FIRE PROTECTION PERFORMANCE OF DIFFERENT INDUSTRIAL INTUMESCENT COATINGS FOR STEEL BEAMS

A Thesis

By

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FIRE PROTECTION PERFORMANCE OF DIFFERENT INDUSTRIAL INTUMESCENT COATINGS FOR STEEL BEAMS

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Dedicated to my father, Mevlüt Kocapınar (1955-2020)

ABSTRACT

This study covers comparison of fire protection performance efficiencies of two commercially available different intumescent coatings on two 1-meters steel beams which have S275 steel grade and UPN 200 steel sections for 2 hours by following ISO 834 fire curve in a furnace in Turkish Standards Institute (TSE) laboratory. Each beam was insulated with different industrial intumescent coatings to explore the efficiency of these intumescent coatings. Hence, all variables containing workmanship quality, period of application of intumescent coatings, steel grade, steel sections, furnace type, fire type and period of the experiment were kept constant except the type of intumescent coatings. First intumescent coating which is the Product A complies to BS 476-20,22 and EN 13381-8 and has an ISO Standards certificate. The Product B complies to ASTM UL-94 and EN 13381-8 and has a TSE certificate. 12 thermocouples were applied on each steel beams before the intumescent coatings performed to get temperature-time curves to determine the time to reach the critical temperatures of steel beams which were isolated. Fin EC software was used for the preliminary analysis to determine the critical temperatures and ABAQUS software was used to define the critical temperatures of each insulated steel beam and heat transfer analysis to compare with the temperature-time curves with experimental ones to have a better understanding of intumescent coating's thermal barrier duty in a case of ISO 834 fire type.

ÖZETÇE

Bu çalışma, ticari olan kullanılan iki farklı intumesan boyanın iki adet S275 çelik kaliteli ve UPN 200 kesit tipli 1'er metrelik çelik kirişe uygulanarak, Türkiye Standartları Enstitüsü'nün (TSE) yangın laboratuvarındaki fırında 2 saat süresince ISO 834 yangın tipine karşı yangına karşı koruma performanslarının verimliliğinin karşılaştırılmasını içermektedir. Her iki çelik kiriş, iki farklı ticari intumesan boya ile izole edilerek bu boyaların verimliliği açığa çıkartılmaya çalışılmıştır. İntumesan boya tipleri hariç olmak üzere uygulayıcı kalitesi, boyama süresi, çelik kalitesi, çelik kesiti, fırın tipi, yangın tipi ve deney süresi gibi tüm değişkenler sabit tutulmuştur. Product A diye adlandırdığımız birinci ürün ISO Standartlarına sahip ve BS 476-20,22 ile EN 13381-8'e göre uygunluk gösterecek şekilde test edilmiştir. Product B diye adlandırdığımız ikinci ürün ise TSE sertifikasına sahip ve ASTM UL-94 ve EN 13381-8 'e göre uygunluk göstermektedir. İntumesan boyaların kaplanmasından önce her kirişe 12 şer tane aynı lokasyonlarda olacak şekilde sıcaklık-zaman eğrileri elde ederek kritik sıcaklıkları belirleyebilmek amacıyla ısıölçerler sabitlenmiştir. Fin EC programıyla kritik sıcaklıkları belirlemek için ön analiz yapılmış olup, ABAQUS programıyla teorik olarak kritik sıcaklıklara ulaşma zamanı belirlenerek, elde edilen sıcaklık-zaman grafikleri karşılaştırılarak ve ısı analizi de yapılarak intumesan boyaların ISO 834 yangınına karşı termal bariyer görevi görerek yangından koruma performansları hakkında daha iyi bilgi sahibi olmaya çalışılmaktadır.

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ABBREVIATIONS

θ_a	Temperature
λ_a	Thermal conductivity
t	Duration in minutes
T_o	Ambient temperature in Celsius
B	Thermal inertia of the enclosure
$F_{o,cr}$	Opening factor
HRR_{max}	Maximum heat release rate
Ao	Compartment's initial area
E	Radiant energy
T	Absolute temperature
c_a	Specific heat capacity
ρ	Density
m	Mass
v	Volume
Δl	Change in length
l	Length
IF	Intumescent factor
d_0	Uncoated steel substrate thickness
d_1	Coating thickness
d_2	Char thickness
$\Delta\upsilon_{a,t}$	Increase of unprotected steel's temperature in the interval Δt
k_{sh}	Correction factor for shadow effect
c_a	Specific heat of steel (J/kgK)
ρ_a	Unit mass of steel (7850 kg/m^3)
Δt	Time interval (max value is 5 sec.)
$h_{net,d}$	Net heat flux
α_c	Convection heat transfer coefficient
υ_g	Gas temperature of the fire compartment
υ_m	Temperature of the steel component's surface

Φ	View factor
ε_m	Emissivity of the steel beam's surface
ε_f	Emissivity of the fire
σ	Stephan-Boltzman constant
k_{sh}	Shadow factor
$\Delta\upsilon_{a,t}$	Increase in temperature of insulated steel beam
λ_p	Thermal conductivity of fire protection
A_p/V	Section factor of the steel beam
$\upsilon_{a,t}$:	Temperature of surface of steel beam
$\upsilon_{g,t}$	Gas temperature of the compartment that's exposed to fire
Δt	Time interval
d_p	Thickness of the fire protection material
c_a	Specific heat of steel
$\Delta\upsilon_{g,t}$	Gas temperature
c_p	Specific heat of the fire protection material
d_p	Unit mass of the fire protection material

CHAPTER I

INTRODUCTION

Remarkable historical fires in steel structures indicated that temperature-dependent features of structural steel buildings' performance at elevated temperatures have vital importance to preserve lives and protect the steel structures against collapsing [1]. Steel structures that are exposed to fires might be results of terrorist attacks or earthquakes that induced fires. That is why any improvement of fire resistance of steel structures has been a critical issue for fire safety of steel design.

Table 1: Remarkable historical fires that exposed to steel structures [1]

Name of Building	Location	No. of Stories	Duration of Fire	Type of Structural Damges	Year
One New York Plaza	New York, USA	50	6-hour	Failure in bolted connections	1970
Alexis Nihon Plaza	Montreal, CA	15	13-hour	Collapse at 11th floor	1986
First Interstate Bank	Los Angeles, USA	62	3.5-hour	No collapse	1988
Broadgate Phase 8	London, UK	14	4.5-hour	No collapse	1990
Mercantile Insurance Building	Basingstoke, UK	12	---	No collapse	1991
One Meridian Plaza	Philadelphia, USA	38	19-hour	No collapse	1991
WTC 7	New York, USA	47	8-hour	Global collapse	2001
Windsor building	Madrid, Spain	32	20-hour	Partial collapse at top 10 stories	2005

Table 1 indicates the fire details of 8 steel structures which were exposed to fire. It is obvious that, there was no often global collapse in historical fires. On the other hand, WTC 7 was globally collapsed, and WTC 5 partially collapsed due to fire loads at elevated temperatures [1]. Hence, limiting fire risks for structural steel constructions is very crucial to prevent steel structure's damage and loss of lives.

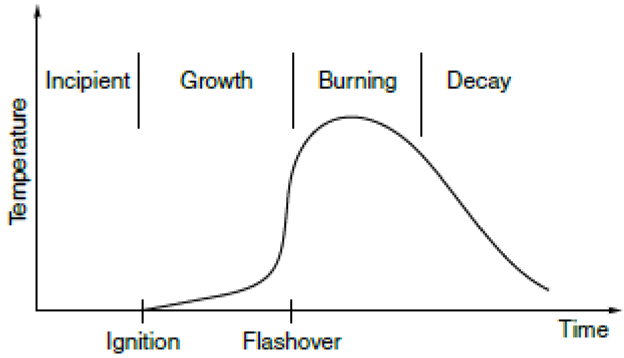


Figure 1: Fire development process [2]

A fire consists of 4 stages which are incipient, growth, burning and decay. Initiation begins with fuel heating process which is the starting point of the in the compartment. Then, it continues with the growth period which includes fire spreading on the surfaces of the compartment with the temperature increasing up to 600 º C. Fire is dominated by ventilation in burning stage by affecting the structural components. Lastly, temperature decreases in the decay period and fire by burning most of the material in the compartment is dominated again by fuel instead of ventilation [2]. Determining fire type in the furnace experiments is crucial due to the difference between the natural fire and the standard fire types. Standard fire types also have differences among each other due to the curve that is following or covering an explosion or not. Another point which is important is that standard fire types including ISO834 and ASTM E119 have an increasing temperature-time curve as fuel source is unlimited.

Two 1-meter UPN 200 S275 grade steel beams were used which were exposed to ISO 834 [3] fire type for 2 hours to determine the response of the steel beams which were isolated with the different commercially available intumescent coatings. The beams were unloaded in the fire test except their own weights. Furnace temperatures and steel temperatures were recorded using thin thermocouples. ASTM E119 (2010) standard [4] give permission to structural steel beams to be tested while they are exposed to or not exposed to axial loading. Under the circumstances of the TSE Laboratory, only thermal loads will be used and analyzed the response of the steel structure components. ASTM E119 and ISO 834 fire types have similar curves. TSE fire laboratory uses ISO 834 fire type if there is no explosion in the fire scenario. ISO 834 has also an advantage about not having a limitation about the compartment size in where fire occurs. Hence, ISO 834 was preferred in this research explaining the differences between them. TSE Fire Laboratory and Efectis Laboratory are the two only centers that furnace fire tests can be performed to be certificated in Turkey.

Figure 2: Test Furnace in TSE Laboratory

Steel surface temperature is the most significant key which determines the strength and essential behavior of steel components. 12 thermocouples were fixed on each steel beam' surface under the coatings to get the steel surface temperatures correctly. An important issue for numerical calculation to predict the temperature of the steel beam is using conduction or not in heat transfer. Conduction is used in addition to convection and radiation for protected steel which is not exposed to fire directly. Heat is transferred by the means of intumescent coating to the steel beam by the conduction with the help of free electrons of the intumescent coatings. Furnace inside temperature or gas temperature is the same as the outer surface of the intumescent coating and steel beam's surface temperature where thermocouples were applied on is the same as the inside surface temperature of the intumescent coating. On the other hand, unprotected steel's temperature increases only by convection and especially radiation which is a dominant factor for heat transfer from the burners to the unprotected steel. 3D finite element models are the important tools which can be used to forecast the steel components' behavior at elevated temperatures. FRR that means fire resistant rating that is defined according to their minimum values by current codes by attending ISO-834 or ASTM E119 standard fire tests. Design FRR values are yielded when the temperature of structural steel beam's cross-section reaches 593 ^{o} C which is indicated at Table 2. Although structural steel's critical temperature was indicated as 538 ^{o} C at Table 2, it is valid only for steel columns. Structural steel beam's critical temperature is greater than steel column and it is 593 ^{o} C.

Table 2: Critical Temperatures of Different Types of Steels [4]

Steel	Standard / Reference	Temperature
Structural Steel	ASTM	538 ^{o}C
Reinforcing Steel	ASTM	593 ^{o}C
Pre-stressing Steel	ASTM	426 ^{o}C
Light - gauge Steel	Eurocode 3	350 ^{o}C
Light - gauge Steel	Gerlich et al	400 ^{o}C

Patade and Chakrabarti [5] showed that tests that apply to steel structures are lack of providing adequate information about the structural mechanics of the systems and interaction between connections and members when they are exposed to a realistic fire.

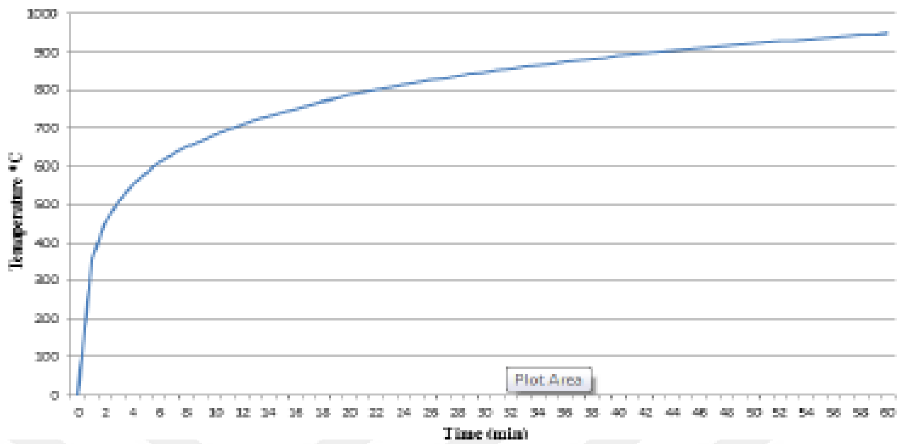


Figure 3: ISO 834 Temperature-time curve [6]

ISO 834 which is shown in Figure 3, was used in the experiment is the international standard which has a time-temperature curve can be formulated as:

$$T = T_o + 345 \log_{10} (8t + 1) \tag{1}$$

t: duration in minutes

T_o: 20 °C which is ambient temperature in °C

1.1 Literature Review

Summarizing the research previously that contributed to the field of thermal responses of steel components and insulated structural steel structure systems at elevated temperatures when they are exposed to fire is the aim of the literature review.

Fire resistance of metallic structures is a crucial field which grabs the attention of structural engineers and researchers. Damage indices are strain and displacement in structural steel components. These displacements generally can be consequences of earthquake or fire with the addition of many other factors. Especially, fire hazard is the basic threats for steel structures which have melting temperatures about 1425 - 1540 °C.

Table 3: Esential physical properties of steel

Metal / Physical properties	**Steel**
Melting temperature	1425 - 1540 °C
Thermal elongation	$12.10^{-6}C^{-1}$
Thermal conductivity	54 W/m°C
Density at 20°C	7850 kg/m^3
Specific heat	440 J/kg°C
Shear modulus	81000 N/mm^2
Poisson's ratio	0,3
Modulus of elasticity	210000 N/mm^2

Crucial fire effects involve: (1) Thermal deformations which lead to internal stresses with second-order effects; (2) Degradation of stiffness and strength of the metals with worsening deformation state by accompanying a decrease in carrying capacity. Mechanical and geometrical nonlinearities, residual stresses, creep phenomena and real evolution of metals' mechanical behavior under fire at various temperatures.

Long span bridges and high-rise steel structures with increased strength and increased lightness are constructed by high strength steel (HSS) that are more fire-resistance at elevated temperatures against fire. High strength steel (HSS) is type of steel that have nominal yield strength more than 460 MPa. There are two methods for determining steels' mechanical properties at high temperatures, transient-state and steady state. Stress-strain curves of HSS determine the mechanical properties of HSS such as yield strength, tensile strength, and elastic modulus [7].

Table 4: Analysis of reduction factor for HSS' elastic modulus [7]

T (°C)	Q460 [3]	S460N [9]	S460M [9]	S460N [11-13]		S690QL [15]		RQT- S690 [16]
				Steady	Transient	Steady	Transient	
20	1	-	-	1	1	1	1	1 (25°C)
100	0.983	1	1	0.985	0.989	1	0.982	1.01
200	0.960	0.885	0.976	0.881	0.870	0.875	0.869	1.02
250	0.945	0.838	0.964	0.840	0.831	0.857	0.857	0.99
300	0.928	0.791	0.952	0.799	0.792	0.839	0.841	0.96
350	0.911	0.730	0.920	0.712	0.702	0.807	0.781	0.99
400	0.885	0.668	0.887	0.669	0.666	0.775	0.736	1.01
450	0.862	0.575	0.796	0.578	0.585	0.730	0.692	0.91
500	0.836	0.481	0.704	0.509	0.482	0.685	0.647	0.77
550	0.809	0.392	0.555	0.374	0.359	0.546	0.537	0.72
600	0.764	0.302	0.406	0.291	0.272	0.372	0.370	0.66
650	0.636	0.219	0.305	0.248	0.222	0.257	0.204	0.38
700	0.480	0.135	0.204	0.153	0.132	0.141	0.099	0.34
800	-	0.049	0.105	-	-	-	-	0.29
900	-	0.017	0.038	-	-	-	-	-

Reduction factor for elastic modulus changes relying on fabrication method, HSS type, tests that are applied and alloy composition as shown at Table 4. Hence, improvement of fire resistance of steel structures can be done by changing the steel grades or their composition without any insulation process on the steel structures. For instance, molybdenum is extremely critical for improvement of steel structure's fire resistance because of boosting steel component's creep and yield strength at elevated temperatures in a case of fire. 300 º C is important temperature in this type of steel structures, when exceeding this temperature, loss of mechanical properties initiates.

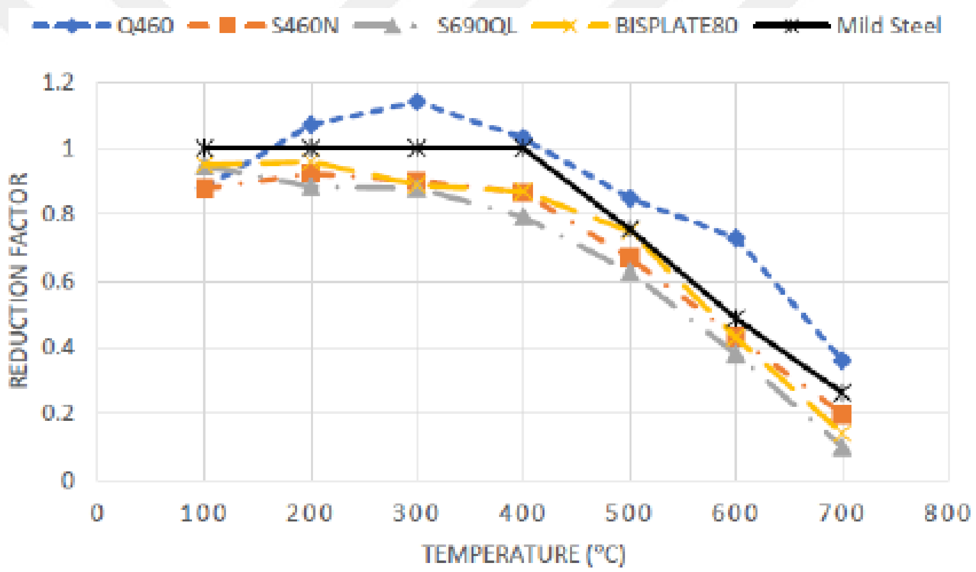


Figure 4: Yield strength reduction factors for different HSS [7]

Mechanical properties for HSS at high temperature do not indicate significant decrease before the HSS's surface temperature's arrival at 300ºC [7].

According to Eurocode design for steel structures, steel's strength loss which is approximately 50 % of its strength at 600 º C is enough for a steel structure to fail. This is the reason why fire safety is one of the principally preferences of designing and constructing the steel structures because of easiness of reaching 600 º C in a case of fire.

Specifically, fire resistance of high-rise steel structures has been a critical field since 9/11 attack in 2001 which indicated that biggest risk for the integrity and serviceability of steel structures and their components is the fire hazard.

Fire safety design for steel structures must be considered effectively to save the lives and properties to save an appropriate structural analysis and design in a fire case. The effect of thermal creep is a crucial determinant which must be get into account during the fire. Complex design complexes can be fulfilled more cost effectively and safer with the help of these steel structures. As Kodur and Dwaikat [8] stated specific heat, thermal expansion, thermal conductivity, high temperature creep and stress-strain curves are steel components' temperature-dependent characteristics which directly affect the steel structure's durability against the thermal loads when the steel structure is exposed to fire. These temperature-dependent thermal properties are critical values for 3D modelling and mathematical calculations for predicting temperature-time curves and thermal analysis.

End restraints have effects on steel structures' thermal behavior when they are exposed to fire. Assuring steel structure's stability before it gets damaged under the fire before the fire explosion and reducing the fire damages to the environment are two demands that must be performed when designing steel structure's performance in the case of fire. After the adoption of Eurocodes about fire design leads to a decrease about the loss of lives during the fire since 1985.

Buchanan [3] asserted that load bearing capacity of a steel structure is affected and determined by fire load, fire characteristics, element geometry and section's mechanical properties when the structural steel is exposed to fire.

A decrease in ultimate strength and yield strength of the steel component is the consequence of grain change of the structure when the steel component's temperature rises to 100 ^{o} C or above as shown in Figure 5 [9]. Temperature increase results in a decline in the yield point of the structural steel which play a key role in structural failure when it is subjected to the fire and loss of determined yield plateau is a result of temperature rise [10]. Buchanan [3] explained that this loss is the result of loss in strength and stiffness of the steel which happens when the temperature is around 600 ° C in a fire case.

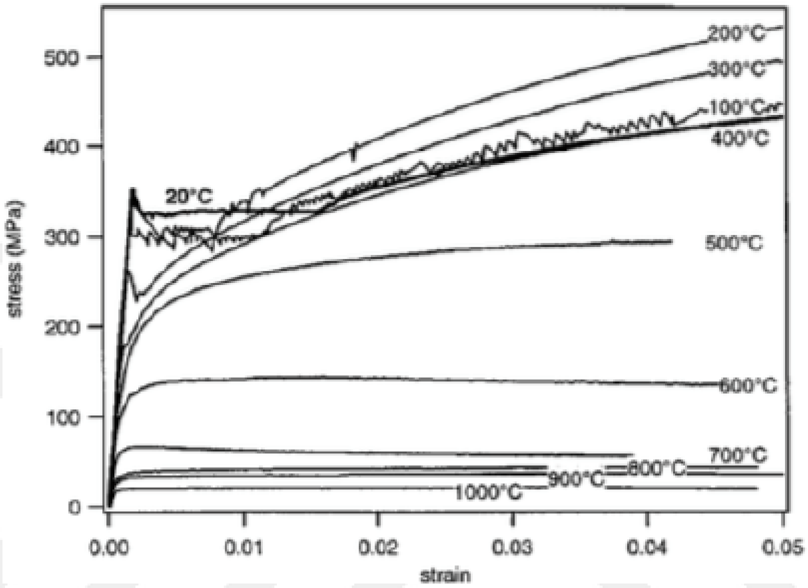


Figure 5: Stress-strain behavior change of steel with respect to temperature change [3]

Fire design approach is based on the steel structure's type and the part of the steel structure which must be analyzed as indicated in Figure 6.

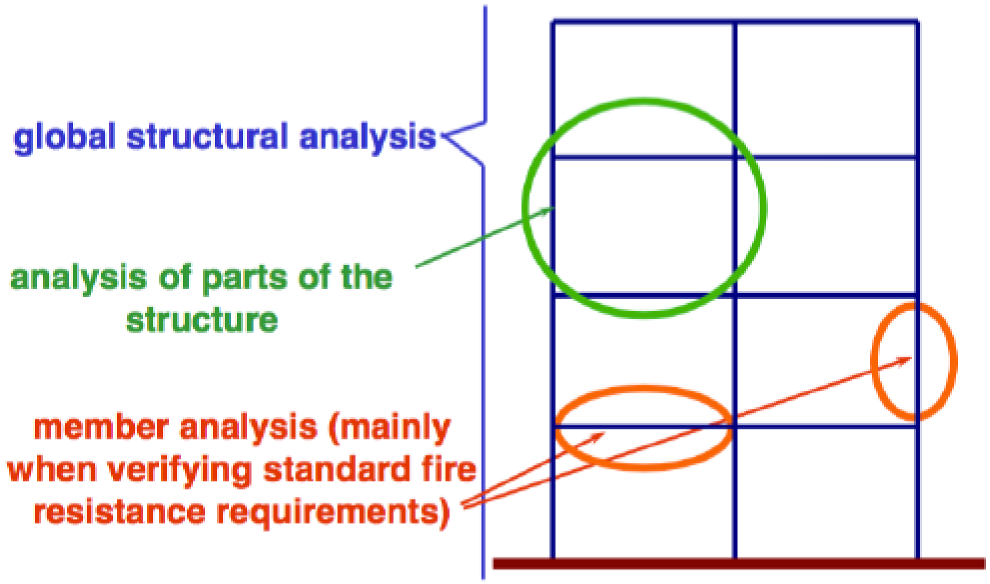


Figure 6: Three major design approaches to ensure fire safety and structural fire analysis [11]

Although Tide [12] asserted that restrain within the structure chiefly leads to rise in steel structures' stress levels in a case of fire, McCann et. al [13] claimed that increase in temperature because of fire that leads to a structural steel failure because of stress addition which is caused by temperature increase.

1.2 Design of a Standard Fire

Eq. 2 as shown below is a requirement which must be fulfilled to have ISO 834 standard time-temperature curve in the heating process.

$$\frac{\left(\frac{Fo}{b}\right)^2}{(0.04/1160)^2} = 1 \qquad (2)$$

Where,

b: thermal inertia of the enclosure that is 497 J/m^2 s$^{1/2}$ K

$$F_{o,cr} = (0.04/1160)^b \text{ (opening factor)} \quad (3)$$

The opening factor of the compartment that will be exposed to fire must surpass the one that is derived by Equation 2. $F_{o,cr}$ is 0.017 $m^{1/2}$ for the realistic fire whereas compartment's opening factor is 0.045 $m^{1/2}$ which ensure the ISO 834 or ASTM E119 fire surroundings with the same ventilation [11].

Compartment's maximum heat release rate can be measured as:

$$HRR_{max} = 1500\ Ao\ \sqrt{Ho} \quad (4)$$

1.3 Comparison of ISO 834 and ASTM E119

Criticisms have been evolved throughout the differences between the real fires and the standard fires' (ISO 834, ASTM E119 etc..) temperature-time curves due to the irrelevances depending on actual construction practices and/or construction materials methods in order to define FRR (fire resistance ratings) relying on realistic structural engineering approaches and limitations have been crucial.

Fire Resitance Rating of the structural steel component is determined by the duration of time that component can endure standard fire exposure by performing specific performance criteria.

Deriving temperature-time curve for defined fire scenario which was preferred as ISO 834 in this experiment and research for the response of thermal behavior of isolated with different commercially used intumescent coatings on two structural steel beams which were exposed to fire in the furnace by following ISO 834 fire curve. Modelling these isolated structural steel beams using ABAQUS software and deriving the critical temperatures of each isolated beams with the help of ABAQUS software from the temperature-time curves have been the basis of my thesis. FIN EC software was used for preliminary analysis to verify the critical temperatures. An important limitation of the experiment at TSE Laboratories was that only two isolated structural steel beams were tested instead of the entire steel structure.

Time to failure and Fire resistance rating (FRR) are two essential criteria for the experiment. Determining and comparison of actual fire values and values that are derived from the ABAQUS software also gave a view for the isolated structural component's thermal behavior and response against the ISO 834 fire.

ISO 834 and ASTM E119 by defining the fire resistance of isolated structural steel systems by using response of the isolated structural steel components in a fire case have been an essential background for defining fire resistance ratings in the applications of building codes for one century.

Discussions of these standards have been focused for not accurate representatives for temperature-time curves of real case fires. A real fire time-temperature curve which is indicated in Figure 7, contains three periods with ignoring initiation period which covers growth, fully developed and decay processes. On the other hand, time-temperature curve of a standard fire consists of a constantly raising time-temperature curve. Standard time-temperature graph in Figure 7 belongs to ASTM E119 or ISO 834 fire types.As it is indicated that it behaves as fuel source is continuous,so it has an increasing fire curve which covers heating phase of a natural fire, on the contrary, fuel source is limited and temperature must decline after 70 % of the fuel in the compartment burned. Hence, ISO 834 or ASTM E119 is used only for guidance instead of following a real fire curve. Another important difference between a realistic fire and a standard fire includes whether the heating is uniform or non-uniform. A realistic fire contains a non-uniform heating processdepending on the fuel capacity of the compartment, on the contrary, a standard fire covering External Fire, Hydrocarbon Fire, ASTM E119 and ISO 834 involves a uniform heating phase in the lfire laboratory conditions.

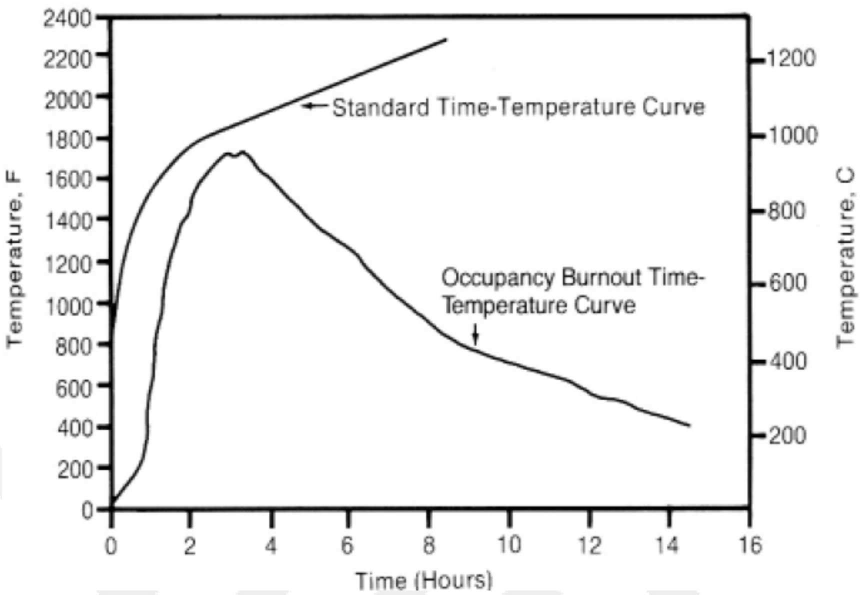


Figure 7: Comparison of Time-Temperature Curve of Realistic and Standard Fire Types [11]

Gas temperature in furnace at TSE Laboratory is the function of radiant heat and convective heat which is an effect of heat source. On the other hand, radiant heat which is affected mainly by furnace walls which might be different in every test laboratory is remarkable to get accurate data after the experiment.

Main drive for the isolated steel structure beam’s entire heat release rate is radiant energy which has a correlation with absolute temperature to the 4^{th} power as shown in (2). Conduction is another way for heat transfer for the isolated steel beams. By the means of conduction, heat transfer slows down and temperature increase rate is slower the furnace inside and gas temperature.

$$E = \sigma T^4 \quad (5)$$

Where,

$\sigma = 5.67 \times 10^{-8}\ W/m^2/K^4$ (Stefan's constant)

E= Radiant energy

T= Absolute temperature

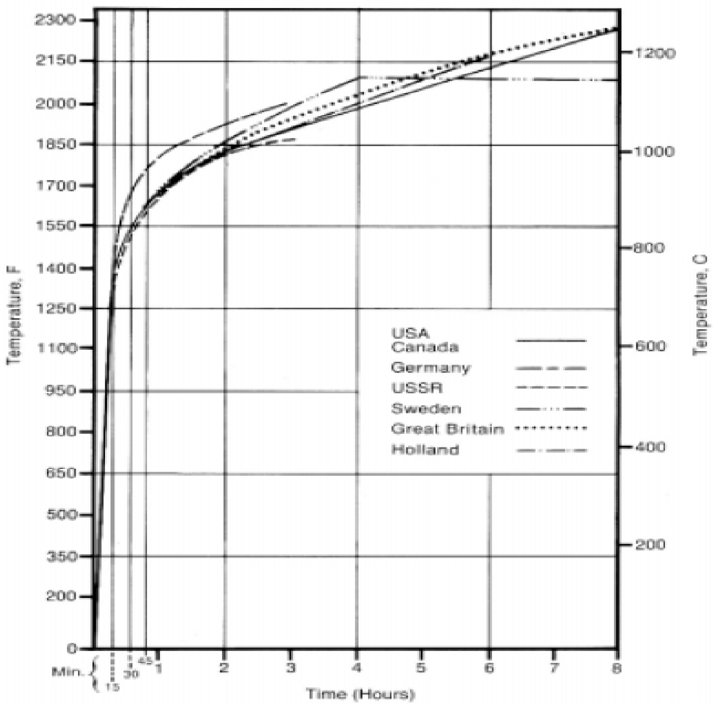


Figure 8: Standard Test Curves of Different Countries [10]

So, furnace wall's type and construction type directly affect the radiation energy in a fire test experiment. This is a weakness point of actual fire test standard and discrepancy between these international standards and realistic fires as indicated in Figure 8.

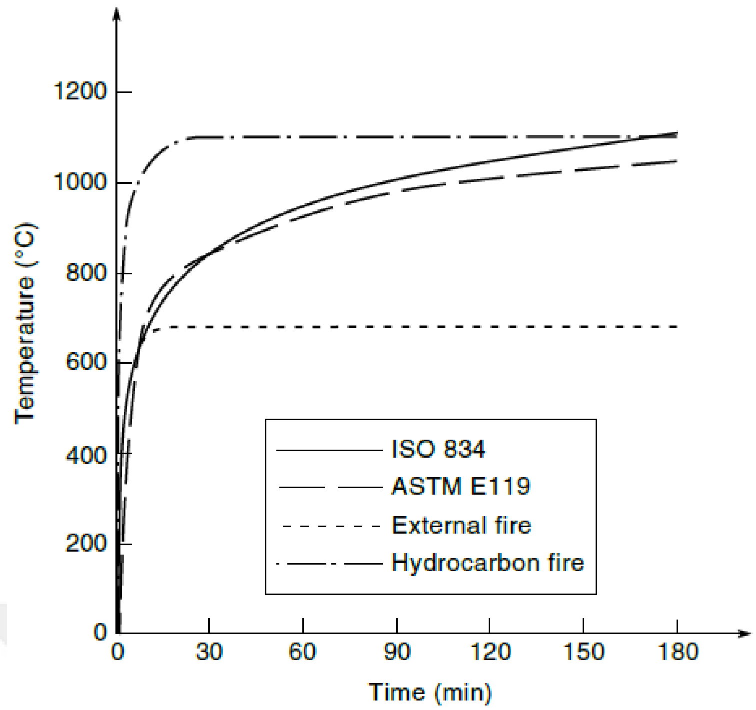


Figure 9: Temperature–time curves of different standard fire types [3]

As mentioned before ISO 834's time-temperature curve can be formulated as:

$$T = T_o + 345 \log_{10} (8t + 1) \quad (6)$$

t: duration in hours

T_o: Ambient temperature in ^{o}C

Another commonly used standard fire curve ASTM E119 temperature-time curve equation is as follows:

$$T_g = 20 + 750 \left(1 - e^{-3.79553\sqrt{th}}\right) 170.41\sqrt{t_h} \quad (7)$$

T_g refers to the gas temperature of the environment and t_h refers to time in hours [3].

1.4 Thermal Conductivity

Thermal conductivity is a kind of heat transfer rate through a unit area including a temperature gradient of 1 degree for every unit displacement. Heat conduction rate of a structural steel component is 50 W/m K at 20 ° C. On the other hand, Buchanan [3] stated that thermal conductivity of steel λ_a can be taken 45 W/m K for simplicity in calculations.

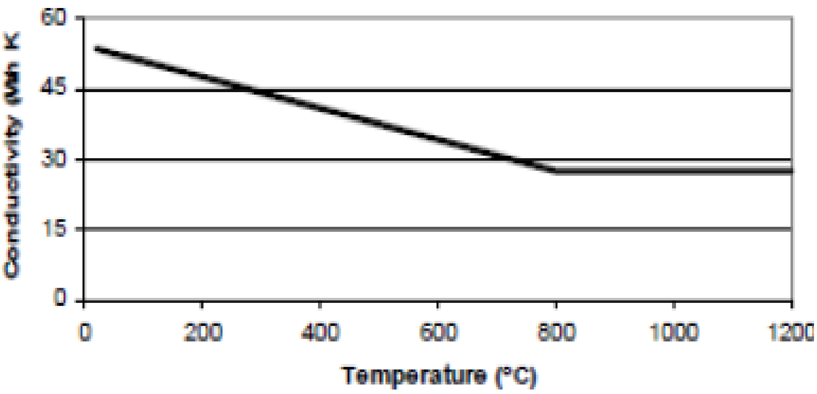


Figure 10: Thermal conductivity of structural steel according to EN 1993-1-2

It is obvious in Figure 9 that steel's thermal conductivity decreases linearly because of temperature increases up to 800 ° C which means that higher the thermal conductivity of steel the lower the temperature needed to heat the steel component.

A steel section's thermal conductivity which varies as the temperature increases formulas in different ranges of temperatures according to EN 1993-1-2, are defined as below:

$$\lambda_a = 54 - 3.33 \times 10^{-2}\, \theta_a \quad \text{where } 800\,^{\circ}C > \theta_a > 20\,^{\circ}C \tag{8}$$

$$\lambda_a = 27.3 \text{ where } 1200\,^{\circ}C > \theta_a > 800\,^{\circ}C \tag{9}$$

θ_a and λ_a are temperature (° C) and thermal conductivity (W/mK) of the steel which are exposed to fire, respectively. An important issue in calculating the surface temperature of isolated steel beam's surface temperature is taking the thermal conductivity of the isolated steel beam's thermal conductivity as constant. Thermocouples were fixed on the surface of the isolated steel beams, So, there is no need to calculate the thermal conductivity change. Although intumescent coating's thermal conductivity changes, it is also taken as constant due the complex process of expansion of intumescent coating.

1.5 Specific Heat of Steel

Specific heat of material is the amount of heat which needed to increase the temperature of the unit mass of a material for 1 ° C. Steel's mechanical properties are likely to be varied about 730 ° C as indicated in Figure 10. Specific heat of structural steel stays constant before it gets the peak value around 730 ° C and extremely decreases to 500 J/kg K as temperature increases as shown in Figure 10.

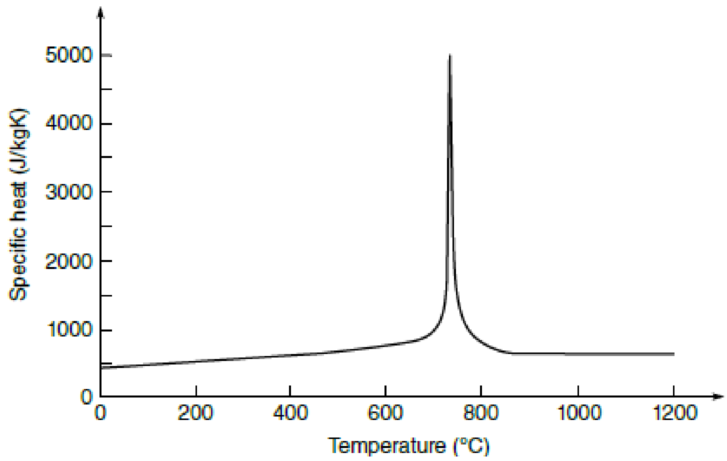


Figure 11: Specific heat of structural steel according to EC 3

EN 1993-1-2 ANNEX E defines the formulas of structural steel's specific heat as below:

$c_a = 425 + 0.773\ \theta_a - 1.69 \text{ x } 10\text{-}3\ \theta_a^2 + 2.22 \text{ x } 10^6 \text{ x } \theta_a^3$ for $600\ ^o C > \theta_a \geq 20\ ^o C$

(10)

$$c_a = 666 + \frac{13002}{738-\theta a} \quad \text{for } 735\ ^o C > \theta_a \geq 600\ ^o C \tag{11}$$

$$c_a = 545 + \frac{17820}{\theta a-731} \quad \text{for } 900\ ^o C > \theta_a \geq 735\ ^o C \tag{12}$$

$$c_a = 650 \quad \text{for } 1200\ ^o C \geq \theta_a \geq 900\ ^o C \tag{13}$$

As seen above specific heat of the steel component is a temperature dependent value and should be calculated in every change in temperature. θ_a and c_a are temperature of the steel component (° C) and specific heat of the steel component (J/kg K), respectively. Specific heat capacity of the steel increases up to around 700 - 735 ° C because of the separation of steel atoms each other which require energy for this situation and the atomic structure transition of steel atoms as indicated in Figure 11.

1.6 Steel Density

The density of the steel can be explained as steel mass per steel volume, which is shown below, and it is taken as 7850 kg/m^3.

$$\rho = \frac{m}{v} \tag{14}$$

ρ, m and v are steel density (kg/m^3), mass (kg) and volume (m^3), respectively.

Steel density doesn't change remarkably, so it is taken constant as 7850 kg/m^3 in numerical calculations for predicting the temperature at a given time in a fire scenario. On the other hand, densities of intumescent coatings, the Product A and the Product B, change as the temperature increases in a case of ISO 834 fire or other types of fire including Parametric fire, ASTM E119 or External fire types. Mass of the intumescent coatings, Product A and the Product B is a function of temperature. In expansion process of the intumescent coatings in a case of fire, mass loss which changes the density of the intumescent coating occurs. Although moisture loss leads to a change in density, it is taken as constant for numerical calculation for simplicity. Duration between the application of the intumescent coating and experiment time is also important because of the density change of the intumescent coating meanwhile. For instance, the density of the Product B is 1350 kg/m^3 when it is wet just after the application process. On the other hand, its density increases up to 1850 kg/m^3 when it's dried and shrinkage. Densities of the steel components and the intumescent coatings are taken as constant for predicting the temperatures of the isolated steel structural components according to EN 1993-1-2.

1.7 Steel's Thermal Elongation

Lack of overall structural integrity and steel component's failure might be the consequences of improper fire design predictions contributing thermal elongation [11].

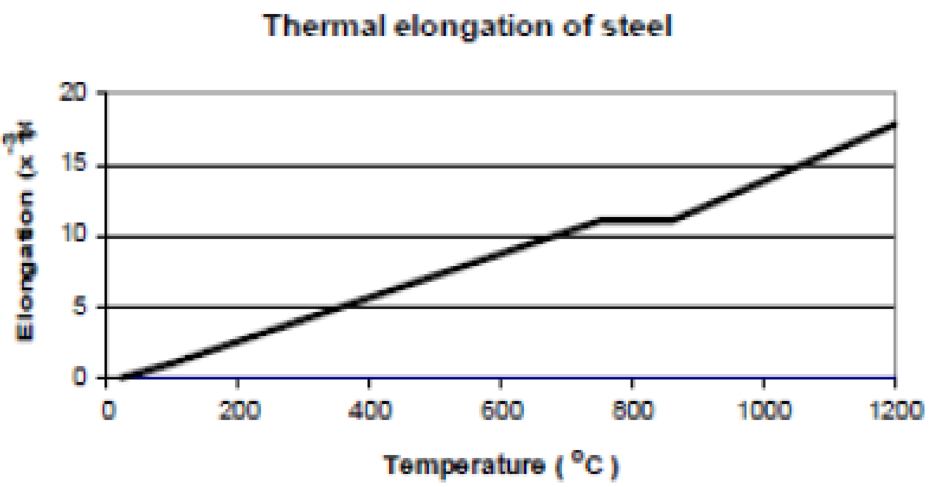


Figure 12: Temperature function of thermal elongation of steel according to EN 1993-1-2

As discussed earlier and explained by Tide [12], the rate at that a steel section under fire raises in length is based on if the steel section is restrained or not. This is not taken into consideration in Eurocode 3 [14] save section's corresponding length and temperature under fire. Depending on the research and studies, end restraints are crucial factors for analyzing steel components as shown in Figure 12.

$$\frac{\Delta l}{l} = 1.2 \times 10\text{-}5\ \theta_a + 0.4 \times 10^{-8}\ \theta_a - 2.416 \times 10^{-4} \quad \text{for } 750\ ^{o}\text{C} > \theta_a \geq 20\ ^{o}\text{C}$$

(15)

$$\frac{\Delta l}{l} = 1.1 \times 10^{-2} \qquad \text{for } 860\ ^{o}\text{C} \geq \theta_a \geq 750\ ^{o}\text{C} \qquad (16)$$

$$\frac{\Delta l}{l} = 2 \times 10^{-5}\ \theta_a - 6.2 \times 10^{-3} \qquad \text{for } 1200\ ^{o}\text{C} \geq \theta_a \geq 860\ ^{o}\text{C} \qquad (17)$$

Δl, l and θ_a are change in length (m), length at 20 ° C (m) and temperature of structural steel (° C), respectively.

1.8 Goals and Objectives

This research's purpose is to evaluate performance of fire protection of intumescent coatings which are applied on two UPN 200, S275 steel beams in a case of ISO 834 fire in a furnace for 2 hours. Thermal analyses and temperature-time curves were derived by using ABAQUS software. Fin EC was used for preliminary analysis. Fire resistant rating (FRR) is taken as the design objective for the structural steel components which are insulated by intumescent coatings.

1.9 Organization of Thesis

Literature review considering steel properties at elevated temperatures and real and design fire requirements are presented in the first chapter. Objectives and the extent of the thesis are presented in the same chapter too.

Chapter 2 covers presenting fire scenarios within the defined limitations. This part also covers the basic part of the research about the intumescent coatings with set up and results of the experiment. Including the thermal analysis and temperature-time curves which were derived by using ABAQUS program is crucial subpart of this chapter.

Lastly, conclusions and further research are explained in the last chapter about the thermal responses of insulated structural steel components with featuring most crucial findings of this research. Some advice is made for further research in the case of this research topic.

CHAPTER II

EXPERIMENT

Mechanical, deformational, and thermal properties are the three crucial characteristics which directly affect the thermal response of steel structures' components and overall structural system. These three properties change with the temperature containing deterioration of stiffness and strength as the temperature rises. Mechanical properties cover proportional limit, Poisson's ratio, yield stress and the modulus of elasticity. Poisson's ratio is generally taken 0.3 as a constant parameter which is independent of varying temperature.

Lie [15] asserted that " a characteristic temperature-time curve that, with reasonable likelihood, will not be exceed during the lifetime of the building." must be developed. Fire design requires some factors which are:

- Amount of gases which burn outside the fire compartment
- Temperature variation within the room which directly results in the time for arriving flashover.
- Location and amount of combustible materials within the compartment .
- Temperature of air at the outside

Burning rate of the fire is a function of compartment size and shape and it is independent of the ventilation factor when the fire is fuel controlled one. Burning rate defines the rate at which the fuel in the fire compartment is releasing volatile gases into the compartment atmosphere and burned by the fire.

Burning rate includes radiative effect which is proportional to T^4 is affected by ventilation rate and Eurocode, Modified Eurocode, Lie and Petterson have parametric design curves. Modified Eurocode satisfies the more trusted results according to a typical compartment fire scenario by giving highest temperature which means the most conservative choice [15]. Modified Eurocode fire curve refers to a more hazardous fire type which is the area under temperature-time curve up to 150 °C as shown in Figure 12 among the others.

Thermal strain due to the thermal expansion at high temperatures, creep strain of structural component's plastic deformation and strain that is caused by instantaneous stress are the 3 factors which lead to total strain. Total strain is crucial for defining deflection history data of the structural component.

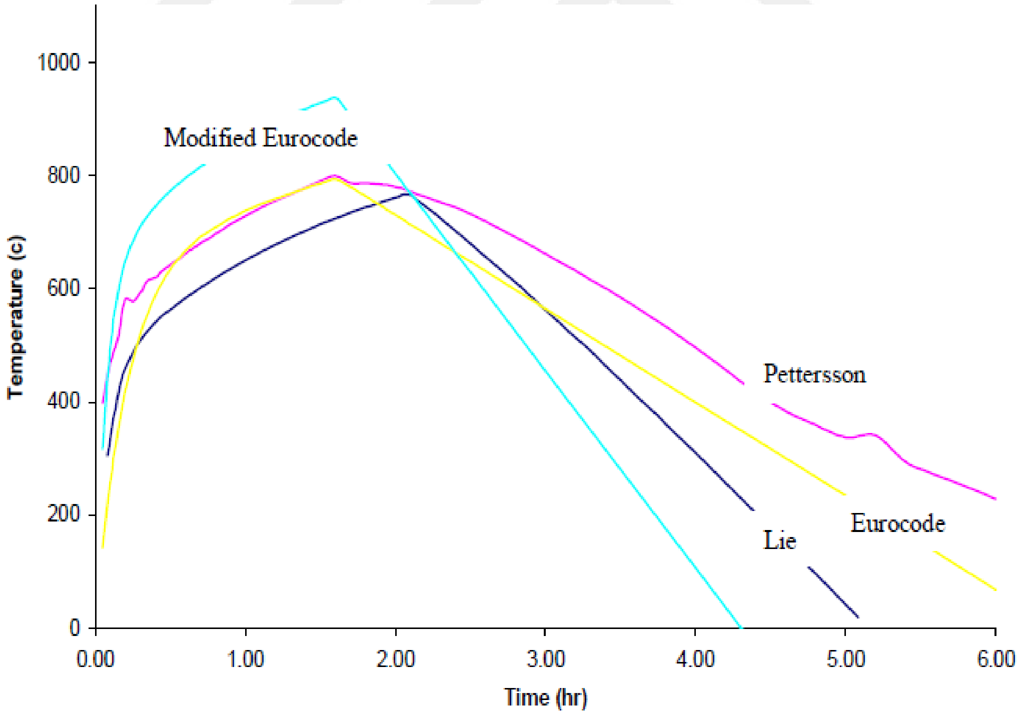


Figure 13: Temperature-time curves of Eurocode, Modified Eurocode, Petterson and Lie [16]

Estimating a realistic and conservative temperature-time curve for compartment fire depends on some properties of the construction such as compartment dimensions and opening sizes and surely fuel load. ISO 834 doesn't consider the compartment size. That's why TSE uses ISO 834 Fire, heat transfer and the structural models are the three elements to determine the structural fire behavior and strength of structural steel components.

2.1 Fire Model

Fire model consists of compartment geometry, fuel loads and fire characteristics according to fire scenario which predicts a realistic fire.

2.1.1 Compartment Geometry, Fuel Load and Fire Characteristics

Determination of the fire compartment is significant for the fire scenario. Room dimensions and vent dimensions are calculated for the room geometry. Keeping in mind that, number of vents is also significant for the fire scenario. After that, defining the area in the fire compartment which has the highest fuel load capacity is remarkable and in the scope of the Fire Protection Engineering.

Anticipated fuel load with respect to type and the mass must be calculated and transforming into the energy value (MJ/kg). After calculating the fire compartment's including with respect to total energy of the fire compartment. Total fuel load is divided to total surface or compartment floor area (MJ/m^2) as shown at Table 5. Number of vents is very crucial for the fire types which are ventilation-controlled ones.

Table 5. Calculation of Fuel Load Density in the Fire Compartment

	Material 1	Material 2	Material 3	Material 4
Mass of Fuel (kg)	M_1	M_2	M_3	M_4
Calorific Value (MJ/kg)	ΔH_{c1}	ΔH_{c2}	ΔH_{c3}	ΔH_{c4}
Energy included in the Fuel (MJ)	$E_1=M_1.\Delta H_{c1}$	$E_2=M_2.\Delta H_{c2}$	$E_3=M_3.\Delta H_{c3}$	$E_4=M_4.\Delta H_{c4}$
Time of Burning (s)	t_b			
Heat Release Rate (MW)	$Q_1= E_1/t_b$	$Q_2= E_2/t_b$	$Q_3= E_3/t_b$	$Q_4= E_4/t_b$
Total Energy in Fuel (MJ)	$E_{total}=E_1+E_2+E_3+E_4$	$E_{total}=E_1+E_2+E_3+E_4$	$E_{total}=E_1+E_2+E_3+E_4$	$E_{total}=E_1+E_2+E_3+E_4$
Floor Area (m^2)	A_f			
Fuel Load Energy Density (MJ/m2)	$e_f=E_{total}/A_f$			

Table 6: Time and Temperature values of ASTM E119 and ISO 834 curves [3]

Time (min)	ASTM E119 Tempetarature ^oC	ISO 834 Tempetarature ^oC
0	20	20
5	538	576
10	704	678
30	843	842
60	927	945
120	1010	1049
240	1093	1153
480	1260	1257

Many national standards are based on ASTM E119 or ISO 834 tests. The difference of temperature and time values are shown at Table 6. Standard fire tests are the ones which are used to get time-temperature graphs in furnace tests to measure fire resistance of structural steels. Fire resistance tests are used to define the structural components' thermal behavioral performance. These curves aren't used to forecast the steel structure's real fire responses but only guidelines for structural steel' fire safety design.

2.2 Fire Resistance

Rating resistance, fire endurance, fire resistance level or fire resistance rating are the terms which are used by other countries to define the fire safety time zone for that a steel structure component is exposed to fire test regarding standard fire resistance.

Evaluating deflections, shrinkage and connections in a furnace fire test are the essential disadvantages of the limited scale fire furnace tests when comparing with full scale fire furnace tests which are expensive and that causes an obstacle for performing it by researchers. So, calculation of a fire resistance of an isolated structural component under the fire represents the built assembly's fire resistance rating (FRR) [3].

International standards for fire resistance testing do not define the furnace properties detailly which results in problems in calculating and appraising fire resistance results. The standards consider mainly about failure criteria and fire temperature which is critical temperature indicating the temperature when structural steel component lose about the half of its load capacity.

Table 7: Construction Elements' Failure Criteria [3]

	Stability	Integrity	Insulation
Partition		X	X
Door		X	X
Load-bearing wall	X	X	X
Floor – ceiling	X	X	X
Beam	X		
Column	X		
Fire resistant glazing		X	

Stability, integrity, and insulation are the three failure criteria that contribute fire resistance rating. As seen on the Table 7, steel beams require to meet the stability criterion which means fulfilling the function of load bearing and carrying the exposed loads without collapsing of the steel structure. On the other hand, there has been an international tendency among the countries' fire codes for defining fire resistance failure criteria individually for integrity, insulation, and stability for the necessity of the fire resistance of the steel structure components [3].

All components must be tested for fire resistance under applied load except ASTM E119 which let steel beams to be tested regarding of fire resistance of the component without any load by supplying average temperature of the columns or beams before reaching the 538 º C that is the critical temperature of the structural steel columns (593 º C for structural steel beams) as indicated at Table 2 at where steel column or beam have about half of its normal temperature load capacity by leading a stability failure. Unloaded steel column or beam does not yield confident results which does not evaluate the impact of deformations under fire that could influence the connections' behavior or restraint from encircling structure in the fire resistance test.

2.3 Mechanical, Thermal and Deformational Properties in ASCE (1992), EUROCODE 3 (2005) and AISC 360-10 (2010)

Testing at different heating rates and/or at various protocols lead to different deterioration models between Eurocode 3 (CEN, 2005) and ASCE (1992) at elevated temperatures as shown in Figure 13. On the other hand, because of depending on the same study, Eurocode 3 (CEN, 2005) and AISC 360-10 (2010) indicate the similar properties. Main difference for the deterioration models of these codes is that proportional limit is incorporated in Eurocode 3's (CEN, 2005) constitutive model by considering inherent creep effects at high temperatures which results in flexible thermal response of steel structures' components.

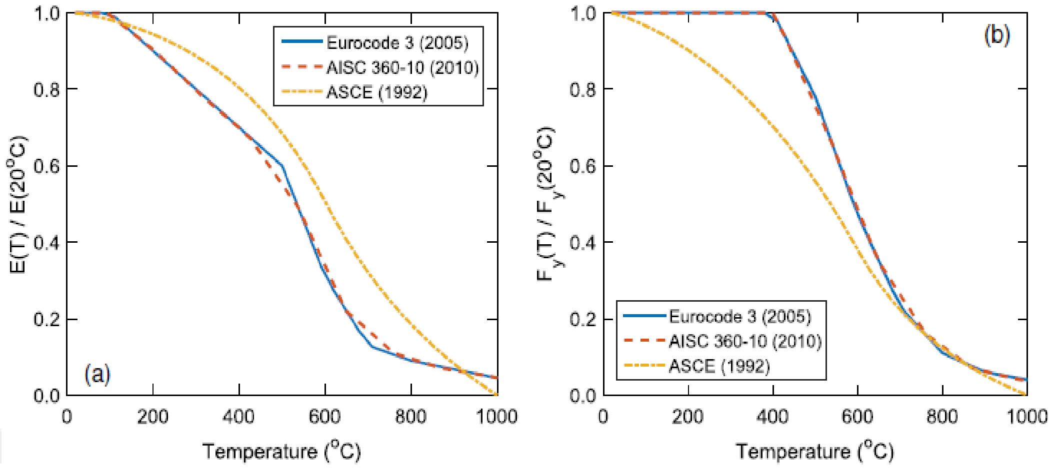


Figure 14: Deterioration models of structural steel at elevated temperatures a) modulus of elasticity b) strength of steel [3]

2.4 Active and Passive Fire Protection Systems

Active fire protection systems include taking actions by manual or automatic response by automatic devices in a case of fire. On the other hand, passive fire protection covers the resistance of fire by preventing spread of fire by delaying the increase of the temperature on the structural steel components with the help of appropriate conditions.

Active Fire Protecting systems contain:

- Automatic sprinkler system
- Smoke detectors
- Thermal detectors

Passive fire protecting systems contain:

- Intumescent coatings
- Fire floors, walls, and doors

- Mortar coating
- Spray applied fireproofing

An important issue for the passive fire protecting system is that they are applied during the manufacturing or construction time which doesn’t mean apply and forget it. That kind of system might be needed maintenance for that kind of systems regularly. Both systems play crucial role for fire safety of the steel structures against the fire. Generally, both systems must be performed together on the steel structure to minimize the fire and fire damage risks.

2.4.1 Insulation of Steels for Fire Protection

Steel components which carry loads under than their full capacity may stay stable around 700 ^{o} C under fire conditions.

Main aim of applying insulation materials or methods is to increase the time which is needed for heat transfer to the structural steel components by using insulation materials which have low heat conductivity and behave as thermal barrier between the fire and the structural steel components which are steel beams in this research.

Fire resistance materials including intumescent coatings can be damaged when they are exposed to deformation due to mechanical damage because of their properties involving brittle failure, low structural resistance, and low adhesive strength [17]. Transferring them to the cite without any mechanical damage is a remarkable point because of weaker mechanical strength of the insulation materials when they are applied on the steel components. That is why almost all applicators perform their fire protection coatings on the cite to minimize the transportation risks of the insulated steel components and reducing the transportation costs.

Harper [18] states main fire protection materials and methods cover intumescent coatings, spray-applied materials, concrete coating, and gypsum. Best energy-absorbing materials among these insulating materials because of their bound water are concrete and gypsum.

Isolating steel by using intumescent coating from the fire is most used way of protecting steel against the fire. Sprayed-on coatings is another way of insulation type because of low thermal conductivity, cost effectiveness, simple application, and low self-weight. This type of insulation covers aggregate, gypsum or cement-based binder and modifiers.

Intumescent coating which is the subject of this thesis and experiment is another way of protecting steel against the fire by means of forming a protective layer to enhance the fire-resistant property of the steel components by swelling up when they are exposed to fire. Adding nano-additives into the intumescent coating is another way for improving the fire resistance performance of intumescent coatings. Nanomaterials are used in the intumescent coating as an organic filler.

Table 8. Common insulation materials and their properties [19]

Protective material	Density (kg/m^3)	% moisture content (by weight)	Specific heat C_i (J/kg^oC)	Thermal Conductivity k_i (W/m^oC)
Normal weight concrete	2350	3	1300	1.3~1.7
Lightweight concrete	1800	4~5	1200	0.6~0.8
Cellular blocks	1000	2.5	1200	0.4
Brickwork	2000	-	1200	1.2
Gypsum boards	800	15~20	1700	0.2
Fibre Silicate sheets	600~800	3	1200	0.15
Perlite or Vermiculite sheets	500~800	10~15	1100	0.15
Mineral wool slabs	800	2	1100	0.2
Vermiculite or Perlite cement	550	20	1100	0.12
Spray Mineral Fibre	300	1	1200	0.10

Fire protection material’s thickness depend on insulation material’s thermal and mechanical properties such as specific heat, thermal conductivity, moisture content and density values. Although thermal response’s less sensitive to the density change of the insulation, thermal conductivity’s change is remarkable as seen in Figure 15 [19].

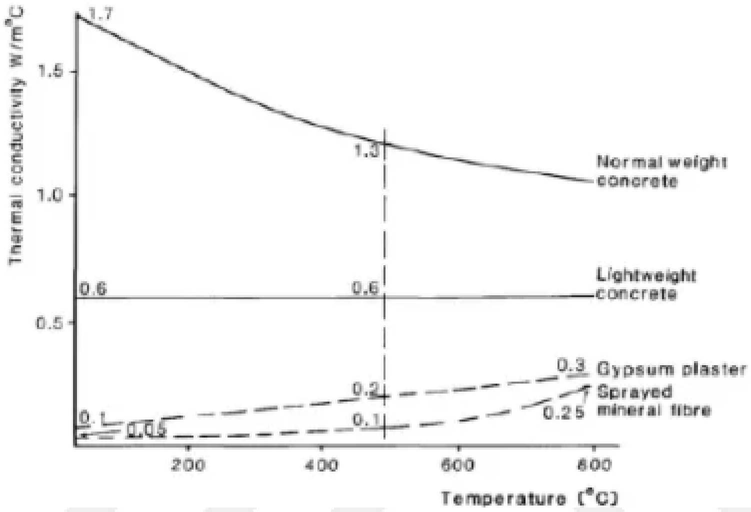


Figure 15: Typical insulation materials’ thermal conductivity – temperature change [19]

Mariappan [20] defines the 5 stages of intumescence mechanisms at elevated temperatures which include:

- Forming mineral acid with the process of catalyst decomposing
- Dehydration process by producing esters because of reaction between acid and the carbonific
- Decomposition process of ester by forming larger volume of carbon and releasing acid

- Formation of a film on the carbonaceous material because of melting process of resinous material

- Lastly, formation of thick and effective insulation over steel component with the help of foam that comes from carbon because of gases that comes from the blowing agents.

2.4.2 Nanomaterials in Insulation

Improving fire resistance and thermal properties of the intumescent coatings with the help of nanomaterials is used to increase the fire resistance of the insulation material when nano particles are dispersed accurately among the polymer matrices. Nano particle's flame retardancy relies on geometry and structure of the particles which have three types including layered, fibrous, and particulate materials.

Thickness of the intumescent coatings has a direct effect with the cost of the intumescent coatings. So, addition of nano particles into the intumescent coatings as filler material makes the intumescent coating thinner which reduces the cost of the intumescent coating. Table 9 indicates 4 types of coatings which have various amounts of nano alumina. Figure 16 shows the relationship between the amount of nano alumina and the fire resistance of the intumescent coatings by assuring that increasing the amount of inorganic filler of nano alumina in the intumescent coating does not always increase the fire resistance of the insulated steel structure that is exposed to fire [21].

Table 9: 4 types of intumescent coatings which have different amounts of nano alumina [21]

Intumescent formulations	Ingredients (wt%)
IF1 (control)	APP = 11.14, EG = 5.57, MEL = 5.57, BA = 11.14, epoxy resin = 66.58
IF2	IF1 + 0.5 nano alumina
IF3	IF1 + 1.0 nano alumina
IF4	IF1 + 1.5 nano alumina

As shown in Figure 15, 1.0 wt.% of nano alumina is best suited to the intumescent coatings for improving the intumescent coating's fire resistance.

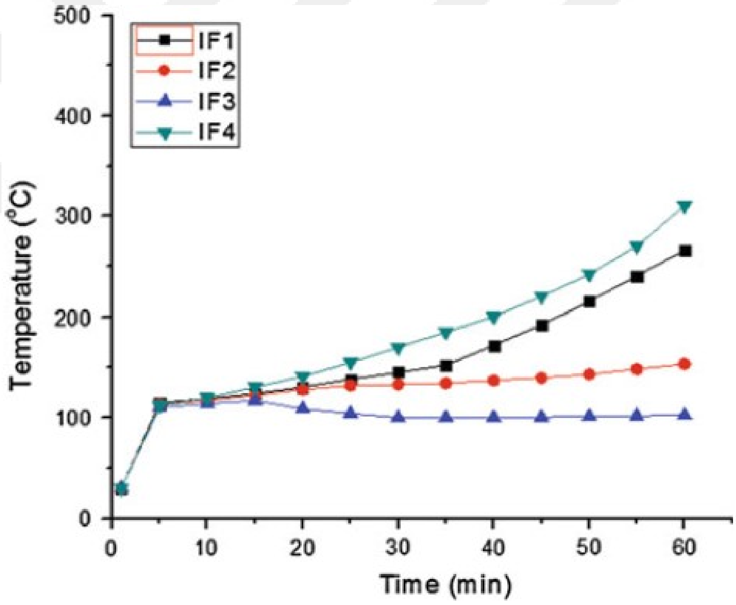


Figure 16: Backside substrate temperature – time graph [21]

Some problems occur during the spraying on cementitious process of steel structures just like large thickness, brittleness, and adhesion of coating on the steel substrates. Main aim of applying fire protection materials on the structural steel components is forming a thermal barrier between the fire and steel. By this way, radiation of hot gases doesn't contact with the steel and doesn't increase the temperature rate rapidly. On the other hand, if adhesion problems occur, insulation cannot behave as a thermal barrier anymore. Manufacturers one of the biggest challenges is to overcome adhesion problems between the steel substrate and the fire protecting material. Polypropylene fibre composites covering carbon nanotubes (CNT's) are used to decrease thickness and increase the strength of the coating by improving the fire resistance of coated structural steel. Nano-SiO_2 particles are distributed regularly among the APP-PER-MEL (Ammonium-polyphosphatepentaerythritol-melamine) intumescent coatings to enhance the fire-resistance of structural steel components [21].

2.4.3 Intumescent Coating (IC)

This type of fire protection contains chemical ingredients which expand in a case of fire with the help of its low thermal conductivity to protect the structural steel components which make structural steel to continue to serve its functionality for the entire structure. Main binders, flame retardant additives and fillers are the three elements of the intumescent coatings that generally protect the steel structures from 30 min. to 120 min. relying on IC's thickness and chemical composition. Thin coating thickness differs from 1 to 3 mm and thick coating thickness varies from 3 to 30 mm. Solvent free, solvent based and waterborne are the three types of IC. Intumescent coatings can be performed off-site or on-site. Application of ICs on-site has been increased by applicators and site owners because of reducing transportation costs and preventing mechanical deformations during the transportation of structural steel components. Colorful finish paint and relatively thin thickness of intumescent coatings are the aesthetically advantages of them.

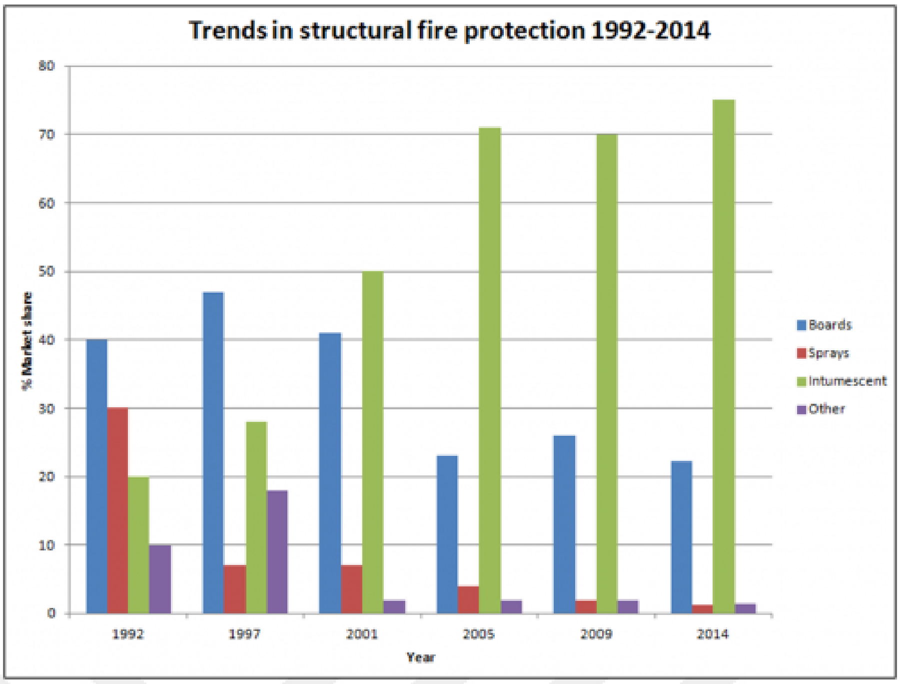


Figure 17: Fire protection market shares of structural steel between 1992 and 2014 [20]

As seen in Figure 16, there is a tendency for the use of intumescent coatings which have dominated the fire protection of structural steel industry. Its market share has increased up to 75 % percent of all structural fire protection market which means that new more effective products will be in the market which are thinner and more protective against the fire because of the competition in the intumescent coatings industry.

Binder, which is a carbon source, acid source and blowing agent which are the three essential ingredients of IC directly affect the IC's fire resistance performance in a case of fire. IC expands during the fire and forms a thick fire proactive char which leads to a change in IC's thermal properties including thermal conductivity which is a time dependent property. Thermal performance of intumescent coatings base on better understanding of thermal properties of intumescent coatings which change as temperature increases in a case of fire.

Intumescent factor (IF) which is also called char expansion is a crucial parameter that indicates the coating's swelling ability and is affected by furnace's initial temperature, heating rate and type.

$$\text{IF} = \frac{d2 - d0}{d1 - d0} \qquad (14)$$

d_0 = uncoated steel substrate thickness

d_1 = coating thickness

d_2 = char thickness

Due to the brittleness of IC's char, tensile test is harder to apply on it whereas chars can be researched in compression test. IC's microstructure covering cell size and cell structure is crucial for fulfilling its fire protection process of steel. Thickness of char raises the thermal gradient across the char and the intumescent coating.

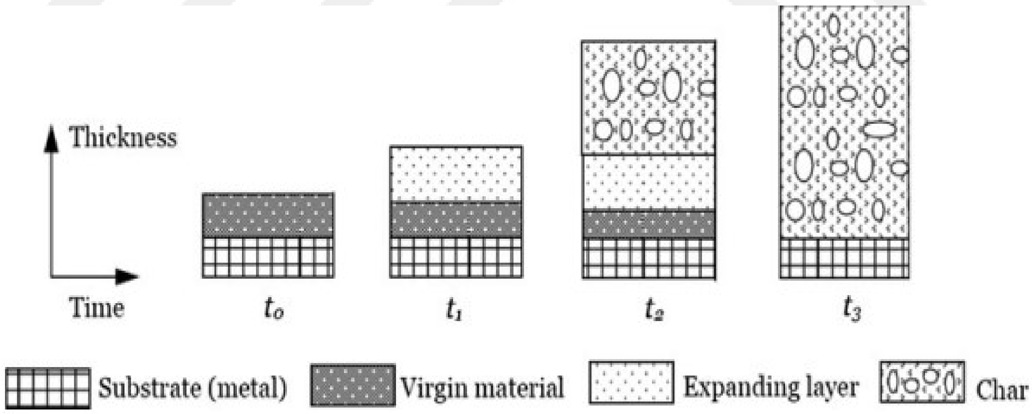


Figure 18: Intumescing process in a case of fire [21]

Char which has an impact on the IC efficiency behaves as a thermal barrier between fire as a heat source and the structural steel component. Experiments indicated that good thermal performance for fire protection of the intumescent coating wasn't much related about large char expansion rate but kinetics performance of char formation. Char' fire protection of the steel beam fails if it is formed at the beginning after dehydration as seen in Figure 18. On the other hand, if the char expansion process occurs at the later stages, formation of harder char occurs before swelling which shows that timing is important factor for char formation process during the fire.

The Product A and the Product B which were preferred in this study are water-based intumescent coatings which mean that they don't emit types of hazardous vapors just like solvent-based ones do in insulating process to the environment and applicators.

2.4.4 Spray Mineral Fibre

Spray applied fire resistance materials relies on cement-based products or gypsum with aggregates which are light such as perlite, vermiculite and expanded polystyrene bead [22]. More than one layers of spray protection are applied on the steel to have an efficient protection on steel beam against the fire. As shown at Table 10, they have many advantages such as low thermal conductivity, low cost, and low weight.

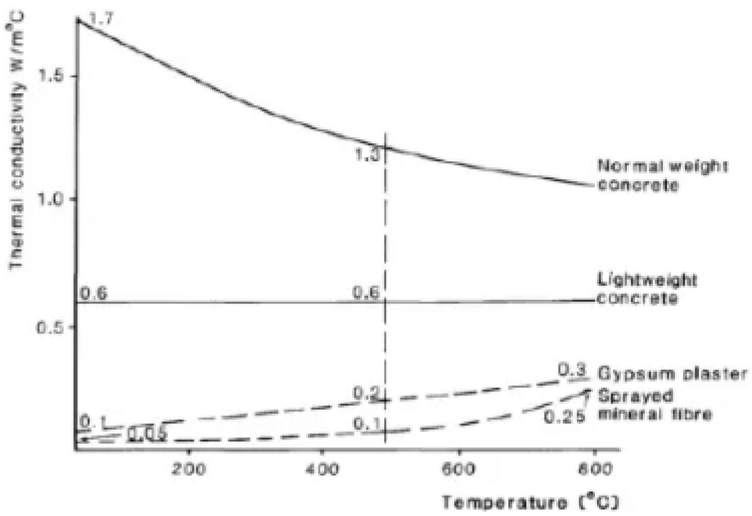


Figure 19: Thermal conductivities of insulation materials [23]

Table 10: Properties of insulation materials [23]

Protective material	Density (kg/m^3)	% moisture content (by weight)	Specific heat C_i (J/kg^oC)	Thermal Conductivity k_i (W/m^oC)
Normal weight concrete	2350	3	1300	1.3~1.7
Lightweight concrete	1800	4~5	1200	0.6~0.8
Cellular blocks	1000	2.5	1200	0.4
Brickwork	2000	-	1200	1.2
Gypsum boards	800	15~20	1700	0.2
Fibre Silicate sheets	600~800	3	1200	0.15
Perlite or Vermiculite sheets	500~800	10~15	1100	0.15
Mineral wool slabs	800	2	1100	0.2
Vermiculite or Perlite cement	550	20	1100	0.12
Spray Mineral Fibre	300	1	1200	0.10

Mess and dust which are caused by during the application of spray protection are the disadvantages of this type of fire protection of steel structures.

Thermal properties of spray applied fire resistance materials at elevated temperatures are affected by material composition and moisture of sprayed insulation material and the percentage of vermiculite and gypsum drives the thermal properties of sprayed insulation material. Temperature variation remarkably affects loss mass of insulation material, thermal strain, and specific heat of sprayed insulation material [24].

2.5 Temperature of Steel Sections and Section Factor

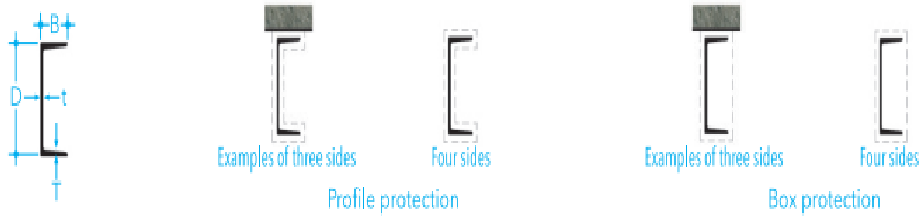
Increased temperature of steel section relies on steel area which is under fire, amount of fire protection material and the compartment's fire temperature. Convection and radiation are two ways for transferring heat from surrounding gases in the fire compartment to the surface insulation and the steel component. On the other hand, conduction is the way for transferring heat throughout the cross-section of insulation material and steel component.

Section Factor (SF) is the ratio which describes the area under fire over the volume of steel component. It is an indicator which accelerates the heat transfer mechanism if it increases. So, section factor is taking into account while doing numerical calculations and modelling in software programs.

$$\frac{A_m}{V} = \frac{\text{Steel Perimeter}}{\text{Cross-section Area}} \quad \text{(For the unprotected steel member)} \qquad (20)$$

$$\frac{A_p}{V} = \frac{\text{Encasement Perimeter}}{\text{Cross-section Area}} \quad \text{(For the protected steel member)} \qquad (21)$$

Table 11: Section factors for UPN sections [6]



Designation		Depth of section	Width of section	Thickness		Area of section	Profile protection				Box protection			
							3 sides (m^{-1})		4 sides (m^{-1})		3 sides (m^{-1})		4 sides (m^{-1})	
Serial size (mm)	Mass (kg/m)	D (mm)	B (mm)	Web t (mm)	Flange T (mm)	(cm^2)	Hp/A	W/D	Hp/A	W/D	Hp/A	W/D	Hp/A	W/D
UPN 50	5.6	50	38	5	7	7.1	278	0.48	331	0.40	194	0.69	247	0.54
UPN 65	7.1	65	42	6	8	9.0	264	0.51	311	0.43	190	0.70	237	0.57
UPN 80	8.6	80	45	6	8	11.0	250	0.54	291	0.46	186	0.72	227	0.59
UPN 100	10.6	100	50	6	9	13.5	239	0.56	276	0.49	185	0.72	222	0.60
UPN 120	13.4	120	55	7	9	17.0	223	0.60	255	0.53	174	0.77	206	0.65
UPN 140	16.0	140	60	7	10	20.4	210	0.64	240	0.56	167	0.80	196	0.68
UPN 160	18.8	160	65	8	11	24.0	200	0.67	228	0.59	160	0.84	188	0.71
UPN 180	22.0	180	70	8	11	28.0	193	0.69	218	0.61	154	0.87	179	0.75
UPN 200	25.3	200	75	9	12	32.2	182	0.74	205	0.65	148	0.91	171	0.78
UPN 220	29.4	220	80	9	13	37.4	171	0.78	192	0.70	139	0.96	160	0.84
UPN 240	33.2	240	85	10	13	42.3	163	0.82	183	0.73	134	1.00	154	0.87
UPN 260	37.9	260	90	10	14	48.3	154	0.87	173	0.77	126	1.06	145	0.92
UPN 280	41.8	280	95	10	15	53.3	149	0.90	167	0.80	123	1.09	141	0.95
UPN 300	46.2	300	100	10	16	58.8	145	0.92	162	0.83	119	1.13	136	0.99
UPN 320	59.5	320	100	14	17.5	75.8	116	1.16	130	1.03	98	1.37	111	1.21

$$\Delta\upsilon_{a,t} = k_{sh} \frac{A_m/V}{c_a\rho_a} h_{net,d}\, \Delta t \qquad (22)$$

$\Delta\upsilon_{a,t}$ = increase of unprotected steel's temperature in the interval Δt

k_{sh} = correction factor for shadow effect

c_a = specific heat of steel (J/kgK)

ρ_a = unit mass of steel (7850 kg/m^3)

Δt = time interval (max value is 5 sec.)

$h_{net,d}$ = net heat flux

Temperature is distributed uniformly within the steel component's cross section which is proposed by EN 1993-1-2 and calculated as

$$h_{net} = \alpha_c.(\upsilon_g-\upsilon_m)+\Phi.\varepsilon_m.\varepsilon_f.\sigma.[(\upsilon_r+273)^4-(\upsilon_m+273)^4] \quad (23)$$

α_c = convection heat transfer coefficient

υ_g = gas temperature of the fire compartment

υ_m = temperature of the steel component's surface

Φ = view factor

ε_m = emissivity of the steel surface

ε_f = emissivity of the fire

σ = Stephan-Boltzman constant ($5.67x10^{-8}$ W/m^2K^4)

Specific heat capacity of steel structural component is temperature dependent variable and calculated as according to EN 1993-1-2-3 4.1.2

$$c_a = 425 + 0.773\upsilon_{a,t} - 0.00169\upsilon_{a,t}^2 + 0.00000222\upsilon_{a,t}^3 \quad (24)$$

c_a = 439.8 J/kgK when the $\upsilon_{a,t}$ = 20 °C

To calculate the net heat flux (h_{net}), iterative procedure must be performed for the net heat flux and the specific heat capacity (c_a) which are temperature dependent factors.

According to EN 1991-1-2 Anex G, view factor equals to 1.0, when the fire is localized, or shadow factor is active it is lower than 1. The profile's concave shapes lead to activation of shadow factor.

$k_{sh} \leq 1$ for I type steel sections under normal fire $k_{sh} = 0.9 \frac{[\frac{Am}{V}]b}{\frac{Am}{V}}$

k_{sh} = 1 for box and other type of steel sections which do not have shadow effect

$$k_{sh} = \frac{\frac{Am}{V}}{\frac{Am}{V}}$$

EN 1993-1-2 gives the steel component's sections with applied intumescent coating insulation and uniform temperature distribution throughout the cross-section and the following formula for the increase in temperature for steel component that's insulated with intumescent coating. So, by applying formula, temperature increment of insulated steel component's surface temperature will be derived by the iteration method. A significant point while doing iterative process is that negative increments of the steel component's temperature isn't allowed, and it is zero for the negative values of the temperature increment.

$$\Delta\upsilon_{a,t} = \frac{\lambda p.Ap/V(\nu g,t - \nu a,t)}{dpca\rho a(1+\Phi/3)}\Delta t - (e^{\Phi/10}-1)\Delta\upsilon_g \quad (25)$$

$$\Phi = \frac{cp.dp.\rho p.Ap/V}{ca.\rho a} \quad (26)$$

Where;

$\Delta\upsilon_{a,t}$: increase in temperature of insulated steel component

λ_p : thermal conductivity of fire protection

A_p/V: section factor

$\upsilon_{a,t}$: temperature of surface of steel element

$\upsilon_{g,t}$: gas temperature of the fire compartment

Δt: time interval

d_p: thickness of the fire protection

c_a: specific heat of steel

ρ_a: unit mass of steel

$\Delta\upsilon_{g,t}$: gas temperature

c_p: specific heat of the fire protection

d_p: unit mass of the fire protection

Some considerations must be cared when applying these formulas. Thermal conductivity of insulation at high temperatures is not same as at room temperature and these must not be applied at high temperatures. Heat transfer by conduction occurs only within the fire protecting material. Hence, thermal resistance against heat conduction is performed only by fire protecting material not by structural steel component. Another crucial limitation for performing these formulas is that equation is valid when view factor is $\Phi < 1.5$.

2.6 Experiment

Insulation materials have inadequate data about the thermal properties just like thermal conductivity at the high temperatures. Thermal properties containing specific heat capacity and thermal conductivity are temperature dependent factors in the range of 20 - 700 ^{o} C which means that their values vary as the temperature increases That situation causes inaccurate FRR values of insulation materials. Thermal properties of insulation materials like intumescent coatings which are known are measured at room temperatures and they are not known exactly at elevated temperatures when they are exposed to fire [24]. Temperature variation and the composition of intumescent coatings are the two key elements which dominate the thermal properties of intumescent coatings under fire conditions. In the experiment, two different commercially used intumescent coatings were applied on two 1-meter UPN 200 structural steel components by keeping constant all other parameters such as sectional properties, insulation thickness, span length and end conditions, applicator, coating period and duration between each layer of intumescent coatings.

2.7 Experimental Setup

TSE (Turkish Standards Institution) test furnace is worked with natural gas which is agree with EN 1363-1 Standards. There are two furnaces in TSE fire laboratory. Small one is used for R&D and the larger one is for the larger specimens. ISO 834 fire type has no limitation about the compartment size. Both furnaces can be used by following ISO 834 fire curve. On the other hand, other standard fires have limitations about the compartment size.

K type thermocouples with length, width and nickel alloy strip folding 150 ± 1, 100 ± 1, and 0.7 ± 0.1 mm, respectively, which comply EN 60584 – 1. TSE Lab have K type thermocouples with 1 mm diameter to get time-temperature (° C - seconds) curve of steel component which is a tested via a software program. Thermocouples are fire resistant up to 1200 ° C with insulating by double ceramics.

EN 1363-1 specifies furnace inside pressure which gradient of it is about 8.5 Pa per meter height of TSE furnace and pressure is controlled by the pressure sensors via a software program in seconds. Pressure must be within the limits of ± 5 Pa in 5 minutes later than the initiation of experiment and 3 ± Pa in 10 minutes later than the initiation of the experiment.

2.7.1 Furnace Pressure

Integrity failure criterion which one of the three failure criteria is influenced by the pressure inside the test furnace. Because of positive pressure of the inside of the furnace, gases which have extremely high temperatures and flames go through the cracks of the specimens that affect the integrity of the structural steel components directly [3].

ASTM E119 doesn't require specific values about the pressure of furnace inside. On the other hand, ISO 834 requires 10 Pa positive pressure at the peak of the steel component and $2/3^{rd}$ of the steel component must be exposed to positive pressure. One T type pressure sensor which is stainless that has inner diameter 7.5 ± 2.5 mm used as defined in EN 1363 – 1 code in the back of furnace to derive furnace inside pressure-time data as temperature increases.

2.7.2 Applied Loads

Applied loads on structural steel components are needed to fulfill the stability criterion for the fire test. Steel beams and columns can be tested according to ASTM E119 without any applying loads before the temperature reaching the 538 ^{o} C at where steel component would lose half of its load capacity. Fire test experiment results might be changed depending on the magnitude of the load that is applied on the structural steel component during the fire test. In this experiment, there is not any load except fire load and self-weight of the insulated steel beams.

2.7.3 Experimental Investigations

This experiment is performed to determine two different intumescent paintings' protection of two steel beams when they are exposed to fire. Intumescent coating delays the time required to reach the critical temperature in a fire case. ISO 834 fire type is used in the experiment. Two 1-meter UPN 200 steel beams are used in this experiment. All the variables including fire type, bolts' type and size that are welded, steel section's types and the furnace and the fire test time are the same in the experiment for two specimens except the intumescent coatings. So, the intumescent coating effect is the only variable that can be analyzed by measuring the time required to reach the critical temperatures. Thermocouple locations are also the same for two specimens.

M20 and M8 bolts are welded according to EN 13381-8:2013 as seen in Figure 19. Two 250mm x 250 mm x 6 mm iron plates are welded on the top of the two beams. This is needed to weld a 450 mm long bolt (M20) which is used to fix the specimen on the ceiling of the furnace during the fire test and to put ceramic wools on it for isolation. Six 100 mm long bolts are used to fix the specimen to fix the specimen on the basement of the furnace during the fire test which is shown in Figure 20.

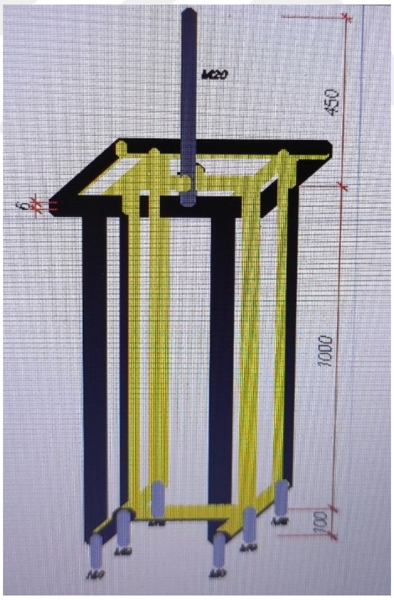


Figure 20: AutoCAD design of bolts on the beam according to EN 13381-8:2013

Figure 21: Welding the bolts to fix the beams in the furnace

Totally 24 wire thermocouples were fixed on the beams (12 for each one) in TSE Laboratories after the welding of the plates and bolts. All wire thermocouples were numbered from 1 to 12 for each beam to see the effect of the fire. Thermocouples 1, 2, 3, 4, 5 and 11 were located 500 mm from the bottom of the beam. Thermocouples 6, 7, 8, 9, 10 and 12 were located 200 mm from the top as seen in Figure 21.

Figure 22: Fixed 12 thermocouples' locations for both Product A and B

Each beam is undercoated and then product A and product B type intumescent paintings are applied on the steel beams for 14 days as shown in Figure 22. Airless paint spray was used for painting. Each spray layer has a thickness between 400 to 600 microns. Next layer was applied after one or two days for waiting the previous spray to dry. Coating had to be dried which made the layer thinner due to the shrinkage. Each layer had a duration for drying 1 or 2 days to agree with the thickness that each manufacturer of the intumescent coatings' advice. Producer A advised at least 3080 microns thickness for Product A after drying. Producer B advised at least 3150 microns thickness for Product B after drying. Product A has 3100 microns thickness and Product B has 3280 microns thickness as seen in Figure 23. Intumescent coatings manufacturers determine the thickness of the intumescent coatings mainly regarding of section factor of the steel components. Section factor which is Hp/A is determined by section type. Section factor is also affected by whether the steel component is exposed to 3-sided or 4-sided fire and insulation method covering profile method or vox method. Additionally, critical temperature, steel grade, and fire period are also important factors for determining thickness of the intumescent factors. All the factors which are mentioned above are the same for both the Product A and the Product B. 180 microns thickness difference was caused by using different safety factors by different manufacturers. For instance, the Product B manufacturer used section factor as 210 although it was 205 for UPN 200 S275 steel beam which was exposed to 4-sided fire.

Manufacturers use a program for determining the thickness of the intumescent coatings. They don't know the thickness difference for the same beams, same fire period and the same fire types Assumptions can be made for exploring the thickness difference of the Product A and the Product B. Section type of the steel and water or solvent-based types of the intumescent coatings and fire period values are the only ones which are wanted to learn by manufacturers. So, only variable might be section factor. Doing simple calculations by assuming that section factor is directly correlated with the thickness, (3080/205)*210=3155 microns which is consistent with the manufacturer of the Product B advice as 3150 microns.

Figure 23: Specimens before the fire test after applying intumescent coatings.

Workmanship and quality of the intumescent coating material are the two essential factors that affect the fire resistance performance of the isolated steel beams against the fire. In this experiment, workmanship factor is the same for the two isolated steel beams. Same applicator applied the intumescent coatings on the same UPN 200 steel beams which were derived and cut from the same beam with the same equipment (airless paint spray etc..) for the same time. So, difference of industrial intumescent coatings is the only factor that determines the fire resistance of them.

Figure 24: Measuring thickness of intumescent coating for Product A (on the left) and Product B (on the right)

Table 12: Thermal and physical properties of intumescent coatings

Product	Product A	Product B
Type of Isolation	Intumescent Coating	Intumescent Coating
Dry Fim Thickness (DFT) (micron)	3100	3280
Density (g/cm^3) (kg/L)	1.4	1.35
Thermal Conductivity (λ_p) (W/m/K)	0.6	0.5
Specific Heat Capacity (c_p) (J/kg/K)	1100	1250
Specimen	Steel beam	Steel beam
Section type	UPN 200	UPN 200
Section Factor	205	210
Height (m)	1	1

It took nearly 60 days to start the fire test in the laboratory after applying the intumescent coatings on the steel beams because of the test laboratory's other appointed experiments. Moisture content was relatively low due to the waiting 60 days for the experiment which might increase the fire resistance of the intumescent coatings if its percentage is high. So, low moisture content of the intumescent coatings is important in the comparison of the two different industrial intumescent coatings.

Figure 25: Specimens in the furnace just before the fire test

There are two burners in the furnace to follow ISO 834 fire type which works with the gas for 2 hours. Fire exposed to the isolated beams through 4 sides of the specimens which have no composite action. Isolated steel beams have dead loads due to their self-weight.

Figure 26: Thermocouples' initial values at the beginning of the experiment

Figure 27: Thermocouple values of steel beams after 30 minutes

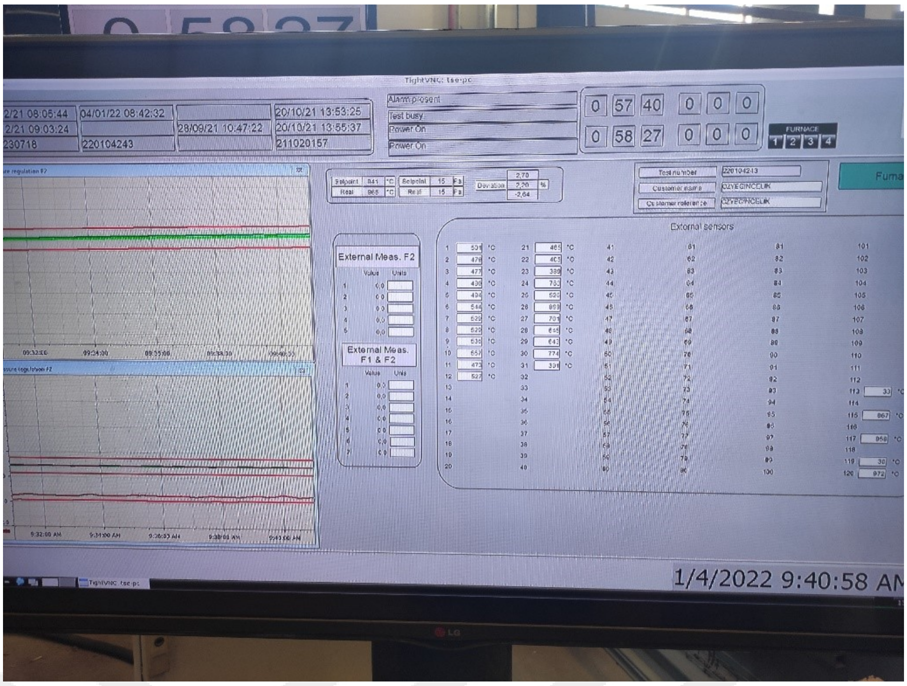


Figure 28: Thermocouple values of steel beams after 60 minutes

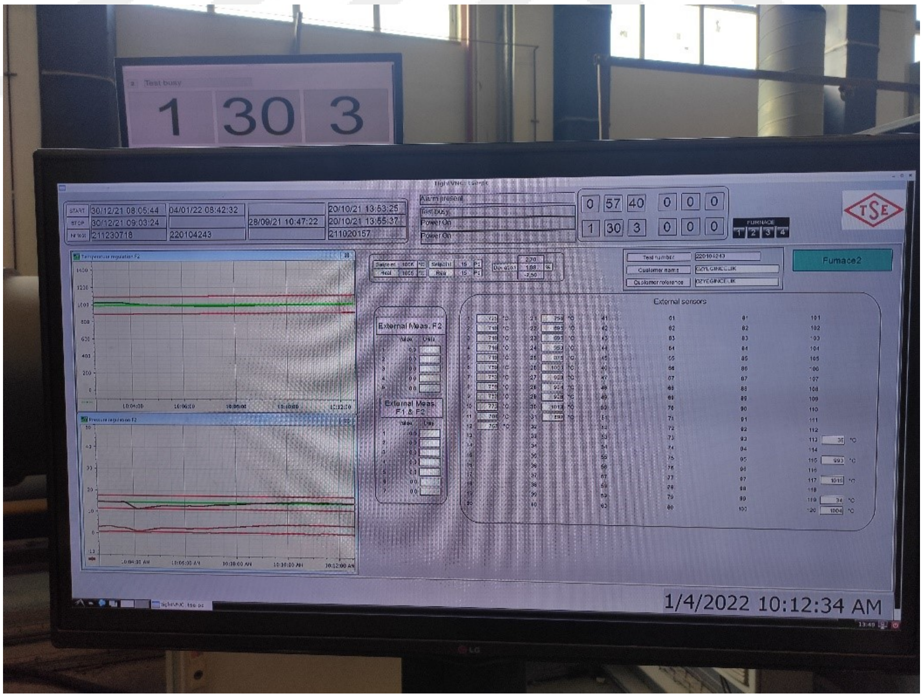


Figure 29: Thermocouple values of steel beams after 90 minutes

Figure 30: Thermocouple values of steel beams at the end of the experiment

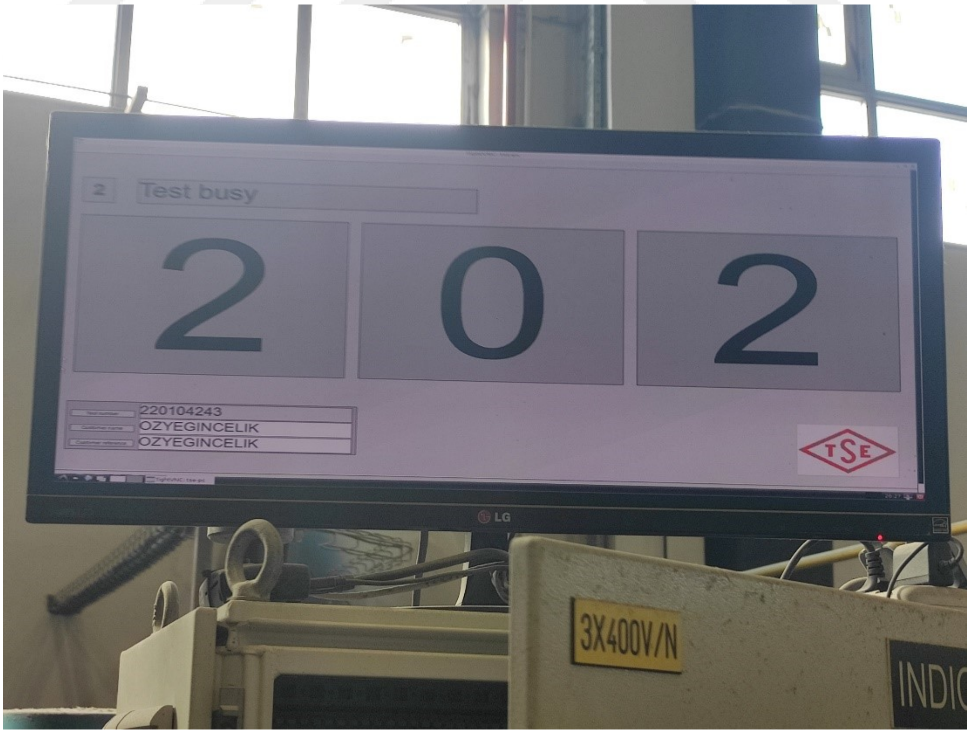


Figure 31: Experiment finished after 2 hours

2.8. Experimental Results

Figure 32: Specimens after the test, Product A is on the left and Product B is on the right

Conduction is crucial for determining the surface temperature of the inner surface of the intumescent coating and the surface of the beam. As seen in Figure 32, adhesion problems occurred, and steel beam had no longer contact with the Product B and radiation became the dominant factor for heat transfer which means intumescent coating no longer protected the steel. So, it can be predicted that steel beam that was protected by the Product B reached the critical temperature earlier than the other steel beam that was protected by the Product A. Steel beam that was protected by the Product B transferred the heat by convection and radiation directly. On the other hand, heat was transferred by the means of the Product A to the steel beam by the conduction with the help of free electrons of the Product A.

Figure 33: Specimens were removed from the furnace after the test to measure char thickness

Figure 34: Char thickness for the Product A after fire test

Figure 35: No char on the steel beam which was coated with the Product B

Time and temperature are the two principal factors which measure the fire resistance of coated steel components whether they withstand the ISO 834 fire or not. Steel component failure is a consequence of a decline in fire resistance which is caused by increasing temperature. Buchanan [3] stated that strength and stiffness loss of steel component because of an increase in temperature about 600 ^{o}C affect the well-defined yield plateau loss. In the experiment, Product A reached the critical temperature in 66th minute and Product B reached the critical temperature in 37th minute as shown in Figure 28 and Figure 29. There are 29 minutes differences between the two intumescent coatings for reaching the critical temperature at when the around 80 % of mechanical properties are lost because of the elevated temperature. The Product A has consistent temperature-time values and has a char after the fire test. On the other hand, the Product B has inconsistent temperature-time values within its thermocouples. The Product B has no char on the steel beam after the fire test which might cause not preventing to reach critical temperature.

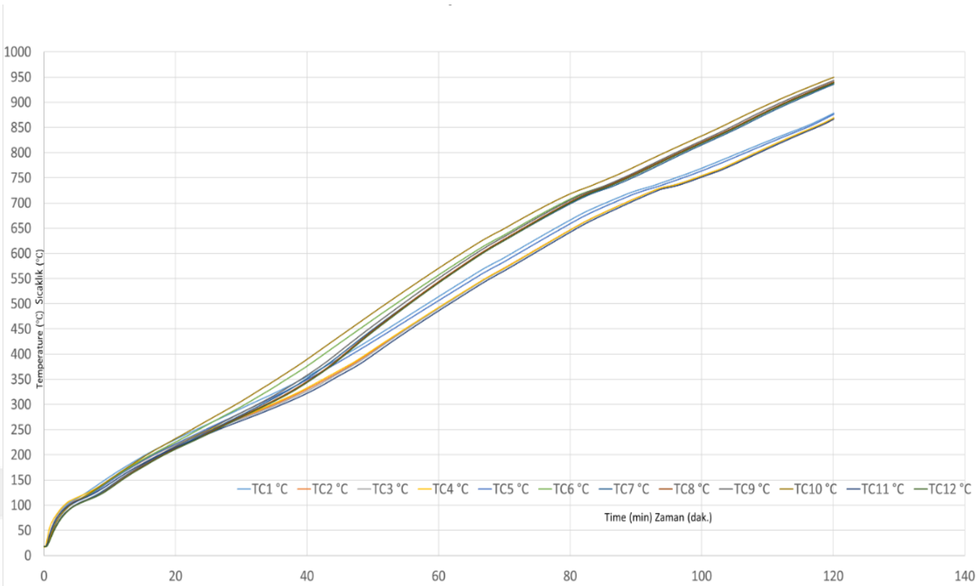


Figure 36: Thermocouple values during the fire test for Product A

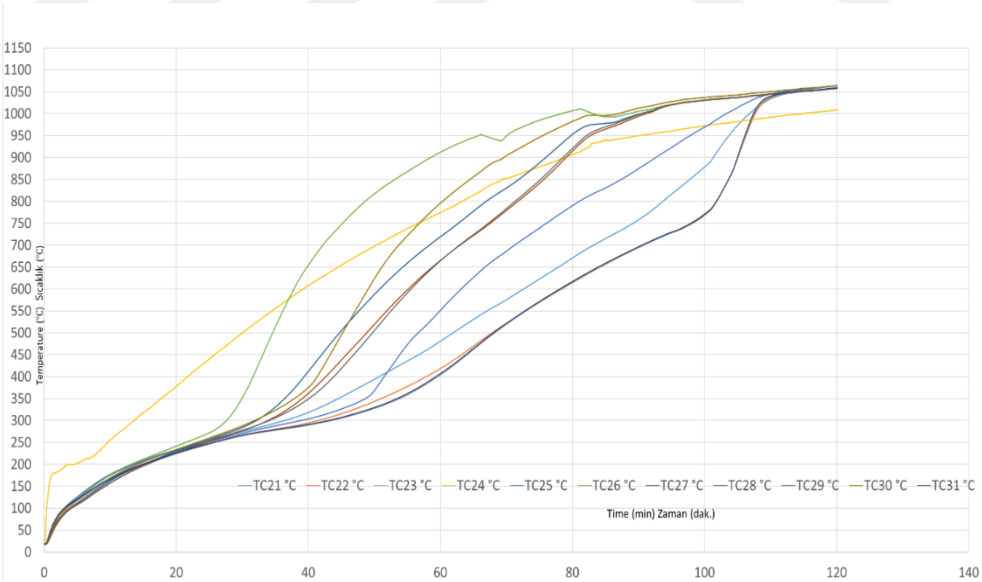


Figure 37: Thermocouple values during the fire test for Product B

As seen in Figure 37, there was a homogeneity problem for the Product B. Thermocouples which were applied on the steel beam under the Product B have different values at the beginning of the furnace test experiment. Thermocouples were placed closely to each other, and their values could not differ so much. This situation is a consequence of homogeneity problems within the Product B. This difference in values occurred especially when the temperature exceeded 250 ° C. After that temperature, expansion process occurs, and elevated temperature activates swelling phase of the Product B. On the other hand, Thermocouple values under the Product A had similar values and curves during the furnace test experiment which are results of The Product A's homogeneity.

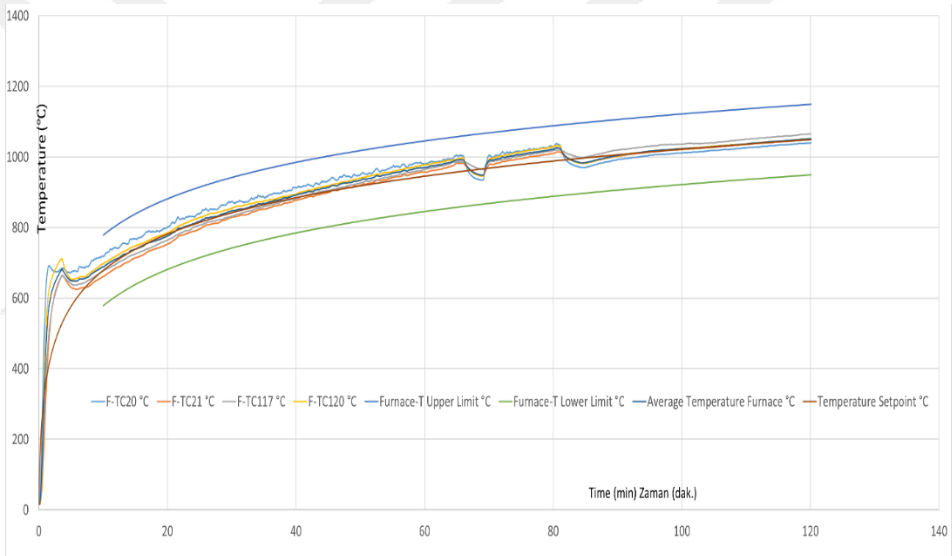


Figure 38: Values of furnace thermocouples during the fire test

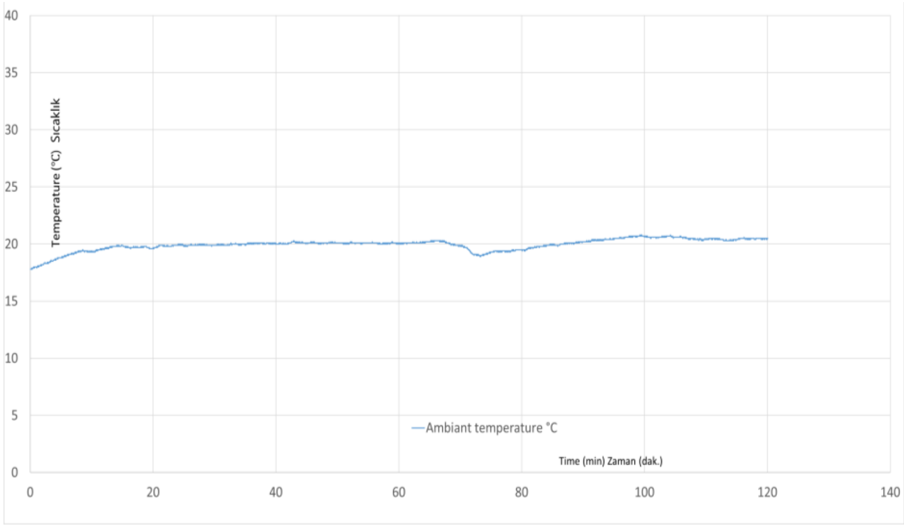


Figure 39: Ambient temperature

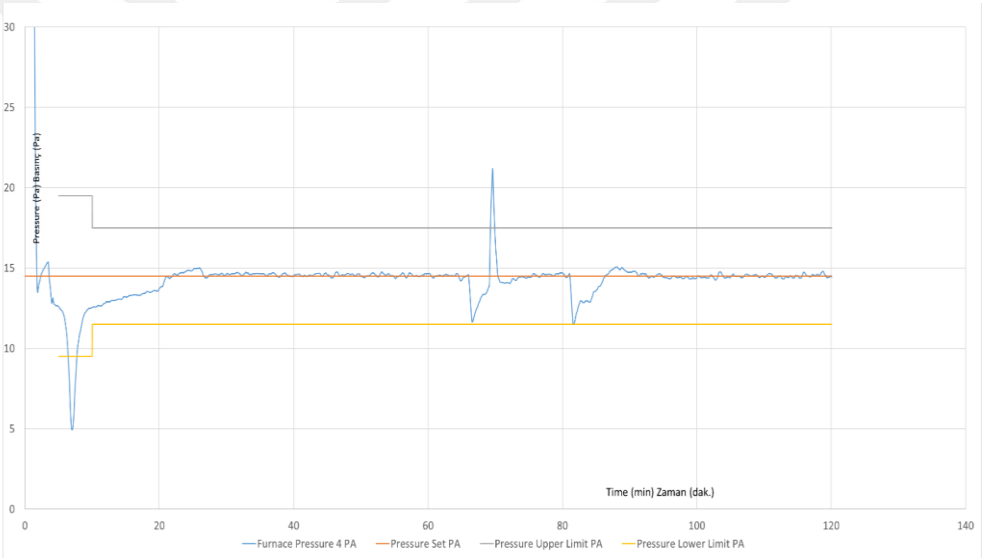


Figure 40: Furnace pressure during the fire test

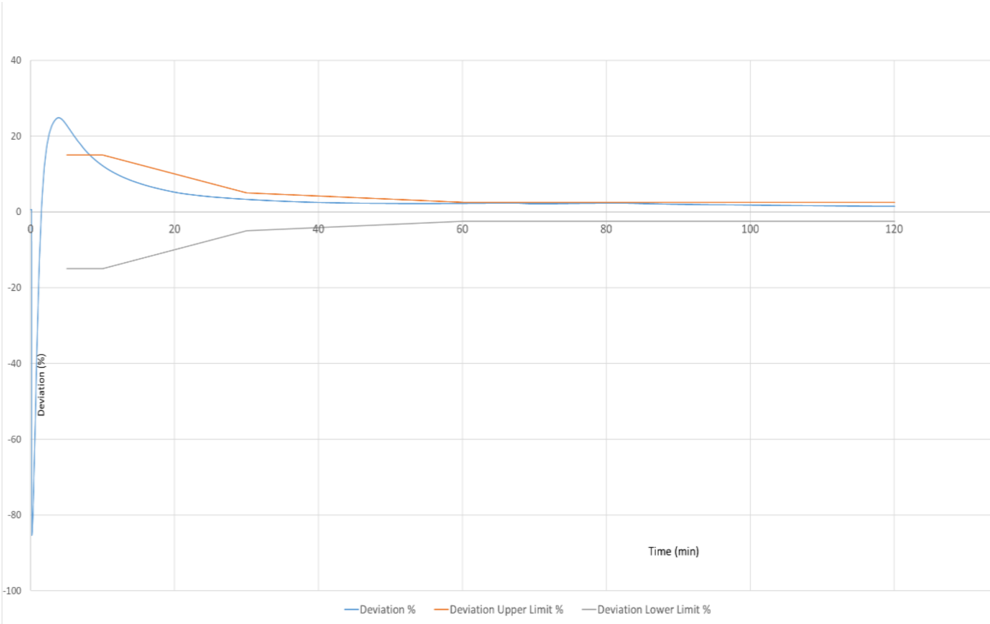


Figure 41: Deviation (furnace)

2.9. Modelling of Intumescent Coatings on Steel Beams

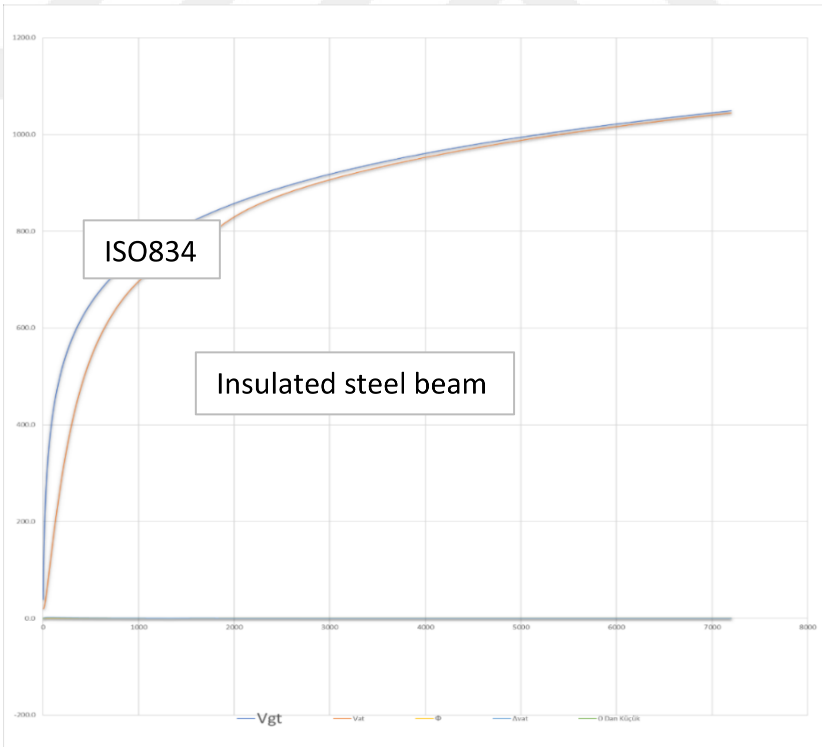


Figure 42: Theoretical temperature-time curve of isolated beam in Excel by considering EN 1993-1-2

Figure 34 was derived from Excel by using the formulas in EN 1993-1-2. Same curve with ISO 834 was followed with the input data. Only temperature dependent variable was the steel's specific heat capacity. Intumescent coating's thermal conductivity and specific heat capacity were taken as constants according to EN 1993-1-2.

ABAQUS software was used to derive temperature-time curve from the 12 points where thermocouples were applied on the steel beam as shown in Figure 35 and Figure 37.

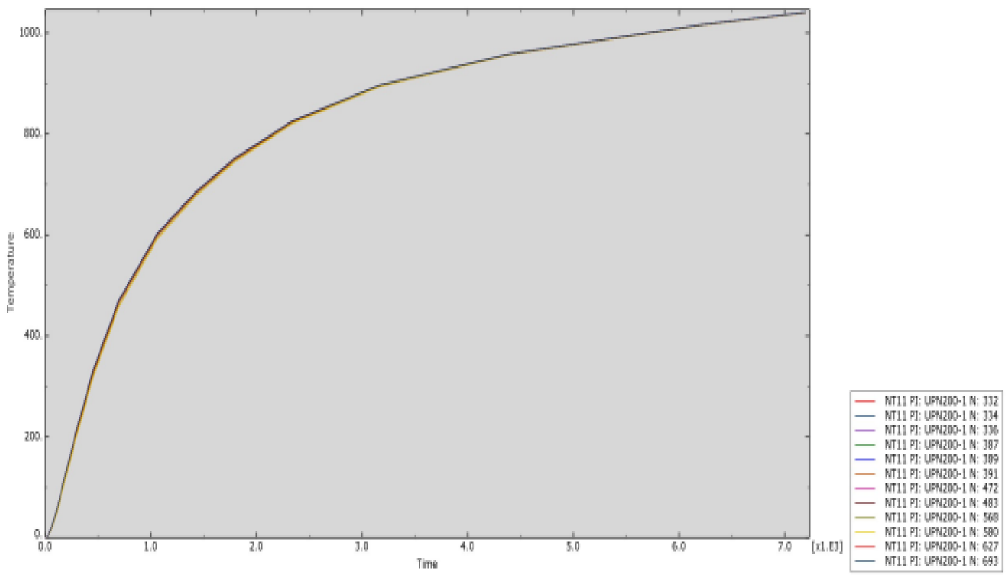


Figure 43: Temperature-time curve of steel beam for Product A in ABAQUS software

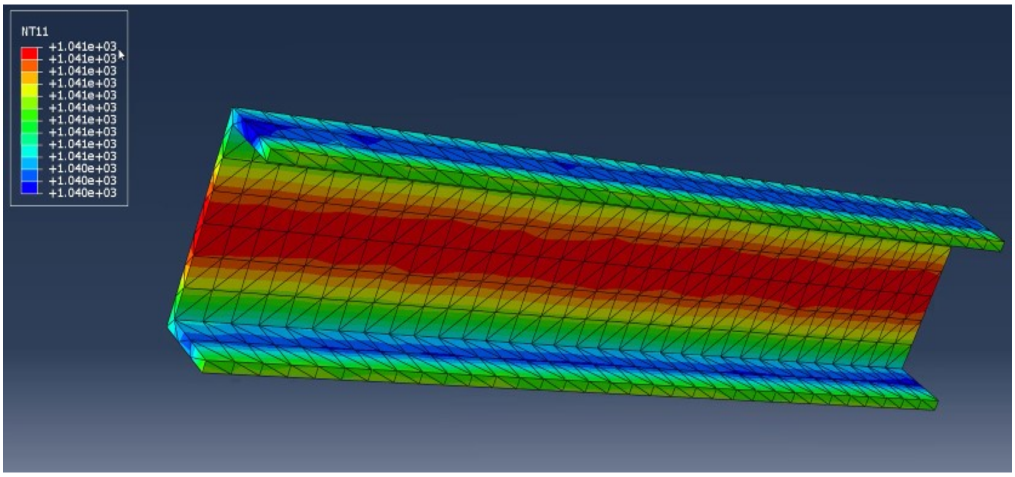


Figure 44: Thermal analysis of steel beam for Product A in ABAQUS software

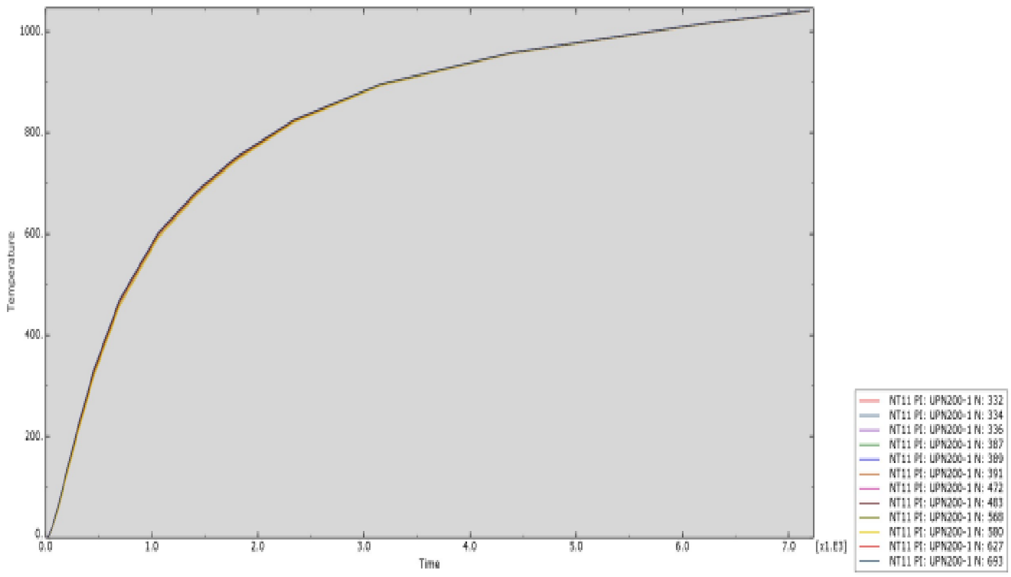


Figure 45: Temperature-time curve of steel beam for Product B in ABAQUS software

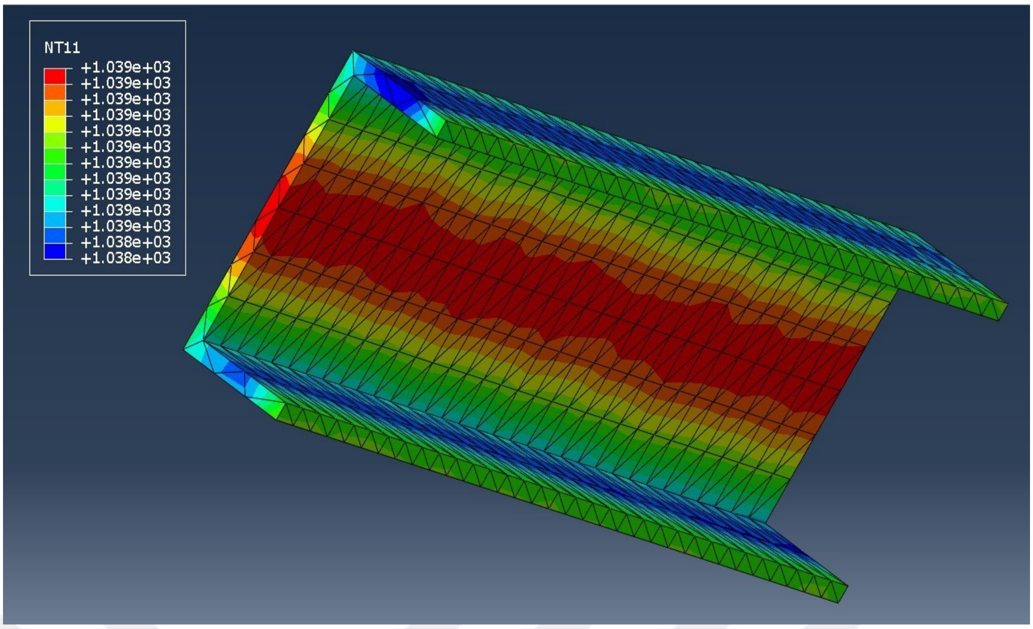


Figure 46: Thermal analysis of steel beam for Product B in ABAQUS software

When analyzing the heat transfer in steel beams which were exposed to fire from 4 sides, steel beams' web part reached the critical temperatures before the flange part of steel beams. So, there might be different thickness of the intumescent coatings can be applied to increase the fire resistance of the steel structural components.

CHAPTER III

CONCLUSIONS

3.1 Summary

Comparison of two different industrial intumescent coatings on steel beams related to protect them against ISO 834 fire type for 2 hours by reducing the temperature increase rate in a case of fire is the basis of this research. Each beam's surface temperature was measured with 12 thermocouples. Temperatures for steel beams and furnace inside temperature were derived with thermocouples for every second and totally for 7200 seconds. There was no applied load except self-loads of the steel beams, so, contradiction was disregarded for the beams. Only failure criterion was the time that steel beam's surface temperature under the different industrial intumescent coatings reached the 593^{o} C which was critical temperature for the structural steel beams.

Researchers prefer calculation method in this type of research rather than experiment. So, the values which were derived from the experiment considering different type of intumescent coatings are important for the further research based on fire safety of the steel structures. Two 1-meter UPN 200 steel beams were insulated with the two different commercially used intumescent coatings which have different thermal and physical properties. They have 3100 microns and 3280 microns thickness, respectively. They had nearly same thickness and all other variables were the same including applicator quality, coating duration, steel grade and type which were coated by intumescent coatings, furnace type, fire type and experiment period. Composition of different intumescent coatings was the only variable that affect fire resistance of the insulated steel beams.

The Product A reached the critical temperature in 66th minute has consistent temperature data set for 7200 seconds which might be consequence of homogeneity of its compositions. The Product A had 38.78 mm char thickness after the experiment which is 12 times greater than its original volume. The Product A had a 3.1 mm thickness at the beginning of the furnace fire experiment.

The Product B which has inconsistent temperature-time values within its thermocouples reached the critical temperature in 37th minute. The Product B has no char on the steel beam after the fire test which could be a barrier for its fire protection for steel beam. The Product B has inconsistent temperature data set for 7200 seconds which might be consequence of non-homogeneous compositions.

After getting the experimental data, numerical calculations were done using the formulas in EN 1993-1-2 and derived a temperature- time graph in Excel. Only temperature dependent variable was the steel's specific heat capacity. Other variables were taken as constant. Thermal conductivity of the steel beam was also taken as constant because of not calculating thermal gradient within the steel beam.

ABAQUS software was used to derive the temperature-time graph for both The Product A and The Product B. All the thermal values of steel beam and the intumescent coatings were used . Heat transfer was also simulated for 7200 seconds in a case of ISO 834.

3.2 Conclusions

This research covers revealing the intumescent coatings' fire protecting effects on structural steel components when they are exposed to ISO 834 fire. Analyzing efficiency of intumescent coatings which are performed on the individual structural steel components is not the accurate way of researching the fire safety design of steel structures but analyzing total structural steel construction. Analyzing all steel structure instead of structural steel components gives a better understanding of Eurocodes which uses critical temperature for structural steel member analysis containing fire resistance, temperature, and time needs for the steel structures. Poh [24] indicated that mechanical properties are affected by the increasing temperature, and it should be considered for an accurate analysis of steel component under fire.

Design codes do not consider the change in values of thermal and physical properties of intumescent coatings. Specific heat and thermal conductivity are the two thermal properties which are temperature dependent, and their values change as the temperature increases. On the other hand, they are taken as constants according to EN 1993-1-2. Magnitude of the density which is a physical property increases because of loss of the moisture content as the temperature increases. For instance, Product B's density increases from 1350 kg/m^3 to 1850 kg/m^3 due to loss of moisture which is a result of increasing temperature in a case of fire. On the other hand, density of the intumescent coating is also taken as a constant value according to EN 1993-1-2. All these variables change with the temperature, but they are all taken as constant values which lead to difference with experimental and theoretical values.

Char which has an impact on the efficiency of the intumescent coatings behaves as a thermal barrier between fire as a heat source and the structural steel component. Thermal conductivity of the char of the intumescent coatings decreases as the temperature increases. Determining the exact value of the char's thermal conductivity cannot be calculated because of the complex expansion process of the char in heating process which causes a difference in experimental and theoretical values. Adhesion problems between the steel substrate and the intumescent coating might occur during the fire experiment. Some adhesion problems occurred in this experiment too with the steel beam and the Product B which caused fire protection problems as reaching critical temperature in 37th minute instead of 120 min. On the other hand, for Product A which had no adhesion problems and had 38.78 mm char thickness, it took 66 minutes to reach the critical temperature instead of 120 minutes. Surely, char is not the only effect time difference for the time to reach the critical temperatures for the Product A and the Product B but an important effect.

Both industrial intumescent coatings are used for 2 hours against the fire exposure, their time for reaching the critical time were the different. There might be several reasons for this situation. Manufacturers might send their best materials for testing to get adequate certificates and there might be quality differences other products that sell in the fire protection industry and ones which were tested in the laboratories.

3.3 Future Work

- Experiments about the fire safety of steel components considering the intumescent coatings' effects on delaying the increase of temperature rate cannot be done rarely due to the high costs both before the experiment and during experiments. Different intumescent coatings should be repeated in the future research and can be compared with the results of the ones that were derived from this research.
- This study covers the fire resistance of individual structural steel components which were insulated by different intumescent coatings by following ISO 834 fire curve which is like ASTM E119. This experiment should be repeated with other types of fires involving hydrocarbon and parametric fire types which have different fire curves.

- Nanomaterials have been used in the intumescent coating as an organic filler for improving the performance of the intumescent coatings as a thermal barrier. New experiments should be done for comparison of intumescent coatings with nanomaterials and without ones to see the fire resistance effect of nanomaterials.
- Dealing with adhesion problems during the fire experiment in the furnace especially in the expansion process is important because of decreasing the thermal conductivity in the expansion process. So, improvements should be done on undercoats and intumescent coatings to overcome the adhesion problems for increasing fire protection of structural components.
- This experiment was performed with the 4-sided fire exposure. Insulated beams with the floor or cell composite assemblies should be evaluated with the 3-sided fire exposure to see the thermal effects of insulated beams with the assemblies.
- Different thickness of intumescent coatings can be applied on the same steel component except various parts. As seen in Figure 36 and 37, web part of steel beam was more affected because of fire exposure than flange part of the steel beam. Without changing the total weight and total cost of intumescent coating, thickness of intumescent coating which is applied on the web part of the steel beam can be increased while thickness of intumescent coating which is applied on the flange part can be decreased. Generally, all the thickness of the intumescent coatings that are applied on the structural steel components is the same in the fire protection industry.

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