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Numerical modal analysis of composite structures coupled with water

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A R T I C L E I N F O

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A B S T R A C T

Dynamic characteristics of polymer composite beam and plate structures were studied when the structures were coupled with water. The effect of Fluid–Structure Interaction (FSI) on natural frequencies, mode shapes, and dynamic responses was examined for polymer composite structures using multiphysics-based computational techniques. Composite structures were modeled using the Finite Element Method. The fluid was modeled as an acoustic medium using the Cellular Automata and finite element techniques. Those techniques were coupled so that both fluid and structure could interact bi-directionally. In order to make the coupling easier, the beam and plate finite elements have only displacement degrees of freedom but no rotational degrees of freedom. Then, the numerical modal analysis technique was applied to the composite structures with and without FSI, respectively, so that the effect of FSI can be examined by comparing the two results. The study showed that the effect of FSI is significant on dynamic properties of polymer composite structures. Some previous experimental observations were confirmed using the numerical modal analysis.

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1. Introduction

Composite materials have been of great interest recently as they prove to have many significant advantages over the 'traditional' materials in shipbuilding, marine, and aerospace industry applications. They possess many beneficial properties, which include, but are not limited to, their superior specific strength and specific stiffness, their excellent resistance to corrosion and marine environmental deterioration, and their ability to conform any shape that designers wish to make. As a result, composite structures have been used in many military and civilian applications. Additionally, a rise in interest in composites is expected to occur in the near future for use in building fuel-efficient and therefore cost-efficient naval ships, vessels, and marine structures.

The vast majority of the past research on composite structures has been conducted for dry structures. A limited amount of research has been undertaken with considerations of the interaction between composite structures and fluids such as water. Some of the Fluid–Structure Interaction (FSI) studies with composite structures were liquid sloshing in composite tanks [1,2]. Other FSI studies were composite structures subjected to underwater explosion [3,4]. More recently, a series of studies have been conducted to understand the effect of FSI on composite structures [5–10]. In those research, responses of composite structures were compared between the two cases with (i.e., in water) and without (i.e., in air) the FSI effect under impact or cyclic loading. The results showed that the effects of FSI on polymer composite structures are significant because densities of polymer composites are very comparable to that of water. The effect of FSI can lead to a premature failure of a composite structure if the effect is not considered in the design and analysis of composite structures.

The previous studies on the FSI effect revealed some results to be noteworthy. When a polymer composite structure was loaded in air and water, respectively, under the same dynamic loading condition, the FSI effect with water resulted in a larger stress in the composite structure. Additionally, the location of the maximum stress could be shifted because of the FSI effect. For example, when a clamped polymer composite plate was impacted in air and water, respectively, the strain gage reading at different locations of the plate showed a drastic difference between the two different impact cases. In other words, the strain responses near the center of the composite plate were qualitatively similar even though there were some differences in magnitudes and phases because of the FSI effect. On the other hand, the strain–time history readings at the location near the clamped corner were significantly different qualitatively and quantitatively between the two impact cases. Fig. 1 compares the strain responses at the two locations. The results suggest that the effect of the added mass is not uniform over the composite plate.

In order to further understand the effect of the added mass resulting from FSI, an experimental study was conducted for polymer composite beams [9]. Free vibrational motions of an e-glass composite beam were measured in air and water, respectively,

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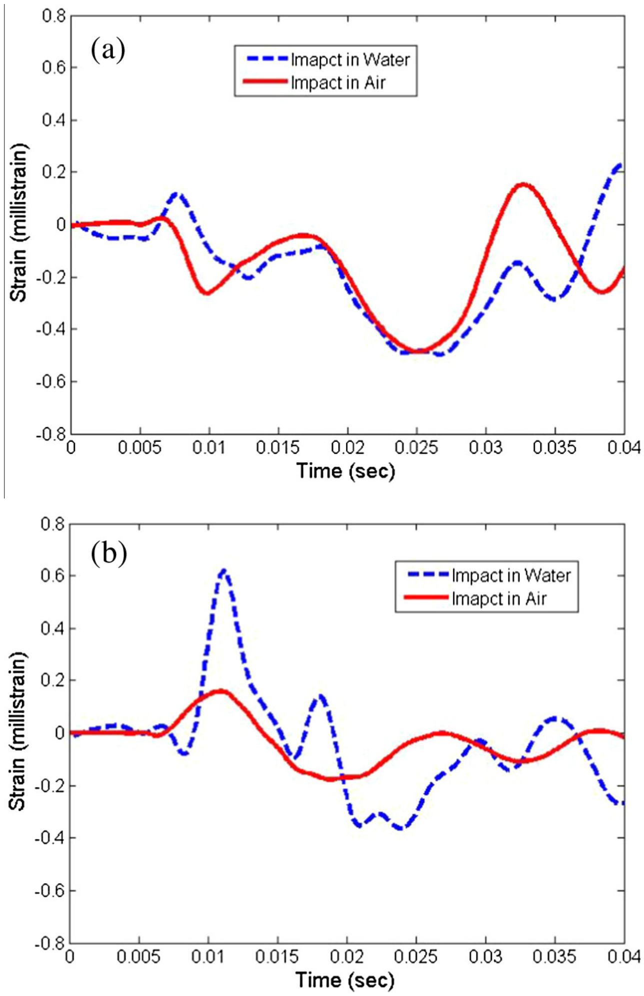

Fig. 1. Comparison of strain–time history plots of a clamped composite plate subjected to central impact loading while the plate is in air and water, respectively. (a) Strains near the center of the plate and (b) strains near the corner of the plate.

using the Digital Image Correlation (DIC) technique. Additionally, modal parameters like natural frequencies, mode shapes and modal curvatures were obtained when a carbon composite beam was in air and water, respectively.

The present study is similar to that in Ref. [9]. A series of numerical experimental studies were conducted for composite beams and plates. In order to measure mode shapes of composite structures accurately, many sensors must be attached to the structure for a physical experiment. However, numerical experiments can be conducted easily with a reasonable mesh of the structure. Therefore, numerical modal analyses were conducted in this study to enhance the understanding of the effect of the added mass on dynamic behaviors of polymer composite beams and plates.

The next section describes computational techniques used for the study. Both the Finite Element Method (FEM) and Cellular Automata (CA) technique were used. The following section shows some examples to verify the program. Then, the study of added mass effect is presented for composite plates and beams, which was subsequently followed by conclusions.

2. Computational modeling

2.1. Multiphysics analysis

A multiphysics-based computational analysis is conducted for this study. Beams and plates were modeled using the Finite Element Method (FEM). In order to make the coupling between the structure and fluid easy, the beam and plate elements have only displacement degrees of freedom like 3-D solid finite elements. As a result, those elements represent the thickness dimension explicitly so that fluid at the bottom and top surfaces can be readily separated by the structure. Additionally, the compatibility conditions at the fluid–structure interfaces can be applied easily. The fluid is considered as an acoustic domain by neglecting fluid flow, viscosity, etc. The governing equation for a linear acoustic field is solved using both FEM and the Cellular Automata (CA) techniques. After time domain solutions are obtained from the multiphysics analysis, the Fast Fourier Transform (FFT) is applied so as to transform the time domain to the frequency domain as the numerical modal analysis. Then, modal parameters of the dynamic structure are determined. The details of the analysis techniques used in this study are discussed below.

2.2. Structural finite element analysis

Since beam and plate finite elements can be easily derived from shell finite elements, this section describes the general shell element formulation. The detailed formulation of the solid-like shell finite element was given in Ref. [11] and it is briefly presented here. The plate/shell element is sketched in Fig. 2 which has eight nodes like a 3-D brick element. There are two nodes along the thickness of the shell because linear interpolations of displacements are mostly good enough along the thickness. However, more nodes can be added to the inplane dimension to improve the accuracy. Such high order shell elements can be developed from the present element in a straightforward matter so that the eight-node element is discussed here. Since the element has nodal displacements at both top and bottom surfaces, the elements can be stacked together to represent a laminated composite. Additionally, fluid on either side of the shell can be readily separated, and the compatibility conditions can be applied at the fluid–structure interface easily because both media can have nodes at the same spatial position.

The mathematical formulation of the shell element is based on a high-order bending theory which includes bending strains, transverse shear strains, and the transverse normal strain. The element stiffness matrix in terms of its local axes is expressed as

$$[K_{local}] = \int_{\Omega^e} [B_b]^T [D_b][B_d] d\Omega + \int_{\Omega^e} [B_s]^T [D_s][B_s] d\Omega + \int_{\Omega^e} [B_z]^T D_z [B_z] d\Omega \quad (1)$$

where the matrix related to the bending strains is expressed as

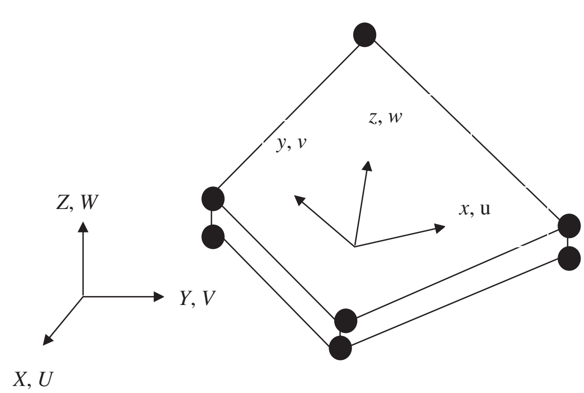

Fig. 2. Eight-node shell element. The lower cases indicate the local coordinate system while the upper cases denote the global coordinate system.