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Verification of a theoretical model of tensor skin under water impact by considering the fluid–structure interaction

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ABSTRACT

Tensor skin is a kind of composite sandwich structure developed to improve the helicopter's crashworthiness when it impacts with water. In our previous theoretical studies, by employing the rigid, perfectly plastic idealization and the pulse approximation method, the static and dynamic responses of tensor skin under uniform pressure loading were obtained.

In this study, a fluid–structure interaction simulation model of tensor skin impinging with water is established by FE method, in order to verify the previous theoretical analyses. It is found that the interaction pressure between the skin plate and water varies with the configuration of the plate. Compared with a solid plate, the pulses generated by a honeycomb-core sandwich plate and a tensor skin are more moderate. By studying the effect of water depth, the theoretical predictions of the tensor skin, as developed in our previous papers, are found valid for the deep water case. From the comparison among the theoretical predictions, pulse loading FE model, and the fluid–structure interaction FE model, the deviation of the theoretical prediction in the final deflection is found to be about 10% compared with that obtained from the fluid–structure interaction FE model. Thereby, the theoretical model and the pulse approximation method are confirmed to have sufficient accuracy for the design of tensor skins.

1. Introduction

As a kind of sandwich structure comprised of cover plies, tensor plies and carrying plies, tensor skin is originally developed by NLR (European National Aerospace Laboratory) in order to improve the crashworthiness of composite helicopter structures subjected to water impact [1], as shown in Fig. 1. 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 and energy absorption of the structure.

Under the loading of tension or bending, the deformation mechanism of the tensor skin strip was found to be unfolding by forming plastic hinges before the failure due to stretching [2,3]. The static and dynamic responses of tensor skin panels were compared with the honeycomb-core sandwich plates [4–7]. In the static transverse loading tests, the fully clamped panels were pushed by a blunt indenter that was perpendicular to the surface. Only 3-layer tensor skin panel was able to transfer sufficient running load to the substructure to initiate crushing. In the dynamic tests performed by dropping an impactor, large damage was found in the honeycomb-core sandwich, while the tensor skin managed to stop the impactor successfully, with broken faces and unfolded core. The failure behavior of the tensor skin was also calculated by using PAM-CRASH [8]. Compared with the above mentioned experimental results [4,7–11], good agreements between the calculated and measured forces and displacement for tensor skin panels were found. Besides, three types of innovative Leading Edge structures that are made of tensor skin were designed, and also tested by the impact of a 4-pound substitute bird [5]. The relative numerical studies by PAM-CRASH were given by Mi and Zhao [12]. Both results confirmed the good performance of tensor skins in the anti-bird strike designs.

A theoretical model was proposed by the present authors [13] to analyze the static and dynamic responses of tensor skin, in which the rigid-perfectly plastic idealization was adopted. It was found that the tensor skin exhibits unique properties in its load–displacement relationship. That is, the load to initiate the plastic deformation is high, but the resistance decreases during the structure's deformation process. Furthermore, the pulse approximation method, initially proposed by Youngdahl, was confirmed to be applicable to this structure: the tensor skin [13]. The main conclusions from the theoretical analysis will be reviewed in Section 2.

As well known, the dynamic response of a structure is an interaction process between the structure and the applied load pulse.

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Nomenclature

ρ	density
E_l, E_t	elastic modulus in the longitudinal and transverse directions, respectively
G	shear modulus
h_1, h_2, h_3	thicknesses of cover, carrying and tensor ply, respectively
H	depth of water
I	momentum
k	geometric parameter of tensor skin
l	a half of the beam length
M_P	fully plastic bend moment
q	pressure applied on the beam
q_s	static critical pressure
$\bar{q}_s \equiv q_s l^2/M_P$	normalized static critical pressure
$\tilde{q} \equiv \bar{q} - \bar{q}_S$	excess pressure
t_d	impulse duration
t_f	total response time
u	central beam deflection
$\bar{u} \equiv u/l$	normalized central deflection

However, in the theoretical approach, both the structure and the applied load have to be idealized in order to make the analysis feasible. For the tensor skin, the rigid-perfectly plastic material model was adopted [14], and the effect of water impact on the structure was simplified as a triangular pulse applied on the tensor skin [13]. In all the previous studies of the tensor skin, including experimental studies, numerical simulations, and theoretical modeling [2,4,5,10,13,14], no fluid–structure interaction effect has been considered. Hereby, it is necessary to verify the existing theoretical model of the pressure loaded tensor skin with the fluid–structure interaction being taken into account.

In the present paper, in order to verify the previous theoretical model, the finite element simulations of the tensor skin under water impact are described, with the consideration of the fluid–structure interaction during the impact process. First, the theoretical analysis on the tensor skin under uniformly distributed pressure is reviewed in Section 2, and then the fluid–structure interactive FE models are described in Section 3, followed by Section 4, in which the dynamic responses of solid plate, tensor skin and honeycomb-core sandwich under water impacts are compared with one another; after a discussion on the effects of water depth in Section 5, the theoretical predictions of tensor skin are finally verified in Section 6.

2. Review of the theoretical analysis of tensor skin

A theoretical model of tensor skin was proposed in our previous paper [14], in which 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. At the beginning of response, elastic deformation takes place in the entire structure, which will end by the fracture of the cover and carrying plies made of brittle composite. The second stage is the unfolding of the tensor ply, which is simplified as rigid segments connected by plastic hinges. The third stage is the stretching of the tensor ply, which may be terminated by tension failure. Among the three stages, the unfolding stage is the main contributor to the energy absorption. Therefore, the theoretical analysis of tensor ply will be reviewed in the following.

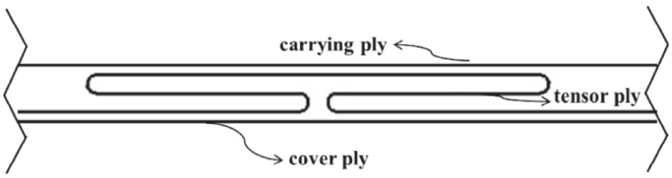

Fig. 1. The schematic of a tensor skin.

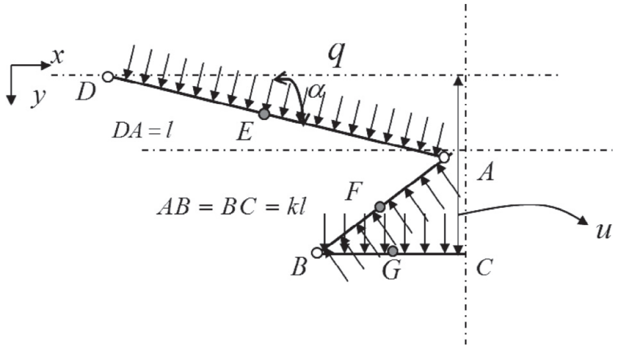

Fig. 2. Tensor ply under uniformly distributed pressure in the unfolding stage [14].

2.1. Static critical pressure

In the unfolding stage, by adopting the rigid, perfectly plastic material assumption, a deformation mechanism with stationary plastic hinges was proposed [14], supposing a uniformly distributed pressure q is applied on the tensor ply quasi-statically, as shown in Fig. 2. Hereby, as angle α increases, the quasi-static critical pressure $q_s(\alpha)$ will vary.

From the energy conservation, the increase in the external work δW should be equal to the variation in the energy dissipation δD. That is:

$$\delta W = \delta D \tag{1}$$

Hence, the normalized static critical pressure is obtained as

$$\bar{q}_s(\alpha) \equiv q_s(\alpha) l^2/M_p \tag{2}$$

where l is a half of the beam length and M_p is the fully plastic bending moment.

It is found that the static critical pressure $\bar{q}_s$ first decreases then increases with the increasing central deflection $\bar{u} \equiv u/l$, as demonstrated in Fig. 3. The shape of the curve indicates a kind of *softening effect*; that is, the pressure to motivate the initial deformation is high, but the structure's resistance decreases as the deformation becomes larger, which is different from the conventional structures that display the stable load-deflection characters.

2.2. Dynamic response of tensor ply

The dynamic response of tensor ply was also analyzed in Ref. 14. Here, the static critical pressure $\bar{q}_s$ is regarded as a kind of *structural friction*. Therefore, the *excess pressure* defined as $\tilde{q} \equiv \bar{q} - \bar{q}_s$ will produce the acceleration or deceleration of the structure.

Suppose a constant pressure $\bar{q} > \bar{q}_{s0}$ is applied on the tensor skin, here $\bar{q}_{s0}$ is the normalized initial static critical pressure, which is given by Eq. (2) for $\alpha = 0$. According to energy conservation,

$$\dot{K} + \dot{D} = \dot{W}(q) \tag{3}$$

where $\dot{K}$ is the rate of kinetic energy, $\dot{D}$ is the rate of plastic dissipation, and $\dot{W}(q)$ is the work rate of the pressure. Eq. (3) leads to a second order differential equation about α. Hereby, the dynamic