Applied Mathematical Modelling 39 (2015) 3317–3330

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

A thermo-elasto-plastic model for a fiber-metal laminated beam with interfacial damage

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ARTICLE INFO

Article history:
Received 22 May 2013
Received in revised form 10 October 2014
Accepted 24 November 2014
Available online 3 December 2014

Keywords:
Fiber-metal laminated beams
Interfacial damage
Orthotropic elasto-plastic
Heat conduction

ABSTRACT

In this paper, a thermo-elasto-plastic model for the fiber-metal laminated (FML) beams is established and the mechanic characterization of a FML beam with interfacial damage under thermal environment is investigated. The elasto-plastic behavior of the FML beam is modeled by a macromechanical orthotropic plasticity theory, where the composite layers in the FML are assumed to be linearly elastic and the aluminum layers are taken as orthotropic elasto-plastic. Additionally, the thermal stresses in the FML beam are studied by introducing heat conduction equation. Considering the mismatch in properties of different layers, the interfacial damage is investigated based on cohesive zone model and shear-lag model, and the evolution of the interfacial damage is addressed as well. The incremental thermo-elasto-plastic governing equations for the FML beams are solved by finite difference method and iteration method. In the numerical simulations, the temperature variation, the elasto-plastic deformation and the interfacial damage evolution of the elasto-plastic FML beam are discussed in detail. The results show that mode II interfacial damage occurs at 1/4 and 3/4 length of the beam and mode I damage is most likely to happen at the center.

1. Introduction

The development of fiber-metal laminates (FMLs) as a new class of advanced engineering materials offers an interesting alternative to traditional engineering materials. FML is one of a class of metallic materials consisting of a laminate of several thin metal layers bonded with layers of composite material. This allows the material to behave much as a simple metal structure, but with considerable specific advantages regarding properties such as metal fatigue, impact, corrosion resistance, fire resistance, weight-savings and specialized strength properties [1–4]. The combination of these aspects in one material makes fiber metal laminates a strong candidate material for fuselage skin structures of the new generation of high capacity aircraft. GLARE (GLAss-REinforced aluminum) is currently applied in the aircraft industry because of the excellent mechanical and damage tolerance properties.

During the cooling process of the FMLs curing, the thermal contraction of the aluminum layers will be greater than the thermal contraction of the fiber layers as result of the difference in thermal expansion coefficients. This results in an unfavorable stress distribution of metal with tensile and fiber with compressive stresses [5]. Skin-core effects resulting from

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http://dx.doi.org/10.1016/j.apm.2014.11.037

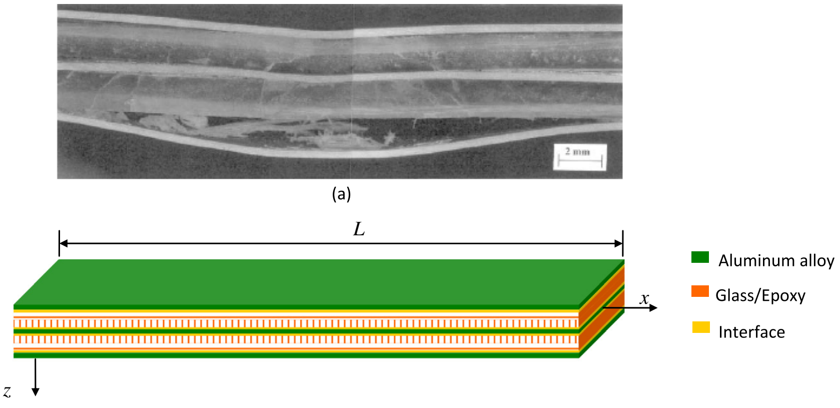
differences in the rate of cooling through the thickness of the part, may lead to the generation of elevated stresses within the laminate [6]. Clearly, the combination of such complex stress fields may cause voids, cracks and delamination, thereby reducing the strength of the component [7,8]. Guillen [9] studied the effect of varying processing conditions on the microstructure and mechanical properties of a fiber metal laminate based on glass fiber reinforced polypropylene. In the other hand, the structural elements made of FMLs also often work in thermal environment with high temperature which induces large thermo-elastic or thermo-plastic stresses and consequently changes the mechanical behavior of these materials. In Aircraft construction, fire resistance is one of the reasons for the increased use of fiber metal laminates an as a skin material. GLARE has shown capability to resist fire conditions for much longer time periods, which will allow the passengers to have enough time to escape from the aircraft in case of an outside kerosene fire. Aluminium alloys have a poor fire resistance because of their low melting point (−520 °C). The high melting point of the glass fibers in GLARE (>ll00 °C) prevents penetration of the fire to the inner aluminium layers, which will therefore remain intact. The high temperature of the flames will cause delaminations in the laminate, which will improve the insulation characteristics of the laminate. The temperature at the inner aluminium layers of the laminate will be relatively low. Hence, GLARE as a fuselage skin material will not only protect the structure as such (skin, stringers and frames) for a long period against an outside fire, but will keep during that period the interior side intact as well [2,10–12]. Hence, the study of the characteristic of the FML under thermal condition is of great interest for engineering design and manufacture. Very little work has been done to investigate the effect of heat conduction on mechanical properties of lightweight fiber-metal laminates.

The mismatch in properties between different constituent plies in the FMLs may generate macrostresses and induce interfacial damage. In order to investigate the mechanical properties of laminated plates with interfacial damage, establishment of appropriate interfacial constitutive relations is the first and key issue. First, a weakly bonded model for the imperfect interface has been proposed [13,14] in terms of linear relations. Then, the Cohesive Zone theory is utilized to establish the interfacial constitutive model [15,16]. A generalized six-freedom displacement field has been adopted [17,18], but the shape functions are complicated and the load is limited to sinusoidal loads. Another Von-Karman type displacement model is presented [19] with shape functions easy to be obtained and no limitations on load, but the transverse normal deformation is not considered. A displacement field model with interfacial damage accounting for transverse shear and normal deformation has been put forward [20]. A refined third-order Hermitian Zig-zag theory with transverse normal deformation has been developed [21], while the geometrical nonlinearity is not taken into consideration. In general, the shape functions have to be determined in all these models. For elasto-plastic laminated structures, solutions of the shape functions cannot be obtained explicitly. In the present study, based on the cohesive zone model and shear-lag model the interfacial analysis is conducted.

This paper investigates the mechanical behavior of the FML beam by using the interfacial damage constitutive model, which is based on the cohesive zone model and shear-lag model. The aluminum lamina in the FML beam is modeled as an elastic–plastic orthotropic solid, and the composite layers are assumed to be linearly elastic. Heat conduction in the FML beam is studied with the assumption that the material in each layer is homogeneous and has the same thermal conductivity in the axial and transverse direction. Based on the established thermo-elasto-plastic model for FML beam, the results of numerical simulation present the temperature variation, the elasto-plastic deformation and the interfacial damage evolution of the elasto-plastic FML beam.

2. Basic equations of the fiber metal laminated beam

Consider a Fiber Metal Laminates (FML) beam (Glare [Al-0°/90°-Al-90°/0°-Al]), composed of three aluminum layers of 0.3 mm with two cross-ply fiber layers in between, as shown in Fig. 1. The length of the FML beam is L and thickness is h.



(a)

(b)

Fig. 1. (a) Micrograph of a FML sample with delamination [9] and (b) schematic of a FML beam.