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# ANALYSIS OF ELASTO-PLASTIC POSTBUCKLING AND ENERGY RELEASE RATE FOR DELAMINATED FIBER METAL LAMINATED BEAMS IN THERMAL ENVIRONMENT**

**Yiming Fu**[1,2] **Yang Chen**[1,2*] **Xuefei Shao**[1,2]

([1] *State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha* 410082*, China*)

([2] *College of Mechanical and Vehicle Engineering, Hunan University, Changsha* 410082*, China*)

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**ABSTRACT** The elasto-plastic postbuckling of fiber metal laminated beams with delamination and the energy release rate along the delamination front are discussed in this paper. Considering geometrical nonlinearity, thermal environment and geometrical initial imperfection, the incremental nonlinear equilibrium equations of delaminated fiber metal laminated beams are established, which are solved using the differential quadrature method and iterative method. Based on these, according to the $J$-integral theory, the elasto-plastic energy release rate is studied. The effects of some important parameters on the elasto-plastic postbuckling behavior and energy release rate of the aramid reinforced aluminum laminated beams are discussed in details.

**KEY WORDS** fiber metal laminated beams, delamination, temperature effect, elasto-plastic postbuckling, elasto-plastic energy release rate

## I. INTRODUCTION

The Fiber Metal Laminates (FMLs)[1], a class of composite materials composed of alternately bonded metal layers and fiber composite layers, exhibit the properties of both metals and composites, and therefore, have high strength and stiffness to weigh ratio, excellent fatigue resistance and damage tolerance properties. With all these advantages, FMLs have gained widespread use in aerospace industry during the last decades. The temperature of working conditions changes greatly when FMLs are used in the field of aerospace industry. In addition, delamination, which can weaken the mechanical properties and notably reduce the service life of the structures, is easily initiated in the laminated structures. Therefore, it is meaningful and essential to study the FMLs with delamination in thermal environment.

Delamination is the main form of damages emerging in the laminated structures, and the growth of delamination has a deleterious influence on the structure behavior. Moreover, the great stress concentration along the delamination front may accelerate the delamination growth in delaminated FML structure subjected to load, and finally result in the failure of structure. Some research has been done on the buckling and postbuckling of delaminated FMLs in thermal environment. For example, Schut et al.[2] conducted delamination tests on glass reinforced aluminum laminates (GLARE) specimens at low and elevated temperatures, and calculated the delamination growth rates based on the Paris type relation.

* Corresponding author. E-mail: YangC88@hnu.edu.cn
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Remmers et al.[3] studied the delamination buckling of GLARE and constructed a numerical model at a meso-mechanical level based on some experimental observations. Such research on delamination growth of FMLs mainly consists of comprehensive reviews and experimental studies, hence, theoretical analyses of delamination growth of FMLs are essential. Khan et al.[4–6] took experimental and analytical investigations on delamination growth in FMLs under variable amplitude loading. Hashagen et al.[7,8] discussed the delamination behavior of FMLs through experiments, proposed a modified Griffith's energy criterion to calculate the delamination resistance to residual stresses in the laminate and plasticity in the metal layers, modeled the delamination using numerical method, and verified the reliability of the analysis and the method by comparing the numerical results with the experimental ones.

On the other hand, as structures can still bear loads after their yield limits are exceeded. In addition, by merely using the theory of elasticity, the mechanical properties of FMLs cannot be truly revealed, and the carrying capacity of structure cannot be completely utilized. Therefore, investigations should be extended to the mechanical properties in plastic state. There have been many investigations on the plasticity of FMLs. Chen et al.[9] established an orthotropic elasto-plastic model of ARALL (aramid aluminum laminates), the accuracy of which was verified upon experiments. Considering the elastic-plastic behavior of the metal layer in FMLs, Esfandiar et al.[10] studied the nonlinear tensile behavior of FMLs subjected to the in-plane tensile loading. Aboudi et al.[11] investigated the plastic bifurcation buckling of ARALL by considering the elasto-plastic relation of metal layer and the elastic relation of fiber layer. Vo et al.[12] established the elasto-plastic constitutive relation of metal layer and the orthotropic elasto-plastic constitutive relation of fiber reinforcement layer, based on which, the low-impulse blast behavior of FMLs was analyzed using a 3D finite element model that coincided with the experimental results.

In sum, research on the elasto-plastic postbuckling behavior and energy release rate of delaminated FMLs in thermal environment are scarcely found in open literature, therefore the present study is significant. First, an incremental orthotropic elasto-plastic constitutive relation describing behavior of the elasto-plastic metal layer and the elastic fiber layer is proposed in this study. Then, considering the geometric nonlinearity, the incremental nonlinear equilibrium equations of delaminated FMLs beams are established, based on which, the energy release rate is studied using the elasto-plastic fracture theory. The space is discretized by means of the differential quadrature method, and the terms of nonlinearity are linearized. After that, the whole problem is solved using the iterative method. Through numerical examples, the effects of some parameters on the elasto-plastic postbuckling and energy release rate of delaminated FMLs beams are discussed in details. Finally, some meaningful conclusions are drawn.

## II. ORTHOTROPIC ELASTO-PLASTIC MODEL

An orthotropic plasticity model was employed by Kenag et al.[13] to describe the plastic behavior of a boron/aluminum composite in a state of plane stress. Based on it, the yield function can be given as

$$f(\sigma_{ij}) = \frac{1}{2}\left(a_{11}\sigma_{11}^2 + \sigma_{22}^2 + 2a_{12}\sigma_{11}\sigma_{22} + 2a_{66}\sigma_{12}^2\right) \tag{1}$$

where $\sigma_{ij}$ are stresses of arbitrary points in the material, with the subscripts 1 and 2 indicating the longitudinal direction and transverse direction of the material, respectively; and $a_{11}, a_{12}, a_{66}$ are constants to be determined by experiments.

By the above equation, the effective active stress $\bar{\sigma}$ is defined as

$$\bar{\sigma} = \sqrt{3f} \tag{2}$$

According to the elasto-plastic constitutive models of mixed hardening orthotropic materials[14], the yield criterion can be given as

$$F_p = f(\sigma_{ij}) - [\bar{\sigma}(\bar{\varepsilon}^p)]^2 \tag{3}$$

where $\bar{\sigma}$ is the effective stress, which is the function of the effective plastic strain $\bar{\varepsilon}^p$, and can be acquired by a simple extension of the experimental curves.

It is assumed that the plastic dissipation function follows the yield criterion, and based on the orthogonality principle, the plastic strain increment $\mathrm{d}\varepsilon_{ij}^p$ is proportional to the gradient of the stress

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