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Numerical study of the dynamic response of Inflatable Offshore Fender Barrier Structures using the Coupled Eulerian–Lagrangian discretization technique

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ABSTRACT

Inflatable Offshore Fender Barrier Structures (IOFBS) are anti-terrorist security structures that function primarily to either stop terror bound vessels from reaching valuable offshore structures, incapacitate its crew or delay the vessel's progress until secondary security measures can be put in place. In this study, an advanced and efficient modelling method for impact simulation of the structure and similar multi-physics systems is presented. Numerical implementation of this modelling technique, using Abaqus finite element code is described and used in the impact simulation of the inflatable structure based on its current design as well as an alternative design of the structure. Results from the two designs provisions were compared and from these results, recommendation for improvement of the current design is also reported. This is desirable in ensuring high reliability in application of the structure in meeting its design objectives.

1. Introduction

The need to protect offshore facilities from deliberate terror attack is of increasing priority especially after the USS Cole (DDG 67) terror incident (Nixon et al., 2001) and more recently the Exxon mobil offshore facility terror attack (Sahara reporters, 2011).

One of the viable and effective anti-terrorist barrier structure used around the globe is the inflatable offshore barrier structure developed by Dunlop Holdings Ltd. Manchester, UK. The barrier is made majorly of neoprene–nylon fibre reinforced composite with characteristic anisotropic mechanical behaviour (Aboshio et al., 2015; Aboshio et al., 2014). The composite is traditionally constructed units of inflatable tubular structures with operating inflation pressure of 7 kPa (see Fig. 1). Each end of the barrier is furnished with mild steel fitting for connections with adjacent segments (units) of the barrier.

Current design of the structure stipulates the dimensions of each segment (Fig. 1) as single-chambered tubular structure of 2.4 m diameter, tapering at its ends and with an overall length of 25 m. 24 mm diameter reinforcing rope is internally connected to the two ends of each unit. The current design follows recommendation made after physical tests of the former 1.8 m diameter structure (Nixon et al., 2001).

IOFBS are traditionally installed at sea sites with support conditions provided by mooring systems anchored at the sea bed and at predetermined intervals based on environmental weather conditions of the site. Study of the current design under impact on one hand (Aboshio et al., 2015) and a combination of the impact and wind gust/loading (Aboshio, 2014) (ignoring wave loadings which are assumed to be less considerable to the wind loadings on the structure), following validation of numerical results of the physical tests (Aboshio, 2014; Aboshio et al., 2013) have identified low surge in pressure of the enclosed fluid after impact with higher stresses on the impacted barriers and especially when under both the vessel's impact and wind loading conditions.

It is important to note that while low surge in pressure after impact is desirable in some crash structures e.g inflatable bridge rail, bumpers and general adaptive structures (Graczykowski and Holnicki-Szulc, 2007; Graczykowski, 2011) (i.e in order to minimise after-shock effects and reactive forces of impactors); it is here conflicting with the overall objective of IOFB structures where high surge of pressure in the enclosed fluid is aimed to be maximised. This condition, if achieved in a design, basically ensures increased instability of the impactor with potential for high reactive forces and deceleration which are desirable design objectives

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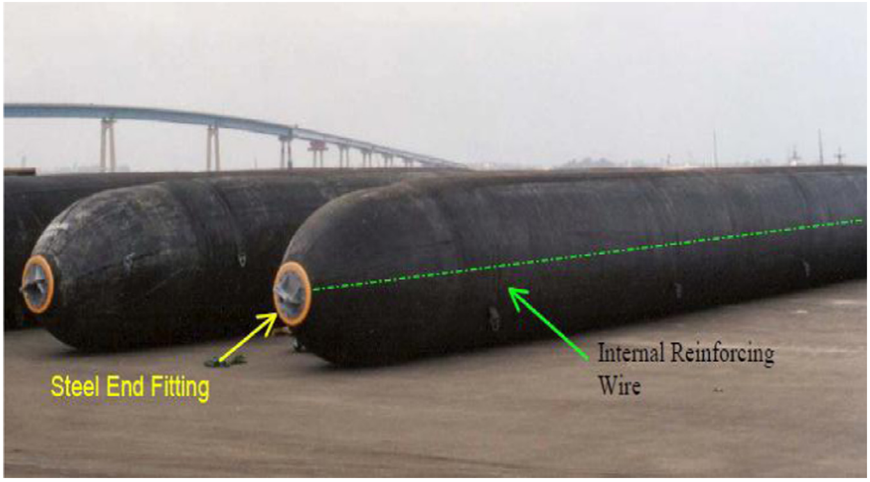

Fig. 1. Typical segment (unit) of Inflatable Offshore Fender Barrier Structures (Nixon et al., 2001).

of the IOFBS. Thus, to ensure high local surge of pressure (i.e at the point of impact) in the enclosed fluid within allowable limits of the physical properties (strength and stiffness) of the material used for the structure, the current design of the Inflatable Offshore Fender Barrier Structure is here modified to meet this important property among others.

Although fluid–structure interaction problems can be modelled and solved using the Arbitrary Lagrangian–Eulerian (ALE) formulation (Donea et al., 2004; Kuhl et al., 2004; Askes et al., 2004), use here is made of the Coupled Eulerian-Lagrangian (CEL) formulation (Legay et al., 2006; Cirak and Radovitzky, 2005; Aquelet et al., 2006) since high structural element distortions are expected and for which, in numerical analysis, the ALE mesh could lead to unrealistic results and could even crash on-going simulation (Aquelet et al., 2006).

The fluid motion in CEL is defined using the traditional Eulerian description/mesh where the numerical grid is fixed in space while the physical material (water) flows through the grid. The inflatable structure however, is defined using the traditional Lagrangian description of motion and discretized using the Lagrange method where in this case, the numerical grids moves and deforms with the material.

Giving the multi-physics and complex nature of the system under study, an advanced modelling technique for numerical analysis of this and similar FSI problems is presented in this paper. Here, mathematical models employed for the description of fluid behaviour were specifically chosen to ensure computational efficiency for analyses of the large fluid structure interaction (FSI) models. The method utilises a single frame, simultaneous solution procedure as well as a unique fluid–structure coupling technique in Abaqus finite element code. For systems with strong coupling between the enclosed fluid and structure as the one being considered here; the simultaneous solution method is normally preferred to partitioned method. In the partition method for numerical analysis of FSI problems, the fluid and structure domains are analysed separately and solution variables are iteratively passed from one field to the other at each time or load step. Hence could be more computationally expensive than the simultaneous method (Rugonyi and Bathe, 2001).

This paper extends the work reported by Aboshio et al. (2013) by explaining the state of the art being addressed and the governing equations for which the numerical results were obtained. Detail description of the FSI model used and numerical implementation of the model for analysis and simulation of the barrier under impact is also presented.

2. Governing equations

In the Coupled Eulerian–Lagrangian formulation both the Eulerian and the Langrangian equations retain their classical definitions. Material time derivative $(\frac{D}{Dt})$ is used for solids or structures while spatial time derivative is used for fluids. These are related by (Reddy, 2010):

$$\frac{D\phi}{Dt} = \frac{\partial \phi}{\partial t} + \mathbf{v} \cdot \nabla \phi \tag{1}$$

where ϕ is an arbitrary solution variable, $\mathbf{v}$ is the material velocity, ∇ is the gradient operator, $\frac{D\phi}{Dt}$ and $\frac{\partial \phi}{\partial t}$ are the material and spatial time derivatives of ϕ respectively.

Thus, the Lagrangian mass, momentum and energy conservation equations are respectively given by:

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0 \tag{2}$$

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \sigma + \mathbf{f} \tag{3}$$

$$\frac{DE}{Dt} = \nabla \cdot (\sigma \cdot \mathbf{v}) + \mathbf{f} \tag{4}$$

where E is the sum of kinetic energy and internal energy (e), given as,

$$E = 1/2 \rho \mathbf{v} \cdot \mathbf{v} + e \tag{5}$$

for which Eq. (4) can alternatively be written as:

$$\frac{De}{Dt} = \sigma : \mathbf{D}$$

where $\mathbf{D}$ is the velocity strain tensor, ρ is the density and $\mathbf{f}$ is the body force (Benson and Okazawa, 2004), σ is the stress tensor and $\nabla \cdot$ is the divergent operator.

The Eulerian mass, momentum and energy conservation equations on the other hand read respectively as:

$$\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot (\nabla \rho) + \rho \nabla \cdot \mathbf{v} = 0 \tag{6}$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) = \nabla \cdot \sigma + \mathbf{f} \tag{7}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{v}) = \nabla \cdot (\sigma \cdot \mathbf{v}) + \mathbf{f} \cdot \mathbf{v} = \sigma : \mathbf{D} \tag{8}$$

where all the parameters are as previously defined.