Ocean Engineering 144 (2017) 118–134

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Review

Nonlinear structural response in jet fire in association with the interaction between fire loads and time-variant geometry and material properties

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ARTICLE INFO

Keywords:
Fire loads
Time-variant geometry and material properties
Structural response
Two-way FSI analysis
Time increments

ABSTRACT

For safety design of structures against fire loads, time-variant geometry and material properties depending on the temperature should be considered with fluid-structure interaction (FSI) analysis. One-way FSI analysis is generally applied due to a time consuming task. But, it has big difference of structural response between conducting one-way and two-way FSI analysis. And two-way analysis is also affected by time increment of analysis for updating the geometry, and fire loads. The aim of this study is to investigate the effect of time increments on two-way FSI analysis of structures subjected to jet fire, and to suggest a proper time increment for two-way FSI analysis. In the present study, geometries and material properties are updated at every time increments, and kinds of two-way FSI analysis are performed with different time increments by using computational fluid dynamics (CFD) and nonlinear finite element analysis (NLFEA) and an interface program between CFD and NLFEA.

1. Introduction

Oil and gas are important sources of energy, produced mainly in demanding oceanic and industrial environments with significant fire and explosion hazards. The topsides of offshore platforms are the most likely structures to be exposed to hazards such as hydrocarbon fire and/or explosion (Czujko and Paik, 2012a, 2012b). A number of major accidents involving the topsides of offshore installations have been reported, such as the Piper Alpha accident of July 6, 1988 in the North Sea and the Deepwater Horizon accident of April 20, 2010 in the Gulf of Mexico, as shown in Fig. 1 (Vinnem, 2007; USCG, 2011).

After the Piper Alpha accident, greater attention was focused on the structural design of offshore rigs to counter the threat of fires and determine the means of minimizing damage from accidents. The Deepwater Horizon accident reconfirmed the importance of structural design to resist hydrocarbon fires.

Structural design and safety assessment both require the identification of the characteristic actions and action effects of fire. The thermal characteristics of steel are the main factors affecting structural integrity in fire. The specific heat of steel varies with temperature, as shown in Fig. 2(a). At temperatures above 400 °C the mechanical properties of steel significantly decrease, as shown in Fig. 2(b) which represents a non-continuous segment plot based on the definition of Eurocode (EN, 2005). The heat from fire flows relatively 'rapidly' in steel, which is a good heat conductor compared to other materials, e.g., concrete. Thus, fire can lead to the collapse of steel structures, and the severity of fire loads usually requires an application of passive fire protection (PFP) for critical structural elements. So, the characteristics of change in the material property should be considered, when analyzing the structural response subjected to fire loads.

In industry practices, simplified methods are usually applied for investigations of structural responses to fire on offshore installations, according to the structural designer's and/or engineer's convenience (UKOOA and HSE, 2003; API, 2006; EN, 2005; NORSOK, 2008). Some of the ways that such analyses may be simplified include the following:

- Simplification of load: Idealized fire loads
- Simplification of structure: 1-dimensional structure
- Simplification of procedure: Numerical calculation

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http://dx.doi.org/10.1016/j.oceaneng.2017.08.028
Received 12 January 2017; Received in revised form 22 March 2017; Accepted 17 August 2017
Available online 4 September 2017

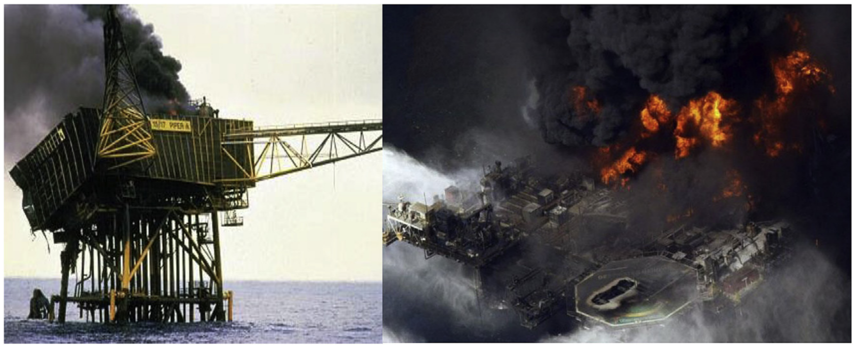
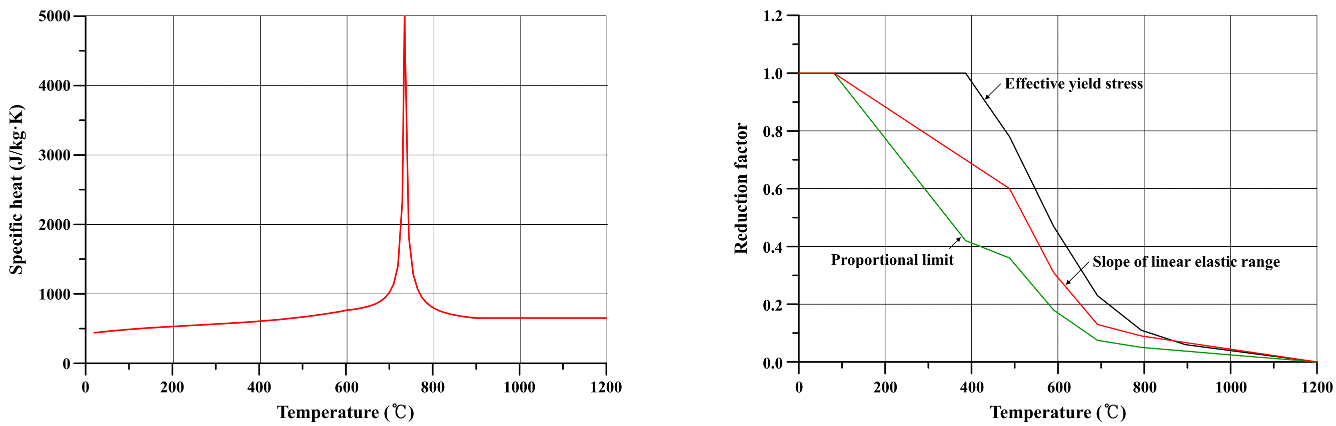


Fig. 1. The Piper Alpha (left) and Deepwater Horizon (right) accidents.



(a) Specific heat of steel (b) Mechanical properties of steel

Fig. 2. Examples of the change of material properties according to temperature (EN, 2005).

The conventional fire safety design approaches are essentially composed of a series of regulations, standards and procedures. As a result, the conventional approaches need to be supplemented by integrated fire safety design approaches that are in principle based on performance. Integrated fire safety design requires taking advantage of fire computational fluid dynamics (CFD) simulations (Paik et al., 2010; Salem, 2010) and nonlinear structural response analyses (Guedes Soares et al., 1998; Shetty et al., 1998; Guedes Soares and Teixeira, 2000; Skallerund and Amdahl, 2002; Paik and Thayamballi, 2007).

The action characteristics of hydrocarbon fires can be modelled using CFD, which is recognized as one of the most powerful modelling approaches currently available. CFD makes it possible to model fire using first principles through solving the basic conservation equations of mass, energy, and momentum and using accurate 3D topological models of structures. This field or CFD modelling approach has successfully solved various fire safety problems (Novozhilov, 2001).

In addition, the action effects of fire on structures can be characterized by the nonlinear finite element method (NLFEM). Therefore, more refined methods for modelling CFD and NLFEM simulations will help improve the prediction of the fire risk associated with offshore installations (Kim, 2014). Generally, structural analysis is performed after CFD fire simulation as named one-way simulation due to time and technical issues. However, it is needed to consider interaction between fire and structure for obtaining more accurate structural response.

The aims of this study are i) to perform a fluid-structure interaction (FSI) analysis of structures on platforms under jet fire through one-way and two-way analyses, ii) to compare the results of these analyses depending on the time increment in two-way analysis, and iii) to propose a proper time increment for two-way FSI analysis.

2. A procedure for nonlinear response analysis in fire

The structural response analysis in fire is performed after obtaining the fire loads such as gas cloud temperature, heat flux, radiation etc. Fig. 3 illustrates a scheme of one-way FSI method of analyzing the nonlinear structural response subjected to fires.

For the nonlinear structural response analysis with a two-way method, it is necessary to consider updates of the time-variant geometry and material properties. Fig. 4 illustrates a scheme of two-way FSI analysis. The structural response assessment becomes more accurate with smaller time increments used in two-way analysis, and this process requires the use of a proper time increment (Δt). If the time increment is the same as the total simulation time, then the process is a one-way FSI analysis.

Fig. 5 shows a procedure for a two-way FSI analysis of nonlinear structural responses under fire proposed in this study. This procedure involved the following steps;

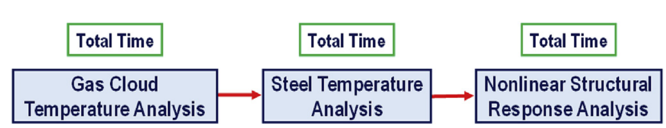


Fig. 3. A scheme of one-way method for analysis of nonlinear structural response to fires.