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Theoretical analysis of the static and dynamic response of tensor skin

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ABSTRACT

Comprised of cover ply, tensor ply and carrying ply, tensor skin is a kind of composite sandwich structure developed to improve the helicopter's crashworthiness in water impacts. In this study, a theoretical model is proposed to analyze the static and dynamic response of a kind of tensor skin. The whole response of tensor skin is divided into three stages: an elastic deformation stage of the whole beam; an unfolding stage of the tensor ply; and a stretching stage of the tensor ply. At the beginning of impact, the whole beam undergoes elastic deformation until the breakage of the cover and carrying plies; then the tensor ply left is unfolded and stretched to absorb more impact kinetic energy.

In the unfolding stage, by adopting the rigid, perfectly plastic material idealization, a deformation mechanism with stationary plastic hinges is proposed. It is found that the static critical pressure first decreases then increases with the increasing central deflection. The static critical pressure varies with the geometric parameters, but the total energy dissipated in the unfolding stage is independent of the geometric parameters. The residual kinetic energy at the end of unfolding stage will be dissipated by the plastic stretching. The dynamic responses of the tensor skin are analyzed for step loaded pressure and rectangular pressure pulse. It is verified that the theoretical predictions display very good agreement with the corresponding finite element simulations.

1. Introduction

When a helicopter crashes on a solid surface, the impact energy can be absorbed by the landing gear, the subfloor structure and the seats, so that the occupants could be protected to some extent. However, in the case of water impact, the bottom skin of the helicopter will hit the water directly since the landing gear will enter the water without much deformation, while large transverse pressure will be applied on the bottom skin of the helicopter. Therefore, metal skin panels tend to crack along the rivet lines with large plastic deformations, or composite sandwich panels may fail by the large transverse pressure. Under both situations, the load transmission path to the subfloor will be cut off, which is designed for energy absorption, will be cut off.

The tensor skin structure is originally developed by NLR (European National Aerospace Laboratory), in order to improve the crashworthiness of composite helicopter structures subjected to water impacts [1]. It is a kind of sandwich structure comprised of cover plies, tensor plies and carrying plies, as shown in Fig. 1. In the structures of a tensor skin, the cover ply is the loading face; the carrying ply provides the structure stiffness; and the tensor ply provides the capability to unfold by forming 'plastic hinges', before it is stretched and fails, leading to an increase in the load bearing capability of the structure.

Published studies about tensor skin include experimental works and numerical simulations. The deformation mechanism of the unfolding 'tensor skin' strip was discussed in Refs. [2,3]. When the strip is loaded in tension or bending, the beam unfolds and deflects by forming 'plastic hinges' before it is stretched and fails in tension. The unfolding process of the 'tensor skin' strip was successfully simulated using PAM-CRASH [2], where a 2D strip was clamped at both edges and loaded by an infinite cylindrical 'rigid wall'. NLR has designed and fabricated several tensor skin panels as well as several equivalent conventional honeycomb core sandwich panels with identical face sheets [4]. The panels were tested under static load and dynamic transverse impact [4,5]. In the static transverse loading tests, the panels were fully clamped and a blunt indenter was pushed perpendicularly to the surface into the skin [6,7], where the indenter represents the water pressure. Only 3-layer tensor skin panel with ±45 fabric was able to transfer sufficient running load to the sine waves in the substructure to initiate crushing. Static shear tests were performed to compare the stiffness

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Nomenclature

$\alpha_f = \arccos((1-k)/(1+k))$	terminal angle of tensor ply in the unfolding stage
$\alpha_m = \arccos(1-k)$	transition angle of tensor ply in the unfolding stage
$\gamma \equiv l/h_3$	ratio of length to thickness
ε_c	failure strain of the cover and carrying plies
ε_t	failure strain of the tensor ply
ε_s	stretching strain of the tensor ply
A	expansion area
$\overline{A} = A/l^2$	normalized expansion area
a_1, a_2, a_3	coefficients of differential equation
b	width of the beam
D	plastic energy in the unfolding stage
$\overline{D} = D/M_P$	normalized plastic work in the unfolding stage
D_s	plastic energy in the stretching stage
$D_s^c = 4\gamma M_p(1+2k)\varepsilon_t$	critical stretching energy of the tensor ply
$E = (1/2)\left[E_1\left(z_1^3 - z_0^3\right) + E_2\left(z_2^3 - z_1^3\right) + E_3\left(z_3^3 - z_2^3\right)\right]$	effective elastic modulus of the whole beam
E_1,E_2, E_3	elastic modulus of cover, carrying and tensor ply, respectively
h_1, h_2, h_3	thicknesses of cover, carrying and tensor ply, respectively
$h = h_1 + h_2 + h_3$	thickness of the beam
$I = qlt_d$	impulse applied
k	geometric parameter
K	kinetic energy
K_r	residual kinetic energy in the stretching stage
l	half the beam length
M_P	fully plastic bend moment
q	pressure applied on the beam
q_s	static critical pressure
$\overline{q}_s \equiv q_s l^2/M_P$	normalized static critical pressure
$\overline{q}_{s0}$	normalized initial static critical pressure
$\overline{q}_e \equiv \overline{q} - \overline{q}_s$	excess pressure
$\overline{q} = q/\overline{q}_{s0}$	normalized pressure
t_d	impulse duration
t_f	total response time
u	central beam deflection
$\overline{u} \equiv u/l$	normalized central deflection
u_f	final deflection of the tensor ply in the unfolding stage
w	beam deflection
W	external work in the unfolding stage
$\overline{W} = W/M_p$	normalized external work in the unfolding stage
W_s	external work in the stretching stage
Y	plastic strength of material
z_0,z_1,z_2,z_3	the distance from center line to the edge of ply

and strength behavior with respect to the operational loading case. It is concluded that the tensor skin panel was not optimized for this operational loading case. Among these tests, a tensor skin with 3-layer polyethylene (PE) core and a skin panel with a honeycomb core were fabricated. Furthermore, three dynamic transverse loading tests were performed by dropping a hemispherical aluminum impactor on clamped panels of the tensor skin and honeycomb configurations. Large damage was found in the honeycomb core panel, while the tensor skin managed to stop the impactor successfully, with broken faces and unfolded core.

Researchers in Patras University analyzed the failure behavior of composite structures using PAM-CRASH finite element code [8]. Their results were compared with the above mentioned experimental results reported in Ref. [4]. A similar numerical study was conducted by the researchers from Limerick University, who found good agreements between the calculated and measured forces and displacement for tensor skin panels. It is concluded that the PAM-CRASH FE-code, which has developed composite material damage models and represented successfully the degradation of the properties, can be successfully applied for the simulation of the failure process of crashworthiness composites [4,7–11], especially for the tensor skin.

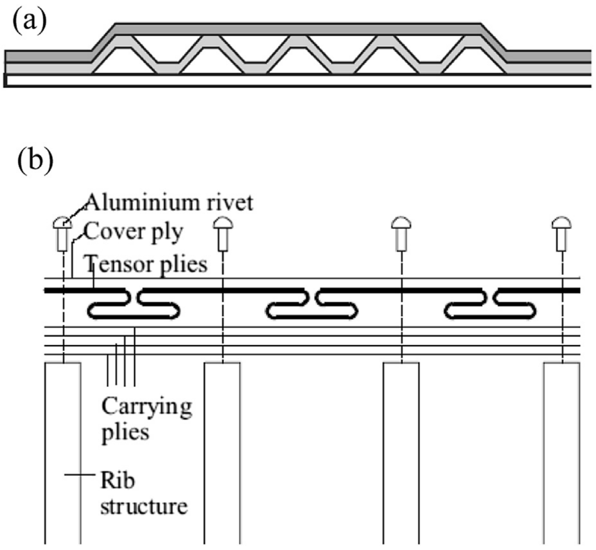

Fig. 1. The schematic of a tensor skin [4,5].

Besides the basic experiments as mentioned above, the NLR group designed three types of innovative Leading Edge structure, which were made of tensor skin, and performed bird strike tests with a 4-pound substitute bird [5]. Accordingly, these tests were simulated using the PAM-CRASH code [5,11]. Their results showed that tensor skin can absorb the bird impact energy sufficiently to prevent spar damage. Similar study was performed by Mi [12], in which four types of composite tensor plates were modeled using PAM-CRASH. The results showed that the innovative Leading Edge structure with tensor plies could be used in the anti-bird strike designs, as it can prevent the bird penetration into the wings.

As far as we know, no theoretical modeling of the tensor skin has been made. Therefore, in all existing experimental and numerical studies, the tensor skin panel used was not optimized for the operational loading. In order to understand the fundamental static and dynamic behaviors of tensor skin under pressure loading and its sensitivities to the geometric parameters, it is necessary to establish a theoretical model.

In this study, a theoretical model is proposed to analyze the static and dynamic response of a kind of tensor skin. The total response of tensor skin is divided into three stages: an elastic deformation stage of the whole structure; an unfolding stage of the tensor ply; and a stretching stage of the tensor ply. The failure criterion of the cover and carrying plies is given in Section 2. In Section 3, a theoretical model with plastic hinges is proposed to analyze the static critical pressure of the tensor ply. In Section 4, the dynamic responses of tensor skin to step loading and impulse pressure loading are analyzed. Finally, the theoretical predictions are validated by finite element simulations in Section 5.