Dynamic impact behavior of syntactic foam core sandwich composites

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Abstract
Sandwich composites and syntactic foams independently have been used in many engineering applications. However, there has been minimal effort towards taking advantage of the weight saving ability of syntactic foams in the cores of sandwich composites, especially with respect to the impact response of structures. To that end, the goal of this study is to investigate the mechanical response and damage mechanisms associated with syntactic foam core sandwich composites subjected to dynamic impact loading. In particular, this study investigates the influence of varying cenosphere volume fraction in syntactic foam core sandwich composites subjected to varying dynamic impact loading, and further elucidates the extent and diversity of corresponding damage mechanisms. The syntactic foam cores are first fabricated using epoxy resin as the matrix and cenospheres as the reinforcement with four cenosphere volume fractions of 0% (pure epoxy), 20%, 40%, and 60%. The sandwich composite panels are then manufactured using the vacuum assisted resin transfer molding process with carbon fiber/vinyl ester facesheets. Dynamic impact tests are performed on the sandwich composite specimens at two energy levels of 80J and 160J, upon which the data is post-processed to gain a quantitative understanding of the impact response and damage mechanisms incurred by the specimens. A qualitative understanding is obtained through micro-Computed Tomography scanning of the impacted specimens. In addition, a finite element model is developed to investigate the causes for different damage mechanisms observed in specimens with different volume fractions.

Keywords
Syntactic Foam, Sandwich Composites, Dynamic Impact, VARTM, Cenospheres

Introduction
Composite materials typically allow for structural properties to be optimized such that the strength and weight constraints are more easily met in the design of everyday structures. This is evident as composites continue to become more prevalent in aerospace, naval, and civil applications. Sandwich composites typically consist of two stiff outer facesheets (away from the natural axis) usually made of fiber reinforced polymer that sandwich a lightweight core between them. This provides stiffness to the cross section and resists majority of the bending stresses. The lightweight core connects the two facesheets and assists with shear transfer in the section.

A large body of research has been conducted by previous researchers to better understand the behavior of sandwich composites using different materials and loading conditions. A few notable works reported on the low-velocity impact behavior of foam core sandwich composites includes, but is not limited to. Schubel et al. investigated the low velocity impact behavior of PVC foam cores with woven carbon fiber/epoxy facesheets and compared the performance to quasi-static tests for the same materials. The results showed that the damage observed in the low velocity impact tests was comparable to the damage in quasi-static tests at the same compressive strain level. Work by Hazizan and Cantwell reported the low-velocity impact response of sandwich structures with foam cores and glass fiber reinforced facesheets. Results showed that for a specific impact energy, the maximum recorded force increased as the shear modulus of the core increased. The failure mechanism transitioned from shear cracks in the core to delamination between the core and facesheet as the density of the core increased. Elamin et. al evaluated the damage of sandwich structures under dynamic impact loading, which were exposed to arctic conditions with temperatures ranging from 23°C to -70°C. Polyvinyl chloride (PVC) foam cores were used with facesheets of 0°/90° woven carbon fiber reinforced laminate with epoxy matrix. The article concluded that the peak impact force recorded decreased as the in-situ test temperature decreased. Also, using micro-computed tomography, the authors noted that the specimens experienced higher degree of damage at low temperatures as compared to higher temperatures.

Syntactic foams are closed cell composite foams with hollow micro-spheres dispersed in a matrix resin. The closed cell structure provides excellent mechanical properties.

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like high strength and low density, in addition to lower moisture absorption as compared to open cell foams. Hence, syntactic foam cores in sandwich composites ensure high rigidity and strength of the sandwich structures as compared to other polymeric foam cores. Few widely known applications of syntactic foams are in components for boat decks, ribs, hulls and floatation modules for offshore structures. In addition, they are also used in deep sea applications like remote operated vehicles, submarines and underwater pipelines. Few potential applications of syntactic foam core sandwich composites could be in building facades, bridge decks, and other civil infrastructure.

In the current study, syntactic foams are used as the core material in sandwich composites. Specifically, cenospheres (fly ash particles) are used as the hollow micro-spheres in these syntactic foams. Past researchers have investigated the behavior of syntactic foams with engineering glass (Sodalime-borosilicate) microballoons as the filler material. However, dealkalization of glass has been shown to degrade such syntactic foams. Fly ash being a byproduct of coal plants primarily consists of alumina and silica. Hence, use of cenospheres in syntactic foams can aid in minimizing waste from the environment, while creating syntactic foams with better properties as shown by previous researchers.

Extensive studies on the mechanical behavior of syntactic foams have been performed by previous researchers exploring their suitability for applications in building facades, bridge decks, and other civil infrastructure. In the work by Gupta et al., it was shown that the compressive strength and modulus of syntactic foams increased as the internal radius of cenospheres was reduced, while holding all other parameters fixed. Different types of tests have been performed on syntactic foams, such as three-point bending tests in flexure and short beam shear tests to determine their response under such types of loading. Previous work by the current authors investigated the behavior of cenosphere reinforced syntactic foams in compression and flexure over a range of temperatures. In Garcia et al., it was observed that the flexural modulus of cenosphere/epoxy syntactic foams increased and the flexural strength decreased with cenosphere volume fraction. In the current study, syntactic foams are used as the core material in sandwich composites. Distribution

Methods and Materials

 Constituent Materials

Sandwich composites in this experimental study consisted of three major constituent materials: a syntactic foam core, woven carbon fiber facesheets, and vinyl ester resin. The syntactic foam core was comprised of cenospheres and Lapox L-12 epoxy resin with K-6 hardener. The cenospheres being hollow particles which are a byproduct of coal production. Each facesheet consisted of 4 layers of 3K plain weave carbon fiber procured from Fibre Glast Developments Corp., and was cut to fit the dimensions of the core. Each facesheet layer had identical orientation and stacking of [(0/90)w4/d][0/90]w4. Here, the subscript w represents woven carbon fiber layers. Commercially available vinyl ester resin and Methyl Ethyl Ketone Peroxide (MEKP), both procured from Fibre Glast Developments Corp., were used as the matrix in the facesheets.

Manufacturing

Foam Core The syntactic foam cores were fabricated by mixing a weight fraction (equivalent to 20, 40 and 60 volume %) of cenospheres with Lapox L-12 epoxy resin and K-6 hardener at room temperature. A homogeneous and uniform slurry was mixed using a stirrer at room temperature for 4 hours and subsequently post cured for 3 hours. Different compositions of foam samples were fabricated by varying the cenosphere volume fraction. Specimens with 0% (pure epoxy), 20%, 40%, and 60% cenosphere volume fraction were prepared for use in sandwich composites. Distribution
of cenospheres in the syntactic foam core is shown via microCT scan in Figure 1.

The weight fractions of the constituent materials (Epoxy and cenospheres) for known volume fractions were calculated using the formulas given in Equation 1.

$$W_f = \frac{\rho_f}{\rho_f + \rho_m} V_f; \quad W_m = \frac{1}{\rho_f + \rho_m} V_m$$

where, $W$ represents weight fraction, $V$ represents volume fraction, $\rho$ represents density, the subscripts $f$ and $m$ represent filler and matrix, respectively. The density of Epoxy and cenosphere particles are considered to be 1192 kg/m$^3$ and 920 kg/m$^3$ based on measurements previously conducted by the authors. Based on the dimensions of a mold, the volume of composite $(V_s)$ to be prepared was found. The weight of cenospheres and epoxy for known volume fractions were calculated using the values of weight fraction.

**Sandwich Composite** The sandwich composites were manufactured with the vacuum assisted resin transfer molding (VARTM) process. The VARTM process was conducted on a flat aluminum mold plate. Vacuum was created between the mold plate, vacuum sealant tape, and vacuum bag (Stretchlon 800 Bagging Film) using two vacuum pumps (60-80 MPa vacuum pressure). 100 parts of vinyl ester resin was mixed with 1.25 parts of MEKP by mass as per the manufacturer’s instructions. The first pump was used to infuse this resin mixture through the specimen and was removed once the infusion process was complete (5 minutes in duration). This pump corresponded to an inner vacuum bag. The outer vacuum bag applied pressure during the resin curing process which lasted for 3 hours from the time the vinyl ester was initially mixed. The specimens were cured for at least 24 hours after resin infusion, after which they were removed from the mold.

Several best practices were employed to ensure the fabrication of high quality sandwich composites. First, a combination of HDPE Infusion Flow Media, cotton breather, and 1586 PTFE Coated FG (all procured from Fibre Glast Developments Corp.) were used in addition to the carbon fiber to ensure a consistent distribution of vinyl ester resin and allow for easy removal of the specimens from the mold upon curing. Second, the vinyl ester resin mixture was degassed prior to the infusion to help prevent voids forming in the facesheets. The degassing continued until air bubbles in the resin were no longer visually detectable in the resin. Finally, resin dams were constructed to direct the flow of resin through the facesheets and not just around the specimen. Due to the relatively low viscosity of vinyl ester resin and large thickness of the sandwich composite, the vinyl ester resin was susceptible to flow around the specimen forming many unwanted voids and poor bonding between the core and facesheets. The dams consisted of extra vacuum forming in the facesheets. The degassing continued until air was degassed prior to the infusion to help prevent voids in the resin. Finally, resin dams were constructed to direct the flow of resin to flow through the carbon fiber facesheets. The red arrows depict the flow path of the resin. The actual average dimensions of the tested specimens were 152.5 mm x 101.5 mm x 28.0 mm with standard deviations of 0.2 mm, 0.3 mm, and 0.3 mm, respectively. The densities of these samples were measured and are summarized in Table 1. These densities were measured after manufacturing the sandwich composite, which allowed for comparison of the in-service state rather than determining those of just the cores. The densities of the specimens decreased as the cenosphere volume fraction increased.

**Dynamic Impact Testing** The sandwich composite specimens were tested under dynamic impact (ASTM D7766) at two different energy levels corresponding to 80J and 160J. These two energy levels were determined via a preliminary testing program of the manufactured sandwich composites. They were chosen due to distinct failure mechanisms observed at the two energy levels. In total, twenty-four sandwich composite
specimens were tested with twelve at each energy level. Of
the twelve specimens at each energy level, four different
volume fractions of cenospheres in the core were used
yielding three specimens for each test case.

Drop-weight impact tests were performed using a CEAST
9350 Accelerated Drop Tower Impact System fitted with
a hemispherical striker at the University of Wisconsin-
Madison. The clamped boundary conditions shown in Figure
3 are consistent with ASTM D7766. Force, displacement,
energy versus time responses were recorded by the data
acquisition system ‘CEAST DAS 8000 Junior’ for each test
at a sampling rate of 500 kHz. A 5 m/s impact velocity, well
within the range of low velocity impact, was chosen for the
tests to ensure uniform propagation behavior between the
striker and specimen at different energy levels. To achieve
this constant impact velocity, additional mass was added to
the striker in order to attain impact energy of 160J. In all,
6.5kg of total mass was used for the 80J tests, while 12.5kg
was used for the 160J tests. The impact testing machine’s
anti-rebound mechanism was activated to avoid multiple
impacts on the sample.

Finite Element Model Description

A finite element (FE) analysis was performed to understand
the micro-mechanical material response of the syntactic
foam at different cenosphere volume fractions. The
indentation of the steel striker onto the syntactic foam was
modeled as a quasi-static loading rather than an impact
analysis to obtain a qualitative understanding of the strain
distribution. Strain rate effects were ignored in the epoxy
as the goal of this analysis was to obtain a qualitative
understanding of the strain distribution in the syntactic foam
core underneath the striker location. With the output from
the FE model, strain contours were analyzed and compared
with failure mechanisms observed in the micro-CT scans to
help explain the possible causes for damage mechanisms at
certain volume fractions.

The finite element model was divided into two subregions
as shown in Figure 4. A finely meshed two-phase region with
the epoxy matrix and hollow spherical cenosphere inclusions
directly under the impact location, and a larger homogenized
media (shown in green in Figure 4) with coarser mesh
away from the impact location. The purpose of the two
subregions was to simulate a larger syntactic foam domain
while capturing the details of the behavior in the vicinity of
the impact location and including the effects of boundary
conditions away from the impact location. A symmetric
boundary condition was considered about the axis of the
striker, which was introduced as a restriction in the horizontal
translation on the left face of the domain as shown in Figure
4. Further, contact conditions between the syntactic foam
core and the steel striker at the top, and the support at
the bottom ensured more realistic boundary conditions. To
reduce the complexity of the FE model, carbon fiber face
sheets were not modeled as the goal of this simulation was to
investigate the damage patterns in the foam core.

Material properties for the homogenized core and
the epoxy matrix were obtained from recent work by
Shahapurkar et. al where the authors investigated the
compressive modulus and strength of cenosphere/epoxy
syntactic foam cores. The average compressive elastic
modulus values from Shahapurkar et. al were used for the
homogenized region of the finite element model. Using a
rule of mixtures approach, the average compressive modulus
of the cenospheres was calculated. In this calculation, the
cenospheres were idealized as hollow spherical particles with
a constant wall thickness of 5µm and a mean diameter of
110µm to back-calculate the equivalent elastic modulus of
the cenospheres which was found to be 40 GPa. The input
values for the modulus are summarized in Table 2.

To account for the crushing of syntactic foam cores,
the cenosphere, epoxy matrix, and homogenized region

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**Table 2. Comparison between calculated homogenized foam modulus values using cenosphere modulus of 40 GPa and reported compressive modulus values for the syntactic foam core.**

<table>
<thead>
<tr>
<th>Cenosphere Volume Fraction</th>
<th>0%</th>
<th>20%</th>
<th>40%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported Modulus (GPa)</td>
<td>3.4</td>
<td>3.9</td>
<td>4.7</td>
<td>4.8</td>
</tr>
<tr>
<td>Calculated Modulus (GPa)</td>
<td>3.4</td>
<td>3.9</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Reported Strength (MPa)</td>
<td>104.8</td>
<td>100.8</td>
<td>98.8</td>
<td>92.1</td>
</tr>
</tbody>
</table>

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**Figure 3. CEAST 9350 Impact Machine with anti-rebound mechanism and testing chamber (inset) with fixture to simulate clamped boundary conditions consistent with ASTM D7766.**

**Figure 4. Domain of finite element model superposed on the experimental test setup.**

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were modeled as elastic-perfectly plastic materials. The matrix in the two-phase region was modeled to yield at 104.8 MPa, which is a mean value of the compressive strength reported by the authors in Shahapurkar et al. for the 0% cenosphere volume fraction. Similarly, the homogenized media was modeled to yield at the mean values reported for the respective volume fractions of 20%, 40% and 60%. The cenospheres were modeled to crush at a stress value vastly different from that of the matrix to help differentiate the materials in the output strain field. An assumed yield stress of 150 MPa was chosen. A verification analysis showed that both higher and lower assumed yield stress values for cenospheres as compared to that of matrix strength produced similar strain patterns, which help with qualitatively explaining the crack propagation.

**Results and Discussion**

**Internal Damage through MicroCT Scanning**

Micro-Computed Tomography (microCT) scans of the impacted specimens were obtained using a Zeiss Metrotom 800 at the University of Wisconsin-Madison. The scans allowed for the analysis of the damage mechanisms in the facesheets and crack propagation in the syntactic foam cores. MicroCT images are shown in Figure 5, which are characteristic images corresponding to each cenosphere volume fraction and energy level. The rows of the table correspond to cenosphere volume fraction percentage and the columns correspond to impact energy. A circular pattern is observed in the center of some of the images, which was a visual anomaly from the microCT process and not a physical characteristic of any specimen.

Figures 5a and 5b show two specimens with 0% cenosphere volume fraction impacted at 80J and 160J each. For both energy levels, a majority of the damage occurred locally around the impact location with minimal damage in the core. For the 80J specimen, a small indentation was observed in the facesheet which corresponded to matrix cracking. For the 160J specimen, in addition to matrix cracking, fiber tearing and delamination between the facesheet and core was visible.

The 20% cenosphere volume fraction specimens exhibited a high degree of shear cracking that propagated through specimen thickness as shown in Figures 5c and 5d. This is an undesirable failure mechanism as it typically leads to loss of structural integrity. On the other hand, localized crushing would be a less undesirable damage mechanism as the damage is contained in a localized region. At 80J, shear cracks emanated conically outward from the impact location. Delamination from excessive deformation was also observed between the bottom facesheet and core. An additional damage mechanism was visible directly underneath the impact location which consisted of a slight discoloration of the core. This was attributed to localized compression of the core caused by the collapse of individual cenospheres and crushing of the surrounding matrix during impact. Similar damage mechanisms manifested at 160J, but to a greater degree.

The microCT images for the 40% cenosphere volume fraction specimens are shown in Figures 5e and 5f. Localized compression was observed under the impacted face at both 80J and 160J impact energies, while shear cracking manifested only in the 160J case. The damage mechanisms for the 60% cenosphere volume fraction specimens were localized as compared to 20% and 40% cenosphere volume fraction specimens, and are shown in Figures 5g and 5h. Under both impact energies, the 60% specimens exhibited localized compression in the foam core and fiber fracture in the top facesheet at the impact location. The localized damage in the 60% cenosphere volume fraction specimens was higher than any of the specimens tested. No shear cracking in the core or non-localized delamination between the core the facesheets was noticeable. The damage trend shown in the microCT images between specimens of different volume fractions translated into distinct mechanical responses from the impact tests, as discussed next.

**Mechanical Response from Impact Tests**

The output data from each impact test was post-processed to determine their mechanical responses. Figure 6 shows characteristic force-displacement responses for the tests. Since the carbon fiber facesheets are stiffer than the foam core, the initial slope of the force-displacement plots are identical up to the point of initial penetration through the top facesheet. However, once the facesheets have been penetrated by the impact striker, the stiffness of the foam core is dominant and the stiffness of the specimen is observed to decrease as the cenosphere volume fraction increases, regardless of the impact energy level. Based on the force-displacement responses, the initial stiffness ranged from 10-13 kN/mm for both the 80J and 160J tests. The peak contact force recorded for 160J impact energy was higher than those corresponding to 80J for all volume fractions of cenospheres. Moreover, for both impact energies, the peak force reduced with increasing cenosphere volume fraction. Sharp vertical drops in the post peak regime of the force-displacement responses were observed for specimens with cenosphere volume fractions of 20% and 40%. This corresponded to more damage in the specimens, which resulted in larger impact striker displacements and lower impact forces. The striker displacements and peak impact forces are summarized in Figure 7. An increase in striker displacement and a decrease in peak impact force was observed for the 20% cenosphere volume fraction specimens tested at 160J. In addition, these specimens experienced the largest variation in test results as compared to the other volume fractions and impact energy levels.

The summary plots shown in Figure 7 do not account for the decrease in density due to increased cenosphere volume fraction in the core. To account for the changing densities, summary plots showing the specific striker displacement and peak impact force are shown in Figure 8. These plots are very similar to those in Figure 7, however, the values were divided by normalized weight ratios which change for specimens with different cenosphere volume fractions. The weight normalization, or in other words specific values, highlights the influence of weight reduction on the properties of the core. As a result, specific striker displacement and specific peak impact force both increased as the cenosphere volume fraction increased.

Both the summary plots and microCT images have implied that the 20% specimens experienced the most damage and
Figure 5. Typical microCT cross sections for each cenosphere volume fraction and energy level tested.
variation in peak impact force among all of the tested specimens. Further, the damage increased at the 160J impact energy level. This is confirmed in Figure 9, which is a summary plot of the normalized absorbed energy for all the tests conducted. The absorbed energy is the amount of energy absorbed by the specimen upon impact by the striker, which is determined graphically from the energy versus time graph as depicted in Figure 9. To determine the normalized absorbed energy, the absorbed energy is divided by the corresponding impact energy, which is the peak value in the energy versus time plot.

It is evident from the normalized absorbed energy plots in Figure 9 that 20% and 40% cenosphere volume fraction specimens were relatively more damaged than 0% and 60% specimens at 160J impact energy as compared to 80J. With that said, specimens with 0% and 60% cenosphere volume fractions experienced similar extent of damage at both energy levels of 80J and 160J. Higher apparent damage manifested by 20% and 40% cenosphere volume fraction specimens can be related to the shear cracking damage mechanism observed in these specimens as compared to the 60% volume fraction specimens that exhibited localized compression and absorbed similar levels of normalized energy at the two energy levels tested.

**Damage Mechanism Observations and Causes**

The volume fraction of cenospheres in the syntactic foam cores influenced the damage mechanisms of the sandwich composites, especially under high impact energy of 160J. This was more evident upon comparing the mechanical response results and microCT images. Large shear cracks and delamination in the microCT scans corresponded to sharp vertical drops in the average maximum impact force recorded and correspondingly higher maximum striker displacements. Shear cracking, a highly undesirable failure mechanism as it typically leads to global failure, was observed in the core along with delamination between the core and the facesheets. This damage mechanism was most commonly observed in the 20% cenosphere volume fraction
Figure 8. Summary plots of impact tests showing average values and standard deviation divided by a normalized ratio of specimen weight. (A) Striker displacement over the range of cenosphere volume fractions. (B) Impact force over the range of cenosphere volume fractions.

Figure 9. (A) Energy vs. Time output for an arbitrary test specimen. (B) Average normalized absorbed energy for all cenosphere volume fractions and energy levels.

Figure 10. In-plane shear strain output of the two-phase media region shown in Figure 4 for the three different non-zero cenosphere volume fractions. (A) 20%. (B) 40%. (C) 60%.

Specimens tested under 160J impact energy, but specimens with 20% cenosphere volume fraction tested at 80J and specimens with 40% cenosphere volume fraction tested at 160J also experienced shear cracking in few specimens.
Localized compression (crushing) was the other common damage mechanism associated with the core and occurred directly underneath the impact striker and manifested itself in a discolored region in the microCT scan images.

From the damage mechanism observations, it can be concluded that the behavior of the sandwich composite is more favorable with higher cenosphere volume fraction in the syntactic foam core. That is, damage was more localized with increasing cenosphere volume fraction. An explanation for this observation stems from the behavior of the cenospheres in the syntactic foam. In the microCT images, it was observed that foam was crushed under the striker regardless of the energy level and cenosphere volume fraction. In samples with low cenosphere volume fraction, stress redistribution would cause a crack to propagate in the matrix between two cenospheres that are situated a distance from each other. On the other hand, as the cenosphere volume fraction increases, the cenospheres are situated close to each other. For the crack to propagate, it is hypothesized that it would either require crushing of more cenospheres or propagating cracks around additional cenospheres in a tortuous path prior to manifesting as large cracks in the core. This supports the observation of large shear cracks at 20% and 40% volume fractions samples, whereas local crushing in the 60% volume fraction samples.

**Corroboration of Damage Mechanisms through Computational Modeling**

The results of the finite element analysis show the correlation between the cenosphere volume fraction and the level of damage underneath the impact striker. Matrix shear strain contour plots are shown in Figure 10 for models with 20%, 40% and 60% cenosphere volume fractions. The pure epoxy model was not included because it did not exhibit stress concentrations within the core. These plots correspond to a striker displacement of 1.6 mm for each case. The purpose of this finite element analysis was to compare the extent of localized strain underneath the striker, which is anticipated to correspond to the level of damage.

From the 60% cenosphere volume fraction model, it is observed that the areas of high strains are more dispersed and intermixed with areas with lower strain values. As a result, a web of cracks are more likely to form in these areas of closely packed cenospheres which helps promote the localized compression failure mechanism under the impact location. This localized web of cracks is expected to decrease as the cenosphere volume fraction decreases due to the larger distances between adjacent cenospheres. As the distance between cenospheres increases, failure mechanism with few large cracks is expected, which can be seen as a continuous region of high strain as depicted in the 20% cenosphere volume fraction model in Figure 10. Therefore, having a higher volume fraction of cenospheres is favorable as the cenospheres help dissipate the strain energy by either crushing or driving the crack around them, thereby, splitting large shear cracks into multiple smaller cracks. These smaller cracks are more localized and are constrained in the vicinity of the impact location, thereby containing the damage to a localized region.

**Conclusion**

Although there has been much effort to individually characterize both syntactic foams and sandwich composites under dynamic impact loading, there has been relatively little work to characterize and quantify the behavior of sandwich composites with syntactic foam cores under the same. In this study, sandwich composites with syntactic foam cores and varying cenosphere volume fractions were tested at two different impact energy levels to gain an understanding of their mechanical responses as well as the damage level and damage mechanisms. In addition, a finite element model was developed to investigate the causes of the observed failure mechanisms.

Syntactic foam cores were fabricated with average cenosphere volume fractions of 0%, 20%, 40%, and 60% in epoxy. Then, sandwich composites were manufactured using vacuum assisted resin transfer molding (VARTM) process. For the facesheets, dry woven carbon fabric was used as reinforcement and vinyl ester resin as the matrix material. Impact tests on sandwich composites were conducted at two energy levels of 80J and 160J. The results of the impact tests showed a higher extent of damage and undesired damage mechanisms as the cenosphere volume fraction decreased for non-zero volume fraction cases (that is, 20%, 40%, and 60%). As observed from the microCT images, shear cracks within the syntactic foam core and face sheet damage were visible in the 20% and 40% cenosphere volume fraction specimens. In contrast, only localized compression underneath the impact location was observed in the 60% volume fraction specimens. An explanation for the observed undesired damage mechanisms in the 20% cenosphere volume fraction specimens was elucidated by developing a finite element model. In the case with high cenosphere volume fraction, i.e. 60%, the strains redistributed around the cenospheres which led to a dispersed web of cracks that did not propagate the entire thickness of the syntactic foam core. For the models with lower cenosphere volume fractions, the distance between adjacent cenospheres was too large to form a web of cracks, and instead larger shear cracks were expected to form. In summary, this study showed that the syntactic foam cores with 60% cenospheres by volume are superior than other volume fractions investigated for the following reasons:

- The sandwich composites with 60% syntactic foams are less dense than the other specimens, being ≈18% lighter than the pure epoxy core samples.
- Even though the initial stiffness of the 60% specimens was the most compliant of all specimens, it had comparable recorded average maximum impact force as compared to the other specimens with non-zero (that is, 20% and 40%) cenosphere volume fractions tested.
- The 60% volume fraction specimens experienced localized compression/crushing underneath the striker impact location at both energy levels. In contrast, other specimens with non-zero cenosphere volume fractions experienced at least some degree of shear cracking under high energy impact loading. Localized compression/crushing as compared to shear cracks does not drastically affect the structural integrity.
of the core. Whereas, cascading effects such as core/facesheet debonding is typically accompanied with large shear cracks in the core as seen in Figure 5. Hence, 60% volume fraction specimens are deemed to perform better compared to other cases considered in this study.

Although sandwich composites with high cenosphere volume fraction syntactic foams are shown to be desirable for containing impact damage, more studies need to be conducted by varying other properties like, core thickness, distribution of cenosphere dimensions (diameter and wall thickness), etc. before they can reliably be used in structural components subjected to dynamic impact loading.

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