Multifunctional Carbon Fiber Composite with Improved Electromagnetic Interference Shielding and Interlaminar Fracture Toughness Characteristics

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Abstract. In this study, multifunctional carbon fiber-epoxy composites with improved electromagnetic interference shielding and interlaminar fracture toughness were manufactured. The interest in manufacturing multifunctional composites has been driven by the need for materials that simultaneously perform structural and non-structural functions. Unidirectional carbon fiber-epoxy composite laminates stitched with Dyneema13, Copper, and Kevlar13 were prepared using resin infusion process. Representative specimens from the unstitched and the stitched composites were tested using rectangular waveguide and Mode I interlaminar fracture tests. The electromagnetic shielding effectiveness experimental results showed that stitched composites exhibited improved shielding effectiveness compared to unstitched composites. For example, composite stitched with copper showed the highest increase of 102.2% in shielding effectiveness whereas composite stitched with Dyneema13 showed the smallest increase of 75.4% in shielding effectiveness compared to the unstitched. Results revealed that the dominant effect of shielding in these composites is absorption. The Mode I experimental results showed that composite stitched with Kevlar13 exhibited the highest crack initiation interlaminar fracture toughness ($G_{IC\text{-initiation}}$), whereas composite stitched with Dyneema13 exhibited the highest maximum crack propagation interlaminar fracture toughness ($G_{IC\text{-maximum}}$). The experimental results comply with the goal of the study to produce multifunctional composite with improvement in the mechanical and electromagnetic properties.

1. Introduction
Nowadays, manufacturing multifunctional materials having simultaneous improvements in the mechanical and the electrical properties is a major area of interest that is driven by the need for materials and systems that simultaneously perform structural and non-structural functions[1]. Composites by nature are multifunctional materials. For example, fiber reinforced polymer (FRP) composites have excellent structural properties such as high specific strength and high stiffness. However, FRPs have poor electrical properties due to the dielectric nature of the polymer matrix. Thus, incorporating conductive nanofillers in the matrix such as carbon nanotubes will improve their electrical and electromagnetic shielding properties [2]–[6]. The superior structural properties of FRP composites made them the best candidate for manufacturing aircraft structures. Whereas the non-structural properties such as the electromagnetic interference shielding (EMI-SE), optical transparency, and thermal conductivity made them perfect candidates in applications such as in stealth applications, electronics, piezoelectric materials.

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Despite the remarkable properties of FRPs, they are susceptible to delamination. Delamination is a serious failure mode in FRPs. It is a separation of the FRP layers caused by out-of-plane loads. Several methods have been developed to strengthen FRPs through-the-thickness and resist delamination such as stitching, z-pinning, 3D weaving and incorporating nanofillers in the polymer matrix\cite{7}–\cite{9}. One effective method in alleviating delamination is stitching the composite fabrics through the thickness using high strength threads such as Kevlar and carbon. Stitching is an excellent method in resisting delamination and improving the interlaminar fracture toughness (IFT) of FRP composites\cite{10}–\cite{12}. Therefore, stitching was the chosen method in this study to investigate its ability in resisting delamination in carbon fiber reinforced polymer composite using non-traditional types of thread (conductive thread copper and nonconductive Dyneema) and compare it with the traditional threads (Kevlar). Embedding conductive materials as threads, layers or particles in the polymer matrix was used in studies to improve the electrical and electromagnetic properties of the FRP composites\cite{13}–\cite{15}. In this direction, the conductive thread (copper) was chosen for stitching to investigate its ability in improving the EMI-SE properties and the IFT of the composite. For comparison purposes, nonconductive threads (Dyneema and Kevlar) were chosen to investigate their abilities in improving the EMI properties of the composite in addition to the anticipated improvement in the IFT. Unstitched laminate was manufactured as pristine (control) laminate.

2. Methodology

2.1. Materials
The carbon fiber composite laminates were fabricated using dry TORAY T-700-300gsm-12K-unidirectional (UD) carbon fibers, CE-R3501 vacuum infusion epoxy and CE-H5000-01 curing agent, all supplied from Composite Envisions-USA. The carbon fiber has an electrical resistivity of 1.6×10^{-3}Ω.cm and 4900 MPa tensile strength. Three types of stitching threads were used: Kevlar 13, Dyneema13 and Copper. The Kevlar thread has 0.3mm diameter and 13Kg maximum tensile load, Dyneema thread has 0.3mm diameter 13Kg maximum tensile load, and copper has 0.25mm diameter, 5.3Kg maximum tensile load, and an electrical resistivity of 8 µOhm.cm.

2.2. Composite Laminate Fabrication
One unstitched laminate as (pristine) control composite and three stitched laminates were manufactured. Each laminate was made of 10 plies of UD carbon fabrics arranged in the 0° orientation [0°]_{10}. In the stitched laminates, Kevlar13, Dyneema13 and Copper were used to stitch the dry carbon fabrics through the thickness as described in \cite{16}. All laminates were manufactured using the vacuum assisted resin transfer molding (VARTM) method following the procedure described in \cite{17}. A total of four laminates (three stitched and one unstitched) were manufactured to study the effect of stitching with different types of threads on Mode I-IFT and EMI-SE of the composites.

2.3. Specimen preparation
Specimens for the Mode I-IFT were cut with dimensions in accordance with the ASTM standard D5528\cite{18} were the unidirectional (UD) fibers were oriented along the length (L), specimens were prepared for the Mode I test as described in \cite{17}. On the other side, specimens for the electromagnetic interference shielding measurements were cut with the dimensions 3cm X 3cm.

2.4. Electromagnetic interference shielding effectiveness measurements
The specimens were tested according to the setup described in \cite{16}. At least five specimens from each laminate were tested for (EMI-SE) properties. Measurements were conducted using E5071CENA series 300 kHz-20GHz Network Analyzer connected to WR90 rectangular waveguide (SIVERS lab – Philips PM-7328-X) via coaxial cables at the X-band high frequency range (8–12 GHz). Each specimen was inserted between the waveguide’s parts and the scattering parameters S-parameters (S_{11}, S_{21}, S_{12}, S_{22}) were recorded. Each specimen was tested in two orientations, the axial direction where the UD fibers of the specimen were aligned parallel to the long side of the waveguide, and the normal direction where the UD fibers were aligned parallel to the short side of the waveguide. Using the S-
parameters, the total EMI-SE, the absorption loss (SE_A), the reflection loss (SE_R) and the electrical conductivity of each specimen were calculated using equations (1-5) [19]–[22]:

\[
EMI \ SE = SE = 10 \log \left( \frac{1}{|S_{12}|^2} \right) = 10 \log \left( \frac{1}{|S_{21}|^2} \right)
\]

(1)

\[
EMI \ SE = SE_R + SE_A
\]

(2)

\[
SE_A = 10 \log \left( \frac{1}{|S_{11}|^2} \right)
\]

(3)

\[
SE_R = 10 \log \left( \frac{1}{1-|S_{11}|^2} \right)
\]

(4)

\[
s^2 = 2 \times \left( \frac{SE_A}{0.74} \right)^2 \times 10^{\left( \frac{SE_R - 39.5}{10} \right)}
\]

(5)

Where \(|S_{ij}|^2\) is defined as the power ratio; \(S_{12}\) is the ratio between the transmitted power through the shield to the incident power and \(S_{11}\) is the ratio between the reflected power from the shield to the incident power, and \(d\) is the sample's thickness.

2.5. Mode I – Interlaminar fracture test

The tensile properties of the stitching threads (Kevlar13, Dyneema13 and copper) were determined in [1]. Mode I tests were conducted following the ASTM D5528 standard using a universal testing machine (jinan-WDW20) equipped with 2KN load cell. The tests were run in a displacement controlled mode with a 2mm/min crosshead speed. Seven specimens from each laminate were tested to calculate mode I-IFT (G_{IC}) at multiple crack lengths (a) following the procedure described in [17]. The Mode I interlaminar fracture toughness (energy release rate) (G_{IC}) was calculated using the Modified Beam Theory with the correction factor Δ (MBT-Δ) using equation (6) shown below [18].

\[
G_{IC} = \frac{3P\delta}{2b(a+|\Delta|)}
\]

(6)

Where \(P\) is the applied load (N), \(\delta\) is the opening displacement (mm), \(b\) is the width of the sample (mm), \((a)\) is the crack (delamination) length (mm), and \(\Delta\) is a correction for crack tip rotation.

3. Results and Discussion

The interlaminar fracture toughness results in section 3.1 were previously reported in reference [17]. However, in this study the main theme was to emphasize on the fact that the author was able to manufacture a multifunctional composite with improved electromagnetic interference shielding and electrical conductivity in addition to the previously reported improved mechanical properties. In this study, Dyneema13 was selected because the composite stitched with it showed the highest IFT in [17] and its EMI-SE properties were not investigated before. Kevlar13 was selected because its EMI-SE properties were not studied before, and copper was selected as a type of conductive thread.

3.1. Mode I interlaminar fracture toughness of unstitched and stitched composites

Figure 1 summarizes all Mode I results of both unstitched and stitched specimens. The mean of all tested specimens’ initial, minimum, maximum, final and average values of \(G_{IC}\) were calculated and plotted as a bar. The figure shows that the initiation fracture toughness (\(G_{IC-initial}\)) of the specimens stitched with copper (1.14 kJ/m\(^2\)) and Dyneema13 (1.43 kJ/m\(^2\)) corresponds to 100% and 150% increase respectively compared to the unstitched composite (0.57 kJ/m\(^2\)). However, specimens stitched with Kevlar13 (2.06 kJ/m\(^2\)) showed the highest increase in \(G_{IC-initial}\) 260% compared to the unstitched. The maximum fracture toughness (\(G_{IC-max}\)) of the specimens stitched with Dyneema showed extremely high increase of 986% compared to those stitched with Kevlar (increase of 291%) and copper (increase of 375%) compared to the unstitched. Note that the highest initial value was for composite stitched with Kevlar whereas the highest maximum value was for the composite stitched with Dyneema. The average fracture toughness (\(G_{IC-average}\)) follows a trend similar to (\(G_{IC-max}\)). This lead to
select these composites to further analyze their electromagnetic shielding characteristics to investigate the possibility of classifying them as multifunctional composites.

![Figure 1](image)

**Figure 1.** Summary of the Mode I-DCB results: The mean values of the initiation, minimum, maximum, final and average interlaminar fracture toughness ($G_{IC}$-initiation, $G_{IC}$-minimum, $G_{IC}$-final, $G_{IC}$-maximum and $G_{IC}$-average) with the standard deviation error bars.

### 3.2. Electromagnetic interference shielding

For each tested sample from the four laminates, the overall electromagnetic shielding effectiveness (SE), the absorption loss ($SE_A$) and the reflection loss ($SE_R$) were calculated in the 8-12GHz frequency range with frequency increment of 0.02 GHz. Figure 2 shows the SE versus frequency of unstitched and stitched composites. It is clear that composites stitched with conductive (Cu) and nonconductive (Kevlar13 and Dyneema13) threads exhibit remarkable increase in the SE compared to the unstitched composite. However, composite stitched with copper exhibits the highest shielding effectiveness values amongst the stitched composites in the 9-12 GHz range.

![Figure 2](image)

**Figure 2.** Electromagnetic interference shielding effectiveness (EMI-SE) of samples representing unstitched and stitched composites in the axial direction.

Figure 3.A&B show the absorption Loss $SE_A$ and the reflection loss $SE_R$ versus frequency of the unstitched and stitched composites. Figure 3.A shows that the absorption Loss $SE_A$ almost follows the same trend as the SE where it increases with increasing the frequency whereas Figure 3.B shows that the reflection loss $SE_R$ decreases with increasing the frequency. This is because the material’s absorptivity of the electromagnetic waves increases with increasing the frequency and its reflectivity decreases with increasing the frequency.
Figure 3. (A) Absorption Loss $SE_A$ and (B) reflection loss $SE_R$ of samples representing unstitched and stitched composites in the axial direction.

The SE results of all the tested specimens from the four laminates are summarized in Table 1. For each shielding effectiveness term ($SE, SE_A, SE_R$), the average value of each tested specimen was calculated over the 8-12 GHz range, then the average SE of the five testes specimens was calculated and included in the table. It is clear that stitched composites regardless the type of stitching thread have higher SE values in the axial direction compared to the unstitched with a maximum increase of 102.2% when stitching with copper and smallest increase of 75.4% when stitching with Dyneema. It is believed based on the findings from previous studies that this behavior is due to the increase in the composite conductivity in the three dimensions (along the fibers, transverse and through the thickness) because stitching compress the fibers together in all three directions which lead to creation of conductive channels for the electromagnetic waves to flow. A more detailed explanation was introduced in [16].

Table 1. Average values of: electromagnetic shielding effectiveness (EMI-SE) in both axial and normal orientations, absorption loss ($SE_A$), reflection loss ($SE_R$) and the conductivity $\sigma$

|        | SE-axial (dB) | SE-Normal (dB) | $SE_A$ (dB) | $SE_R$ (dB) | $\sigma$ (S/m) |
|--------|--------------|----------------|-------------|-------------|----------------|
| Unstitched | 22.8          | 63.5           | 19.5        | 3.5         | 13             |
| Copper  | 46.1          | 58             | 42.1        | 3.7         | 25.5           |
| Dyneema13 | 40            | 50             | 35.7        | 3.9         | 27.5           |
| Kevlar13 | 41.5          | 69.7           | 36.9        | 4.5         | 31.14          |

In the case of composites in the normal direction, there is no effect of stitching on the SE values. This is because the carbon fibers are aligned with the polarization direction of electric field in the TE mode (fibers parallel to the short wall of the waveguide) which increases the overall conductivity of the composite. In fact stitching with Dyneema and Kevlar lead to a slightly smaller SE in the normal direction compared to the unstitched. This is because Dyneema and Kevlar have larger thread diameter with multi filaments compared to the single filament copper, which led to the creation of the nonconductive resin pockets between the fibers. These resin pockets lower the conductivity along the fiber directions and block the flow of the electrical charges. Finally, Table 1 shows the absorption loss ($SE_A$) for each type of composite is higher than the reflection loss ($SE_R$). This means the dominant effect of shielding in these composites is absorption. The results achieved were in line with previous research studies. It is also clear that $SE_A$ is higher for stitched composites compared to the unstitched with a maximum increase of 116% when stitching with copper and smallest increase of 83.1% when stitching with Dyneema. This is because the electromagnetic wave's wavelength decreases at high frequency ranges (X-band) and becomes closer to the fiber size; therefore, it is easier to be absorbed than reflected by the composite.
4. Conclusions

This study experimentally investigated the possibility of manufacturing a multifunctional composite with improved mechanical and EMI-SE properties. Composites stitched through the thickness with conductive (copper) and nonconductive (Kevlar and Dyneema) threads with a pristine composite were prepared using resin infusion process. EMI-SE test results showed that stitched composites have higher shielding effectiveness (SE) compared to the unstitched composites. The maximum SE was achieved by stitching with copper whereas the least was achieved by stitching with Dyneema13. Results showed that the dominant effect of shielding is absorption. Mode I-IFT tests revealed that composite stitched with Dyneema13 has the highest maximum IFT whereas composite stitched with Kevlar 13 has the highest initiation IFT. Goal of the study was fulfilled by manufacturing composites with improved resistance to delamination and EMI-SE using conductive and non-conductive threads.

5. References

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