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Failure maps for rectangular 17-4PH stainless steel sandwiched foam panels

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Abstract

A new and innovative concept is proposed for designing lightweight fan blades for aircraft engines using commercially available 17-4PH precipitation hardened stainless steel. Rotating fan blades in aircraft engines experience a complex loading state consisting of combinations of centrifugal, distributed pressure and torsional loads. Theoretical failure plastic collapse maps, showing plots of the foam relative density versus face sheet thickness, *t*, normalized by the fan blade span length, *L*, have been generated for rectangular 17-4PH sandwiched foam panels under these three loading modes assuming three failure plastic collapse modes. These maps show that the 17-4PH sandwiched foam panels can fail by either the yielding of the face sheets, yielding of the foam core or wrinkling of the face sheets depending on foam relative density, the magnitude of *t*/*L* and the loading mode. The design envelop of a generic fan blade is superimposed on the maps to provide valuable insights on the probable failure modes in a sandwiched foam fan blade.
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Keywords: 17-4PH; Stainless steel; Metallic foams; Sandwiched foam panel; Theoretical failure maps; Design

1. Introduction

Recent advances in cellular theory [1–20] and manufacturing techniques [21,22] have created an interest in developing new applications for foam materials in the fabrication of lightweight engineering components [23]. Specifically, metallic foams provide several advantages to the designer due to their diverse multifunctional characteristics and ductility [21,24,25]. For example, metallic foams possess low density, energy absorption and vibration dampening properties along with the ability to be fabricated with curvatures as three-dimensional structures.

The fact that the densities of foams are extremely low compared to that of the solid material is especially advantageous in conceiving new innovative concepts for many common applications. For example, metallic foams made of relatively inexpensive and common alloys, such as high strength and high toughness aerospace grade 17-4PH stainless steel, can be used in fabricating aircraft engine fan blades to replace more expensive titanium alloys and polymeric composite materials. The proposed blade architecture is a lightweight sandwich construction made up of thin contoured solid face sheets either brazed or solid-state diffusion bonded to a space-filling metallic foam core (Fig. 1) [26]. The embedding of a lightweight stainless steel foam core between the two face sheets considerably increases the stiffness of the sandwich blade as compared to simply brazing two sheets. Fig. 2 shows a schematic of a NASA[1]-designed blade used in the modeling studies [26]. Detailed analytical studies using this fan blade design have demonstrated that 17-4PH stainless steel fan blades are superior to solid Ti–6 wt.% Al–4% V fan blades, and possibly even hollow titanium alloy blades, both in terms of rigidity, weight and vibration analyses, simulated impact loading due to a bird strike, and cost [26]. The mechanical properties of 17-4PH sandwiched foam specimens are reported elsewhere [26,27].

Gibson and Ashby (GA) [2] proposed constructing failure[2] plastic collapse maps for specimens consisting of a rigid polyurethane foam core sandwiched between two Al face sheets subjected to bending loads. Since no such maps exist for 17-4PH sandwiched foam panels, the objectives of this paper

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[2] Gibson and Ashby [2] define the “failure” of foams as the point of plastic collapse or extensive creep and not fracture.

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Nomenclature

a_T	acceleration of the rotating sandwiched foam panel
A_c	cross-sectional area of the foam core
A_s	cross-sectional area of the face sheets
b	width of a sandwiched foam cantilever panel
B_1	constant equal to 2 for a sandwiched foam cantilever panel
B_2	constant equal to about 2
C_1	constant equal to about unity
E_c	Young's modulus of the foam core
E_{cs}	Young's modulus of the solid unfoamed core
E_{eff}	effective Young's modulus of the sandwiched core
E_s	Young's modulus of the solid material
G	shear modulus
G_c	shear modulus of the foam core
$G_{critical}$	critical fracture toughness of brazed interface at which debonding occurs
G_s	shear modulus of the solid material
I_{pc}	polar moment of inertia for the foam core under torsional loading
I_{ps}	polar moment of inertia for the face sheets under torsional loading
L	length of the sandwiched foam panel
m_T	total mass of the sandwiched foam panel
P	axial, bend or impact load
P_c	axial load acting on the foam core
P_{ind}	localized indentation load due to foreign object damage (FOD)
P_s	axial load acting on the face sheets
q	distributed pressure load acting on a sandwiched foam cantilever panel
r	radial distance across the cross-section of a sandwiched foam panel
t	face sheet thickness
t_c	thickness of the foam core
t_P	thickness of the sandwiched foam plate ($2t+t_c$)
T	total torque on the sandwiched foam panel
T_c	torque on the foam core
T_s	torque on the face sheet

Greek letters

γ	shear strain
ε_c	elastic strain of the foam core
ε_s	elastic stain of the face sheets
ε_T	total strain
ρ_c	density of the foam core
ρ_{eff}	effective density of the sandwiched foam structure
ρ_s	density of solid material
σ_c	axial stress acting on the foam core
σ_s	axial stress acting on the face sheets
σ_{yc}	yield strength of the foam core
σ_{ys}	yield strength of the solid metal
$(\tau_c)_{max}$	maximum shear stress acting on the foam core
τ_{max}	maximum shear strength of a sandwiched foam shear specimen
$(\tau_s)_{max}$	maximum shear stress acting on the face sheets
υ_c	Poisson's ratio of the foam core
υ_s	Poisson's ratio of the solid material
ϕ	twist angle
ω	angular velocity of the rotating sandwiched foam panel

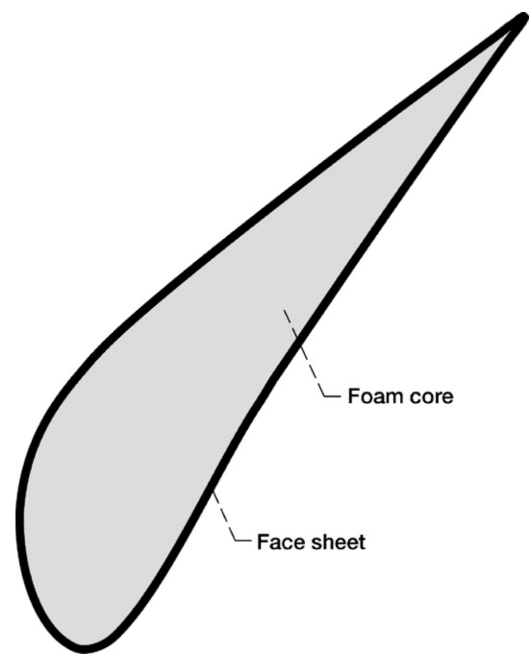

Fig. 1. Schematic of the cross-section sandwiched foam fan blade showing the foam core enclosed by the face sheet skin.

are to construct similar failure maps. The present paper extends the earlier work by Gibson and Ashby [2] to centrifugal and torsional loading modes for cantilevered 17-4PH sandwiched foam panels. The construction of these maps can provide useful insights into probable failure modes for a 17-4PH sandwich foam fan blade for different combinations of relative densities and fan blade geometries under different loading conditions. A fundamental assumption made in this paper is that the face plates are brazed under proper conditions to the metallic foam core so that failure by debonding at the brazed interfaces is ignored. It is noted that this mode of failure is very likely when the brazed interfaces are weak.

2. Loading conditions on a fan blade

A fan blade in an aircraft engine is fixed to a rotating shaft at its root. The actual geometry of a fan blade is fairly complex including a twist and a varying cross-sectional area for aerodynamic reasons, which complicates the development of failure maps. Thus, for simplicity, this paper assumes that the fan blade geometry is a simple cantilevered panel with a uniform rect-