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Experimental study on dynamic buckling of submerged grid-stiffened cylindrical shells under intermediate-velocity impact

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ABSTRACT

Dynamic buckling prediction of submerged structures under impact loads is a challenging problem for both theoretical and numerical approaches, and the experimental data is very limited. In the present paper, dynamic buckling of grid-stiffened cylindrical shells submerged in a large opening pond at a depth of 5 m and subjected to radial intermediate-velocity impact was experimentally investigated. In order to increase load durations under the condition of fixed peak pressure, explosive depth and standoff distance, airbags composed of O_2 and C_2H_2 were used and exploded underwater to generate impact load. Amplitudes and durations of shock waves and pulsating bubbles were characterized by using pressure transducers. Measurements of hoop and axial strains reveal that global buckling of skin and stiffeners of the grid-stiffened cylindrical shell occurred under bubble pulsation loads, which features mutation and separation of strains and a sudden change in the vibration period of the stiffened shell with a small increment of impulse. 6 half waves and 1 half wave are observed along the circumferential and axial directions of the shell, respectively. Larger bubble pulse impulse, greater deformation and vibration of the shell under larger impact are the main reasons for global dynamic buckling of the grid-stiffened cylindrical shell.

1. Introduction

The wide application of grid-stiffened cylindrical shells in naval engineering, aircraft and aerospace engineering has stimulated motivation for investigating dynamic buckling behaviour of stiffened shells subjected to explosive and impact loads, such as submarines subjected to underwater explosive loads, and high-speed underwater vehicles under cavitation induced by the motion of vehicles. This is an important design consideration and very complicated by fluid-structure interaction (FSI) [1–4], wave propagation [1,4,5], geometrical parameters [6], and material properties [7].

Although high-velocity impact loads with large decay rate and short duration (in an order of microseconds) [8–10], and low-velocity impact loads with small decay rate and infinite duration [8–10] have been studied intensively, the analysis of dynamic buckling of submerged structures under intermediate-velocity impact (in an order of milliseconds) is very limited and has not been addressed yet. Meanwhile, experimental data is relatively scarce.

A considerable amount of research on buckling behaviour of submerged structures has been undertaken. With local instabilities of stiffeners and shell neglected, Pédron and Combescure [11] developed a perturbation method to analyse dynamic buckling of infinitely long stiffened cylindrical shells subjected to a radial shock wave. Cui et al. [8,10] studied columns and plates under FSI by experimental and numerical approaches. Effects of boundary conditions, load durations and initial imperfections were discussed. Gupta et al. [12] experimentally studied dynamic buckling of cylindrical shells subjected to shock waves by high-speed photography and modified 3-D digital image correlation technique. Influences of the initial hydrostatic pressure and the added mass of the surrounding water were analytically evaluated. Bitter and Shepherd [13] developed an experimental facility to study buckling behaviour of submerged tubes. Although the duration of the applied pressure was 50–100 times the period of axisymmetric vibration, the critical buckling pressure was 5–10 times greater than the static buckling pressure, which indicates the importance of inertial effects. Matos et al. [14] experimentally studied dynamic buckling of a thick-walled cylindrical tube subjected to axially impacted pressure generated by underwater explosion (UNDEX). Farhat et al. [15] studied dynamic buckling of submerged aluminium cylindrical shells by using a cylindrical pressure vessel filled with water leaving a small amount of air at the top. Amplitudes of pressures gradually

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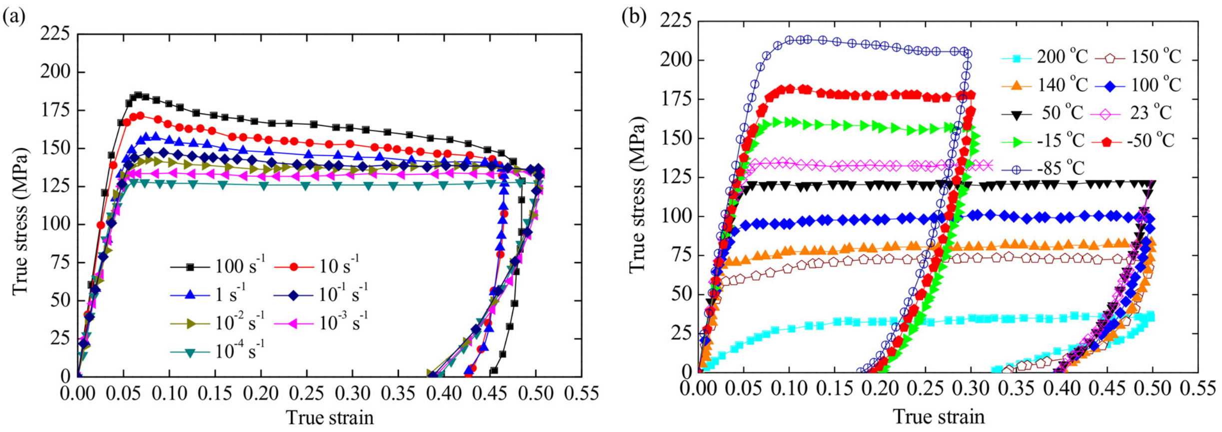

Fig. 1. Compressive behaviour of PEEK 450G (a) different strain rates at room temperature, (b) different temperatures at strain rate of 0.001 s^{-1} (Figures are from references [19,20]).

increased by compressing air until structures elastically buckled. Wang et al. [16] experimentally and theoretically studied dynamic buckling of a stiffened plate subject to underwater explosive loads.

Review of the open-literatures shows that previous work focuses on quasi-static buckling and high velocity impacted buckling. Meanwhile, research on dynamic buckling of grid-stiffened structures is very limited. The background of the present work is the dynamic buckling behaviour of high-speed underwater vehicles subjected to cavitation induced by the motion of vehicles. Compared to UNDEX of trinitrotoluene (TNT), load duration caused by such impact is in an order of milliseconds and can be influenced by speed and geometry of vehicles. Because load duration of cavitation induced by the vehicle we studied is between 5 and 50 ms, airbags composed of O_2 and C_2H_2 explode underwater to generate such intermediate-velocity impact in the present work. Meanwhile, small-scaled grid-stiffened cylindrical shells were used to simulate the high-speed underwater vehicles, and submerged in a large opening pond. Strains of grid-stiffened cylindrical shells subjected to radial impact were measured to reveal the dynamic buckling mechanisms.

2. The test grid-stiffened cylindrical shell

2.1. Material parameters

Although metallic materials have been widely used in engineering fields, there still exist some thorny problems, such as high cost and high processing difficulty, when conducting the test of metallic grid-stiffened cylindrical shells, especially for a thin-walled one. In order to solve above problems, a new polymer named polyether ether ketone 450G (PEEK 450G) was selected to replace the metallic material, which has been widely used in aerospace, automotive, oil and gas industries [17] and replaced parts that were formerly fabricated from metal [18].

Compressive behaviour of unfilled PEEK 450G is shown in Fig. 1 [19,20], which behaves in a ductile manner for a wide range of strain rates and temperatures [21]. More detailed mechanical properties of unfilled PEEK 450G can be found in Ref. [20].

Elastic modulus of PEEK 450G is nearly constant under low strain rates. For high strain rates, it can be described as [20]

$$E = E_0 + \eta\dot{\bar{\varepsilon}}^k \tag{1}$$

where E_0 is the quasi-static elastic modulus, η is the consistency parameter, k is the material coefficient, and $\dot{\bar{\varepsilon}}$ is the equivalent strain rate.

Table 1
Mechanical properties of unfilled PEEK 450G [20].

Elastic	E_0 (MPa)	ν	η (MPa)	k		
	3600	0.4	1.25	0.9		
Plastic	A (MPa)	B (MPa)	n	m	C	$\dot{\bar{\varepsilon}}_0^p$(s^{-1})
	132	10	1.2	0.7	0.034	0.001
Fracture	D_1	D_2	D_3	D_4	D_5	
	0.05	1.2	−0.254	−0.009	1.0	

The strain rate and temperature sensitivity plastic behaviour of PEEK 450G can be simulated as Johnson-Cook (JC) model, which is described as [20,22]

$$\bar{\sigma} = [A + B\cdot(\bar{\varepsilon}^p)^n]\left[1 + C\cdot\ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0^p}\right)\right][1-\Theta^m] \tag{2}$$

$$\Theta = \frac{T - T_0}{T - T_m} \tag{3}$$

where $\bar{\sigma}$ is the equivalent flow stress, $\bar{\varepsilon}^p$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}^p$ is the strain rate, A is the yield stress at the reference strain rate $\dot{\bar{\varepsilon}}_0^p$ and the reference temperature T_0, B is the strain hardening constant, n is the strain hardening exponent, m is the thermal softening exponent, C is the strain rate sensitivity parameter, and Θ is the homologous temperature which is related to the absolute temperature T, the melting temperature T_m and the initial temperature T_0.

Fracture of PEEK 450G occurs when the damage parameter D exceeds 1.0, which is defined as [20]

$$D = \sum \frac{\Delta\bar{\varepsilon}^p}{\bar{\varepsilon}_f^p} \tag{4}$$

where $\Delta\bar{\varepsilon}^p$ is the increment of accumulated equivalent plastic strain, and $\bar{\varepsilon}_f^p$ is the critical failure strain, which is defined as [20]

$$\bar{\varepsilon}_f^p = [D_1 + D_2\cdot\exp(D_3\cdot\sigma^*)]\left[1 + D_4\cdot\ln\left(\frac{\dot{\bar{\varepsilon}}^p}{\dot{\bar{\varepsilon}}_0^p}\right)\right][1 + D_5\cdot\Theta] \tag{5}$$

where D_i are material constants, and σ^* is the dimensionless pressure-stress ratio.

Material parameters of unfilled PEEK 450G are listed in Table 1, where ν is Poisson's ratio [20].