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Influence of structure on radiation shielding effectiveness of graphite fiber reinforced polyethylene composite

A. Emmanuel, J. Raghavan *

Composite Materials & Structures Research Group, Mechanical Engineering Department, University of Manitoba, Winnipeg, MB R3T 6A6, Canada

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Abstract

While LEO and GEO are used for most satellite missions, Highly Elliptical Orbits (HEOs) are also used for satellite missions covering Polar Regions of Earth. Satellites in HEO are exposed to a relatively harsher radiation environment than LEO and GEO. The mass of traditionally used aluminum radiation shield, required to attenuate the radiation to a level below a certain threshold that is safe for the satellite bus and payload, scales with the level of radiation. It has been shown (Emmanuel et al., 2014) that materials with low atomic number (Z) such as polyethylene (PE) can result in a lighter shield than aluminum (Al) in HEO. However, PE has to be reinforced with relatively high Z fibers such as graphite (G) to improve its mechanical properties. The effect of introduction of G and the resulting composite structure (that meets the requirements on mechanical properties, manufacturing and service) on the radiation shielding effectiveness of PE was studied through simulation using a layered PE–G composite. The Total Ionization Dose (TID), deposited in a silicon detector behind the composite shield, has been found to be function of layer volume fraction, layer thickness and stacking sequence of the PE and G layers. One composite configuration has resulted in a TID lower than that for PE, demonstrating the possibility of tailoring the mechanical properties of PE-based composite radiation shield with minimal negative impact on its radiation shielding effectiveness.

Keywords: Radiation shielding; Simulation; Highly Elliptical Orbit; Composite shield; Multi-layered shield; Composite structure

1. Introduction

Aluminum has wide range applications in space industry. For instance, it is used to manufacture satellite buses dedicated to Low Earth Orbits (LEOs) or Geo-stationary Earth Orbits (GEOs) as well as other space missions. In addition to its structural function, Aluminum acts as a protective shield against harmful radiation in space, which causes failures of spacecraft's electrical- and mechanical-components and also malfunctioning of satellite payload. The aim of radiation shielding is to attenuate the energy and flux of incident radiation to a level below a certain threshold that is safe for satellite bus electronics and payload. This attenuation is a result of energy loss due to elastic and inelastic collision with constituents of the shield and change in particle identities due to nuclear fragmentation (Sen et al., 2009; Mangeret et al., 1996).

While LEO and GEO are used for most satellite missions, Highly Elliptical Orbits (HEOs) are also used for satellite missions covering Polar Regions of Earth. The type and intensity of radiating species experienced in space by a satellite is determined by the mission parameters such as orbit and mission duration. A relatively harsher radiation environment than LEO and GEO is expected in HEO due to its trajectory passing through Van Allen radiation belts with high energy trapped protons and electrons (Trishchenko et al., 2011). A comprehensive analysis

* Corresponding author. Tel.: +1 204 474 7430.
E-mail address: Raghavan.Jayaraman@umanitoba.ca (J. Raghavan).

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radiation environment in HEO orbits has been published by Trichtchenko et al. (2014). The thickness and the mass of the aluminum shield, required to attenuate the incident radiation to the desired level, scale with the level of radiation. In other words, for a given areal density (obtained by multiplying density with thickness) of the aluminum shield, the Total Ionization Dose (TID) deposited in a silicon detector behind the shield by the attenuated radiation transmitted through the shield, is the highest for HEO as observed in Fig. 1. Details on the simulation used to obtain this result are presented in the next section. Table 1 shows the orbital parameters for the three orbits used in this simulation. The TID for the LEO is the least and that for the GEO is between that for the LEO and the HEO. Emmanuel et al. (2014) have shown that materials with low Z such as polyethylene would result in the lightest shield to yield a desired TID (for example, 100 krad in Fig. 1) behind the shield for a mission duration of 15 years in Molniya (HEO) orbit. This is also true for GEO as shown in Fig. 1. The difference among the three materials (Al, PE, G) is not significant in LEO suggesting that the radiation shielding effectiveness of low Z materials such as PE is significant in orbits with harsher radiation environment, as suggested by other studies for interplanetary missions (Sen et al., 2009; Adams et al., 2005).

PE has lower mechanical properties than Al and has to be reinforced to meet the requirements of structural design. However, the reinforcement may reduce the radiation shielding effectiveness of the PE. PE fiber reinforced epoxy composite has been shown to have a good combination of radiation shielding and mechanical properties (Sen et al., 2009). However, the effect of volume fraction of reinforcing fibers and its arrangement within the composite (i.e. structure of composites) on shielding effectiveness is not known and is the focus of this research.

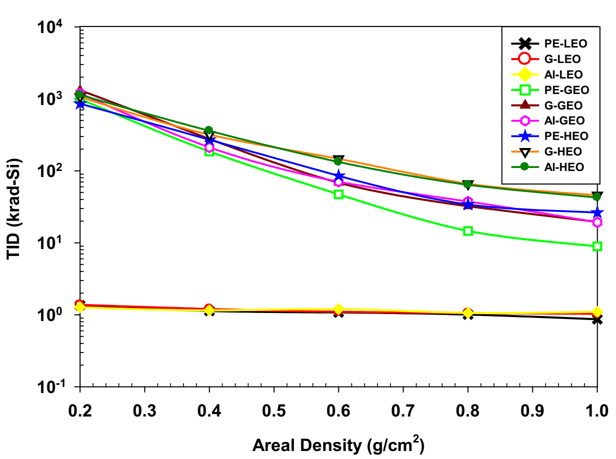

Fig. 1. Comparison of radiation shielding effectiveness of polyethylene (PE), graphite (G) and aluminum (Al) in LEO, GEO and HEO.

The building block of a continuous fiber composite laminate is a unidirectional tape prepreg with parallel fibers impregnated with a matrix or a fabric prepreg with fibers woven in two orthogonal directions (0° and 90°) and impregnated with matrix. The fiber volume fraction (V_f) in the prepreg would be in the range of 55–65%. The prepreg, ~0.2–0.4 mm in thickness, is stacked in a particular stacking sequence to form a multidirectional composite of required thickness, as shown in Fig. 2(a). The stacking sequence defines the orientation of fibers in various layers with respect to loading direction (X-axis in Fig. 2(a)) as well as location of these layers within a laminate. The number of layers per orientation is determined by dividing the required thickness per orientation (dictated by the mechanical properties) by the thickness of the prepreg. The volume fraction of a layer with an orientation ($V_{[0]}$ or $V_{[90]}$ in Fig. 2(a)), determined by the ratio of the total thickness of all layers with an orientation to the total composite thickness, the stacking sequence, and volume fraction of the fibers (V_f) in each layer, determine the in-plane mechanical properties of composite laminates. A change in the thickness of each layer (i.e. prepreg), would not affect the in-plane properties as long as the volume fraction of each orientation ($V_{[0]}$ or $V_{[90]}$ in Fig. 2(a)) is maintained. Similarly, interchanging the location of each layer within the composite (for example, [90/0/0/90] instead of [0/90/90/0] shown in Fig. 2(a)) would not affect the in-plane properties. However, same cannot be said about the radiation shielding effectiveness of the composite material.

The level of attenuation of an incident radiation, within a material with a given areal density, depends on its path length (i.e. thickness) and the atomic number the shield material. In addition, it would depend on the sequence of interaction if a shield contains more than one material; for example, in a two layered composite made up of PE and G, the intensity and the energy of the beam incident on PE in PE/G lay-up would be different from that incident on PE in G/PE lay-up resulting in difference in attenuation and TID behind the shield. The path length and the sequence of interaction in a composite consisting of materials with differing Z would vary in a complex manner as illustrated in Fig. 2(b) for irradiation along the Z axis. The beam could travel parallel to the reinforcing fibers in

Table 1
Orbital properties for three satellite orbits used in the simulation of results in Fig. 1.

	Period	Perigee altitude (km)	Apogee altitude (km)	Inclination angle í (deg)	Eccentricity
LEO (ISS)	1.55 h	411	417	51.6	0
GEO	24 h	35786	35786	0.1	0
HEO (Molniya)	12 h	500	39850	63.4	0.74