TÜRKİYE'DEKİ ÜNİVERSİTELERDE YANGIN MÜHENDİSLİĞİ MÜFREDAT PROGRAMI

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ÖZET: Yangın, yapılar üzerinde deprem kadar ciddi etkisi olan doğal bir afettir. Yapılarda ciddi yangın hasarları nadir görülmekle beraber, Türkiye'deki milyonlarca yapı stoku düşünülünce yangının ekonomide yarattığı yıllık ortalama maddi kayıp, depremin yarattığı kayıptan daha büyüktür. Kentsel dönüşüm ile Türkiye'de sayısı hızla artan yüksek katlı konut binalarında yangının etkisi incelenmelidir; çünkü bu binalar her ne kadar depreme dayanıklı yapılsa da bu konutların çoğu depremin ardından oluşabilecek bir yangına dayanıklı değildir. Bu yüzden, günümüzde yangın mühendisliğinin önemi ve donanımlı yangın mühendislerine olan ihtiyaç giderek artmaktadır ve yangın danışmanlarının çoğu teorik altyapıda yetersiz kalmaktadırlar. Bu altyapıyı sağlayacak tek yer üniversitelerdir ve maalesef Türkiye'deki yüksek öğretim kurumlarında yangın mühendisliği üzerine verilen dersler yok denecek kadar azdır. Yangın bilimi, ısı transferi, yapı analizi ve malzeme bilimi gibi birçok farklı araştırma alanını bir arada bulunduran yangın mühendisliğinin, inşaat mühendisliği lisans eğitiminde son sınıf ve yüksek lisans öğrencilerine verilmesi önerilmektedir. Bu çalışmada, farklı araştırma alanlarını tek bir çerçevede toplayan bilgisayar destekli yazılım uygulamalı bir ders programı tanıtılmıştır. Kapsamlı bir yangın mühendisliği analiz raporu çıkarabilecek bir altyapıyı öğrencilere verebilmek hedeflenmektedir.

Anahtar kelimeler: Yapısal yangın, yangın mühendisliği, eğitim.

Fire Engineering Curriculum in Turkish Universities

ABSTRACT: Fire is a natural disaster which can be as hazardous as earthquake on structures. Despite being a rare event, fire on structures has a higher consequence in terms of financial burden when compared with earthquake mainly because of millions of structure inventories in Turkey. With the advent of Urban Transformation Act, there is unprecedent rise in tall residential buildings in Turkey and fire safety in such structures must be investigated even though they are designed to perform well under earthquake. These structures are not resilient for fire conditions after a possible earthquake. The importance of fire engineering and the demand for expert fire engineers rapidly grows in Turkey and most of the fire counselors lack the theoretical foundation to guide in fire engineering. The only place to address this problem is the higher education institutions such as universities and unfortunately, fire engineering is almost non-existent in curriculum of Turkish universities. The multi-disciplinary fire engineering course, which encompasses fire science, heat transfer, structural analysis and material science is suggested to be introduced to senior undergraduates and graduate students. In this paper, a new framework in structural engineering curriculum is created to include multi-disciplinary fire engineering concepts backed up by computational software. The main goal is to provide students a proper foundation to create advanced fire strategy reports essential for performance-based engineering.

Keywords: Structural fire, fire engineering, education.

1. INTRODUCTION

The increase in number of tall residential buildings and current industrial buildings that require fire investigation due to vast amount of combustible materials that is stored in them, creates a high demand for fire consultants. Many fire consultants in the field are not academically trained due to the lack of fire engineering courses in Turkish universities. Fire engineering is a multi-disciplinary field which has three main pillars; fire science, heat transfer and thermomechanical analysis of structures. Therefore, course content suggested in this paper elaborates on these pillars.

Step by step procedure of writing a fire strategy report can be simplified as creating a design fire (time-temperature curve), estimating egress time from a structure, calculating the temperature distribution in structural members and finally conducting a structural system analysis with thermally induced forces. This procedure can be visualized with a flow chart shown in Figure 1 (Selamet, CE549 Course Lecture Notes). Students who successfully complete the fire engineering course should be able to combine the theoretical knowledge provided in the course with design applications of real-life case studies and learn how to write fire strategy reports.

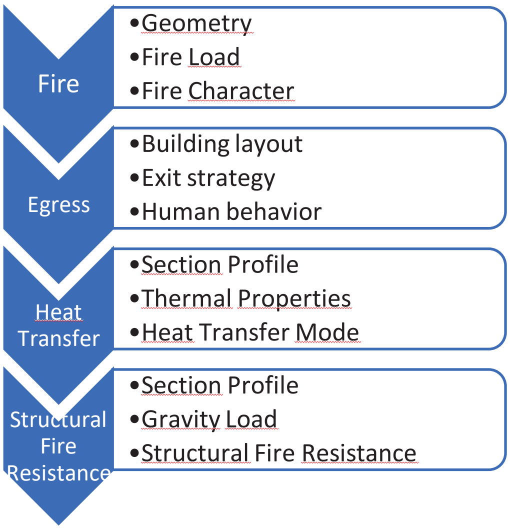


Figure 7:Flow Chart for Fire Engineering Pillars for Design

2. FIRE SCIENCE

Fire is an exothermic chemical reaction of an organic carbon based material which releases heat, carbon-dioxide, water vapor and reaction products based on the burning material. The simplest form of the complete combustion reaction is given in Equation 1. Here, "*other*" is the poisonous gases such as CO, SO_2, nitrogen oxide.

$$Fuel + O_2 = Heat + H_2O + CO_2 + N + Other \quad (1)$$

Complete combustion occurs repeatedly until the fuel or oxygen in the fire area runs out. Fire science is the first pillar in fire engineering and it investigates fire characteristic, fire growth and fire spread, which depends on the type of fire load as well as fire compartment ventilation.

2.1. Fire Event

In order to observe a fire event, an external source of heat is needed to raise the temperature of an object to its ignition temperature (Buchanan, 1999:39). Some of these external heat sources are; gas heaters, cigarettes, candles, etc. After the ignition, fire keeps growing until it reaches to a point where the external heat source is no longer necessary, which is defined as self-sustained fire. Fire starts to spread through other flammable objects and hot gases and smoke form a thick layer on the ceiling due to buoyancy. When the ceiling temperature due to the hot gases reaches

600^{o}C flashover occurs. Flashover causes every flammable material in the room to burn simultaneously, which leads to an accelerated increase in temperature and heat release rate. Beyond flashover, no human being can survive in the fire compartment. Fire curve shown in Figure 2 summarizes the fire event. Figure 3 visualizes pre-flashover stage and flashover stages.

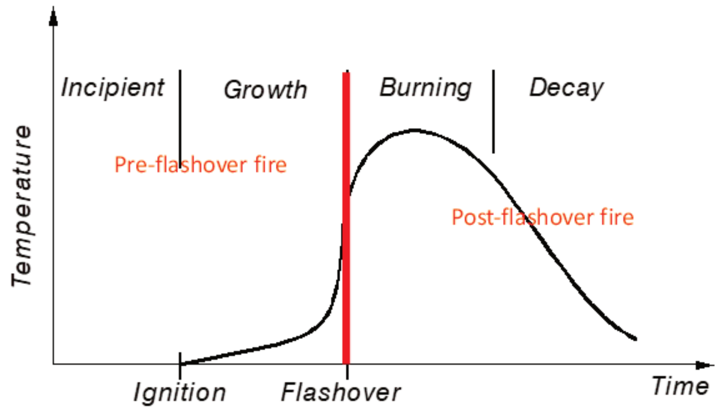


Figure 8:Fire Curve (Selamet, CE549Lecture Notes)

Figure 9: (a) Pre-flashover, (b) Flashover Stage

2.2. Fire Load (*E*)

The load for conventional structural engineering is due to mass of objects. The load for fire arises from the energy content of all the combustible objects inside the structure. Fire can occur in any region of the structure, which is defined as the fire area (A_f). Energy released by a combustible material is found by Equation 2. M represents the mass of the material and ΔH_c represents the energy released per kg burned. Equation 3 is used to calculate fire load per area.

$$E = M\Delta H_c (MJ) \tag{2}$$

$$q_f = E/A_f \ (MJ/m^2) \tag{3}$$

2.2.1. Heat Release Rate (*Q*)

Heat release rate (*Q*) in Watts (MJ/s) characterizes the fire growth and duration of the fire. The area under a heat release rate curve over the duration of fire (*t*) defines the energy content (*E*) as shown in Equation 5. Every combustible material has a different heat release rate. Generally, in a fire region, the heat release rates of all the different combustible materials are added to estimate the total *Q*. It is essential to know as the heat release rate is the single most important variable in determining fire hazard (Babrauskas and Peacock, 1992:255-272). Heat release rate is calculated with Equation 6. Fire growth is assumed to spread radially (Selamet, TBE:26) and therefore is proportional to the time squared and called t^2 - fire. Here represents the fire intensity coefficient (MJ/s^2). t^2-fires are used to construct pre-flashover phase of fire. Eurocode categorizes the fire growth as slow, medium, fast and ultra-fast depending on the material character in the fire compartment as shown in Table 1 (CEN, 2002).

3 L '/P:/,/O; (5)

3 L P6 (6)

Table 1: Fire Growth Rates of Typical Real Fires

Fire Growth Rate	**α ($1x10^{-3}$) MJ/s^2**	**Typical Material Contents**
Slow	0.00293	densely packed wood products
Medium	0.0117	Solid wood furniture such as desks, individual furniture items with small amount of plastic
Fast	0.0466	high stacked wood pallets, cartoons
Ultra-Fast	0.1874	upholstered furniture, thin wood furniture such as wardrobes

2.3. Compartment Fires

Unlike an open fire, compartment fires can be ventilation-controlled. Heat release rate in compartments depends not only on the burning rate of combustible materials but also on the fresh air inflow / hot gas outflow from compartment windows and radiation effects from hot gases accumulated in the ceiling. In order to calculate the fire time-temperature in a compartment fire, energy and mass balance equations must be formed as illustrated in Figure 4. The compartment is divided into hot and cold layers and mass and energy balance and interaction between layers are calculated for each layer at each time step as in Equation 7. Here, the first term is work done by hot gases, the second term defines the work done by pressure of hot gases and the third term relates to the net energy intake of the compartment by ventilation. On the right hand side of the equation, the heat release rate of fire as well as heat loss rate into the thermal boundaries (walls, floor and ceiling) are stated. The solution of this differential equation is performed at each time step and such numerical procedure is called “Zone Modeling”.

$$\rho c_p zA\frac{dT}{dt} - zA\frac{dp}{dt} + c_p \sum_{j=1}^{J} \dot{m}_j\left(T_j - T\right) = Q_f - Q_{wall} - Q_{rad} \qquad (7)$$

Most commonly used Zone Modeling Program is CFAST (Peacock et al., 1993). CFAST calculates the distribution of smoke and temperature throughout the rooms of a building during a fire. OZone (Cadiron et al., 2001) is another Zone Modeling Program to calculate the temperatures in the hot and cold layer, however, it does not estimate smoke distribution. Compartment fires can also be modelled and solved using computational fluid dynamics field analysis, which is a more complex approach compared to zone models. Field models give thermo-dynamic and aerodynamic variables for all discrete points in a fire region (Selamet, CE549 Course Lecture Notes).

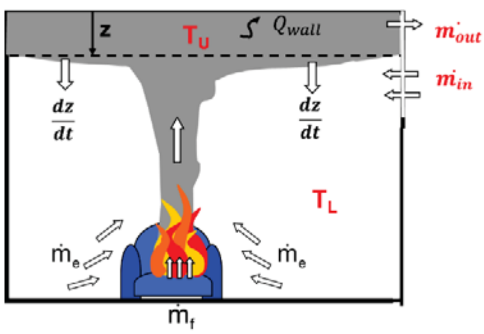


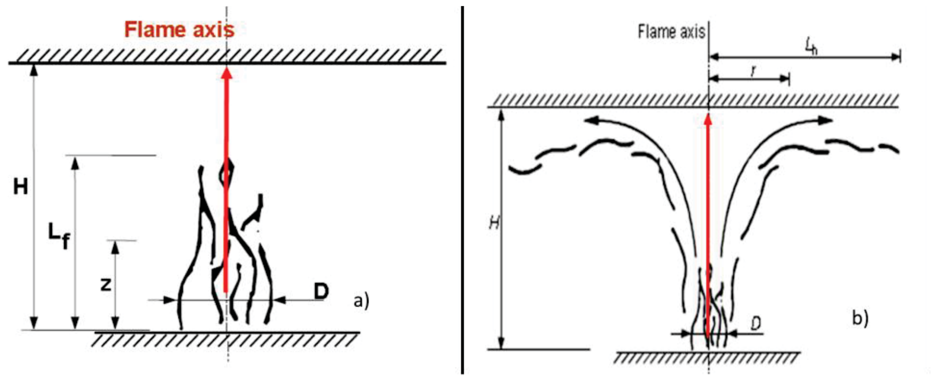
Figure 10: Compartment Fire Illustration (Zone Model)
(Selamet, CE549 Course Lecture Notes)

2.4. Localized (Open-air) Fires

A localized fire is described as an open-air fire with unlimited ventilation where the fire keeps growing as a function of time. Hot gases and smoke are generally unconfined. Most of the fires in growth stage are considered as local fires. These types of fires may be observed in large spaces such as atriums, theaters and car parks. Local fire burning duration is controlled only by fuel type and fuel amount not by ventilation. In local fires there are two different methods to calculate the temperatures at a specific flame height. Flame height is calculated with Equation 8 and here, D (m) represents fire diameter, Q (W) represents the heat release rate. Flame height determines which method to use for temperature calculations. As fire gets larger, the flame height decreases, and as fire intensity gets larger, the flame height increases. If fire impacts the ceiling Hasemi method is used, otherwise Heskestad method is used Heskestad Method and Hasemi Method localized fire illustrations are shown in Figure 5. The temperature calculations for localized fires can be found in Eurocode 3: Part 1-2 (2005).

$$L_f = -1.02D + 0.148Q^{0.4} \tag{8}$$

Figure 11: Fire Illustrations: (a) Heskestad Method, (b) Hasemi Method



3. HEAT TRANSFER

Energy difference in a material during a fire event results in a temperature increase. This energy difference is caused by the heat generated from fire transferred to material with conduction, convection and radiation. Therefore, temperature in structural members subjected to fire is calculated with these heat transfer modes.

3.1. Conduction

Heat is transferred in the structural material via conduction and governed by the 2nd order partial differential equation developed by Fourier. Here, T is the temperature, t is time and x, y, z are the space dimensions. Equation 9 is called the transient heat equation. The structural material properties density (ρ), thermal conductivity (k) and specific heat (c) are needed. Using classical approach such as Fourier Series or numerical approaches such finite difference or finite element method are needed to solve this equation for temperature *T(x,y,z,t)*.

$$\frac{pc}{k}.\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \tag{9}$$

3.2. Convection

Convection is the heat transfer between the structural material's surface and the surrounding gas (i.e. fire) and it is governed by Newton's Law of Cooling. The temperature difference causes heat exchange between fire (T_f) and structural material and heat flow per unit area q (W/m^2) is calculated with Equation 10. Here, h (W/m^{2}K) is the convective heat transfer coefficient and is generally taken as 25 W/m^{2}K for most of the fire exposed structural elements (Eurocode 3: Part 1-2, 2005).

$$q = h\,(T_f - T) \tag{10}$$

3.3. Radiation

Radiation is the heat transfer between fire (hot gas) and structural material or sometimes between two structural materials. The heat is transferred with electromagnetic waves (Buchanan, 1999:52). Radiation is the most important heat transfer process for fire engineering because at high temperatures, radiation dominates over other heat transfer modes. Heat flow via radiation is calculated with Equation 11, where the temperature is in Kelvin. Here, σ is 5.67x10^{-8} W/m^{2}K^4 (Stefan – Boltzmann constant) and ε is the resultant emissivity. Resultant emissivity is assumed as $\varepsilon = 0.7$ for steel and concrete materials ((Eurocode 3: Part 1-2, 2005, Eurocode 2: Part 1-2, 2004).

$$q = \varphi\,\varepsilon\,\sigma\,(T_f^4 - T^4) \tag{11}$$

3.4. Lumped Mass Method

Calculating the temperature distribution within the structural member is analytically cumbersome and numerically computer extensive. If only the average temperature of the structural member is sought, the calculation can be simplified using "Lumped Mass Method", where the structural member is seen as one single point which receives heat per unit time (Q) from fire from its fire exposed surface (A_m). Equation 12 shown the heat intake of the structural member per area and per unit time (Selamet, TBE: 51). The heat intake causes the structural member's temperature to increase according to Equation 13. Here, V is the volume of the structural section, A_m is the fire exposed surface and $\frac{A_m}{V}$ is called the section factor. The temperature increase ΔT is calculated at each time step Δt. Figure 6 illustrates this idealization. Lumped mass method is more suitable for steel and other highly conductive structural materials. For concrete material, the cross-sectional temperature distribution will vary significantly and therefore calculating an average temperature might not be sufficient.

$$\frac{Q}{A_m} = h(T_f - T) + \varepsilon\sigma(T_f^4 - T^4) \qquad (12)$$

$$\Delta T = \frac{A_m}{V}\frac{1}{\rho\, c}\left[h\left(T_f - T\right) + \varepsilon\sigma(T_f^4 - T^4)\right]\Delta t \qquad (13)$$

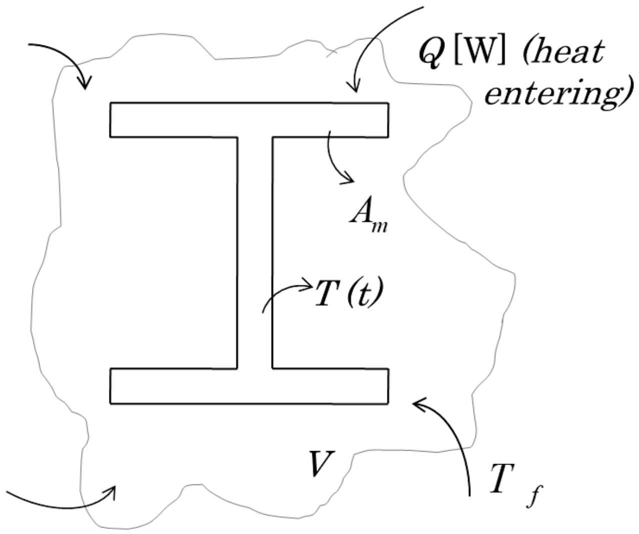


Figure 6: Illustration of lumped mass method used for a steel profile

4. FIRE RESISTANCE OF STRUCTURES

In fire engineering calculations, the first step is to design the fire scenario, then estimate the average temperature increase and the temperature distribution in the cross section of structural members and finally to calculate fire induced forces and moments created due to fire exposure of the structural system.

4.1. Thermal Strain

Thermal strain (ε_{th}) is the change in material length when the material is heated or cooled. It is called as free strain, because it does not create (mechanical) stress. Thermal strain depends on the thermal expansion coefficient α (1/°C) and average temperature increase (ΔT) as in Equation 14. α of steel and concrete are taken as 1.2×10^{-5} 1/ºC and 1.0×10^{-5} 1/ºC, respectively.

$$\varepsilon_{th} = \alpha \, \Delta T \tag{14}$$

4.2. Thermal Gradient

Temperature in a structural member's cross section is either uniformly distributed or non-uniformly distributed. Non-uniformly distributed temperature has a significant effect on the fire performance of a structural member. To account of such temperature distribution, thermal gradient concept $T_{,y}$ is used. A structural member can undergo an average temperature increase ΔT which causes elongation and thermal gradient $T_{,y}$ which creates bending deformation.

4.3. Structural Analysis of Restrained Members

Structural members in a structural system can be fully restrained, partially restrained or unrestrained in axial direction or in rotation at member ends. Depending on the degree of restraint boundary conditions, axial force and moment are induced in members during fire. Figure 7 illustrates a structural column member in a frame under both axial (k_{s1} and k_{s2}) and rotational (k_{r1} and k_{r2}) restraints at both ends.

4.3.1. Axial restraint

The thermally induced axial force P due to restraints on member ends is calculated as follows, where EA/L is the axial stiffness of the structural member:

$$P = \frac{AE\,\alpha\,\Delta T}{\left(1 + {}^{(EA/L)}\!/_{k_{s1}} + {}^{(EA/L)}\!/_{k_{s2}}\right)} \tag{15}$$

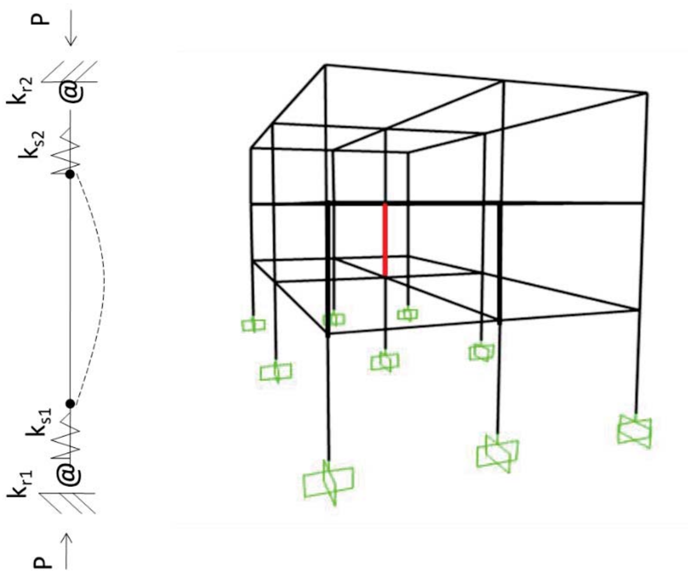


Figure 7: Partially Restrained Column Member (Red) in a Structural System of 3-Story and 2-Bay Frame (Selamet, CE549 Course Lecture Notes)

Simple capacity calculations can be performed to calculate the critical temperature (T_{cr}) of structural members under axial restraint. Critical temperature gives the failure temperature of the structural member. Members are categorized either slender or stocky and they are assumed to have elastic-perfectly plastic behavior. Slender members will fail from Euler-buckling while stocky members are expected to reach full yielding (σ_y) of the cross section. The critical temperature of slender and stocky members are calculated according to Equation 16 and Equation 17, respectively. Here, the members are assumed to remain straight. Here, k is the buckling coefficient, which depends on the rotational restraint boundary conditions. Figure 8 illustrates how T_{cr} depends on the slenderness ratio $\lambda = L/\sqrt{I/A}$ and degree of axial restraint k_s.

$$T_{cr} = \frac{\pi^2}{\alpha\,\lambda^2}\left(1 + \frac{E\,A/L}{k_s}\right) \tag{16}$$

$$T_{cr} = \frac{\sigma_y \left(1+\frac{E\ A/L}{k_S}\right)}{E\ \alpha} \tag{17}$$

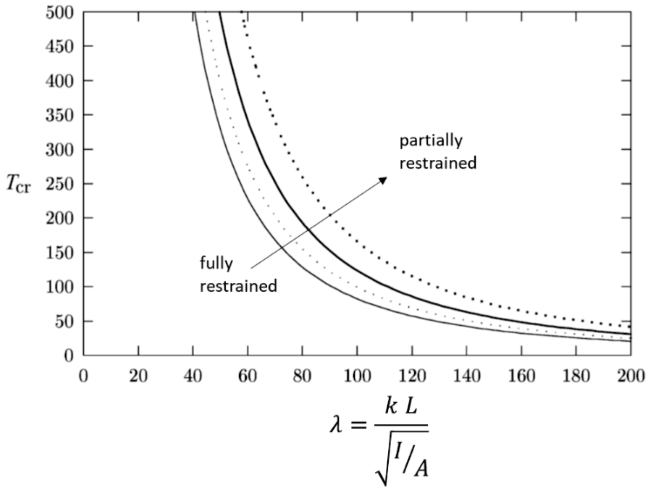


Figure 8: T_{cr} of slender cross sections with varying degree of axial restraint

4.3.2. Rotational restraint

Thermal gradient causes thermal curvature κ in the cross-sectional depth *d* due to thermal strain difference between the cold and hot region as shown in Equation 18. This difference over the cross section creates thermal bowing (bending) in the structural member. If the member is rotationally unrestrained (i.e. pinned), such bending does not create any bending moment, it only creates thermal (stress free) end rotation θ_T (Equation 19). For rotationally restrained members however, depending on the degree of restraints k_{r1} and k_{r2}, member end moments M_1 and M_2 along the structural member can be calculated using the beam-slope deflection method as in Equation 20, where the member end rotations θ_1 and θ_2 can be estimated with rather cumbersome Equation 21.

$$\kappa = \frac{\alpha T_{hot} - \alpha T_{cold}}{d} \tag{18}$$

$$\theta_T = \frac{L}{2}\ \alpha\ \frac{T_{hot}-T_{cold}}{d} \tag{19}$$

$$M_1 = 2\frac{EI}{L}(2\theta_1 - \theta_2) \qquad M_2 = 2\frac{EI}{L}(2\theta_2 - \theta_1) \tag{20}$$

$$\theta_1 = \frac{\theta_T\left(\frac{2EI/L}{k_{r1}}+1+\frac{4EI/L}{k_{r2}}\right)}{\left(1+\frac{4EI/L}{k_{r1}}\right)\left(1+\frac{4EI/L}{k_{r2}}\right)-\left(\frac{(2EI/L)^2}{k_{r1}\,k_{r2}}\right)} \qquad \theta_2 = \frac{\theta_T\left(\frac{2EI/L}{k_{r2}}+1+\frac{4EI/L}{k_{r1}}\right)}{\left(1+\frac{4EI/L}{k_{r1}}\right)\left(1+\frac{4EI/L}{k_{r2}}\right)-\left(\frac{(2EI/L)^2}{k_{r1}\,k_{r2}}\right)} \tag{21}$$

Bending capacity of structural members generally depends on the plastic moment resistance M_p about the plastic neutral axis PNA as shown in Equation 22. Since each layer in the cross section (see Figure 9) has a different temperature, the yield stress is reduced by k_y according to Eurocode 3: Part 1-2 (2005). Once, the moment capacity is estimated, the critical temperature of the member T_{cr} can be found.

$$M_p = \sigma_y \sum A_i\, y_{i,PNA}\, k_{y,i} \tag{22}$$

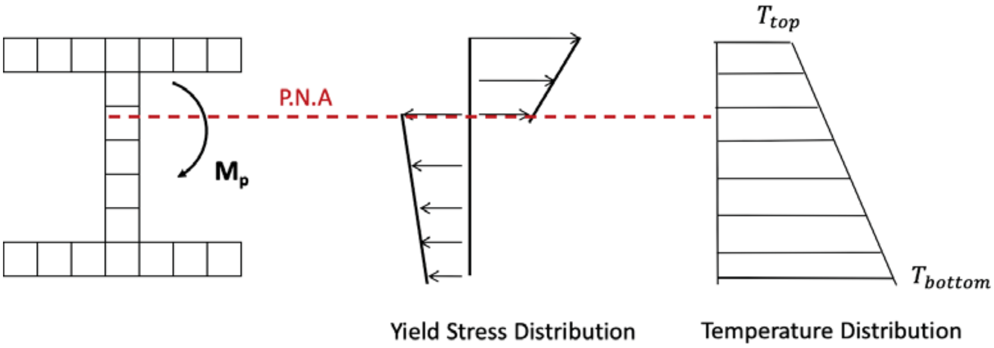


Figure 9: Illustration of the plastic moment resistance (M_p) calculation of an I-section where the section is heated from the bottom

4.4. Structural Analysis of the Entire Structure

Previous section estimated the axial force and moment demand on the heated structural member in a system with axial and rotational restraints. In order to estimate the effect of fire on the entire structure, it is necessary to solve simultaneous equations in matrix form (i.e. by using direct stiffness method or finite element method). For such analysis, simple hand calculations are not possible, hence commercial numerical software such as Abaqus and Ansys can be utilized. This procedure can involve material and geometric nonlinearity as well.

5. EGRESS

Safe egress is assumed to be achieved if RSET (i.e. time taken to reach safety) is sufficiently shorter than ASET, which defines the time when fire conditions within the building become untenable. Hydraulic model (SFPE)

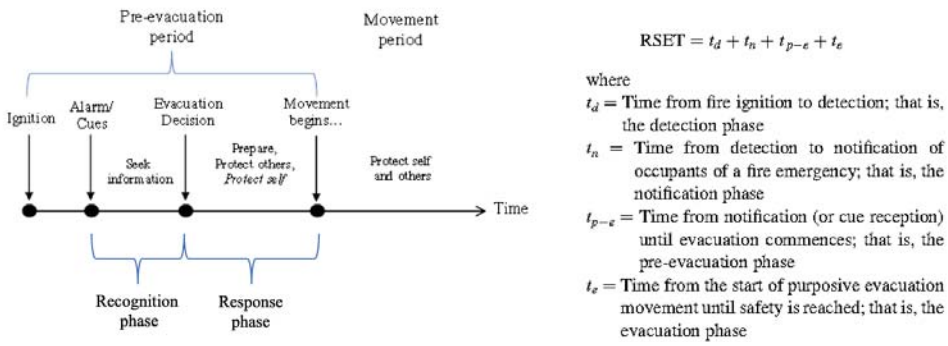


Figure 10: Egress time components

6. CONCLUSION

This paper gives a framework of a fire engineering design course which covers most of the fundamental theoretical knowledge for fire engineering principles such fire growth and heat transfer to structural fire design. Without having a good understanding of these concepts, fire engineering practice cannot improve in Turkey.

7. ACKNOWLEDGEMENTS

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