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Dynamic response and critical temperature of a steel beam subjected to fire and subsequent impulsive loading

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ABSTRACT

This paper presents a numerical approach for the analysis of dynamic response of a steel beam subjected to fire followed by an impulsive load. The approach is based on the minimum principle of acceleration in dynamics of elastic–plastic continua at finite deformation. The governing equations in the form of finite difference are obtained by the direct discretization of Lee's functional. The equations can adequately describe the response of a steel beam under combined effects of fire and impulsive loads, in which both the thermal and strain-rate effects on the constitutive equation and the thermal expansion effects on the dynamic equations are taken into account. The present model can predict the static behavior of the beam in fire condition and the subsequent dynamic response to an impulsive loading. As an example, the influences of temperature, strain-rate and thermal expansion on the dynamic response of a steel beam with rectangular cross section are investigated. A modified rigid-plastic prediction for the permanent deflection to impulsive loading is proposed when temperature effect is considered, which may be used as a simplified method to assess the beam response to a fire followed by an impulsive loading. For a beam with I-shaped cross section, an iso-damage curve on temperature and impulsive velocity plane with the consideration of dead loading is introduced to distinguish safe and unsafe regions, which could be used in the structural design for the resistance of fire and impulsive loads.

1. Introduction

The response and failure of engineering structures under combined effects of impact, explosion and fire have attracted great attention since 9.11 event in 2001. Bažant [1] attributed the direct cause of the failure of twin towers of WTC to the progressive buckling of the main load-bearing steel columns when the upper part of the building collapsed to the lower structure of the building after the stories hit by the hijacked aircraft were softened by the fire. This may be considered as a scenario of 'impact loading during a fire'. Nevertheless, fire and impulsive load are frequently connected although they may happen in different time scales. The characteristic times of fire and impulsive load are approximately in the order of 10^4 and 10^{-1} s, respectively. In general, the structural response to fire and impulsive load can be catalogued by following two cases:

(a) Impulsive load followed by a fire (IFF):

Since the duration of the impulsive loading is normally much shorter than the characteristic time duration of temperature increase, this case can be further divided into two stages, i.e. Stage-1: dynamic structural response to impulsive load, during which there is no need to consider the thermal effect of fire; and Stage-2: thermal response of the impulsively-deformed (and/or -damaged) structure to the fire, during which thermal and dynamic responses can be decoupled. The fundamental research methods for Stage-1 and Stage-2 in IFF case have been established in the fields of impact engineering [2,3] and fire engineering [4,5], respectively, although integration is needed to consider the consequence of impulsive load in the fire analysis. The interested reader is referred to [6–12] for relevant studies about the IFF case, which will not be further considered in the present paper.

(b) Impulsive load during a fire (IDF):

In this case, the thermal deformation and the thermal effect of fire on the mechanical properties of structural material should be considered in the analyses of the dynamic structural response to impulsive load. Based on authors' best knowledge, no research has been reported for this case, and therefore, IDF in Case (b) will be the focus of this paper.

According to ISO standard, the fire temperature curve is $T = 20 + 345\lg(2t/15 + 1)$ where time and temperature units are in second and degree Celsius, respectively [13]. The effect of transient temperature change on the structural response to impulsive load may need to be considered only in the early phase of the heating process, as shown in Fig. 1(a) for the time history of the

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normalized temperature (T/T_h) where T_h is a characteristic temperature (i.e. $T_h = 945$ °C at time $t = 3600$ s is used here) and the normalized temperature change rate $(dT/dt)/(dT/dt)_0$ where $(dT/dt)_0 = 46/\ln 10$ is the rate of temperature change at $t = 0$. It is evident that the temperature change is much fast in the early stage, and thus, its transient effect in the early stage may need to be considered in the dynamic structural response. However, the temperature change tends to become much slower after a short time, which means that the dynamic structural response can be studied without considering the transient temperature change during the concerned response period. If the characteristic time duration of the dynamic structural response to the impulsive load is t_{im}, the transient temperature change may be neglected during t_{im} when $(dT/dt) \times t_{im} \leqslant T_c$ where T_c is the maximum temperature change that can be neglected in a structural analysis. Without losing generality, we conservatively assume $T_c = 1$ °C. If $t_{im} \leqslant 1/(dT/dt)$, the dynamic structural response can be decoupled from the thermal response, which is shown in Fig. 1(b) to distinguish coupled and uncoupled zones (i.e. Zone-I and Zone-II). For a given time from the initiation of fire, the maximum time duration (t_{im}) for the uncoupled structural analysis can be predicted from Fig. 1(b). For example, $t_{im} = 100$ ms at 7.5 s from the start of fire (the temperature is increased from 20 °C to around 123 °C). This implies that if the dynamic structural response is completed within 100 ms, there is no need to consider transient temperature change in the dynamic structural analysis. In this study, we will focus on the event in Zone-II where the thermal and impulsive responses of structure can be decoupled, which means that mechanical properties of the structure are constant and there is no transient thermal deformation during the dynamic structural response to the impulsive loading. We term this scenario as 'fire followed by an impulsive load (FFI)', which is the most common scenario in the Case (b) of 'impulsive load during a fire (IDF)'.

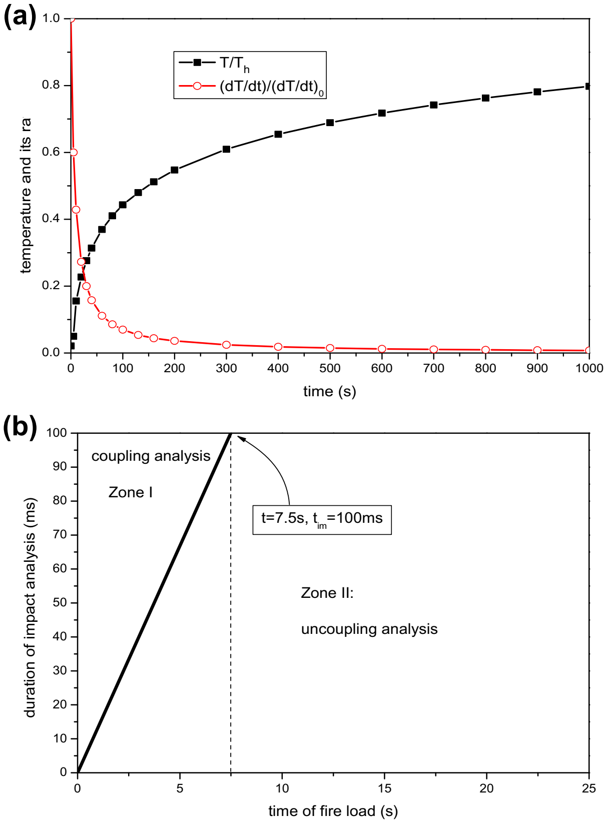

Fig. 1. (a) Curves of normalized temperature and its rate against time. (b) Two zones for coupling and uncoupling analyses.

Beam, as an important structural element, will be the subject of this study. Frequently, an impulsive load can be simplified into an initial velocity because the blast load is normally much shorter than the structural response [2]. For a steel beam subjected to an impulsive load during fire, the analysis can be divided into two phases. The first phase concerns the deformation of the structure and the change of structure's mechanical properties in responding to the fire. In the second phase, the dynamic response of the structure, which has been heated to an elevated temperature, to the impulsive load is considered. Standard finite element codes such as ABAQUS [14] need separate models for these two phases and have difficulty to connect these separate models. Therefore, it is necessary to develop a model for the above-mentioned problem.

It has been realized in previous studies [15,16] that the fire resistant performance of a restrained beam in the frame is very different from an isolated simply-supported beam, the main reason is that the catenary action occurs due to thermal expansion and large deflection of a restrained beam under fire conditions. When under catenary action, a beam will be in tension and its resistance to the applied transverse load is mainly from the catenary axial force in the beam, which means that the catenary action becomes the dominant load carrying mechanism of the beam and the axial restraint at the end of the beam cannot be ignored. Thus, it is unrealistic to study the behavior of a beam under fire condition when no axial constraint is applied. As an extreme case, we consider a fully-supported beam, i.e. a beam that is restrained in rotation, translation and axial movements at its two supporting ends, in the study of the thermal expansion deformation in this paper.

The aim of this study is to investigate the behavior of a steel beam subjected to an impulsive load after a certain time period of fire. In order to model the beam behavior, a unified mathematical model in the time domain is developed for thermal and impulsive loads with considering the effects of strain-rate, temperature and thermal expansion. Then, a relationship between critical temperature and impulsive velocity is established, based on which a safety concept is proposed.

2. Numerical model

2.1. Description of the problem and basic assumptions

A fully-supported steel beam with constant cross-section is exposed in fire for a period of time and is then subjected to an impulsive loading described by a uniformly distributed velocity of magnitude V_o over the entire span L. It is assumed that T is the temperature when the impulsive load is applied and the temperature change is negligible during the dynamic structural analysis. The elastic modulus and yield stress of the beam material are E^T, σ_s^T, respectively, at temperature T.

The proposed beam model is based on following assumptions:

(1) The plane of the beam cross-section remains plane during deformation. The effects of transverse shear deformation and shear stress on the plastic yield of beam material are neglected.
(2) Temperature is uniformly distributed in the beam, and thus, the thermal bowing effect is not present [17].
(3) The standard fire curve recommended by ISO is used for the calculation of the increase of the surrounding temperature. Although the temperature of the beam in fire may not be exactly the same as the surrounding temperature T_g, the insignificant difference between them is neglected in order to simplify the analysis. Therefore, for structures in fire