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Static deflection and thermal stress analysis of non-uniformly heated tapered composite laminate plates with ply drop-off

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ABSTRACT

The effective design of tapered laminated composite structures subject to non-uniform temperature fields requires a thorough understanding of their static behaviour. In this study, a finite element analysis of tapered laminated composite plates with ply drop-off has been carried out to study the static deflection and normal stress patterns developed under non-uniform heating. The study revealed that the nature of the taper configuration, the nature of the applied temperature field and the structural boundary conditions influence the static deflection behaviour and the normal stresses developed in the tapered composite plates. It is found that the static deflection pattern of a tapered plate subject to a particular temperature profile is not sensitive to the nature of the taper configuration. It is also observed that the static deflection pattern of a tapered plate is significantly influenced by the nature of temperature field. Normal stress variation of tapered plates subject to various temperature fields reflects the nature of the temperature profile. Maximum normal stress occurs at locations where the highest temperature exists for that particular temperature field. The stresses are also influenced by the nature of the taper - Taper D plates experience low stresses while Taper B and Taper C plates experience similar values. It was also found that large variations in stresses are observed at resin pockets.

1. Introduction

Laminated composite structures are finding extensive use in automobiles, high-speed aircraft, rockets and space vehicle components. In all these situations these structures are subjected to thermal stresses arising due to heating of these components. Similarly these structures find use in a number of nuclear and chemical plant components, wherein they are regularly subjected to high temperature profiles. In some of these applications, requirements of variabilities in properties through the component arise. In most cases, some parts of the component need to show high stiffness while others need to be flexible. Some common examples of such components include helicopter yokes and blades, wing structures of aircraft, robotic arms, flywheels and turbine blades. Hence, it is usually desirable to tailor the material to match the requirements of localized strengths and stiffness.

Tailoring of properties through the length of a composite laminate structure can be achieved by changing the number of plies associated with a uniform laminated structure across it's length. This is known as ply drop-off of laminated composite structures. A typical laminated tapered composite with ply drop-off and resin-rich pockets is shown in Fig. 1. Single or multiple laminate plies are abruptly dropped to bring about a change in layer thickness which in turn modifies the stiffness properties of the composite. By controlling the number of plies dropped and the locations where they are dropped, the properties of the resulting component can be tailored as per the requirements of the application. These abrupt changes in thickness, however large, induce stress concentrations which affect the behaviour of these tapered composites under a variety of loading conditions. In most of these situations, large deflections as well as compressive and shear loadings are regularly encountered. As a result laminated composites in general and tapered laminated composites in particular are receiving much attention from researchers.

Exhaustive amount of research work has been carried out on static bending and stress analysis of laminated composite plates subject to thermal loads. Kant and Swaminathan [2] presented analytical solutions for the static analysis of laminated composite plates by making use of higher order refined theory. Matsunaga [3] evaluated inter-laminar stresses and displacements in cross-ply multilayer composites subject to thermal loading using a 2D global higher order deformation theory. Their results are in good agreement with published results based on 3D layerwise theories. Ganapathi et al. [4] analysed the stress and deflections in a laminated composite plate subject to thermal loads using a plate element formulated based on the first order shear deformation theory and studied the effects of various parameters such as ply-angles,

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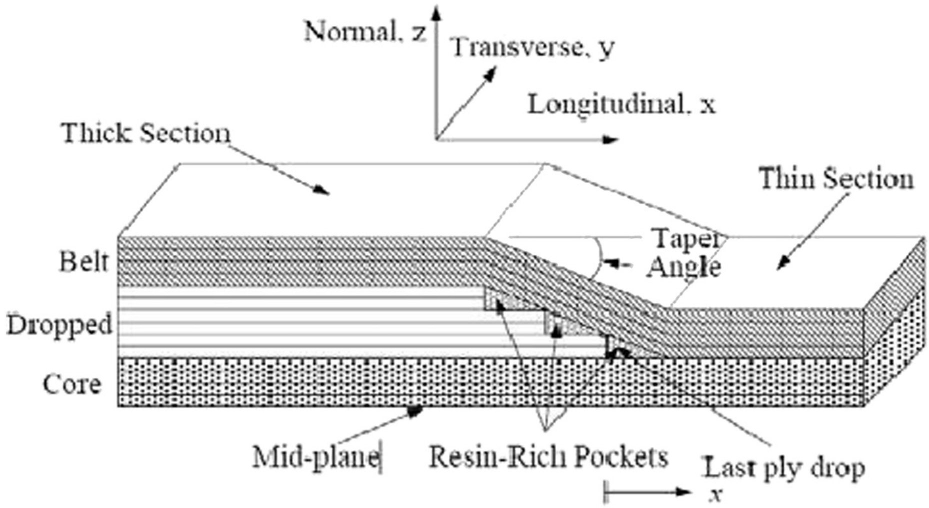

Fig. 1. A Typical tapered composite with ply drop([1]).

number of layers as well as layer thickness on the deflection and stress patterns. A thermomechanical bending response analysis of thick Functionally Graded Material (FGM) plates resting on Winkler-Pasternak elastic foundations was performed by Bouderba et al. [5]. They developed an efficient and accurate theory to predict an FGM plate's bending response under thermomechanical loads. Zidi et al. [6] made use of a four variable refined plate theory to predict the bending responses of a functionally graded material plate resting on elastic foundations. This plate was also subject to hygro-thermo-mechanical loading. The study simulated rocket launchpad structures subject to high thermal loads. A 3-D thermal stress analysis of laminated composite plates by using sampling surfaces was carried out by Kulikov and Plotnikova [7]. A computationally economic global-local theory with 3-D elasticity correction was developed by Khalili et al. [8] for stress and deformation analysis of multi-layered and sandwich composite plates. The transverse shear stresses calculated using this approach showed very good agreement with those obtained from 3D theory of elasticity thus verifying the approach. Hebali et al. [9] developed a new quasi 3D hyperbolic shear deformation theory to study the bending and free vibration of FGM plates. The novelty in this approach was the division of the transverse displacement into bending, shear and thickness stretching parts, thus reducing the number of governing equations. A highly generalised yet accurate analytical approach for the bending and stress analysis of angle-ply laminated composite and sandwich plates was developed by Alipour [10]. This method is applicable to composite plates subject to a variety of arbitrary boundary conditions.

Studies on laminated tapered composite structures with ply drops is limited in comparison to the studies on laminated composite with uniform thickness. Poon et al. [11] developed a finite element method to predict strain fields in carbon-fibre/epoxy composites with dropped plies subjected to in-plane bending. The effects of the strain concentrations at ply-drops and free edges were assessed and their implications on the mechanisms of failure of tapered composites were presented. Polyzois et al. [12] analysed the free vibration behaviour of tapered poles using finite element methods. He et al. [13] conducted a review of various studies on tapered laminated composites and concluded that the most common areas of research included parametric studies on tapered laminated composites and, stress and delamination analysis. Studies on the effects of resin pockets at ply drops on tensile behaviour of tapered laminated composites were carried out by Vidyashankar and Murty [14]. The variations which arise in stress and displacement distributions around the ply drops were studied in detail. It was found that at these locations, local bending occurs due to taper and has an effect on the stress at the ply drop location. An extensive review of various studies on composite plates with ply drop-offs was undertaken by Dhurvey and Mittal [1]. The effects of deformation and stress on delamination of tapered composites were presented.

Investigations on the effect of taper models, laminated configurations and boundary conditions on free undamped vibration responses of tapered composite beams by using a higher-order finite element method were performed by Ganesan and Zabihollah [15]. Shamloofard and Movahhedy [16] made use of special tapered and spherical super-elements to model and analyse tapered and spherical structures subject to thermo-mechanical loading. Sudhagar et al. [17] investigated a tapered laminated thick composite plate for its vibration characteristics by making use of a finite element method which included the effects of shear deformation and rotary inertia. Parametric studies of the effects of ply drop-offs, taper angle and taper configurations were undertaken to study their effects on free and forced vibration.

Most of the studies related to static and dynamic behaviour of heated structures have been carried out by assuming that the structure has been heated uniformly. Very few researchers analysed the effect of non-uniform temperature on static and dynamic behaviour of structures exposed to thermal load. Since cooler substructures function as heat sinks the temperature distributions across the structure will not be uniform even under a uniform heat flux (Gossard et al. [18], Ko [19]). The effects of such non-uniform temperatures on thermal modelling and stress/strain analysis of electronic packages were studied by Wakil and Ho [20]. They found that thermal loading due to internal power dissipation produced significantly different strains than a uniformly heated sample. A non-linear finite element approach was used by Barut et al. [21] to analyse the effects of non-uniform temperature variation across a shell surface and through the thickness of flat and curved laminates. A stiffening/softening type large deflection response was observed for flat plates subject to non-uniform temperature variations. The structural behaviour of simple steel structures with non-uniform longitudinal temperature distributions arising under fire was analysed by Becker [22]. He found that longitudinal non-uniform temperature distributions affect the patterns of structural behaviour, resulting in an increased period of structural stability. Jeyaraj and Rajkumar [23] used a finite element method to study the static behaviour of functionally graded composite plates heated non-uniformly. They found that the nature of the temperature field strongly influences the static behaviour of the plate. Mayandi and Jeyaraj [24] studied the bending characteristics of FG-CNT-reinforced polymer composite beam under non-uniform thermal load. They found that the functional grading of the composite significantly affected the static-bending deflections of the beam significantly.