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Three Dimensional Finite Element Analysis of Functionally Graded Radiation Shielding Nanoengineered Sandwich Composites

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Abstract**—**In recent years, nanotechnology has played an important role in the design of an efficient radiation shielding polymeric composites. It is well known that, high loading of nanomaterials with radiation absorption properties can enhance the radiation attenuation efficiency of shielding structures. However, due to difficulties in dispersion of nanomaterials into polymer matrices, there has been a limitation in higher loading percentages of nanoparticles in the polymer matrix. Therefore, the objective of the present work is to provide a methodology to fabricate and then to characterize the functionally graded radiation shielding structures, which can provide an efficient radiation absorption property along with good structural integrity. Sandwich structures composed of Ultra High Molecular Weight Polyethylene (UHMWPE) fabric as face sheets and functionally graded epoxy nanocomposite as core material were fabricated. A method to fabricate a functionally graded core panel with controllable gradient dispersion of nanoparticles is discussed. In order to optimize the design of functionally graded sandwich composites and to analyze the stress distribution throughout the sandwich composite thickness, a finite element method was used. The sandwich panels were discretized using 3-Dimensional 8 nodded brick elements. Classical laminate analysis in conjunction with simplified micromechanics equations were used to obtain the properties of the face sheets. The presented finite element model would provide insight into deformation and damage mechanics of the functionally graded sandwich composites from the structural point of view.

Keywords**—**Nanotechnology, functionally graded material, radiation shielding, sandwich composites, finite element method.

I. INTRODUCTION

DESIGNING a multifunctional, lightweight, efficient radiation shielding structure with structural integrity, has been subject of several researches in recent years [1]-[4]. In this study, polymer composites functionalized with various nanomaterials are investigated from the radiation shielding point of view. Since polymers are typically hydrogen-rich materials, they are known to be effective in blocking different types of radiation including electrons, protons and secondary neutrons [1]. In addition, different types of nanomaterials such as carbon nanotubes, boron based nanomaterial and gadolinium (Gd) nanoparticles exhibit superior properties and they can not only enhance the mechanical properties of polymer composites, but also improve the radiation absorption efficiency [3], [5]-[7]. Jung et al. [2] fabricated a low density polyethylene (LDPE) nanocomposite reinforced with multi-walled carbon nanotube (MWCNT) as radiation resistance material. The analytical and experimental results of their research show that incorporation of MWCNT into polymer improved the radiation resistance of the material. In another study, Shin et al. [8] developed radiation shielding structures by incorporating modified boron nitride into high density poly ethylene (HDPE), and their investigation demonstrated significant enhancement in various properties including thermal conductivity, tensile modulus and neutron shielding capability.

It has been demonstrated that the sandwich structural composites fabricated using multifunctional nanoparticles exhibit superior radiation shielding properties as well as have excellent structural integrity [9], [10]. Sandwich composites consist of two thin, rigid and high strength face sheets bonded to a thick and lightweight core. Face sheets are primary load carrying components of sandwich structure and core has high specific mechanical properties such as high flexural strength and stiffness. Some of the advantages of sandwich structures as compared to the conventional laminate constructions include higher moment of inertia, higher buckling resistance and efficiency in carrying flexural loads [11]-[13]. Although literature review indicates significant amount of research work has been done in the area of radiation shielding structures, there is still a need to develop more efficient radiation shielding materials, which are lightweight, high strength and are cost effective. Therefore, the main objective of this research is to present a shielding architecture by dispersing of Gd nanoparticles in the core of the sandwich composites. In addition, paper also presents a detailed finite element analysis to predict the progressive deformation and damage mechanics of the functionally graded sandwich composites under compressive loading.

II. .DESIGN OF FUNCTIONALLY GRADED SANDWICH STRUCTURE

A. Components of Sandwich Composite

The presented radiation shielding sandwich structure is composed of two face sheets, each made of six layers of

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UHMWPE. Basically, UHMWPE fabrics have high modulus, high-energy absorption and high ballistic protection characteristics. The core material consists of epoxy system (Diglycidyl Ether of Bisphenol F (EPON 862) and curing agent Diethyltoluenediamine (DETDA "W"). The nanoparticles used in the present study are Gd nanoparticles with the size range of 500-700 nm.

B. Shielding Architecture

As Gd nanoparticles have excellent neutron absorption properties (elemental Gd has highest neutron capture cross section of any element (49,000 barns)) [14], higher loading of Gd nanoparticles into epoxy resin can effectively enhance the radiation shielding efficiency of sandwich structure. However, it is very difficult to increase the loading of nanoparticles into polymer resin. Generally, higher mass density of nanoparticles and lack of interaction or bonding of nanoparticles with polymer molecules results into settlement of nanoparticles during the cure cycle and usually affects the dispersion quality of nanoparticles. Therefore, in this research a method is developed to functionally grade the core material of sandwich structure by gradually dispersion of nanoparticles. In this method, the core is fabricated in controllable gradient dispersion of nanoparticles, with the purpose of having highest loading of Gd particles in the top layer of core, where it is more exposed to the radiation. Fig. 1 schematically represents the proposed functionally graded structure.

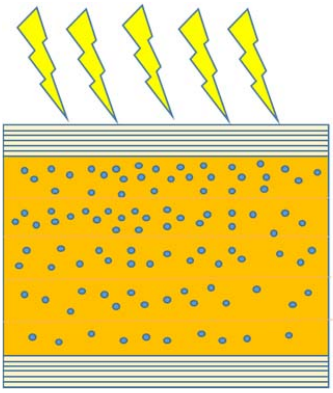

Fig. 1 Schematic of functionally graded shielding sandwich composite

TABLE I
MATERIAL PROPERTIES

Material Property	**UHMWPE**	**Neat epoxy**
E_x (GPa)	8.28	3.50
E_y (GPa)	1.80	3.50
E_z (GPa)	1.80	3.50
ν_{xy}	0.28	0.35
ν_{yz}	0.28	0.35
ν_{xz}	0.28	0.35
G_{xy} (GPa)	0.784	1.30
G_{yz} (GPa)	0.703	1.30
G_{xz} (GPa)	0.784	1.30

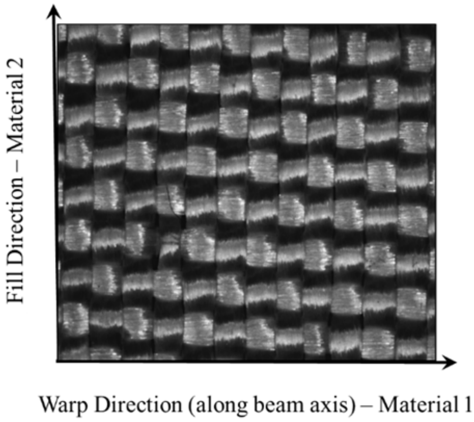

Fig. 2 UHMWPE plain weave fabric

III. MATERIAL PROPERTY CALCULATIONS

The material properties for the face sheets were obtained using the micromechanics equations [15]. Here the fiber volume fraction in the face sheet is considered as 60-wt%. Table I represents the material properties for UHMWPE fabric and epoxy resin.

Table I shows the properties of the components of face sheet. Face sheets had architecture of plain weave and were made of UHMWPE (see Fig. 2). The warp fibers were oriented along the length of the composite specimen and were designated as material 1. The fibers in the fill direction were oriented across the width of the specimen and were designated as material 2. Materials 1 and 2 (Fig. 2) in the model are the same materials but their anisotropy and orientation require two different sets of material properties. The material properties of material 1 and material 2 were calculated using the micromechanics equations and rule of mixtures [15]. The longitudinal modulus of elasticity values were calculated using the rule of mixtures.

$$E_{l11} = k_f E_{f11} + k_m E_m \tag{1}$$

where: E_{l11}= Longitudinal Modulus of elasticity, laminate; E_{f11}= Longitudinal Modulus of elasticity, fibers; E_m= Modulus of elasticity, matrix (resin); k_f, k_m= Fiber volume fraction, Matrix volume fraction. The transverse tensile modulus was calculated with:

$$E_{l22} = E_{l33} = \frac{E_m}{1-\sqrt{k_f}\left(1-E_m/E_{f22}\right)} \tag{2}$$

where: E_{l22}, E_{l33} = Transverse Modulus of elasticity, laminate; E_{f22}= Transverse Modulus of elasticity, fibers. The shear moduli were calculated using:

$$G_{l12} = G_{l13} = \frac{G_m}{1-\sqrt{k_f}\left(1-G_m/G_{f12}\right)} \tag{3}$$

$$G_{l23} = \frac{G_m}{1-\sqrt{k_f}\left(1-G_m/G_{f23}\right)} \tag{4}$$

where: $G_{l12}, G_{l23}, G_{l13}$= Shear modulus, laminate; G_{f12}, G_{f23} =

Shear modulus, fiber; G_m = Shear modulus, resin. Poisson's ratios are calculated using:

$$\nu_{l12} = \nu_{l13} = k_f \nu_{f12} + k_m \nu_m \tag{5}$$

$$\nu_{l23} = \frac{E_{l22}}{2G_{l23}} - 1 \tag{6}$$

where: $\nu_{l12}, \nu_{l13}, \nu_{l23}$= Poisson's ratio, laminate; ν_{f12}= Poisson's ratio, fiber.

Using values obtained from (1)-(6) and classical laminate theory, the material properties for the face sheets, which consisted of 6 layers of UHMWPE fabric, were obtained and are shown in Table II.

TABLE II
MATERIAL PROPERTIES OF FACE SHEETS

Material Property	Material 1	Material 2
E_x (GPa)	6.37	2.02
E_y (GPa)	2.02	6.37
E_z (GPa)	2.02	2.02
ν_{xy}	0.308	3.06
ν_{yz}	0.289	0.308
ν_{xz}	0.308	3.06
G_{xy} (GPa)	0.86	0.861
G_{yz} (GPa)	0.78	0.784
G_{xz} (GPa)	0.86	0.816

In the present model, the core material was made of 5 layers of epoxy nanocomposites. These layers had different weight percentages of Gd nanoparticle (5, 10, 15, 20, 25 wt %) respectively. These varying percentages of Gd particles resulted into an overall average loading of 15 wt% of Gd particles in the core material. The thickness of each layer is 2.8 mm and the properties of each of the layers were treated as isotropic material and were calculated based on rule of mixture. Table III shows the properties of these layers.

TABLE III
MATERIAL PROPERTIES OF FACE SHEETS

Material Number	Particle Loading Wt%	Modulus GPa
3	5	3.7
4	10	4.14
5	15	4.62
6	20	5.15
7	25	5.74

IV. FINITE ELEMENT MODEL

Three dimensional finite element analysis was performed using ANSYS software to predict the behavior of the sandwich composite under compressive loading. The face sheets and nanocomposite core were modeled using 3-D 8 noded brick elements. Fig. 3 illustrates the finite element model of functionally graded sandwich composite. The size of the finite element model in the present study was 25.4 mm x 25.4 mm x 19 mm. There were totally 9600 brick elements in face sheets and 4000 elements in the core material.

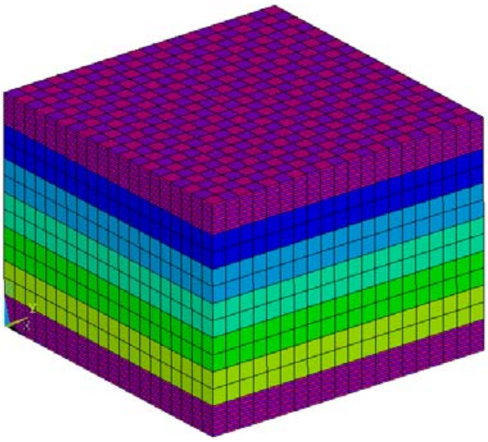

Fig. 3 Finite element model of functionally graded sandwich composite

The finite element model was subjected to an incremental compressive displacement on the top face sheet. It was observed that when displacement of 0.5 mm was applied, the Von Mises stress reached the failure strength of the core material, which in our current model was about 120 MPa (Fig. 4). The fabricated sandwich coupons were tested to determine the compressive strength of the specimens using flatwise compressive test (ASTM C365). The results obtained by using the present 3-D finite element model agreed well with the experimental results. Both experimental and analytical results indicate that buckling of the core material is the major failure cause for the radiation-shielding sandwich composites under compressive loading.

V. CONCLUSION

To optimize the design of multifunctional radiation shielding structure, a method is developed to fabricate the functionally graded sandwich composite. In the method, core material was divided into five slabs. Each slab was fabricated with varying weight percentages of Gd nanoparticles. The fabricated sandwich composite was then subjected to compressive loading to study the deformation and damage mechanics. Study indicates that the sandwich composites failed due to buckling of the core material. A detailed 3-D finite element analysis of the sandwich composite material was performed using maximum stress failure criteria. Von Mises stresses in the core material were valuated and when they exceeded the strength of the core material the core was declared as failed and the corresponding displacements and loads were recorded. Finite element model predicated failure of the sandwich composites accurately.

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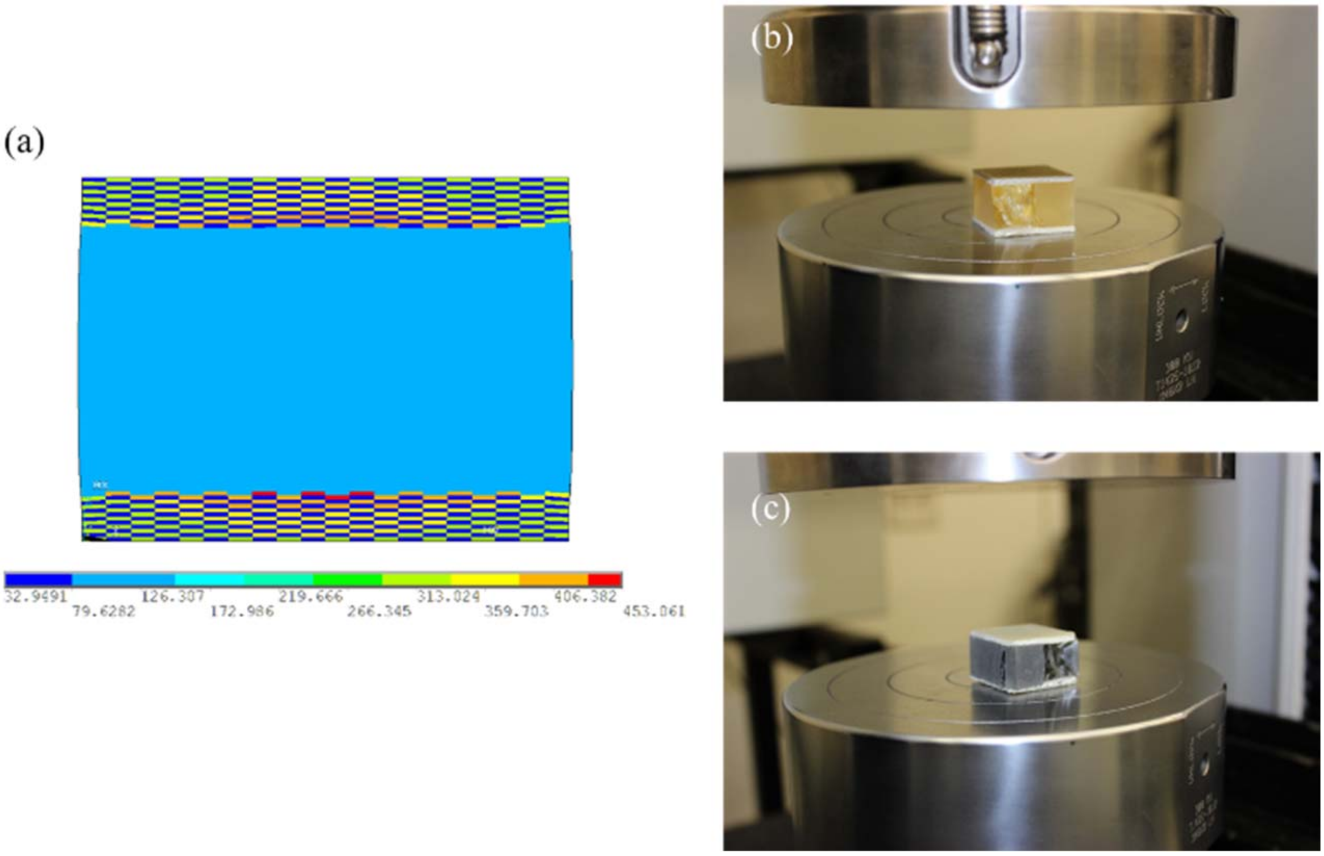

Fig. 4 (a) Analytical stress distribution through thickness after compression, (b) Sample with neat epoxy as core and (c) Sample with Gd nanocomposite as core after flat-wise compression test representing the failure mode

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