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The influence of deformation limits on fluid–structure interactions in underwater blasts

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ABSTRACT

This paper revisits a classical fluid–structure interaction (FSI) problem on the momentum and energy transfer to a structure from an underwater blast. Hitherto, the majority of analytical models assume a rigid (non-deformable) and free-standing (unsupported) structure where resistance to its translational motion – apart from that offered by its inertial mass – comes from 'ad-hoc' backing spring(s) introduced to simulate compression of the fluid medium and/or the resistance to transverse deformation encountered by a real structure. These limitations/assumptions are relaxed in this paper by adopting a physically realistic fully-clamped ductile beam system that takes into account large elasto-plastic deformation, limits to material deformation, boundary compliance and boundary failure; the analytical framework was developed previously by Yuan et al. (2016). By coupling the fluid (water) domain to the analytical model of the ductile beam system, the momentum and energy transferred by the blast wave are critically re-evaluated for non-impulsive loading régime; in particular, on how the beam's deformation mode and boundary compliance affects fluid and structure interaction, up until the point of complete beam detachment from its supports. Detailed finite-element models were also developed to simulate the interactions between the fluid and structural beam where predictions were in good agreement with those by the analytical model. Sensitivity analyses were carried out that offer new insights on the influence of the beam's aspect ratio and inertial mass.

1. Introduction

The beneficial effects of fluid–structure interaction (FSI) in reducing the impulse imparted to a rigid free-standing plate from an underwater blast are well-known. Taylor have shown that the momentum acquired by the plate reduces dramatically with its inertial mass: a direct consequence of early cavitation at the fluid-structure interface [2]. Over the past two decades, this 'peculiar' property has been extensively exploited to design sandwich panels with a greater resistance, compared to its monolithic equivalent of the same mass, to underwater blast loadings [3–9]. However, the majority of these studies on FSI, including those on sandwich panels, have largely ignored limits to deformation – from its supports and the structural material – which could potentially limit the external validity of any model predictions. There are two important factors that influence energy and momentum transfer to a submerged structure in underwater blasts: (1) development and evolution of cavitation zone(s); and, (2) limits to material deformation, boundary (supports) compliance and its failure. In the present study, we shall be concerned only with FSI in the 'pre-boundary failure' régime, i.e. before the complete detachment of the structure from its supports.

Treating water as a linear-elastic medium, Kennard [10] found that if the pressure at any point drops below the cavitation limit, two 'breaking fronts' emerge from there and propagate in opposite directions, creating an expanding pool of cavitated liquid. These breaking fronts can arrest, invert their direction of motion and become 'closing fronts', forcing the contraction of the cavitation zone. Schiffer et al. [11] studied the effects of initial hydrostatic pressure on cavitation for a rigid plate with a linear backing spring. Their model is able to capture the propagation of both breaking and closing fronts, as well as their interactions with the structure, in a blast event. It was found that increasing hydrostatic pressure reduces the transmitted impulse since it moves the point of incipient cavitation away from the structure; however, reducing inertial mass does not always lead to a reduction in the transmitted impulse whilst increasing the supporting stiffness always will. Schiffer and Tagarielli [12] further reported a 'double-cavitation' event where early plate deformation, due to the propagation of flexural waves, gives rise to a localised cavitation zone at the fluid-structure interface and in the central portion of the plate. This zone quickly collapses upon coalescence of the flexural wave at the centre. Subsequent plate deformation

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Nomenclature

A	cross-section area of beam
B	width of beam
c_w	acoustic wave speed in water
D	damage variable
$\overline{E}^F$	non-dimensional maximum total energy transmitted to freestanding beam
E^T, E^K	transmitted energy and kinetic energy of the elasto plastic beam
$\overline{E}^T, \overline{E}^K$	non-dimensional maximum E^T and E^K
E_S^b, E_S^s, E_S^m	bending, shear, membrane energy obtained from rotational, axial and vertical springs
E_B^b, E_B^s, E_B^m	bending, shear, membrane energy of the elasto-plastic beam
E_i	incident energy of blast wave per unit area
H	beam thickness
I_i	incident impulse per unit area
I^T, I^K	transmitted impulse, momentum
$\overline{I}^F$	maximum total impulse per unit area of free-standing beam
$\overline{I}^T, \overline{I}^K$	non-dimensional maximum I^T and I^K
$\overline{I}_1^T,$	maximum non-dimensional transmitted impulse
$\overline{I}_2^T,$	reduction of transmitted impulse due to failure
$\overline{I}_3^T,$	reduction of transmitted impulse due to deformation
I^*	non-dimensional impulse
$\hat{I}$	impulse per unit area
K_ϕ	rotational spring stiffness
L	half length of beam member
L_e	characteristic length of the first-order element in FE
L_w	length of water column in FE
M_0	fully plastic bending moment
N	membrane force
N_0	fully plastic membrane force
$\overline{N}$	N/N_0
p_I	incident pressure wave
p_s	peak incident pressure
p_{R1}	reflected pressure wave
p_{R2}	rarefaction pressure wave
p_{Int}	interface pressure
$\tilde{p}_{\text{Int}}$	average interface pressure
Q	transverse shear force
Q_0	fully plastic shear force
t_1, t_2, t_3	termination time of Phases I, II and III
t_c	cavitation time
t_i	decay constant
$\hat{W}$	average transverse deflection
W_0	maximum mid-span deflection
W_B, W_S	deflection at mid-span & support
Z	Lagrangian coordinates
β	ratio of the plastic work absorbed through shear deformation to the total plastic work done
β_c	critical value of β separating modes II and III
β_w	FSI index
ΔW_0	relative mid-span displacement
ω_d, ω_s	state variable for ductile and shear damage
$\phi_i(x)$	admissible mode functions
ρ	density of beam material
ρ_w	density of water
σ_Y	static yield strength

induces an additional cavitation at a finite distance from the plate as previously described.

It is, as yet, unclear how limits to material deformation, support compliance and support failure affects previously known results since the impulse imparted by an underwater blast loading is often sufficiently intense to induce significant plastic deformation in a structure with which it interacts leading to, in extreme circumstances, a loss of structural integrity through partial/complete detachment from its support. In this paper, the limitations/assumptions of previous studies are relaxed by considering a fully-clamped ductile beam system – the analytical framework for this was developed previously by Yuan et al. [1] in a companion paper. The model of the ductile beam system is able to capture the three different modes of deformation observed in blast experiments, the initiation and evolution of damage with increasing transverse beam deflection, and its consequential detachment – by fracture – from the supports. By coupling the fluid (water) domain to the aforesaid model of the ductile beam system, the momentum and energy transferred by the blast wave are critically re-evaluated for the coupled, non-impulsive loading regime; in particular, on how the beam's deformation mode and boundary compliance affects the fluid and structure interaction, or vice-versa, before the onset of boundary failure, defined as the complete detachment of the beam from its supports.

The outline of this paper is as follows: Section 2 summaries the key features of the ductile beam system developed in [1] and outlines the fluid-structure coupling strategy; details of the three-dimensional (3D) FE model are given in Section 3; Section 4 compares the predictions of the analytical and FE models; and, finally, results for the elasto-plastic and rigid free-standing beams are compared and sensitivity analyses carried out to elucidate the dependence of the model predictions on the beam's aspect ratio and inertial mass in Section 5.

2. Analytical model [1]

The analytical framework for the fully-clamped ductile beam system – developed by Yuan et al. [1] in a separate study – are briefly outlined with particular attention paid to highlighting the key elements that had been introduced to incorporate elasto-plastic constitutive behaviour, boundary compliance and boundary failure. This is followed by details on coupling strategy between the fluid domain and beam system, and on the limitations of the current FSI model.

2.1. Fully clamped ductile beam system – key features

The ductile beam system incorporates the following: (1) large elasto-plastic deformation with catenary action; (2) interactions between bending, membrane stretch and transverse shear; and, (3) limits to deformation through a loss of integrity at the support and the subsequent beam detachment by rupture. Fig. 1 shows a schematic of the slender beam supported at each end by three springs

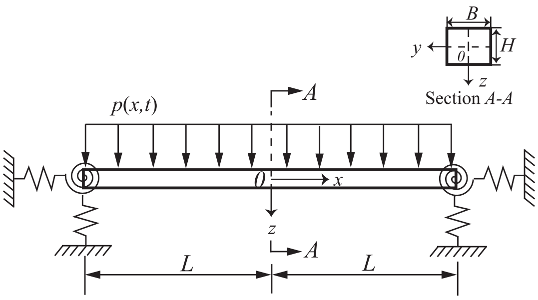

Fig. 1. Schematic of the fully clamped ductile beam system by Yuan et al. [1]. A plane of symmetry exists along $x=0$, $-B/2 \le y \le B/2$, $-H/2 \le z \le H/2$ so that only the right-half needs to be analysed.