Towards light weight multifunctional hybrid composite housing for satellite electronics

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Abstract
The present paper provides an overview of the fabrication and testing of multifunctional hybrid composite radio frequency (RF) electronic housing for satellite applications. An oversized hybrid composite block containing carbon fiber (CF) and multiwall carbon nanotubes (MWCNTs) as reinforcement in epoxy matrix were fabricated through hand layup and compression molding technique. Fabricated block was machined to desired size and shape to form multifunction hybrid composite housing for satellite electronics. DC electrical resistivity was measured on sample panels to assess the influence of MWCNTs on CFRP and 30 times decrease in volume resistance was observed. EMI shielding effectiveness (SE) and Radiated Emission Electromagnetic Compatibility (EMC) tests were performed on developed prototype RF electronic housing. Results showed that the addition of MWCNT in CFRP has increased the overall electrical conductivity leading to higher EMI SE than neat CFRP without MWCNTs. Moreover, the developed electronic unit also qualified the RE EMC test in 10 kHz to 18 GHz range. The increment in electrical characteristics was attributed to formation of MWCNTs conductive network inside the epoxy matrix. Hybrid composite housing was also subjected to vibration test and compared with aluminum alloy (AA 6061-T6) housing, which is typically used in satellite structure. Finite element analysis (FEA) for vibration test was also carried out on both housings and obtained results are in great agreement with experimental findings. It can be concluded that hybrid composite housing can replace the metallic counterpart with an added advantage of 50% lighter in weight for satellite electronics applications.

Introduction
Weight is a major factor of concern in space industry when selecting any material for use in satellite structure since it directly affects the overall cost of the space project. At present, launching cost ranges between 10k to 15k dollars per pound of payload which can sometime reach as much as 50% of the total mission cost [1]. Mass saving by using lightweight advanced materials can therefore cut down thousands of dollars of launch cost or alternatively the payload can be increased. The satellite electronic enclosures generally represents a large fraction of its weight; therefore it is important to choose most suitable material and structural configuration to minimize the weight without compromising performance [2]. With the increase in demand for lightweight material for spacecrafts, carbon fiber reinforced plastic (CFRP) have been developed and in use for the past many years. CFRP composite is extensively used in numerous structural components of spacecraft [3] because of their excellent mechanical characteristics, particularly higher stiffness-to-weight ratio, and fatigue resistance [4, 5]. Despite attractive attributes, the application of CFRP in fabrication of electronic housings for satellite is limited due to lack of electrical conductivity particularly in through-thickness direction. For use as electronic housing, composite needs to be electrically conductive to fulfill electromagnetic interference (EMI) and electromagnetic compatibility (EMC) requirements. EMI/EMC problem is usually avoided by using EMI-tight shielding materials (like metals in most cases) for construction of housings and ensuring good electrical grounding of all electronic equipment. Although, CFRP has replaced metallic counterparts in many space applications but CFRP
is deficient in electrical conductivity due to insulating host matrix which results in only moderate level of EMI shielding; generally, in between 20–40 dB [6]. The EM radiations in CFRP mostly absorbed and dissipated as heat. Electrical performance of CFRP composite can be improved by using conductive fillers in matrix or coating with metals. New trend is to add conductive nano-fillers in polymer matrix to impart conductivity. Carbon nanotubes (CNTs) have received immense attention in the past few years because of their inherent excellent electrical, thermal and mechanical properties [7–10]. Therefore, CNTs were selected and added into CFRP to make it electrically conductive. It is also expected that the CNTs addition in CFRP alters its damping capacity and impact resistance [11–14].

Another important functional requirement of electronic housing is to protect the inside electronics from severe broadband random vibrations imposed during launch phase. Satellite has to face extreme dynamic loads during flight, like: at lift-off, stage separation, fairing jettisoning, etc. Therefore, vibration testing of housing is critical to ensure strength, dynamic stability and structural integrity against launch environment. Generally, satellite has its first natural frequency below 100 Hz in all three directions [15]. Usually electronic housing structure is designed to have first natural frequency well above 130 Hz to avoid resonance with satellite modes and have positive margin of safety against all design loads [16, 17]. The vibrations produced during launch are of irregular nature and probability access method is used to get the acceleration power spectral density (PSD). It has been observed that small size electronic housing units usually experience maximum random excitation loads of 9–14 G_rms for different types of launchers [18].

This research campaign presents the development and testing of light weight multifunctional hybrid composite (MWCNTs-filled CFRP) material for satellite structural applications. A prototype radio-frequency (RF) housing was manufactured on which EMI and Radiated Emission EMC tests were conducted to assess its suitability for use in future satellite projects. The role of CNTs in improving conductivity and EMI shielding effectiveness of the CFRP is also discussed. Random vibration tests have been performed on RF housing to verify that the developed material meet specifications. Further, experimental results were compared with numerical analysis and discussed here in detail.

Materials and methods

Multiwall carbon nanotubes (MWCNTs) of 10–20 nm outer diameter and 10–30 μm length were purchased from Cheap Tube, US. Carbon woven fabric (areal density 270 ± 5 g m⁻² and 0.4 ± 0.005 mm thickness) was used as reinforcement in fabrication of composite laminate. Bisphenol-A based epoxy resin containing a reactive diluent was selected as a matrix because of its low viscosity and excellent properties. Cycloaliphatic amine hardener was used with epoxy resin in ratio of 10:3.5 (by weight). Hybrid composite was fabricated by solvent-assisted blending technique. Electrical percolation threshold value was found to be around 0.2 wt% MWCNTs by present author in previous research therefore 0.2 wt% MWCNTs were used in all experiments [19]. MWCNTs were dispersed in acetone through bath sonication for 60 min. Epoxy resin was mixed in this colloidal suspension and further sonicated at 50 °C for 60 min to evaporate the acetone. Finally, hardener was added and thoroughly mixed for 15 min with magnetic stirrer to obtain a uniform suspension. This MWCNTs-modified resin was used to impregnate carbon fabric (4 plies) to make a multiscale laminate through hand lay-up and compression molding technique. Laminate was then cured at 100 °C for 1 h and 160 °C for 2 h in an autoclave under vacuum according to supplier’s prescribed cycle. Hybrid composite sample of 2 mm thickness was fabricated for measurement of electrical resistivity. Neat CFRP sample was also formed in similar way for comparison.

Fabrication of MWCNT-CFRP electronic housing

To ensure feasibility and suitability of hybrid composite for satellite structural application, a prototype housing for RF X-band power amplifier (XPA) circuitry was fabricated via same bath sonication and curing cycle. The housing architecture was monolithic without joints and rivets to minimize radiation leakage. Moreover, in-house available raw materials and commercial off-the-shelf components were used in fabrication to keep manufacturing cost as low as possible. A solid oversized block of hybrid composite was fabricated in a custom-made aluminum alloy die set. XPA electronic housing of required final dimensions was machined through CNC (figure 1). All the machining steps like milling, drilling and tapping were carried out on CNC machine under strict process control. XPA PCB was properly fit in the housing through M2 screws. The original RF XPA housing of similar dimensions was made from machined AA60601-T6 aluminum alloy (commonly use in satellite structure) for reference (figure 2(a)). Weight comparison of both empty housings showed that the hybrid composite housing was about 50% lighter than aluminum housing. Power amplifier PCB was fabricated in-house and mounted inside the housing and connectors were installed as shown in figure 2(b).
Electrical resistivity and EMI test

The surface and volume (through-thickness) electrical resistivity was measured on neat CFRP and hybrid composite sample (150 × 75 × 2 mm) through indigenously developed test setup in accordance with ANSI/STM 11.11–2015 and ANSI/STM 11.12–2007 respectively as shown in figure 3. The 10 V was applied to the sample from the dc power supply for 5 s electrification period and the resulting resistivity was measured.

The EMI shielding performance was measured on Vector Network Analyzer (VNA) through waveguide method in 7–15 GHz microwave frequency range. The sample under test was sandwiched between two waveguides of the network analyzer. The EMI SE along with reflection and absorption components were calculated from scattering parameters using indigenously developed algorithm as per procedure given in [20]. Testing was done on both hybrid composite and AA6061-T6 doughnut shaped samples of same thickness (4 mm) for comparison.
Radiated emission EMC tests

To evaluate the shielding performance of developed housing against radiated emissions a preliminary debugging RE pre-compliance test was conducted on XPA RF unit in energized condition in clean room environment (figure 4). RF power was given from power source through RF cables and possibility of EM wave emissions in the vicinity of housing was detected through horn-type antenna (1 GHz to 18 GHz) within a close proximity. All the open holes in housing were sealed with copper tape to avoid radiation leakage. The RF output power was measured on power meter. The signals emitting from the housing were observed in the form of spectrum on spectrum analyzer (Rohde & Schwarz) as shown in figure 5. The fundamental frequency of 8.25 GHz was neglected and other signals radiating from the unit were analyzed. However, no emissions were detected from the housing.

After qualification of preliminary RE debugging test, the unit was subjected to RE102 EMC test in anechoic chamber using four antennas to cover frequency range from 10 KHz to 18 GHz. The unit was tested for emission and immunity compliance against the MIL-STD-461E standards. This is a more detailed EMC test to check the EMI shielding performance of electronic housing. The schematic of RE102 EMC test plan is illustrated in figure 6 and the schematic of device under test (DUT) i.e. RF XPA housing with electrical wire connections with PCB is shown in figure 7. Radiated emission (i.e. air-transmitted interference) test was conducted using following antennas to cover the entire frequency range.

- Antenna1 - (10KHz–20MHz)
- Antenna 2 - (20 MHz–200 MHz)
- Antenna 3- (200 MHz–1 GHz)
- Antenna 4- (1 GHz–18 GHz)

Antenna measure the intensity of electric field at a specified distance away from the DUT. The DUT acts as EMI transmitter and the antenna act as receiver. The DUT was place on turn-table and rotated during the test so that all four sides of the unit face the antenna in turn.

Dynamic mechanical analysis (DMA)

The loss modulus and storage modulus as a function of temperature were assessed by dynamic mechanical analysis (DMA) using a Mettler Toledo DMA SDTA861. DMA spectra were taken in the tension mode at 1Hz
frequency from room temperature to 120 °C below \( T_g \). Test specimens were typically 56 × 13 × 3 mm, cut from the center section of tensile bar. Testing were performed on hybrid composite as well as on neat CFRP for comparison.

**Vibration testing**

Vibration testing was performed on composite as well as aluminum alloy housings using an Electrodynamics shaker (ETS Solution, China) of 50kN capacity. Electronic housings with assembled PCB inside was subjected to modal and random vibrations testing in X, Y and Z direction. Housing was mounted on the shaker through four M2 size screws using in-house developed fixture. Figure 8 shows the location of accelerometers placed on the longitudinal and lateral faces of housings. A data acquisition system having four channels was used to retrieve the test data. Channel S-1 was used to monitor the input of random vibration by using a closed loop control system with power amplifier which drives the shaker to provide the demanded level of acceleration to the housing. Channels S-2, S-3 and S-4 were used to gather the response acceleration of housings. The accelerometers recorded the dynamic response of structure against the vibration loads. The data obtained from these channels were used to verify the natural frequencies, vibration characteristics, and response of the structure against the applied vibration loads. Modal survey test was performed before and after random vibration testing to verify the integrity of electronic housing because in case of damage to the housing a significant change in its natural frequencies occurs after random vibration test. Low sine sweep test was run between 5 Hz and 2000 Hz using 0.5g amplitude at 2 Oct/min in X, Y and Z direction before and after the random vibration test. Moreover, NDT radiographic testing (RT) was also conducted on housing before and after test to examine the possibility of any delamination, cracking, etc caused by vibration test.
Finite elemental model (FEM) for vibration testing was generated and results of natural frequencies and acceleration response of finite elemental analysis (FEA) were compared with the experimental data. FEM of electronic housing containing PCB was developed and solved using MSC PATRAN/NASTRAN 12.2. In this case, CQUAD4 shell elements were used to model the PCB and electronic housing as shown in figure 9. Woven CRFP composite was developed as multiple plies that were laminated at 45˚ apart from each other. The connection of top plate (Lid) and PCB with housing is made using RBE2 elements. All other connections of the laminates in the composite housing are modeled as bonded at nodes contact because they are machined from a single oversized block of hybrid composite. The components on PCB were modeled as nonstructural mass distributed on the elements of PCB. The properties of materials used in this study are tabulated in table 1. The damping ratio of MWCNT-CFRP was found out by Shafi et al [11] NASTRAN perform modal analysis using Method of Lanczos for extraction of eigen values. The random vibration test was performed with total 9.3 Grms according to the DNEPR safety control requirements (DSCR). DSCR specifies the environmental testing requirements for the light weight (<1 Kg) CubeSat satellites [21]. The Grms for both housings were calculated by taking square root of area under the curves obtained by random vibration test.

Results and discussion

Electrical resistivity
Ability of housing material to shield EM radiations primarily depends on its electrical resistivity therefore material intended for use in satellite applications shall have low resistivity [22]. The surface and volume resistivity of hybrid composite was markedly decreased with reference to neat CFRP as listed in table 2. Although the neat CFRP exhibits conductive behaviour, however it is not adequate for certain applications requiring higher EMI SE. Volume resistivity of MWCNT-CFRP was 30 times lower than neat CFRP. This behaviour was
attributed to conductive nature of MWCNTs and formation of interconnected percolating network inside the matrix through which electrons move (figure 10). Incorporation of MWCNTs into the CFRP composites led to increased number of mobile charge carriers. Electrons tunnel from one nano-filler to other adjoining nano-filler and in this way a conduction path is created for passage of current particularly in through-thickness direction \[23, 24\]. Volume resistivity in the range of \(10^2\) to \(10^3\) \(\Omega\)-cm is typically considered sufficient for shielding EM radiations \[25\]. Volume resistivity of hybrid composite was measured to be \(8.8 \times 10^1\) \(\Omega\)-cm therefore good EMI SE is expected.

### EMI shielding effectiveness

Reflection and absorption are primary EMI shielding mechanisms among which the former is dominant in metals. CFRP also offers EMI protection to some extent because of conductive carbon fibres \[26\]. Figure 11 presents the total EMI \(SE_T\) (i.e. \(SE_T\) is sum of \(SE\) due to reflection, absorption and multiple reflections) of hybrid composite and AA6061-T6 sample as a function of frequency. It was found that the EMI \(SE\) of hybrid composite was frequency dependent and higher than the AA6061-T6 in most part of the tested frequency. The \(SE_T\) of hybrid composite decreases with rise in frequency up to 10.5 GHz after which it again increases. The hybrid composite has appreciably higher attenuation in 11.5 GHz to 15 GHz range than AA6061-T6. Mostly, communication and navigation satellite operates in X-band (8 to 12 GHz) and Ku-band (12 to 18 GHz) frequency region and \(SE_T\) around \(-60\) dB is considered satisfactory for space applications \[27\]. In our case, EMI \(SE_T\) was \(< -80\) dB in wide frequency band for hybrid composite which was better than AA6061-T6. The higher EMI \(SE\) of MWCNT-CFRP was attributed to good electrical conductivity (because of presence of conductive

![Figure 10. Interconnected network of CNTs inside the matrix.](image)

### Table 1. Material Properties.

| Property                | Composite | Aluminum |
|-------------------------|-----------|----------|
| Elastic Modulus \(_{11}\) | 70000 MPa | 68900 MPa |
| Elastic Modulus \(_{22}\) | 70000 MPa | \n| Poisson Ratio \(_{12}\)     | 0.1       | 0.33     |
| Shear Modulus \(_{12}\)   | 5000 MPa  | \n| Density                  | 1.6 g/cc  | 2.7 g/cc |
| Shear Stress Limit        | 90 MPa    | \n
### Table 2. Average surface and volume electrical resistivity of neat CFRP and MWCNT-CFRP.

| Sample            | Surface resistivity (Ohm/sq) | Volume resistivity (Ohm-cm) |
|-------------------|------------------------------|-----------------------------|
| Neat CFRP         | \(1.5 \times 10^2\)          | \(2.7 \times 10^1\)         |
| MWCNT-CFRP        | \(5.8 \times 10^1\)          | \(8.8 \times 10^1\)         |
carbon fibres and CNTs) and contribution of both absorption and reflection factors in overall attenuation. Detail EMI SE results have been discussed by present authors in a study earlier [24].

Radiated emission EMC

Figure 12 depicts the results of RE102 EMC test conducted on hybrid composite housing. Test results plot the measured emissions against the limits set by the standard. Pink line in the graphs represents ambient range and red line represents permissible emission range. Blue line was the response of XPA unit (DUT) during RE test. It was seen in figure 12 that over the entire frequency range the DUT was within permissible emission range of reference standard. No appreciable emission was observed from the graphs. A peak in figure 12(d) at a frequency of 8.25 GHz was fundamental frequency of the XPA unit and exempted. In short, the EMI/EMC tests findings suggested that the hybrid composite material effectively shield the EM signals in wide frequency range and can be employed in manufacturing of electronic housings for satellite.

Dynamic mechanical analysis

CFRP is known for good stiffness but it has low damping capacity resulting from poor viscoelastic nature of carbon fibers and poor damping at the CFRP interface [28]. However, CNTs have higher specific area and increases the interfacial adhesion between CF/resin which in turns improves the damping characteristics [12]. Moreover, the damping effect is also pronounced due to the relative motion of the MWCNTs against the epoxy surface. As a results large amount of energy absorption takes place, thereby improving the overall damping capability of hybrid composite. Similar kind of phenomena was also discussed by Tehrani et al [29]. Figure 13 shows SEM micrograph of hybrid composite in which CNTs bridging and strengthening of CF/resin interface is observed. DMA test results showed that the hybrid composite has higher value of loss modulus, storage modulus and damping factor or loss factor ($\tan\delta$) as compared to neat CFRP. Loss modulus indicates the materials ability to dissipate energy, which is related with damping capacity. Damping factor ($\tan\delta$) provides information on the relative contributions of the viscous and elastic components of a viscoelastic material. Increase in the damping factor of hybrid composite (figure 14(c)) indicates better damping capacity because of mechanical reinforcing effect of CNTs.

Experimental and numerical analysis for vibration test

Figure 15 shows first three mode shapes of the housing obtained by FEA. It can be seen that the first and second mode corresponds to the global translational modes in Z and Y direction respectively. The third mode is the rotational mode along Y direction. Figure 16 shows the experimental results for Modal Survey Test in longitudinal Z direction for both housings. Channel S-2 results illustrated that the natural frequency values are very high due to small size and high stiffness of housings structure. It fulfills the spacecraft requirement of natural frequencies for avoiding resonance with modes of spacecraft. The FEA results are in good agreement with the test results in longitudinal Z direction for both housings (table 3). Table 3 also represent that composite housing has higher natural frequency for all modes because of low density as compared to the aluminum housing. Although the natural frequencies in lateral X and Y direction were predicted to be very high using FEM.
Figure 12. RE102 EMC test results in frequency range of (a) 10 kHz to 20 MHz, (b) 20 MHz to 200 MHz, (c) 200 MHz to 1000 MHz and (d) 1 GHz to 18 GHz.

Figure 13. SEM micrograph of hybrid composite showing the bridging effect of CNTs.
as shown in table 3, but could not be verified through testing due to limited range of available frequencies during modal survey test.

Figures 17(a), (b) shows the response power spectral density (PSD) on channel S-2 during random vibration of both housings in longitudinal Z direction. PSD response was also obtained from FEA using the node corresponding to the location of channel S-2. Both the FEA and experimental response show good agreement as per the input load. Further, the RMS values of both housings predicted by FEA are quite close with experimental results (table 4). The results suggested that the hybrid composite housing has effectively sustained random vibrations owing to its higher damping ratio.

Hybrid composite housing has successfully passed the random vibration test which was verified by pre and post modal survey test in which the change in natural frequency is less than 1%. This reflects that the internal structure of composite housing was intact and confirmed from comparison of pre and post-vibration x-ray radiographs (figure 18). Few manufacturing defects like voids and cracks visible in radiographs were present before vibration test and it was noted that these defects did not propagated as a result of loading. Absence of delamination, cracking, de-bonding, etc in post-vibration x-ray radiographs proved that the housing has successfully survived the vibration loads. Physical examination also does not show any loosening of screws after
Figure 16. Modal survey test results for aluminum and composite housings in longitudinal direction.

Figure 17. Shows (a) Experimental and (b) Numerical and random vibration results of aluminum and composite housings in longitudinal direction.

Table 3. Numerical and experimental natural frequencies of aluminum and hybrid composite housings.

| Mode | Aluminum FEA | Aluminum Experimental | CFRP FEA | CFRP Experimental |
|------|-------------|-----------------------|---------|------------------|
| 1st  | 1493        | 1518                  | 1702    | 1784             |
| 2nd  | 2421        | 2571                  | 2571    | 2571             |
| 3rd  | 2764        | 2837                  | 2837    | 2837             |

Table 4. Numerical and experimental random vibration response acceleration in longitudinal direction.

| Channel | Aluminum FEA | Aluminum Experimental | CFRP FEA | CFRP Experimental |
|---------|--------------|-----------------------|---------|------------------|
| S-2     | 14.1         | 14.6                  | 12.2    | 12.9             |
vibration test. Alignment of screws and functioning of electrical components was also checked and found satisfactory.

**Conclusions**

A prototype RF housing was manufactured using hybrid composite to demonstrate its viability for use in satellite electronics. Electrical resistivity, EMI and RE EMC tests were conducted and results were compared with reference neat CFRP and AA6061-T6 electronic housing. Moreover, experimental and numerical analysis for vibration testing on housings was also performed for qualification purpose. Following conclusions have been drawn:

(a) Overall electrical conductivity of CFRP was significantly improved by incorporation of MWCNTs.

(b) Microscopic examination revealed that MWCNTs formed conductive network inside the host matrix responsible for good conductivity and EMI shielding properties.

(c) MWCNT-CFRP exhibited higher EMI SE than AA6061-T6 due to higher absorption and multi-layered structure. EMI SE of −80 dB was achieved in wide frequency band.

(d) The developed XPA housing successfully qualified the radiated emission EMC tests in 10 kHz to 18 GHz range.

(e) Vibration test results shows that hybrid composite housing has very high value of first mode of natural frequency in all three directions and can easily avoid the resonance with satellite primary structure.

(f) It has been observed that hybrid composite housing can easily withstand random vibrations during the launch phase without any damage to the PCBs inside the housing.

(g) All findings clearly showed that the MWCNT-filled CFRP housing satisfies the basic electrical and mechanical requirement and can replace the metallic counterpart for satellite electronics with an added advantage of 50% light in weight.

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