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Fire Resistant Design of Steel Structure

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Abstract: When the steel structure is exposed to fire or elevated temperature is an extreme condition that leads to change in materials properties, consequently, change in overall behavior is expected. The strength of steel at high temperature of 550°C, hot rolled structural steel will retain 60% of its room temperature load capacity and would withstand before collapse. Research has shown, however, that the limiting temperature of a structural steel member is not fixed at 550°C but varies according to two factors, the temperature profile and the load. Many research efforts were devoted toward evaluation of materials performance when exposed to fire and high temperature events. Therefore, design of structures should incorporate measures to mitigate or prevent destruction of the structure while safeguarding safety issues related to human occupancy. Structures exposed to high temperature events (fire) are usually investigated to evaluate their structure integrity and performance. Several active and passive fire protection approaches could be taken to minimize or control the impact of fire on structures and their components; however, the change of materials properties and the loss of structure stiffness require comprehensive evaluation of the structure's performance to recommend the subsequent actions. In this paper, design recommendations and codes requirements for fire resistant design of steel structure according to Eurocode 3 are discussed.
Keywords: Firet; temperature; load; collapse; structure; strength; design.

I. INTRODUCTION

Fire is destructive which causes injury, death and loss of property followed by negative environmental consequences. Therefore, design of structures should incorporate measures to mitigate or prevent destruction of the structure whilst safeguarding safety issues related to human occupancy.

Steel elements have relatively low resistance to elevated temperatures thus causing failure of the overall structure. The expected behaviour is dependent upon the severity of the fire, material properties and the degree of protection provided.

II. FIRE RESISTANCE

The fire resistance plays an important role to ensure enough safety level of any building in case of fire. According to the European standards, this fire safety functionality is furthermore divided into three criteria on the basis of different safety objectives that a structural member can provide. The definition of above fire resistance criteria are:

1) Criterion "R" **-** load bearing capacity, which is assumed to be satisfied where the load bearing function is maintained during the required time of fire exposure
2) Criterion "E"–integrity separating function
3) Criterion "I" – thermal insulation separating function which is assumed to be satisfied where the average temperature rise over the whole of the non-exposed surface is limited to a certain level. In case of standard fire, this criterion may be assumed to be satisfied where the average temperature rise over the whole of the non- exposed surface is limited to 140 K, and the maximum temperature rise at any point of that surface does not exceed 180 K.

III. FIRE RESISTANCE ASSESSMENT OF STEEL STRUCTURE

The fire resistance of various steel members can be assessed with the help of the fire part of Eurocode 3 but it is necessary to have good knowledge about the following features:

1) Material properties of steel at elevated temperatures
2) Design approaches and tools
3) Partial factors for fire resistance assessment of steel structures

A. Material Properties of Steel at Elevated Temperatures

The steel structural fire design needs to deal with two different features, one relative to heating and another one concerning the load-bearing capacity of steel structures. In consequence, two types of material properties are necessary, that are:

1) Thermal Properties of Steel

The Thermal properties of steel changing with varying temperature as shown in Fig. 1. The thermal properties should be considered to be useful only for developing estimates of the thermal response of a concrete structural member.

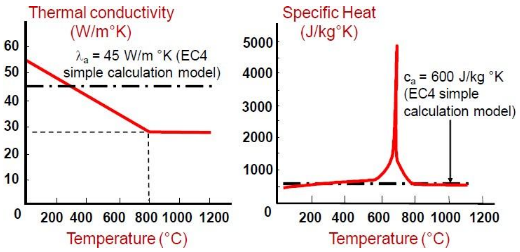

Fig. 1. Thermal properties of steel

The thermal properties of steel as a function of temperature includes the following factors are given below:

- Thermal conductivity
- Specific heat
- Density

2) Mechanical Properties of Steel at Elevated Temperatures

Structural steel begins to lose its strength and stiffness at temperatures above 300°C and eventually melts at about 1500° C. The mechanical properties of steel at temperatures above 450° C are strongly affected by creep, i.e., both stress and temperature histories influence steel deformations.

In the combined heating and deformation of steel, the total strain in this temperature range can be separated into three components:

- The thermal strain
- The instantaneous stress-related strain
- The time-dependent creep strain

Steel properties change with temperature. For a member at a nearly uniform temperature, the critical steel temperature in defined as the temperature for which, the load bearing capacity becomes equal to the effect of the applied loads. Failure will then occur.

B. Design Approaches and Tools

The fire resistance design of steel structure concerning the one of the following three approaches given below:

1) *Member Analysis*: Member Analysis**,** in which each member of the structure will be assessed by considering it fully separated from other members and the connection condition with other members will be replaced by appropriate boundary conditions.
2) *Analysis of Parts of the Structure*: Analysis of parts of the structure, in which a part of the structure will be directly taken into account in the assessment using appropriate boundary conditions to reflect its link with other parts of the structure.
3) *Global Structural Analysis*: Global structural analysis, in which the whole structure will be used in the assessment.

According to the fire part of Eurocode 3, three types of design methods can be used to assess the mechanical behaviour of steel structures in the fire situation in combination with different design approaches explained above.

One can use notably:

a) *Simple Calculation Models:* This type of design method comprises all the simple mechanical models developed for steel structural member analysis.
b) *Advanced Calculation Models:* This kind of design tools can be applied to all types of structures and are in general based on either finite element method or finite difference method. In modern fire safety engineering, it becomes more and more employed design approach due to the numerous advantages that it can provide.
c) *Critical Temperature Method:* This method is the most commonly used simple design rule for fire resistance assessment of steel structural members. As the most common design method for fire resistance assessment of steel structures remains the critical temperature method, it is very useful for all designers to get an accurate idea about the details of this design method.

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The step by step calculation procedure taking account of all necessary parameters for determination of the critical temperature of a considered steel member can be summarized as follows:

- Step 1: Determination of applied design load to a steel member in the fire situation
- Step 2: Classification of the steel member under the fire situation
- Step 3: Calculation of design load-bearing capacity of the steel member at instant 0 of fire
- Step 4: Determination of degree of utilization of the steel member
- Step 5: Calculation of critical temperature of the steel member
- Step 6: Calculation of the section factor of steel members
- Step 7: Calculation of the heating of steel members

C. Partial Factors for fire Resistance Assessment of Steel Structures

According to Eurocodes, the design values of the mechanical material properties Xfi,d are defined as follows:

$X_{fi,d} = k_\theta X_k / \gamma_{M,fi}$ (1)

where:

Xkis the characteristic or nominal value of a mechanical material property for normal temperature design.

kθis the reduction factor for a mechanical material property Xfi,d /Xk, dependent on the material temperature.

$\gamma_{M,fi}$is the partial factor for the relevant material property, for the fire situation.

TABLE I

PARTIAL FACTOR FOR YIELD STRENGTH OF STEEL UNDER THE FIRE SITUATION

Type of members	Ambient temperature design	Fire design
Cross-sections	$\gamma_{M0} = 1.0$	$\gamma_{M,fi} = 1.0$
Members with instability	$\gamma_{M1} = 1.0$	$\gamma_{M,fi} = 1.0$
Tension members to fracture	$\gamma_{M2} = 1.25$	$\gamma_{M,fi} = 1.0$
Joints	$\gamma_{M3} = 1.25$	$\gamma_{M,fi} = 1.0$

IV. CALCULATION OF PARAMETERS FOR FIRE RESISTANCE

A. Calculation of the Section Factor of Steel Members and Correction factor for Shadow Effect

The section factor is defined as the ratio between the "perimeter through which heat is transferred to steel" and the "steel volume". In addition, the following (conventional) rules apply:

- For box protection, the steel perimeter is taken equal to the bounding box of the steel profile
- For steel sections under a concrete slab, the heat exchange between steel and concrete is ignored.

Section factor including shadow effect for I-sections:

$K_{sh} = 0.9\,[A_m/V]_b / [A_m/V]$ (2)

Where:

$[A_m/V]_b$ is the box value of the section factor.

In all other cases the value of Ksh shall be taken as:

$K_{sh} = [A_m/V]_b / [A_m/V]$ (3)

B. Calculation of the Heating of Unprotected Steel Members

The increase of the temperature $\Delta\theta_{a.t}$ in an unprotected steel member during a time interval Δt (≤ 5seconds) may then be determined from:

$\Delta\theta_{a.t} = K_{sh}/c_a\rho_a . [A_m/V] . h_{net.d} . \Delta t$ (4)

where

Ksh is the correction factor for the shadow effect $\rho_a = 7850$ kg/m3

$c_a = 600$ J/kgK

C. Calculation of the Heating of fire Protected Steel Members

$$\Delta\theta_{a.t} = \frac{\lambda_p / d_p}{c_a \rho_a} \frac{A_p}{V} \left(\frac{1}{1+\phi/3} \right) \left(\theta_{g,t} - \theta_{a,t} \right) \Delta t - \left(e^{\phi/10} - 1 \right) \Delta\theta_{g,t} \quad (5)$$

where:

Δt is the time interval of which the value shall not exceed 30 seconds

$\theta a,t$ is the steel temperature at time t [°C]

$\theta g,t$ is the ambient gas temperature at time t [°C] $\Delta\theta a,t$ is the increase of the ambient gas temperature during the time interval Δt[K].

V. CONCLUSION

1) The fire resistant method is a new simplified approach based on Eurocode 3 part 1&2 which gives simple design basis by considering the various parameters for the fire resistant design of steel structure are discussed.
2) The heating up of a structural element depends on the type of element (e.g. pure steel or composite steel/ concrete) and of the nature and amount of fire protection.
3) To know the temperature of the structural elements as a function of time, it is necessary to calculate the heat flux to these elements.
4) The material properties, design approaches, design methods and design parameters according to fire resistance criteria followed by European standards are presented.

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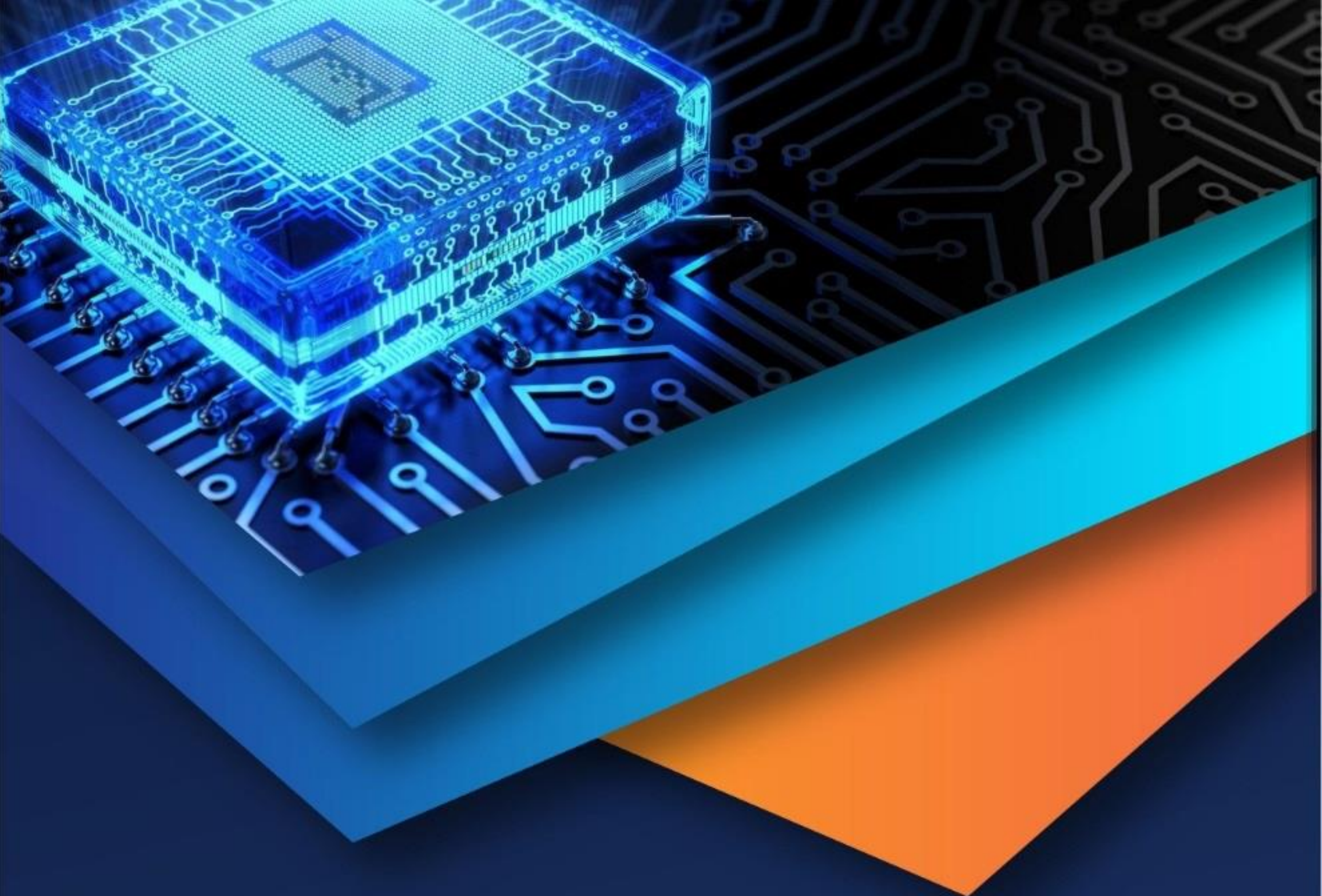

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