FIRE RESISTANCE EVALUATION FOR THE STEEL ROOF STRUCTURE OF A TYPICAL WAREHOUSE

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Abstract

The fire resistance of the steel roof structure of a typical warehouse is investigated in the current study. Various fire scenarios are simulated using the Fire Dynamics Simulator (FDS) program. The simulation considers the fuel type and the clearance height of the warehouse as the varying parameters. The fire modeling results demonstrate that the fuel types significantly affect the behavior of the modeled fire in terms of the fire growth and the spread of flames. For each of the modeled fire scenarios, the behavior of the roof structure is examined using nonlinear structural analysis, taking into account the varying properties of steel under fire, with and without fire protection. It has been found that the failure time of the roof structure depends upon the fuel type and whether or not the roof members are protected from fire and that the fire resistance of protection for structural steel sections based on ASTM E 119 may not be conservative.

Keywords: Failure time, Fire modeling, Fire resistance, Roofstructure, Structural analysis

Introduction

The use of structural steel sections in construction has continuously increased because of the advantages of steel in terms of short erection time as well as high ductility and strength/weight ratio. The types of structures in which the structural steel sections are typically used include long-span bridges and roofs for industrial buildings. Even with the increasing popularity, steel structures have been well known to suffer from exposure to high temperature. Under the high-temperature conditions (i.e., fire), certain properties of the structural steel, e.g. the yield and the ultimate strengths, the modulus of elasticity, etc., would drop significantly while the coefficient of expansion would simultaneously increase [1]. This poses a direct threat to the load-carrying capacity of the steel structures that are designed to be used in the normal-temperature condition, or unprotected steel structures.

Many national institute of standards such as the British Institution of Structural Engineers [2] and National Institute of Standards and Technology [3] have called for the development of performance-based approach as an alternative to the traditional prescriptive requirement. The performance-based approach can be used to achieve a more economical design of steel structures for fire resistance. However, this approach requires a thorough understanding of the behavior of fires as well as the exposed structures [4,5]. The related subjects include fire modeling, air-steel heat transfer, variation of mechanical properties of steel with respect to temperature, and nonlinear finite element analysis of steel structures. To design structures for fire resistance using the performance-based approach, fire modeling is the key to obtaining the design parameters [4].

Even though many fire safety protocols have recommended using performance-based approach, most steel structures are currently designed for fire resistance based on standard fire tests [6]. These standard fire resistance tests focus mainly upon the properties of a steel member and fire protection without taking into consideration as the overall behavior of the structural system and level of fire severity. For a warehouse where the fire severity varies with its content and may differ from the standard fire, the standard tests may overestimate the fire resistance of the structure. The current study therefore aims to investigate the effect of the severity of fire on the safe egress time for the roof structure of a typical warehouse prior to its failure. It is expected that the outcome of the analysis can more or less be used to set an initial step towards design of steel structures for fire safety as well as fire risk assessment of similar structures in accordance with the existing fire regulations.

Performance-based Approach

In order to investigate the safe egress time as well as the behavior of the steel roof structure subjected to fire using the performance-based approach, fire modeling, heat transfer analysis and structural analysis are required. Fire modeling is the key to investigating the fire behavior and the temperature distribution. In order to assess the effect of the varying air temperatures, which is obtained from fire modeling, upon the structural performance, an analytical model of heat transfer between the surrounding air and the structural steel members is required. Once the temperature distribution of each steel member is obtained, the nonlinear finite element analysis can be employed to evaluate the structural behavior taking into account the varying mechanical properties of steel due to the enclosing fire. The structural analysis results are examined in terms of the structural behavior and failure time for each of the distinct fire scenarios under consideration. The framework of the performance-based approach can be illustrated schematically in Figure 1.

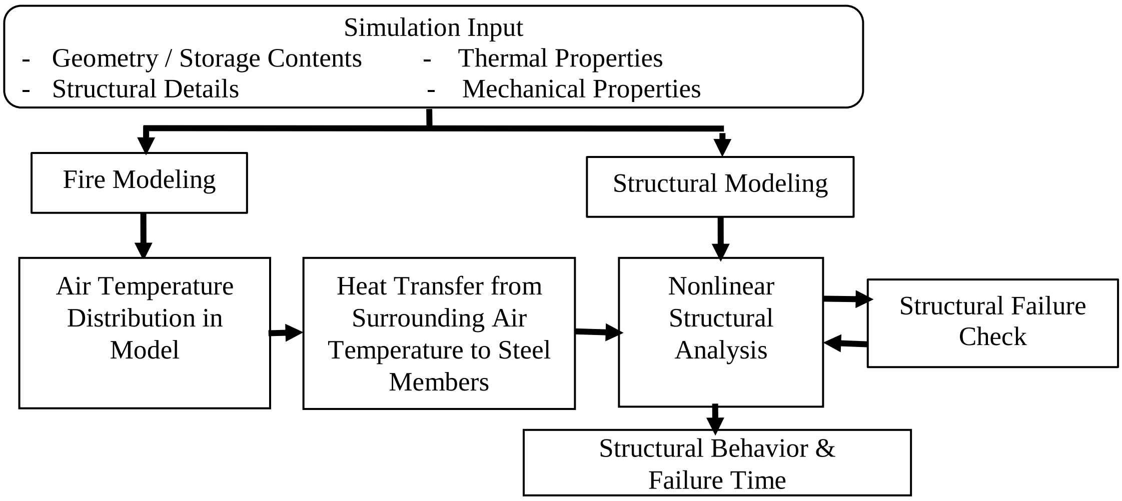

Figure 1. Framework to analyze the safe egress time based on the performance-based approach

Fire Modeling

The current study uses the FDS program for modeling different fire scenarios. In general, the output of a fire model is the temperature distribution of air within a specified enclosure due to the simulated fire scenario which depends upon the various parameters of fire initiation (e.g. ignition source, fuel, etc.) and fire growth (e.g. ventilation, compartment openings, heat release rate of the fuel, etc.). Fire modeling in FDS employs the computational fluid dynamics (CFD) model of fire-driven fluid flow [7]. The analysis is performed numerically in the form of Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The equations describing the transport of mass, momentum, and energy by the fire induced flows is simplified by [8] to be efficiently solved for the fire scenarios of interest. The simplified equations are solved numerically by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. Within each cell the gas velocity, temperature, etc., are assumed to be uniform; changing only with time.

Heat Transfer Analysis

The heat transfer analysis between the surrounding air obtained from fire modeling and the structural steel members is required to input for the thermal load input of the structural analysis. The study employs spreadsheet calculations for temperatures of a steel member using the principles of heat transfer to estimate the energy being transferred to the steel member, and thus the rate of temperature rise in the steel section [9–10]. As a result of the heat transfer analysis, the temperature increment of an unprotected steel section can be obtained based upon the difference in the temperature of steel over a time step Δt [10]:

$$\Delta T_s = \left(\frac{H_p}{A}\right)\left(\frac{h_t}{\rho_s c_s}\right)\left(T_f - T_s\right) \tag{1}$$

in which H_p/A is the section factor of the steel section (m^{-1}); ρ_s is the density of steel (kg/m^3); c_s is the specific heat of steel (J/kg-K); h_t is the sum of the radiation and convection heat transfer coefficients; T_f is the temperature of the surrounding fire within the specified time step Δt; and T_s is the temperature of steel at the beginning of the time step Δt.

The value of the convection heat transfer coefficient used in the current study is 25 W/m^2-K as recommended by [11]. Since the radiation heat transfer depends on the temperature of the steel member and its surroundings, this component of the total heat transfer coefficient must be calculated at each time step, using the following formula [11]:

$$h_t = 25 + \sigma\varepsilon\left(\frac{T_f^4 - T_s^4}{T_f - T_s}\right) \tag{2}$$

in which σ is the Stefan-Boltzman constant, which is taken as 5.67 x 10^{-8} kW/m^2-K^4 [11]; and ε is the emissivity of the fire, which is taken as $\varepsilon = 0.5$ as recommended by [12].
To determine the temperature of steel sections with fire protection, the exterior surface of the insulation is assumed to have the same temperature as the surroundings—i.e., the fire—the heat transfer coefficient is not required. It is also assumed that the temperature of steel is the same as the internal surface of the insulation. As such, the change in the temperature of the protected steel over a time period can be computed. The current study adopts the method proposed in EuroCode 3 [13] for calculating the temperature of steel with fire protection:

$$\Delta T_s = \left(\frac{H_p}{A}\right)\left(\frac{k_i}{d_i \rho_s c_s}\right)\frac{\left(T_f - T_s\right)\Delta t}{(1+\phi/3)} - \left(e^{\left(\frac{\phi}{10}\right)} - 1\right)\Delta T_f \tag{3}$$

in which

$$\phi = \left(\frac{H_p}{A}\right) d_i \left(\frac{\rho_i c_i}{\rho_s c_s}\right) \tag{4}$$

and

$$\Delta t = \left(\frac{H_p}{A}\right)\left(\frac{\rho_s c_s}{k_i}\right)\left(1+\left(\frac{\phi}{3}\right)\right) < 60 \qquad (5)$$

In the above equations, d_i is the thickness of the insulation (m); ρ_i is the density of the insulation (kg/m^3); k_i is the thermal conductivity of the insulation (W/m-K); and ΔT_f is the change in fire temperature over the time step (in seconds).

Structural Analysis

A commercial nonlinear finite element analysis program, ANSYS, is used to assess the behavior of the steel roof structure with respect to the varying temperatures from the heat transfer analysis. The structural element examined in the current study consists of six degrees of freedom (DOF) at each node—nodal translations and rotations in the local coordinates—as shown in Figure 2. The finite element discretization yields a set of simultaneous equations. Since the coefficient matrix is itself a function of the unknown DOF values (or their derivatives), these equations are nonlinear. The Newton-Raphson iterative method is used to solve the nonlinear equations [14]. The structural analysis is controlled by time step analysis. The temperature varies within each time step but the dead load is assumed to be constant.

In addition to the yielding failure, the present analyses also consider buckling criteria in which the compression strength of the sections, according to ANSI/AISC 360-05 [1], can be summarized below:

- the flexural buckling strength for uniformly compressed elements
- the limit state of flexural-torsional and torsional buckling for singly symmetric sections
- the lateral-torsional buckling moment for doubly symmetric sections

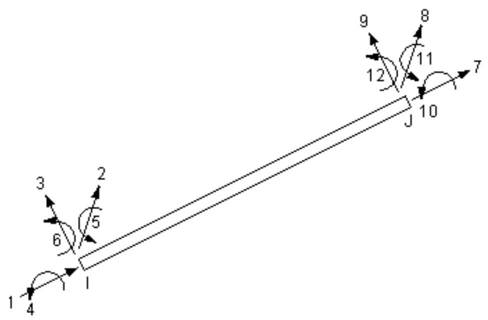

Figure 2. Degrees of freedom of a frame element

The interaction of flexure and compression in doubly symmetric members and singly symmetric members is governed by [1]

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \le 1 \qquad \text{for } P_r / P_c \ge 0.2 \qquad (6)$$

$$\frac{P_r}{2P_c} + \left(\frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}}\right) \le 1 \qquad \text{for } P_r / P_c < 0.2 \qquad (7)$$

in which P_r is the required axial compressive strength obtained from nonlinear analysis; P_c is the available axial compressive strength from the buckling strength analysis; M_r is the required flexural strength obtained from the nonlinear analysis; M_c is the available flexural strength from the buckling strength analysis; x and y are the subscripts relating symbols to strong-axis bending and weak-axis bending, respectively. The buckling failure for each member is examined at each time step of the analysis. The buckled members are removed from the structural model in the subsequent time steps.

Case Study of the Steel Roof Structure of a Typical Warehouse

To investigate the effects of fire upon the steel roof structure, various fire scenarios are simulated for a typical warehouse with a system of steel roof frames that are commonly found in most warehouse structures. For the present simulation studies, a typical warehouse with a 20 m x 40 m layout is investigated. The warehouse contains 18 piles of storage contents. The dimensions of each storage pile are 4 m in width, 4 m in length and 3 m in height. The spacing between the storage piles is 2 m in both horizontal directions. The ventilation openings of the warehouse are located along the wall, taking up the area of 140 m^2. Figure 3 illustrates the geometry of the warehouse as modeled by the FDS program.

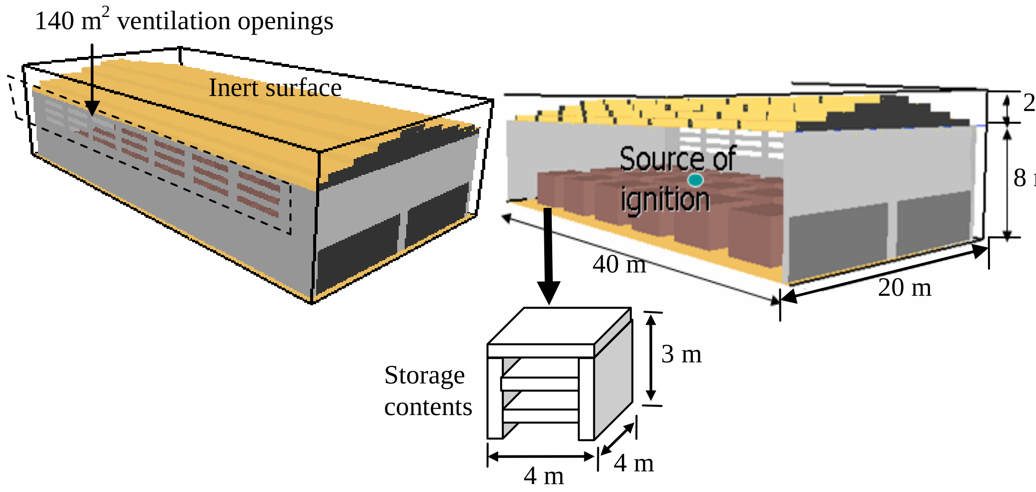

Figure 3. Details of a warehouse and storage contents simulated in the FDS program

In modeling the fire scenarios, the enclosures within and outside of the warehouse are simulated using the FDS program. Due to the limitations of the computer program, all calculations are performed within a domain that is made up of rectangular blocks, each with its own rectilinear grid. All obstructions and vents are thus forced to conform with the numerical grid(s) established by the user. In the current study a 0.5-m grid spacing is used. Therefore, the roof frames are modeled as thin plate obstructions with edges that align with the specified grid lines and the slope of the roof.

The current study investigates two types of fuel (i.e., warehouse contents) in fire modeling: wood and plastic. The thermal properties of these two fuel types are obtained from the FDS database which can be summarized in Table 1. Note that the ambient temperature is set as 30 ˚C. The values of the clearance height of the roof structure above ground are taken as 8 m and 10 m. The ignition source is considered to locate at the middle of the warehouse. The variation of each of the above parameters essentially characterizes the distinct fire scenarios investigated in the current simulation studies. These scenarios can be summarized in Table 2.

The key output of the FDS program is the temperature distribution of air inside the specified enclosure. The temperature data are collected at the nodal points (i.e., joints) of all the members of the roof structure. Note that because the roof frames are modeled as thermally-inert thin plates the heat transfer in steel frames is not considered in the FDS model. The temperature data are taken at the surface of the thin plates, i.e. the air temperature. The heat transfer from the surrounding air to the structural steel members is computed using the heat transfer equations for members with and without fire protection, respectively. The thermal properties of steel are taken from [13]. The following thermal properties of perlite-based material [15] are used in modeling the fire protection of steel: specific heat 980 J/kg-K, thermal conductivity 0.11 W/m-K, density 900 kg/m^3 and thickness 0.02 m. The fire resistance of the fire protection material is approximately one hour based on the ASTM E 119 standard test.

The comparison of the structural performance under different fire scenarios is based upon the same initiating time line, i.e. the instant in which the fuel reaches its flaming point. This is done through the modification of the source of ignition in the FDS program to allow the fuel to become flammable instantly.

Table 1. Thermal Properties of Wood and Plastic Contents

Plastic Contents		**Wood Content**	
Type:	**Standard Plastic Commodity**	**Type:**	**Pine Wood**
Heat release rate:	500 kJ/kg	Heat of vaporization:	2500 kJ/kg
Specific heat:	1.0 kJ/kg-K	Heat of combustion:	12044 kJ/kg
Ignition temperature:	370˚C	Thermal conductivity:	0.14 W/m-K
		Thermal diffusivity:	8.3E-8 m^2/s
		Ignition temperature:	390˚C

Table 2. Various Fire Scenarios Investigated in the Simulation Studies

Varying Parameters			
Fuel Type	**Height of Warehouse**	**Fire Protection**	**Coding Representation**
Plastic	8 m	Unprotected	P8-U
		Protected	P8-P
	10 m	Unprotected	P10-U
		Protected	P10-P
Wood	8 m	Unprotected	W8-U
		Protected	W8-P
	10 m	Unprotected	W10-U
		Protected	W10-P

The structural model of the steel roof that is used in the nonlinear finite element analysis is a frame structure consisting of steel pipes for the main span, steel rods for bracing members, and C-shape sections for purlins. The supports of the main roof frames are hinges and rollers in the transverse direction. The structural model is illustrated in Figure 4. For the current simulation studies, fire-temperature loading is imposed upon the structure in conjunction with the self weight and the 30-kg/m2 superimposed load. The element temperature is taken as the average temperature of the joints of each element. The finite-element model of the roof structure consists of 2934 elements and 2935 nodes. Each of the element nodes is characterized by the six degrees of freedom shown in Figure 1.

Under the high-temperature condition, the variation in the mechanical properties of steel —i.e., the modulus of elasticity and the coefficient of thermal expansion—as summarized in Table 3 are used in the analysis. Note that for the current study the strength hardening property of steel is neglected and the buckling strength limitation of ANSI/AISC 360-05 is employed.

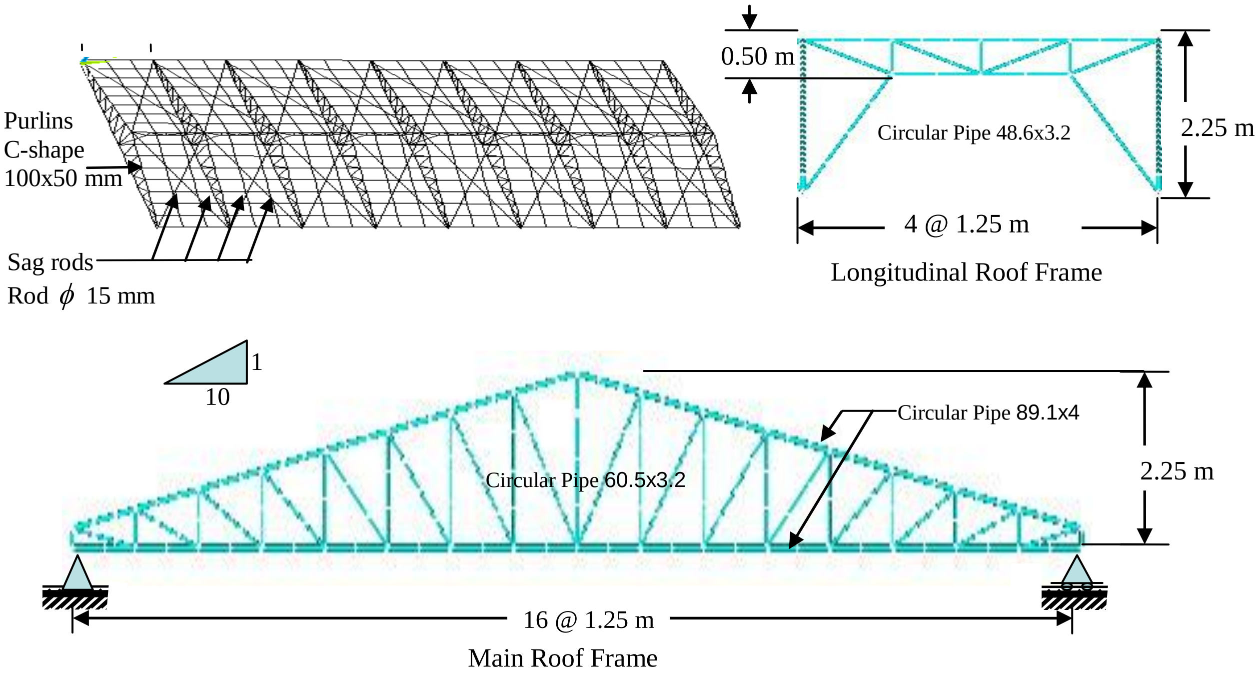

Figure 4. Structural Modeling of the Roof Frame

Table 3. Mechanical Properties of A36 Steel with Respect to Varying Temperatures (ANSI/AISC 360-05)

Temperature (°C)	**Modulus of Elasticity** (kg/m2)	**Yield Strength** (kg/m2)	**Coefficient of Thermal Expansion** (1/°C)
20	2.10E+10	2.40E+07	1.12E-05
100	2.06E+10	2.35E+07	1.17E-05
200	1.98E+10	2.26E+07	1.23E-05
300	1.90E+10	2.17E+07	1.29E-05
400	1.84E+10	2.12E+07	1.36E-05
500	1.63E+10	1.93E+07	1.42E-05
600	1.28E+10	1.32E+07	1.48E-05

Analytical Results

Fire Modeling Results

Cases P8 and W8 are designed primarily to investigate the effect of the fuel type: plastic and wood contents. Figure 5 illustrates the hot air layer within the enclosure radiating towards the burning fuel and the flames rising upward to the ceiling and spread horizontally. It is seen that for Case P8 the enclosure temperature rapidly rises in the area above the ignition source. The hot air then flows to the roof of the warehouse and gradually extends to the other parts of the roof. Subsequently, the hot air flows down to the lower layer of the warehouse enclosure, resulting in a considerable feedback of heat to the fuel and hence a rapid fire growth, the so called localized flashover. It is also observed that high temperatures are concentrated near the ventilation openings because enormous amount of oxygen is consumed in these areas. For Case W8, it is observed that the heat feedback from the growing fire is negligible. The fire growth in this case rather occurs through direct radiation from the flames to nearby objects, resulting in a slow fire growth in which the spacing and the surface of the combustibles become relevant.

The variation of the temperature at the middle of the roof structure with time are depicted in Figure 6. It is seen that, in the early stage, the temperature curve of the plastic content is close to the ASTM E 119 standard fire curve but significantly drops after reaching the maximum temperature. The temperature curve for the wood contents slower increases and more gradually decreases compared with the plastic contents whilst the clearance height of the warehouse is observed to slightly affect the maximum temperature.

Structural Analysis Results

The current study adopts the nonlinear finite element method taking into consideration the decreasing mechanical properties and the expansion of steel with respect to the increasing temperature. The criteria for yielding and buckling are employed to determine failure for each of the roof frame members. The coupled effects of compressive buckling and bending moments are investigated. To capture the various modes of structural failure for different fire scenarios, the maximum time in which the roof structure is subjected to fire is set to 120 minutes (7200 seconds). Note that even though the roof structure consists of various components—i.e., the main roof frames, the longitudinal roof frames, bracing members and purlins—the structural system is deemed to fail only when the stresses within the top or the bottom chords of the main roof frames reach their yield strength or buckling strength criteria. The sequence of failure for the structural members can be shown in Figure 7 for each of the scenarios investigated.

The longitudinal and transverse thermal expansions of the overall roof structure for Case P8-P are illustrated in Figure 8. The maximum thermal expansion of the roof structure is approximately 10 cm in the both horizontal directions. The longitudinal and transverse elongations of the roof frames are partially resisted by the bracing members which results in increasing tensile stresses. These tensile stresses are highly concentrated in the area at which the longitudinal elongations accumulate—i.e., the edge spans. As a result, it is observed that the bracing member in the edge spans yield first, followed by the inner spans.

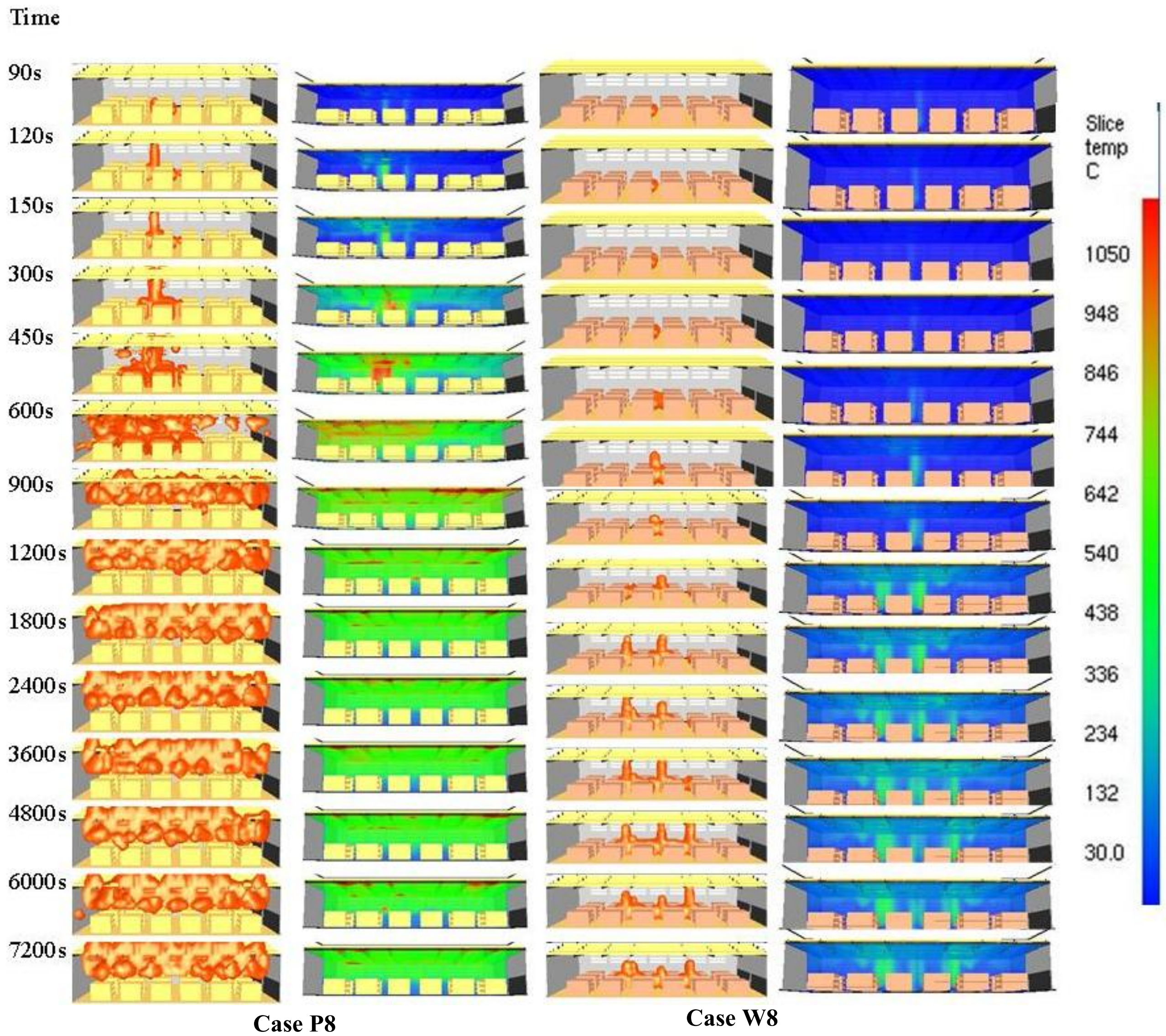

Figure 5. Flame Spread and Enclosure Temperature at Different Time Steps

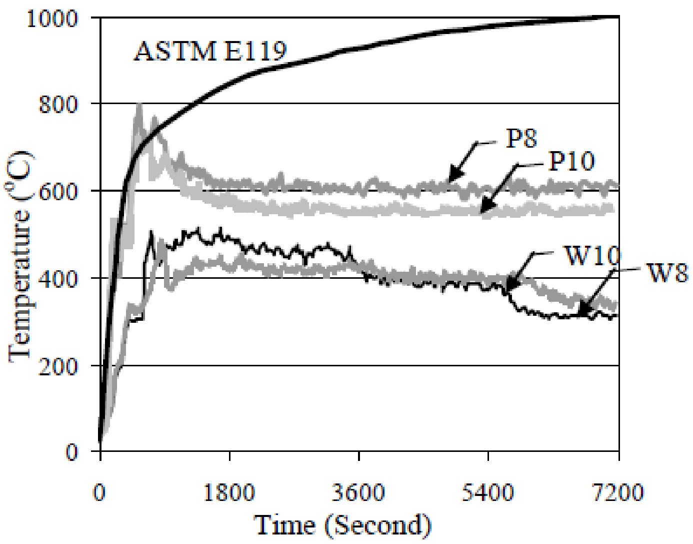

Figure 6. Variation of the Temperature at the Middle of the Roof Structure with Time

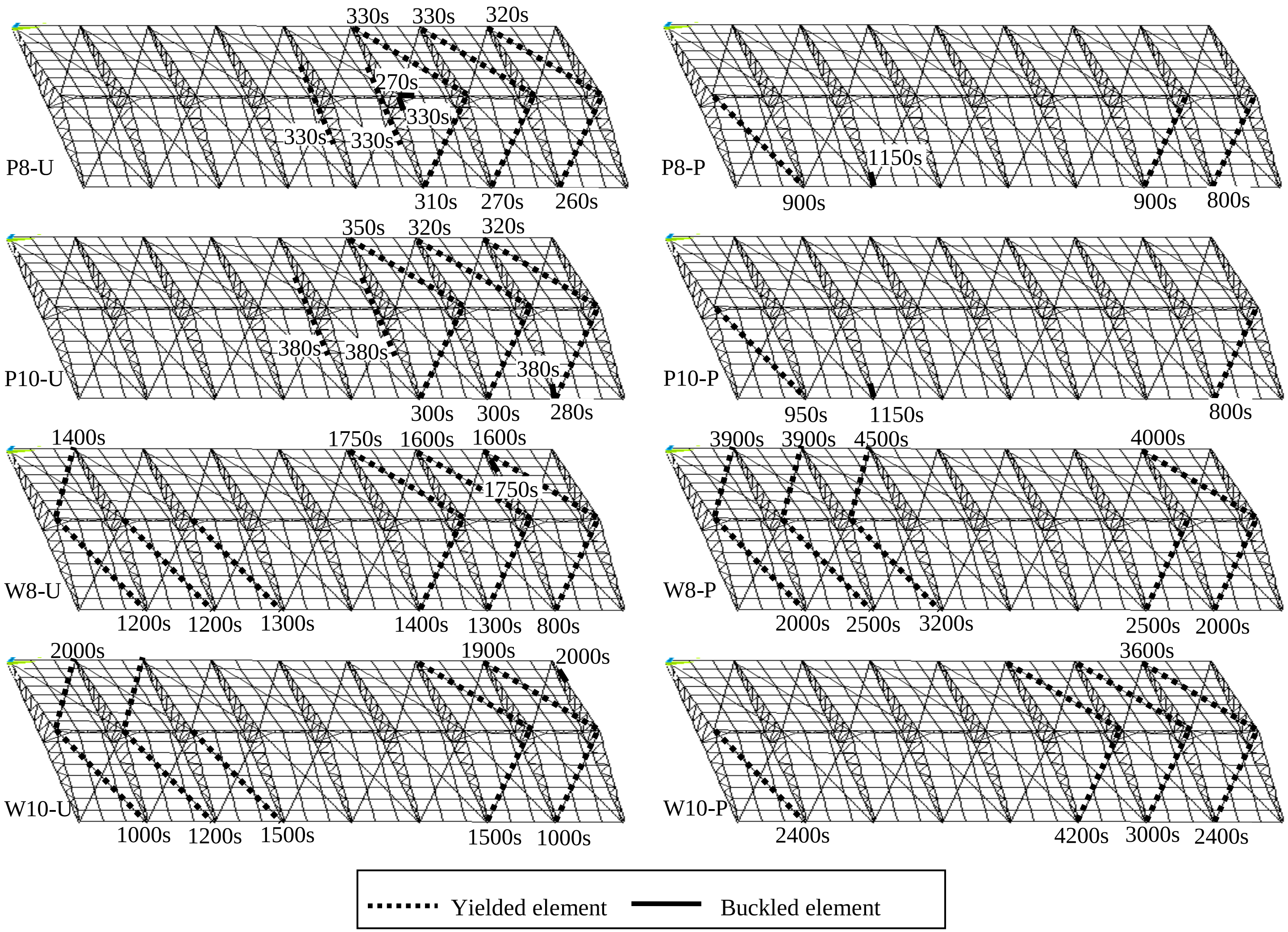

Figure 7. The Sequence of Failure for the Structural Member

The high temperature gradients between the upper and lower frame members induce higher tension in the bottom chords and higher compression in the top chords. The expansion of the roof structure in the longitudinal direction causes the main roof frames to sway horizontally with respect to their supports. This results in additional torsion, shear and moments due to the second-order ($P\text{-}\Delta$) effect. The situation can be illustrated in Figure 9. In particular, the combination of the increasing force, the deteriorating mechanical properties and the $P\text{-}\Delta$ effects causes some of the top chord members to fail in flexural buckling as shown in Figure 7. The failure of these members essentially indicates the failure of the structural system as shown in Figure 10.

The results obtained from the various fire scenarios can be summarized in Table 4. Based on the simulation results, it is found that the fuel type and fire protection of steel roof members significantly affect the time to failure. The scenarios in which the wood fuels are used and the roof members are protected yield considerably longer time to failure compared with the cases in which the plastic fuels are used and the steel is unprotected. The clearance height of the roof structure and the location of the ignition source are considered supplementary factors to the structural failure time. The 10-m clearance height slightly extends the failure time because of a slower feedback of heat from the burning contents. It should also be noted that for the plastic burning scenarios the failure time of the structural system with fire protection is significantly lower than the 1-hour fire resistance period as determined by the ASTM E 119 standard test.

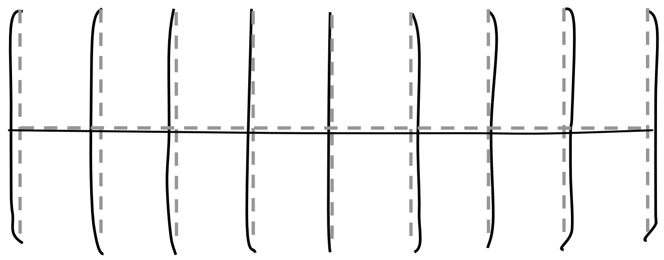

Figure 8. Longitudinal and Transverse Thermal Expansions of the Roof Structure for Case P8-P

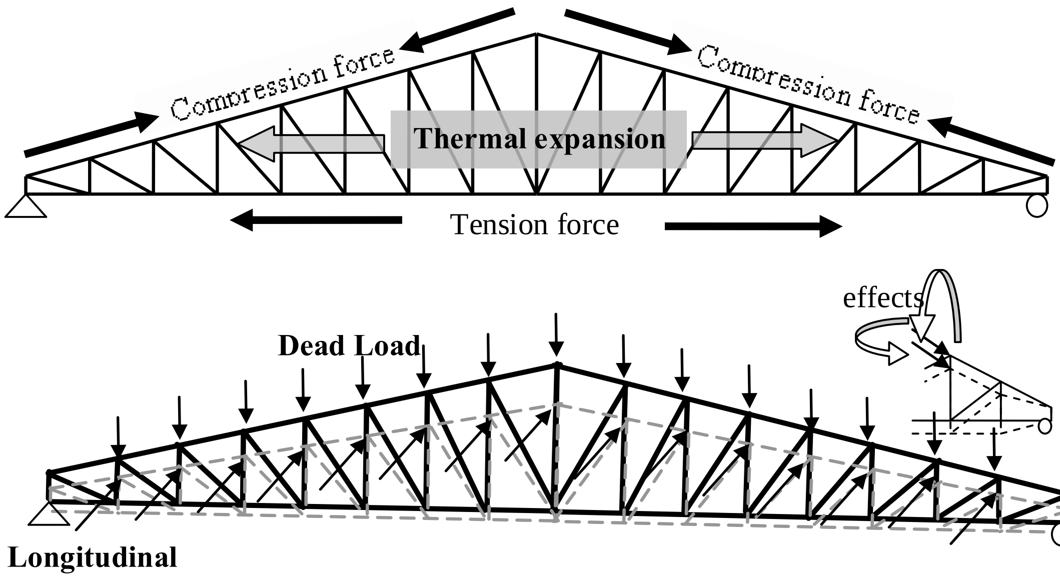

Figure 9. High-temperature Effects upon the Main Roof Frame

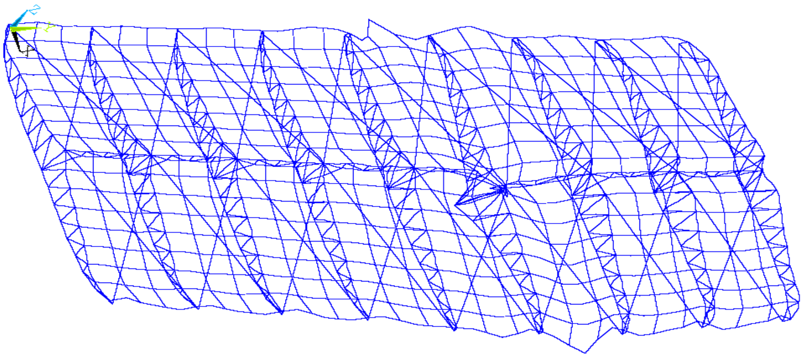

Figure 10. Failure of the Structural System

Table 4. Summary of Structural Failure Time

Case	Failure Time (second)	Maximum Temperature in Structural Members (°C)
P8-U	330	639
P8-P	1150	292
P10-U	380	639
P10-P	1150	275
W8-U	1,750	561
W8-P	>7200	565
W10-U	2,000	561
W10-P	>7200	521

Conclusions

Various fire scenarios are simulated in the current study to investigate the behavior of the steel roof structure of a typical warehouse. The fuel type (wood or plastic) and the clearance height (8 m or 10 m) of the roof structure are taken as the varying parameters. The different fire scenarios are modeled using the FDS program and the behavior of the steel roof frames is examined through a series of nonlinear finite element analyses. Based on the fire modeling results, it is found that the fuel type significantly affects the behavior of the modeled fire in terms of the fire growth and the spread of flames. The plastic contents result in a rapid fire growth due to the significant feedback of heat from the flames. The wood contents result in a considerably slower fire growth that occurs through direct radiation from the flames to nearby objects. Furthermore, the clearance height of the roof is found to have slight effects on the fire behavior.

Through the use of the simulation study, various aspects of the structural behavior under fire are observed. The failure of the roof structure is due to three key factors: the increasing axial force in tension and compression due to thermal expansion; the significant drop of the mechanical properties of steel due to the increasing temperature; and the P-Δ effects from the movements of the structure. In addition, the failure time of the roof structure depends upon the fuel type and whether or not the roof members are protected from fire. The highest risk is found for the cases of plastic storage contents without fire protection for the steel roof frame members. Note that, comparing with the investigated safe egress time or the failure time of the structure, the fire resistance of the fire protection based on ASTM E 119 may not be conservative for plastic contents.

It should, however, be noted that even though the proposed approach may be used as a framework for fire risk assessment of steel structures in accordance with the fire safety regulations. Further studies should be conducted to verify the assumptions adopted as well as to overcome the limitations of the proposed procedure.

Acknowledgement

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