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Pulse shape effects on the dynamic response of a steel beam under combined action of fire and explosion loads

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ABSTRACT

Numerical analysis of the responses of steel beam under the combined action of fire and explosion loads are performed by using the ABAQUS general finite element program. The pulse shape effects on the fire and blast resistance capabilities of steel beam are investigated. The peak amplitude of the pulse load–impulse curve and the critical temperature–impulse curve is proposed to distinguish safe and unsafe areas. Two scenarios that apply fire and explosion loads in different orders are considered. Numerical analysis results show that the blast resistance capability of steel beam sequentially decreases under the action of exponential, triangular, and rectangular pulse loads; the effects of rectangular, triangular, and exponential explosion pulse loads on the fire resistance performance of steel beam consecutively decrease; and the pulse shape effects on the fire resistance capability of steel beam decreases with the increase in dynamic load ratio.

1. Introduction

Energy- and land-saving steel structures are vigorously developing, and most of these structures are green environmental protection structures. Many landmark steel structure buildings have been built around the world. However, catastrophic events, such as explosion and fire, could inflict high costs on human lives and property security. Therefore, assessing the fire and explosion resistance performance of steel structures is necessary.

Numerous studies have been conducted to analyze the response of steel structures under separate fire or explosion loads. Zakrisson et al. [1] performed numerical simulations of air blast loading in the near field acting on deformable steel plates and compared their results with those of the test results. A simplified blast model based on empirical blast loading data representing spherical and hemispherical explosive shapes has been tested as an alternative to the Eulerian model. Ribeiro et al. [2] adopted T-stub evaluation supplemented with dynamic increase factors to predict the response of T-stubs subjected to rapidly applied dynamic loads and concluded that less ductile failure modes are activated with the increase in strain rate. Moghimi and Driver [3] investigated the potential application of a few forms of steel plate shear wall as a protective system in industrial plants possibly subjected to accidental explosions by means of isoresponse curves.

Porcari et al. [4] provided a brief overview of conventional fire protection strategies for steel buildings and described current work conducted by researchers in the area of mechanisms involved in fire-induced progressive collapse of steel building structures. Moreover, they presented a summary of two possible design methodologies for improving resistance to fire-induced progressive collapse. Naser and Kodur [5] presented critical factors that influence the onset of local buckling in steel beams when exposed to fire conditions. A three-dimensional nonlinear finite element model capable of accounting for critical factors that influence local instability in fire-exposed steel beams is developed. Numerical simulation results are utilized to evaluate the failure of beams under different limit states, including flexure, shear, sectional instability, and deflection. Luongo and Contento [6] resolved the nonlinear elastic problem for planar frames made of rectilinear beams subjected to thermal loadings.

Research on the properties of steel structures under the combined action of fire and explosion loads is relatively less. However, the response analysis of steel structures under the combined action of fire and explosion loads have become more important after the “9/11” event in the United States.

With regard to the nonlinear response of steel frame under fire and explosion loads, Song and Izzuddin [7,8] proposed an adaptive numerical analysis method to evaluate the influence of blast loading on the fire resistance capability of steel structures. Mirmomeni et al. [9] implemented a comprehensive test program to investigate the post-impact fire properties of Grade 350 steel under well-defined conditions. The test results indicate that the effects of these combined actions are

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profoundly different from those in which the structure is individually subjected to either high strain rate or thermal loading. Xi et al. [10] adopted the governing equations in the form of finite difference to describe the response of steel beam under the combined effects of fire and impulsive loads. Liew et al. [11,12] adopted the mixed element method to analyze the steel frame that was locally impacted by blast loading and caused the fire. The response behavior of steel structures under blast and fire loadings were investigated, and the influence of blast loading on the fire resistance capability of multistory steel frames was elaborated.

The sequence of fire and explosion loads applied on the steel structures was rarely considered in previous studies. Two scenarios that apply fire and explosion loads in different orders all have strong engineering backgrounds. A substantial amount of research results has recently emerged for the scenario in which the explosion load is applied followed by a fire. However, related research results for the scenario in which explosion load is applied during a fire are currently rare. As indicated in our previous study [10], the strain rate constitutive model related to the temperature should be considered in this situation. However, relevant experimental data are currently generally lacking. Two scenarios are discussed in this study. In this study, the blast resistance capability of steel structures during a fire is represented by the peak amplitude of pulse load–impulse (*P*–*I*) diagram, while the fire resistance performance of steel structures after the action of explosion load is represented by the T_{cr}–I diagram.

Accurately simulating the time course curve of explosion load in real terrorist attacks is difficult. Therefore, scholars [13,14] usually adopt the ideal pulse load to simulate an explosion load in the analysis. Simple and commonly used pulse shapes, such as rectangular, triangular, and exponential pulses, are adopted in this study. The pulse shape effects cannot be ignored to ensure accurate analysis of the dynamic response of structures.

The earliest study on the pulse shape effect can be traced back to 1953 when Symonds [15] investigated pulse shape effect on the final deflection of a free beam subjected to a concentrated force. The final dynamic plastic deformation is strongly dependent on the pulse shape with regard to the four classical problems in dynamic plasticity: the circular plate under uniform pressure, the reinforced circular cylindrical shell under uniform pressure, the free–free beam with a central concentrated force, and the circular cylindrical shell with a ring load. Youngdahl [13] used effective load and total impulse as correlation parameters to eliminate the dependence of the final plastic deformation of four different structural configurations on the pulse shape. A number of studies [16–19] confirmed that the pulse approximation method can eliminate the pulse shape effects on the dynamic plastic bending response of various structural members, such as beams, circular plates, and cylindrical shells; this method is also applicable to geometrically unstable structures.

The pulse shape effect on the fire and blast resistance capabilities of steel structures has not been previously investigated. In this study, the fire and blast resistance capabilities of steel beam under different shapes of explosion pulse load combined with fire are analyzed.

2. Finite element model of steel beam under fire and explosion load

2.1. Constitutive model with temperature and strain rate effect

The elastic–perfectly plastic model shown in Fig. 1 is adopted for the stress–strain relationship. Thereinto, E and E_T are the elastic moduli at normal temperature T_0 and temperature T, respectively; σ_s^T and σ^T are the quasi-static and dynamic yield stresses at temperature T, respectively; and σ_s^0 and σ^0 are the quasi-static and dynamic yield stresses at normal temperature T_0, respectively.

In general, the elastic modulus and yield stress of mild steel all decreased with the increase in temperature. The reduction factors under different temperatures are determined according to the Eurocode 3

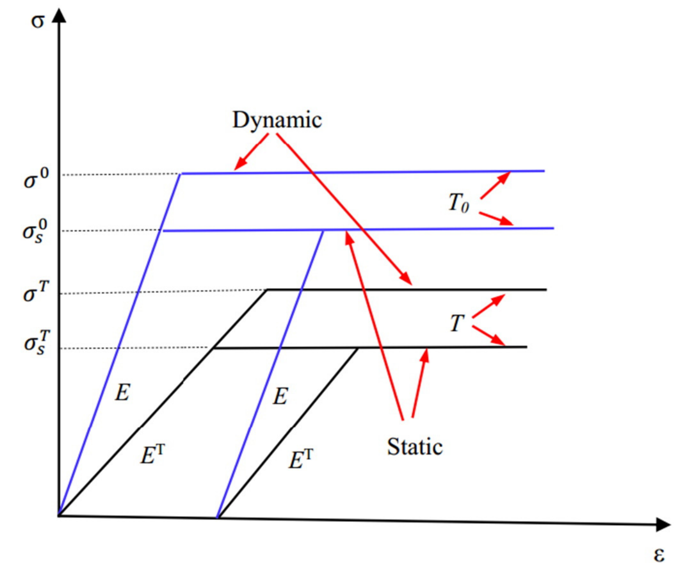

Fig. 1. Stress–strain relationship.

(EC3) [22]. The reduction factors provided by the EC3 are listed in Table 1.

At normal temperature T_0, mild steel is a strain-rate sensitive material. The relationship between quasi-static and dynamic yield stresses can be expressed by the Cowper–Symonds equation. At elevated temperature, the strain rate effect of the material is weakened. However, this effect can still be expressed by the Cowper–Symonds equation, where the two strain rate parameters should be related to temperature, that is,

$$\sigma^T = \left[1 + \left(\frac{\dot{\varepsilon}}{D(T)}\right)^{\frac{1}{q(T)}}\right]\sigma_s^T, \tag{1}$$

where $\dot{\varepsilon}$ is the equivalent plastic strain rate, and $D(T)$ and $q(T)$ are the strain rate parameters at temperature T.

Strain rate parameters D and q of steel at normal temperature are 40 and 5, respectively, as proposed by Symonds and Jones [23]. In reference to the literature [24], the strain rate parameters D and q are 400 and 1, respectively, at 1000 °C. The two strain rate parameters $D(T)$ and $q(T)$ between $T = 20$ °C and $T = 1000$ °C, which are related to temperature, are obtained through linear interpolation by using the assumption presented in [10].

Material constants of steel at normal temperature are elastic modulus $E = 205$ GPa, yield stress $\sigma_s^0 = 399$ MPa, mass density $\rho = 7850$ kg/m^3, and Poisson's ratio $\upsilon = 0.3$ [20,21].

By referring to the stipulation of the code BS5970: Part 8, the expansion coefficient of steel is assumed to be a constant $\alpha = 1.4 \times 10^{-5}$.

2.2. Loading scheme and failure criteria

The ABAQUS general finite element program is used to simulate the responses of steel beam under fire and explosion loads and analyze the interplay of these loads. The computational model of ABAQUS is provided as follows.

Table 1
Reduction coefficient of the elastic modulus and yield strength under various temperatures.

T (°C)	20	100	200	300	400	500	600	700	800	900	1000
E_T/E	1.0	1.0	0.9	0.8	0.7	0.6	0.31	0.13	0.09	0.0675	0.045
σ_s^T/σ_s^0	1.0	1.0	1.0	1.0	1.0	0.78	0.47	0.23	0.11	0.06	0.04