured and compared, which was tested in a 4-point bending configuration according to ASTM D7250. Results of the stiffness tests showed that all of beams have similar stiffness; the carbon fiber-natural cork agglomerate core beam averaged a stiffness of 24.6 N-mm^2, with the carbon fiber beams with Rohacell 110 WF and 110 IG cores averaging a stiffness value of 27.9 N-mm^2 and 24.9 N-mm^2, respectively. Thus, bending stiffness remained almost uncompromised in the cork-based sandwich composite with dramatically improved acoustic and vibrational performance. The reason for such a similar result is that for sandwich composites subjected to a bending load, the majority (at least 95%[26]) of the stresses are carried by the face sheets. Thus for sandwich composites with identical face sheets, it is expected that they would have similar bending stiffness, as well as mechanical strength, for bending and in-plane loads.

Discussion

This study shows that a solution to the sandwich structure-noise radiation problem can be achieved by coupling carbon fiber face sheets, one of the strongest materials ever made, with natural cork agglomerate as a core material. Using cork agglomerate as a core material also provides a natural, renewable alternative to traditional synthetic materials, which often release harmful carbon emissions during their fabrication. Such a combination of carbon fiber composite and natural cork agglomerate, if optimally designed, provides unparalleled performance in both acoustics and vibration, without the need of additional materials or a compromise in mechanical performance or weight. Moreover, cork agglomerate shows desirable thermal properties similar to synthetic foams, which is important in certain applications in the aircraft and aerospace industries. This has a strong and broad impact in various engineering applications, such as wind power, aerospace or automobiles, all of which can substantially benefit from such a solution.

Methods

Monotonic Compressive Characterization. Monotonic compressive tests were conducted on cylindrical specimens measuring 10.65 mm diameter x 10.63 mm high at a quasi-static loading rate of 0.5 mm/min using Instron E3000 System. The specimens were compressed to 90% strain by flat platens and then allowed to relax[19,20,27].

Sandwich Beam Fabrication. The carbon fiber-epoxy tape is a two-ply, 0°–90° composite laminate, which is commercially available through the M.C. Gill Corporation. The tapes were provided as fully cured laminates. Each beam contained the same structural geometry with a 505 mm length, 25.4 mm width, and 10.7 mm core thickness; also the densities of the cork and Rohacell are similar, at 120 and 110 kilograms per cubic meter, respectively. The carbon fiber laminates, cork agglomerate and Rohacell foams were cut to required dimensions. Loctite 1 L-1 V epoxy was used to bond the face sheets to the core. To ensure the bond between the face sheets and core was uniform and that the epoxy was fully cured, the specimen was placed on a table, covered with a vacuum bag and subjected to vacuum pressure for 48 hours.

Wave Number Domain Characterization. Each beam was fixed into a clamped-clamped condition on a vibration-proof table. Using a shaker, each beam was exposed to random vibrations ranging up to 10 kHz, and frequency response measurements were taken a 64 equidistant points along the beam with a 0.6 gram micro-accelerometer. Performing a Fourier Transform of this spatial frequency response functions transforms the data into the wave number domain[11,14].

Bending Stiffness. Using the same test system with monotonic compressive characterization, the bending stiffness was measured according to ASTM D7250 with a case using one 4-point quarter-span loading configuration and one 4-point third-span loading configuration.

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Author contributions

J. Suhr supervised the project, J. Sargianis fabricated the sandwich composite beams and performed wave number and damping tests, and H.I. Kim. carried out compression testing, stiffness testing and SEM characterization. J. Suhr and J. Sargianis wrote the manuscript. All authors discussed and interpreted the results.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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