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Topology optimization of laminated composite structures with design-dependent loads

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ABSTRACT

A solution for the topology structures of composite laminates with design-dependent loads is presented. The methodology is based on the isoline method, the sensitivity filter with density gradient weighting, and the solid isotropic material with penalization (SIMP) method. In addition, the element stiffness matrix for composite layups is derived. Two- and three-joint constraint examples of the topology optimization design for composite structures are presented. The work efficiency of the isoline method and the distance regularized level set evolution (DRLSE) method are compared; five other filtering methods are also studied. The distribution rule of solid material and the relationship between the minimum compliance of optimal structures and the principal angle of composite layups are discussed.

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1. Introduction

Compared with metallic material, composite material exhibits a superior strength-to-weight ratio, so composite materials have increasingly been substituted for metallic alloys in the manufacturing of high-performance structures during the last two decades. Today, composite material plays an important role in the manufacturing of high-performance structures. In the field of underwater vehicles, there is a common understanding that the conventional shape of the pressure vessel used in shallow water is always cylindrical and that in deep water is spherical and made of metallic material. In particular, China's 7000-m-depth manned submersible "Jiaolong" adopts a titanium alloy spherical pressure vessel, while the submarine adopts a ring-stiffened cylindrical pressure vessel. However, with the development of composite material, Woods Hole Oceanographic Institution (WHOI) developed a ceramic pressure hull with a cylindrical shell (shown in Fig. 1) for the 11,000-m depth Hybrid Underwater Robotic Vehicle (HROV) "Nereus" [1], which is definitely different from the traditional design concept. The ceramic pressure hull enabled "Nereus" to successfully dive to 10,902 m (6.8 miles) at the deepest part of the Marianas Trench. Among the families of composite material, composite laminates are the most common type of composite material used for manufacturing high-performance structures and structural components.

A pressure hull comprised of composite laminates is a high-performance structure for underwater vehicles. In 2004, with the support of the Deepglider program of The U.S. Office of Naval Research, the Boeing Co.'s Phantom Works Division [2] developed a composite laminate pressure hull for a 4000-m-depth underwater vehicle, and the hull imploded under a hydrostatic pressure of 40.3 MPa, which is shown in Figs. 2 and 3. With the use of composite laminates, the weight-to-displacement ratio of a pressure hull is less than 0.47, which increases the diving capacity of an underwater vehicle 4 times. Therefore, in order to reduce the experimental effort, composite laminates are a promising material for the pressure hulls of submersibles.

However, traditional methods of pressure hull design focus on sizing optimization under a prescribed topological structure. For composite laminates, the unidirectional fiber-reinforced composite plies are stacked in a predefined layup sequence to form the composite structure; therefore, the fiber orientation and stiffness drastically affect the ultimate pressure capacity of the pressure hull. Thus, how to obtain an optimal topology considering the fiber orientation and stiffness under water pressure is a challenging problem for designing composite laminate pressure hulls.

Topology optimization transforms the problem of structural design into one of optimal material distribution to make the outline of an optimized structure satisfy the demands of design. Topology optimization is a kind of optimal design related to

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Fig. 1. Ceramic pressure hull of 11,000-m HROV "Nereus."

Fig. 2. Boeing Co. machine shown fabricating a composite laminate pressure hull by laying hoop fibers.

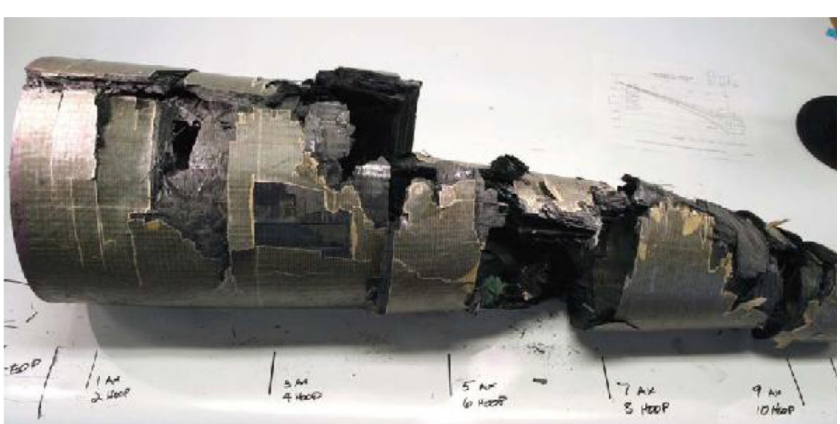

Fig. 3. Effects of implosion of a composite laminate pressure hull at 40.3 MPa.

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