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Experimental and theoretical investigation of the thermo-mechanical deformation of a functionally graded panel

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ABSTRACT

An aluminum/high-density polyethylene (HDPE) functionally graded material (FGM) has been fabricated as a key component of a multifunctional building envelope for energy efficiency and sustainability. Because of the gradual phase change of aluminum and HDPE across the thickness direction, when a free-standing FGM panel is subjected to a temperature variance, it will exhibit considerable curling deformation, which causes challenges to assemble the FGM panel into a flat multifunctional roofing panel and also to assure structural integrity under cyclic temperature change. Therefore, it is crucial to predict the thermo-mechanical behavior of the FGM panel. For this purpose, an axisymmetric refined plate theory was developed in this study for a circular FGM panel subjected to externally applied thermo-mechanical loading. The theoretical solutions are verified with experimental results, it demonstrates that the presented solution can accurately predict the thermo-mechanical behavior of the developed FGM panel and be used in the design of the proposed solar panel.

1. Introduction

Conventional laminated composite materials exhibit a discontinuity of material properties at the interface, which commonly results in stress concentrations and thus damage in the form of delamination, matrix cracking and adhesive bond separation when they are subjected to environmental and mechanical loadings. Functionally graded materials (FGMs), however, possess continuously graded material properties such as mechanical, electrical, and thermal parameters at the macro level that are generally not founded in conventional materials. Therefore, FGMs have gained much attention as advanced structural materials in recent years and has been widely used in many applications such as aerospace, electric engineering, biomedical engineering, nuclear and civil engineering [1–3].

Our recent research work [4–6] has shown great potential to harvest solar energy efficiently by developing a building integrated photovoltaic thermal (BIPVT) roofing panel with FGM as an essential component. The innovation idea of this BIPVT is schematically illustrated in Fig. 1, where a photovoltaic (PV) solar cell (laminated by a protective layer) directly transfers solar energy into electricity; the PV layer is bonded to a structural substrate through an FGM layer, in which water tubes are cast to harvest heat energy by water flow and also control the panel temperature. The FGM layer was developed to enhance the energy conversion efficiency which is lost at higher ambient temperature, and improve the lifetime of a PV module as well. The FGM layer gradually transits material phases from metal dominated to polymer materials. The high aluminum concentration in the top part creates high thermal conductivity so that heat can be immediately transferred to water tubes in all directions; while at the bottom part of FGM layer, pure high-density polyethylene (HDPE) is used to insulate the solar heat from entering to the building and thus improve the thermal comfort in the building.

Because of the gradual phase change of aluminum and HDPE across the thickness direction, the thermal expansion coefficient of the FGM varies in the thickness direction. Considerable curling deformation was found in the final product of the designed FGM panel when it was cooled down from the higher processing temperature (140 °C). Extra deformation may also exist in field applications due to a considerable variance of service temperatures. In this sense, the structural integrity of the BIPVT panel significantly relies on the thermal deformation of the FGM layer. To address this issue, one needs to accurately predict the thermos-mechanical performance of the designed FGM panel for a design purpose to secure the integrity of the assembled BIPVT panel.

The grading nature of FGM makes the thermal expansion coefficient vary along the thickness, which results in the thermal

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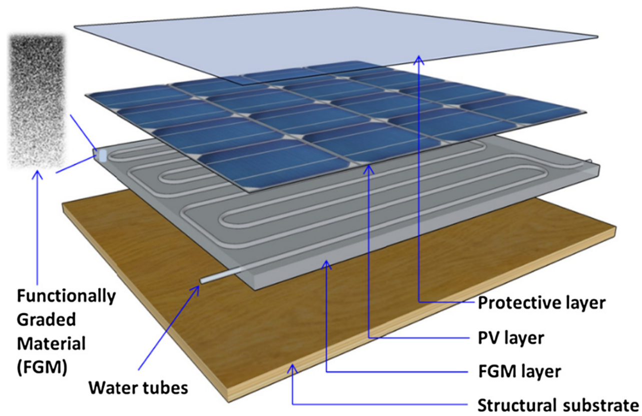

Fig. 1. A hybrid solar roofing panel integrating an FGM plate with other layers for heat harvesting and temperature control.

bending subjected to a temperature variance. Extensive studies have been conducted in the literature to predict the thermo-mechanical behavior on FGM beams, plates or shells by the first-order shear deformable theory (FSDT) [7,8] and higher-order shear deformable theories (HSDT) [9–13]. Among them the FSDT is the most widely used one due to its simplicity. Nevertheless, the traction free boundary condition on top and bottom of the plate cannot be satisfied because of the assumed constant shear strain across the thickness. To avoid such a conflict, various HSDTs were developed to capture the distribution of shear strain along thickness. Although the HSDT provides a more accurate prediction of the global response of the structure, it often involves more invariables thus requires much more computational efforts. Based on different assumptions and corresponding shape functions, the number of unknowns involved in a HSDT varies. It could be as much as eleven [14]. However, with certain simplifications, it could be reduced to four [15,16]. Recently, Houari and Tounsi [17,18] developed a new HSDT for FGM rectangular plate with only three variables by employing non-polynomial shape functions through the thickness of the plate. It agrees well with other HSDTs. Among various HSDTs, the one developed by Reddy et al. [19] which involves five unknowns is currently one of the most widely used owing to its efficiency and simplicity. To select a proper HSDT for a specific study, one needs to tradeoff the simplicity of the theory (reflected by the number of the unknowns) and its effectiveness and accuracy to capture the physics (such as the distribution of shearing strain, the in-plane extension and out-of-plane stretching).

Most of the studies on rectangular plate start with simply supported boundary conditions, which makes the Navier-solution-typed double summation suitable for the analysis. However, the infinite terms in the solution make the result difficult to comprehend and computational expensive. While for a circular FGM plate, especially in the axisymmetric case, explicit and simple solution with clear physical meanings could be generated. Though it has gained wide application as engineering structural components, circular FGM plate has been relatively overlooked compared with the rectangular one. Many studies on the circular plate with simple isotropic materials can be found in the literature [20–22], but the studies on the circular FGM plate by HSDT are quite less [23–26]. To the authors' knowledge, no relevant closed-form solutions for an FGM circular plate subjected to thermo-mechanical loadings has been developed yet.

As the first step to understand the thermo-mechanical behavior of the solar panel shown in Fig. 1, and to improve the accuracy of the FSDT by reducing the complexity of HSDT, an explicit solution based on the refined plate theory (RPT) is developed in this study for the FGM circulate plate subjected to asymmetric thermo-mechanical loading. The RPT assumes a separation of the displacement into bending and shear parts [27–29], which shows a clear physical meaning compared with other HSDTs. In its original version, the in-plane extensions were neglected while only two unknowns were used to trace the bending and shearing deformation. Compared with the FSDT, the RPT leads to a parabolic shear deformation distribution across the thickness direction thus automatically satisfy the traction free conditions. Therefore, it not only reduces the number of unknowns but also shows a clearer physical meaning and provides more accurate solutions than the FSDT [30].

Since the in-plane extension and out-of-plane stretching are not the primary factors here, the RPT will be perfect to predict the behavior of the solar panel shown in Fig. 1. The purpose of this study is to provide an experimental and theoretical investigation of the thermo-mechanical deformation of an FGM circular panel. A RPT will be developed for the functionally graded plates subjected to thermos-mechanical loading and closed-form solutions will be accordingly provided. Material characterizations of the FGM panel and its deflections subjected to thermo-mechanical loading are provided in Section 2. Theoretical modeling of a circular FGM plate is presented in Section 3. Theoretical predictions are compared in Section 4 with experimental results and finite element analysis. Brief summary and conclusions are provided in Section 5.

2. Experimental characterization of the FGM panel

The FGM was made by coarse aluminum powder and high-density polyethylene (HDPE) through the vibration method. Coarse aluminum powder (Al-111) was chosen to mix with the finer high-density polyethylene (HDPE) powder. The desired gradation of the AL-HDPE FGM in terms of volume fraction of aluminum to the FGM is to be from 0 to 50% across its thickness. Aiming at this gradation, a mixing design of the FGM with an appropriate volume ratio of Al to HDPE as 1:3 was applied and the ethanol added for the mixing was chosen by the weight ratio of ethanol to the mixed powder as 28%. The detailed mix design and fabrication processes are provided in reference [5]. The cross section of one sample element (12.7 mm height $\times$ 20.3 mm width) cut from the FGM panel is shown in Fig. 2, which shows that a well-controlled graded FGM was achieved. According to the gradation analysis of the present FGM, a linear gradation of the components along its thickness direction was obtained, which can be expressed via the relationship between the volume fraction of the aluminum to HDPE (ϕ) and its height location (z/h) as:

Fig. 2. Microstructure of the FGM panel containing aluminum particles dispersed in the HDPE matrix with the concentration changing in the thickness direction.