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Finite element analysis of thermoplastic composite plates in forming temperature

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Abstract

An implicit mixed finite element formulation is developed based on the plate theory to analyze thermoforming process of thermoplastic plates reinforced with unidirectional continuous fibers. The plate thickness variations and the rotation of transverse planes are considered using Reissner–Mindlin approximation in order to model the predominated deformation mechanisms of the transverse fiber flow and intra-ply shear in these highly kinematical constrained materials. The kinematical constrains due to material incompressibility and fiber inextensibility are considered in the plate theory formulations and taken into account in the finite element method by introducing penalty numbers. A new analytical approach is developed to analyze the forming procedure of a composite plate on the single curvature geometry to compare the numerical results with analytical approach. The forming of thermoplastic plates to the hemispherical configuration is also studied by means of finite element technique. The geometry of panel in blank holder region is estimated considering both the effect of blank holder normal pressure and the viscous layers in die contact surfaces. The finite element results show that the geometry and defects due to wrinkling during the shaping procedure may be conventionally predicted using the derived formulations.

Keywords: Thermoplastics; Composite plate; Finite element analysis; Sheet forming

1. Introduction

Reinforced thermoplastic plates associated with convenient characteristics, such as high structural strength and stiffness, infinite shelf life, high toughness and ease of processing, have found increasing applications in most industries. Forming is an appropriate method for mass production of complex parts from composite sheets. In order to produce high quality parts and preventing a trial and error manufacturing procedure, modeling of the forming process is very helpful. Finite element analysis is an appropriate technique to model the sheet forming procedure by which the fiber arrangement, deformation and stress field may be obtained in a part with complex geometry.

Forming of thermoplastic composite plates starts with heating of panels to the temperature that the fibers may move easily to match the die geometry. Then the heated panels are formed in the die while the blank holder controls the flow of the plate by applying pressure as shown in Fig. 1. Experiments have shown that fibers exhibit negligible elongation during forming [1]. Due to the high ratio of bulk to shear viscosity, thermoplastic reinforced sheets behave like incompressible materials at forming temperature [2]. For the analysis of forming process of thermoplastic laminates reinforced with unidirectional continuous fibers, Rogers [3] developed a constitutive equation for each ply. Ó Brádaigh and Pipes [4] proposed a finite element formulation assuming incompressibility and inextensibility behavior for composite panels considering both plane stress and plane strain conditions [5]. In their plane stress problems, inter-ply slide between layers was ignored and each ply was analyzed independently

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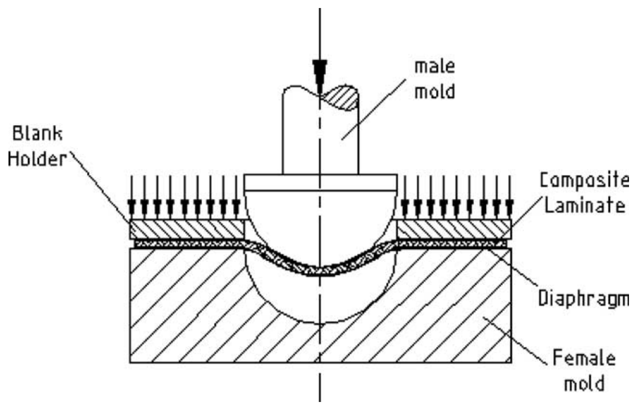

Fig. 1. Schematic of stamp forming process of reinforced thermoplastic sheets.

calculating average properties for the whole plate. They also ignored the normal and shear stresses induced by boundary conditions. The numerical analysis of plane strain problems for thin plies often leads to using high aspect ratios for element dimensions, which decreases the accuracy of the solution [6]. Johnson and Pickett [7] developed explicit finite element formulations using shell theory assuming elastic behavior for the fibers under plane stress conditions. In their formulations, shear strains across the laminate thickness were ignored. Thus, the effects of the transverse intra-ply shear deformation mechanism are eliminated. Simacek and Kaliakin [8] derived the appropriate equations for rectangular thermoplastic plates reinforced with continuous fibers parallel to plate edge at forming temperature using the plate theory and solved these equations employing finite difference method.

In the present work, an implicit mixed finite element method is developed to characterize the deformation mechanisms during forming process of fiber-reinforced thermoplastic plates. Hence, the finite element formulations are derived using Reissner–Mindlin approximation in the plate theory in order to analyze the thickness variation and the rotation of the transverse planes during the mid plane deformation as well as the effects of the normal and shear tractions on the plate surfaces. The kinematical constrains due to material incompressibility and fiber inextensibility which cause highly anisotropic behavior are considered in the plate theory and the finite element equations are solved defining the penalty numbers. The method is employed to analyze the part of plate under blank holder in stamp forming and the results are compared with an analytical model and experimental results in the literature.

2. Kinematics

Thermoplastic plates reinforced with unidirectional fibers is considered as *ideal fiber-reinforced fluid* at forming temperature in which each laminate is modeled as a transversely isotropic Newtonian fluid with assumptions of matrix incompressibility and fiber inextensibility constraints for the materials. The incompressibility constraint is given by:

$$\mathbf{c}^{\mathrm{T}}\mathbf{d} = 0, \tag{1}$$

where the vectors $\mathbf{c}$ and $\mathbf{d}$ are defined as:

$$\mathbf{c} = [1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0]^{\mathrm{T}}, \tag{2}$$

$$\mathbf{d} = [d_{11} \quad d_{22} \quad d_{33} \quad 2d_{23} \quad 2d_{31} \quad 2d_{12}]^{\mathrm{T}}. \tag{3}$$

The components of $\mathbf{d}$ are the components of Eulerian strain rate tensor defined by

$$d_{ij} = \frac{1}{2}\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right), \tag{4}$$

where V_i are the components of velocity vector and x_i are spatial coordinates. Due to the small diameter of continuous fibers in a composite plate, fibers are considered flexible with negligible bending stiffness. Experiments show that at forming temperature, a curvilinear form of deformation is expected for fibers with negligible elongation [1]. The inextensibility constraint is stated as follows:

$$\mathbf{m}^{\mathrm{T}}\mathbf{d} = 0, \tag{5}$$

where $\mathbf{m}$ is defined in term of components of unit vectors a_i in fiber direction as:

$$\mathbf{m} = \begin{bmatrix} a_1^2 & a_2^2 & a_3^2 & a_2a_3 & a_3a_1 & a_1a_2 \end{bmatrix}^{\mathrm{T}}. \tag{6}$$

During forming process, the ply thickness changes and the rotation of transverse planes and normal stress play effective roles in the evaluation of sheet forming. Therefore, the Kirchhoff approximation for plate analysis is inconsistent. Hence, the Reissner–Mindlin approximation is an appropriate method to consider the effects of thickness change, transverse planes rotation and normal stress in deformation process. The components of velocity vector are assumed to be [8]:

$$V_1(x_1,x_2,x_3) = v_1(x_1,x_2) + x_3\phi_1(x_1,x_2), \tag{7a}$$

$$V_2(x_1,x_2,x_3) = v_2(x_1,x_2) + x_3\phi_2(x_1,x_2), \tag{7b}$$

$$V_3(x_1,x_2,x_3) = v_3(x_1,x_2) + x_3\alpha(x_1,x_2) + \frac{1}{2}x_3^2\beta(x_1,x_2), \tag{7c}$$

where v_i is the velocity component of mid plane, ϕ_i is the rate of transverse plane rotation, α is the rate of thickness change and β is the rate of mid plane movement in thickness direction. From Eqs. (3), (4) and (7) the strain rate tensor becomes:

$$\mathbf{d} = \mathbf{d}^{(1)} + x_3\mathbf{d}^{(2)} + \frac{1}{2}x_3^2\mathbf{d}^{(3)}, \tag{8}$$

where