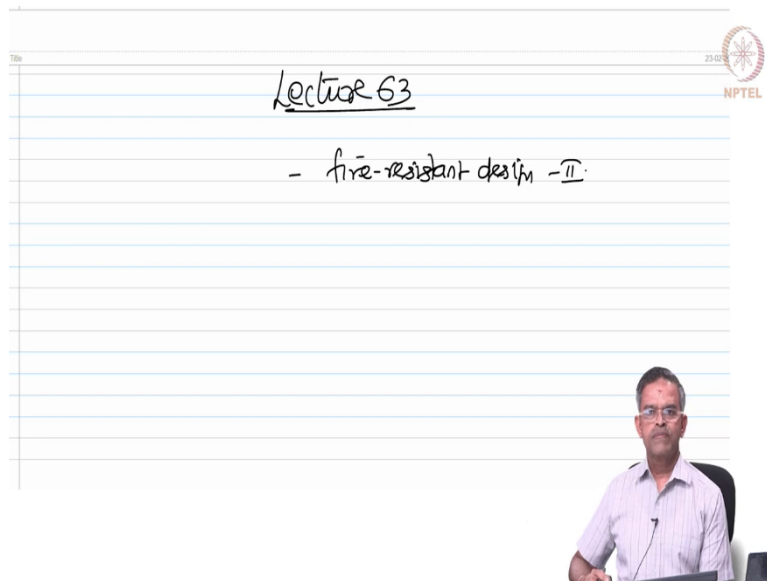


Advanced Design of Steel Structures
Dr. Srinivasan Chandrasekaran
Department of Ocean Engineering
Indian Institute of Technology, Madras

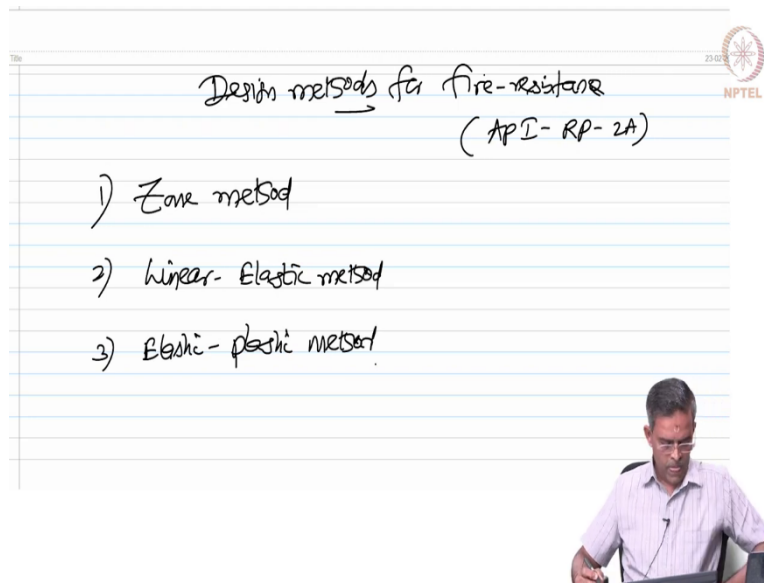
Lecture - 63
Fire - resistant design - 2

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Friends, welcome to lecture 63 of Advanced Steel Design, where we are continuing to discuss the procedures for Fire resistant design as a part of this course. In the last lecture, we discussed about some essential characteristics of fire, what are the tips for good fire-resistant design buildings, and so on. Now, we will focus more on design methods for fire resistance. This is what specific reference to API-RP 2A, American Petroleum Institute Recommended Practice 2A.

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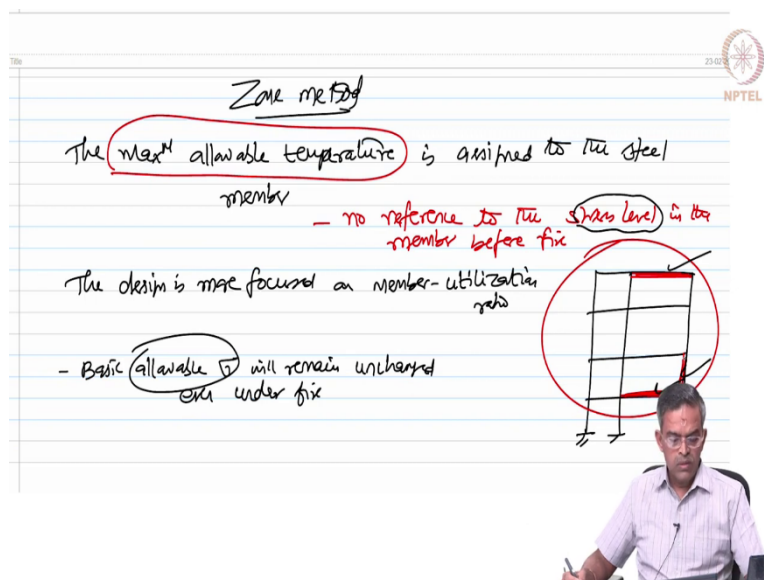


Design methods for fire-resistance
(API-RP-2A)

- 1) Zone method
- 2) Linear-Elastic method
- 3) Elastic-plastic method

This specific course says there are 3 possible ways by which you can design fire resistance structures. 1 is by what is called as a zone method, 2, linear-elastic method and the 3rd one is elastic-plastic method.

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Zone method

The max allowable temperature is assigned to the steel member
- no reference to the stress level in the member before fire

The design is more focused on member-utilization ratio

- Basic allowable stress will remain unchanged even under fire

In the zone method, the maximum allowable temperature is assigned to the steel member. This method has no reference to the stress level in the member before fire.

Let us say, in a given building, there are zones where there is a possibility of fire, let us say this member, and let us say in this member, column and this beam. These are the possible locations where a fire could outburst.

So, now these steel members are assigned to a maximum allowable temperature up to which it has to sustain. When you do that, you do not have any cross reference to the stress level in these members before fire. So, the design is more focused on member utilization ratio. The basic allowable stress will remain unchanged even under fire.

That is the reduction in stress level due to high temperature is not accounted in the design as the allowable value. They remain unchanged. So, this method is focusing only on certain areas, on certain members which has got high proximity of fire, probability of fire occurrence is higher. So, that is why this method is called zone method.

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The yield strength (σ_y) is reduced by a factor of 0.6

disadvantages

i) Not applicable with the unmatched reduction in both σ_y and E

— This affects the design criteria

In this method, the yield strength σ_y is reduced by a factor of 0.6. Now, there are disadvantages of this method. 1, it is not applicable with the unmatched reduction in both σ_y and E , because you have a constant number. So, this affects the design criteria.

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The slide contains handwritten notes on a lined background. At the top right, there is a small circular logo with 'NPTEL' written below it. The main title is 'II Linear Elastic method'. Below the title, there are three bullet points written in black and green ink. The first bullet point is in black ink and states: '- The Max^t allowable stress is assigned to the steel member based on the σ level before fire.' The second bullet point is in green ink and states: '- The main focus is to maintain the member utilization ratio close to Unity'. The third bullet point is in black ink and states: '- σ_y - corresponds to the assigned temp level - during fire'. Below this, there is a green note: '- a core average temp is considered - $(\sigma_y)_{temp}$ '. In the bottom right corner of the slide, there is a small video inset showing a man in a light-colored shirt speaking.

The 2nd method is linear elastic method. In this method, the maximum allowable stress is assigned to the steel member based on the stress level before fire. So, here the main focus is to maintain the member utilization ratio close to unity. So, effective utilization is ensured and this is done even at increase in the temperature.



In this design method, the stress level corresponds to the assigned temperature level. So, you have to pick up the yield value with respect to the corresponding temperature level of steel during fire. So, when you talk about the temperature variation during fire, then you may ask me a question what temperature should I consider for estimating σ_y from the material property? That is a good question.

You can have a maximum temperature; you can have a minimum temperature. So, what we generally consider is, your core average temperature is considered and the equivalent σ_y at that temperature is taken for design.

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disadvantages

- It also proposes an unmatched value of σ_y & E
- serious concern

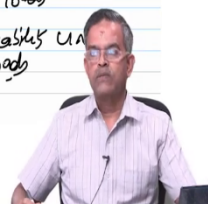



This method has some disadvantages. This method also proposes an unmatched value of σ_y and E , which is a serious concern because the degradation in young's modulus and the yield strength are not same at a specific temperature. It considers an average core temperature value for which σ_y is considered, but E is not accounted with respect to the temperature variation.

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III Elastic plastic method

- Maxⁿ allowable temp is assigned to the member, based on the stress level before fire - *It is only assigned to critical members*
- the member utilization in this procedure < 1.0 w/its \uparrow in temp
- we need to verify the structure under collapse loads -
- but the design should ensure serviceability under fire loads



The 3rd method is elastic plastic method, where the maximum allowable temperature is assigned to the member, based on the stress level before fire. Friends, this is not assigned to all the members. It is only assigned to critical members. What do you mean by critical members? The members whose stress level is maximum before fire.

As a result, the member utilization in this design procedure is lesser than 1.0 with the increase in temperature.

So, all members are not subjected to uniform stress range, only those critical members subjected to higher temperature during fire is assigned a specific stress value. So, therefore, one need to verify the structure under collapse. So, you need to verify the structure under collapse loads, but the design should ensure serviceability under fire loads. So, that is the design criteria what this method ensures.

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disadvantages

- commonly used strain value is 0.2 which matches with the reduction in σ_y with increase in temp
- selection of higher ϵ , will result in increase in temp, which will not match with (σ_y, ϵ) for the design

This method also has couple of disadvantages. Commonly used strain value in the design is 0.2 which matches with the reduction in σ_y with increase in temperature. But selection of higher strain, will result in higher temperature. See, you are looking for an average temperature for which the strain value may not be 0.2. In the last lecture, we discussed about the strain variation in steel with respect to temperature.

So, either you pick up the strain value for a specific temperature or for a specific strain pick up the temperature. So, the procedure says you pick up the stress value for a specific

temperature for the critical members, but when it assigned the strain value it is 0.2. So, a higher strain value assigned to the members will result in higher temperature, which will not match with the stress and young's modulus for the design. So, that is a concern in this method.

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Energy released during fire

If the ignition fluid is present in the building, then the total energy released during fire - 'FIRE load'

$$E = \sum_{i=1}^n m_i C_i \quad (1)$$

✓ m_i - mass of combustible materials (kg)

✓ C_i - calorific value, each material (J/kg or MJ/kg)

NBC - Part IV

Having said this let us talk about energy released during fire. If the ignition fluid is present in the building, then the total energy released during fire can be given by what is called as fire load. So, fire load is the total energy which is sum of $M_i C_i$, where M_i is the mass of combustible materials present in the building in kgs.

$$E = \sum_{i=1}^n M_i C_i$$

C_i is the calorific value of each material which is either in joules per kg or of course, megajoules per kg. For common materials being used in buildings, national building code part 4 gives the value of M_i and C_i value of different materials.

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Table 9 Calorific Values of Common Materials (Clause A-1)				Table 9 -- (Concluded)			
Sl. No.	Material	Calorific Value ($\times 10^3$ kJ/kg) ^a	Wood Equivalent	(1)	(2)	(3)	(4)
(i)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
(i) Solid Fuels				(v) Common Solids			
a)	Anthracite	28.6	1.66	a)	Asphalt	38.3	2.13
b)	Bituminous coal	30.8	1.75	b)	Bitumen	33.4	1.90
c)	Charcoal	28.4	1.61	c)	Carbon	32.1	1.83
d)	Coke (average)	27.5	1.56	d)	Cotton (dry)	15.8	0.90
e)	Peat	20.9	1.19	e)	Flax	14.3	0.81
f)	Sub-bituminous coal	22.0	1.25	f)	Fur and skins	18.7	1.06
g)	Woods (hard or softwood)	17.6	1.00	g)	Hair (animal)	20.9	1.19
(ii) Hydrocarbons				(vi) Foodstuffs			
a)	Benzene	39.6	2.23	a)	Bread	11.0	0.63
b)	Ethane	49.1	2.79	b)	Butter	29.5	1.68
c)	Ethylene	47.7	2.71	c)	Meat	18.1	1.03
d)	Fuel oil	41.6	2.36	d)	Corn meal	14.1	0.80
e)	Gas oil	42.9	2.44	e)	Flour	14.1	0.80
f)	Hexane	44.9	2.55				
g)	Methane (natural gas)	52.8	3.00				
h)	Octane	45.3	2.58				
i)	Paraffin	39.6-44.0	2.32-2.5				
m)	Pentane	46.0	2.61				
n)	Propane	47.3	2.69				
p)	Propylene	46.2	2.63				

Ex 1
 200 kg of benzene hydrocarb
 $C_i = 39.6 \text{ MJ/kg}$
 average heat release rate (HRR)
 can last for 1 hr
 $E = 200 \times 39.6$
 $= 7920 \text{ MJ}$
 Energy released @
 $= \frac{7920}{60 \times 60} \text{ kW}$

Look at this table which is extracted from the national building code for different material. Let us say solids, hydrocarbons, common solids, even foodstuffs.

A calorie value and the wood equivalence are given in the code. Let us do a small example. Let us say there is a presence of 200 kg of benzene hydrocarbon. If you look at benzene hydrocarbon, the calorific value is 39.6, I can say megajoules per kg; plus 10 power 3 I have taken as megajoules.

Now, the average release rate which is called as HRR can last for 1 hour. So, we can say E is going to be 200 into 39.6 that is 7920 megajoules. So, the energy released Q can be 79; 7920 by 60 into 60, which is 2200 kilowatts.

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Ex2 Mixed Mass

100 kg of Benzene (C = 39.6 MJ/kg)

50 kg of Butane (C = 47.1 MJ/kg)

200 kg of Ethane (C = 49.1 MJ/kg)

Average energy released during one Hr.

= HRR (60 x 60 s)

$$E = \sum M_i C_i$$

$$= (100 \times 39.6) + (50 \times 47.1) + (200 \times 49.1)$$

$$= 16135 \text{ MJ}$$

$$Q = \frac{16135 \times 10^3}{60 \times 60} = 4481.9 \text{ kW}$$

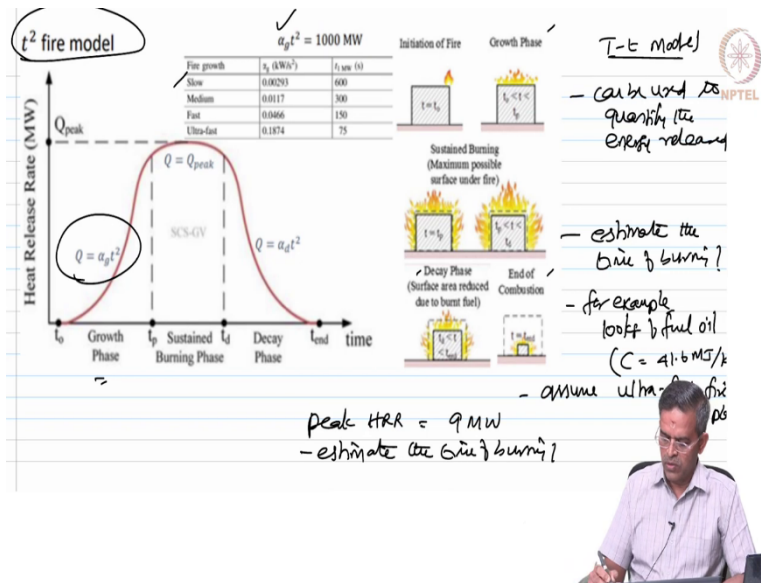
Let us do one more example of a mixed mass. You can see on the screen the NBC table extracted. Let us say the building contains 100 kg of benzene whose C value is 39.6, 50 kg of butane whose C value is 47.1, 200 kg of ethane C value is 49.1.

So, the average energy released during 1 hour is called as HRR, heat release rate that is 60 into 60 seconds is given by sum of $M_i C_i$. In our case going to be,

$$E = \sum_{i=1}^n M_i C_i = (100 \times 39.6) + (50 \times 47.1) + (200 \times 49.1) = 16135 \text{ MJ}$$

$$Q = \frac{16135 \times 10^3}{60 \times 60} = 4481.9 \text{ kW}$$

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Let us look into the t^2 fire model which is a very common time temperature curve, which is being used is also called as T-t model or a t^2 square fire model. This can be used to quantify the energy released.

Furthermore friends, you can also see the time temperature or time heat release rate curve where, the $\alpha_g t^2$ which is the heat release rate depends on a factor which is there for different kind of fire. Let us say, if it is a slow fire growth α_g is different compared to ultra-fast fire growth.

Now, if the fire growth rate is known to us, we can estimate the time of burning. We can easily find out how long the fire will be sustained. Furthermore, there are different phases of fire growth initiation, growth phase, decay phase and end of combustion. So, in the growth phase, there is a significant rise in the heat release rate with reaches its peak and then it gets decay as you see here in the figure.

So, now let us say for example, I have 100 kg of fuel oil. The fuel oil has got C as 41.6 megajoule per kg from the table. Let us assume an ultra-fast fire to take place. The peak HRR, that heat release rate is 9 megawatts. We want to estimate the time of burning. Let us do that.

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$E = (100 \times 41.6) = 4160 \text{ MJ}$
 Growth factor for ultra-fast fire $\alpha_g = 0.1874 \text{ kW/s}^2$
 Time taken to reach the peak HRR, t_p
 $t = \sqrt{\frac{9000}{0.1874}} = 219 \text{ sec}$
 Total energy released in the growth stage, E_1
 $E_1 = \frac{Q_p t_p}{3} = \frac{9 \times 219}{3} = 657 \text{ MJ} < 4160$
 Total burning time = $t_b = t_p + \left(\frac{4160 - 657}{\theta_p}\right) = t_p + 10.1 \text{ min}$

$$E = (100 \times 41.6) = 4160 \text{ MJ}$$

The growth factor for fire or ultra fast fire that is α_g from this table, you can see, it is 0.1874, 0.1874 kilowatt per second square. Therefore, the time taken to reach the peak HRR that is t_p is 9000 because we already said the HRR is about 9 megawatts divided by 0.1874 root which will be 219 seconds.

$$\alpha_g = 0.1874 \frac{\text{kW}}{\text{s}^2}$$

$$t = \sqrt{\frac{9000}{0.1874}} = 219 \text{ sec}$$

Now, the total energy released in the growth stage let us call this E_1 can be computed as

$$E_1 = \frac{Q_p t_p}{3} = \frac{9 \times 219}{3} = 657 \text{ MJ} < 4160 \text{ MJ}$$

Since, the 657 megajoule in the growth stage is much lesser than the heat release which is the energy present because of the oil or because of the fuel oil. We can say the total burning time will be

$$t_b = t_p + \left(\frac{4160 - 657}{\theta_p}\right) = 10.1 \text{ min}$$

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Time-temp behaviour of fire

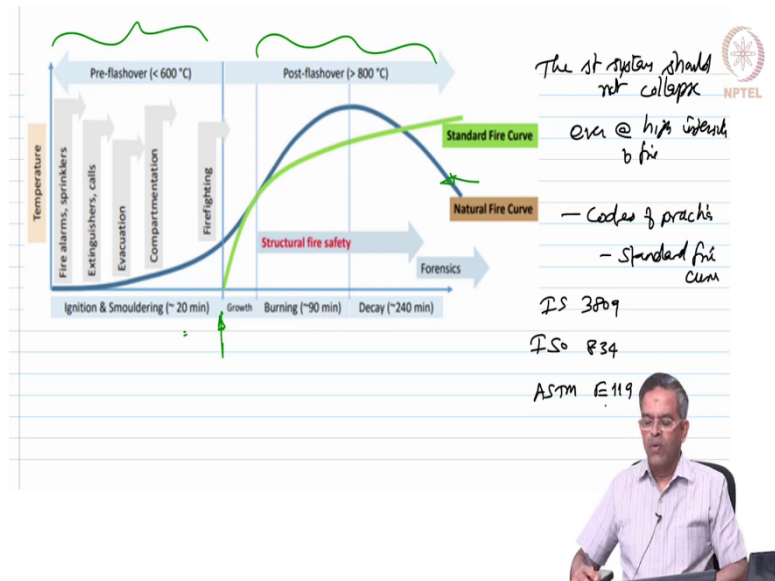
significant difference b/w real fire & standard fire

- fire has a starting phase - which is initially small \approx 20 min.
- activate the fire-fighting m/c
- It is always good to provide a compartment design
- fire-fighting is initiated during the fire growth phase

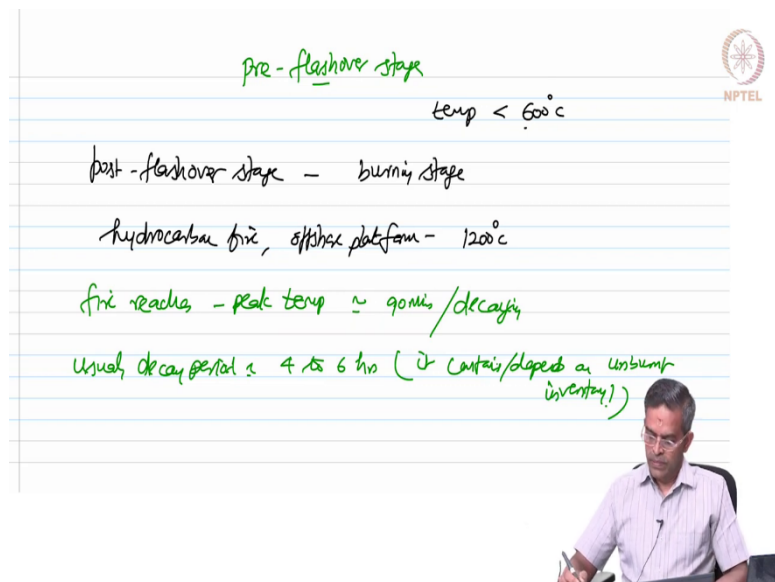
fire alarm
sprinklers
extinguishers
call to fire station
evacuation plan

Let us discuss about the time temperature behavior of fire. Friends, there is a significant difference between the real fire and the standard fire. Fire has a starting phase which is initially small about 20 minutes. So, it is during this time, one can activate the firefighting equipment's like fire alarms, sprinklers, extinguishers, call to fire station, evacuation plan etcetera. All can be activated during this time. It is always good to provide a compartment design. So, the fire does not spread to the places where device and equipment's are kept. So, friends, we must understand that firefighting is initiated during the fire growth phase during the fire growth phase.

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Following by this, let us have something called pre-flash over stage. This is true up to a temperature less than 600 degree Celsius. The post-flash over stage is called as the burning stage. It is interesting friends for you to know that hydrocarbon fires which happen in offshore platforms, can reach the temperature as high as 1200 degree Celsius.

Therefore friends, in such cases fire reaches its peak temperature approximately within 90 minutes and then starts decaying. Usually, the decay period of fire is about 4 to 6 hours. But it contains and depends on the unburned inventory. Let us look at this curve which is the pre-flash over and post-flash over stage. The pre-flash over stage is about approximately 20


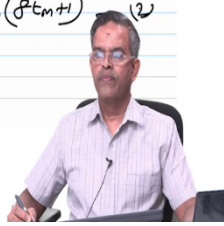
minutes on initial ignition and smoldering. Then, the burning takes for 90 minutes, then the decay is about 240 minutes. The natural fire curve is what you see here.

Whereas, the standard fire curve always starts after the pre-flash over stage, after this stage. So, the philosophy for design is that the structural system should not collapse even at high intensity of fire. There are various codes of practices which ensure this fire safety which shows the standard fire curve. For example, IS 3809, ISO834, ASTM E119, helps you by providing the standard fire curve.

(Refer Slide Time: 33:37)



Location	Year	Area surveyed (m ²)	Mean FLED (MJ/m ²)	Reference
London, UK ✓	1970	2418	330 ✓	3
Nationwide, US	1975	7246	130-4805	4
Kanpur, India	1993	11,720		348 ✓
Wellington, New Zealand	1995	3999	426-947	7
New Zealand Building Code	2001	-	800	16
Ottawa and Gatineau, Canada	2011	935	550-852	13
Ahmedabad, India	2015	938	1334 ✓	Present study

The Standard fire curve $T = T_0 + 345 \log(t + 1)$ (2)

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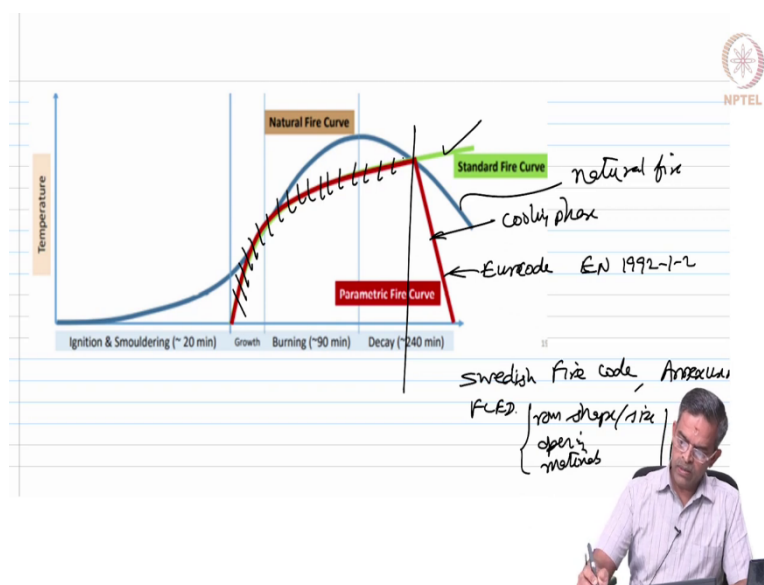
Fire load Energy density (FLED)

Furthermore, we can also estimate the fire load energy density which is called as FLED. The fire load energy density depends on different code provisions which are also carried and revised by different countries. For example, in London, the mean FLED energy density is about 330 megajoules per square meter, whereas in India it is about 348. So, it keeps on varying and these effects are reflected in the respective national standards of the countries.

A recent study carried out by IIT, Gandhinagar in 2015 shows that the mean value of fire load energy density is much higher in reality. This was tested in the laboratory and people have reported that the FLED value for design which is referred as different codal provisions are far lesser than the actual value. Now, for the standard fire curve T is given by $T = T_0 + 345 \log(8tm + 1)$, for standard fire. We call this equation number 2.

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Now, look at this fire curve back again it says that the natural fire curve has got a cooling phase. The standard fire curve closes here, whereas the parametric fire curve, which indicate in Euro code which is EN 1992-1-2 indicates a cooling phase for about short period.

So, now, there is a cooling phase which is shown in the red color here. So, this is for the natural fire which also indicates a cooling phase whereas, in standard fire curve this cooling phase is missing. Whereas, if you look at the Swedish fire code in Annexa A, FLED is revised based on the room shape and size, and openings present in the room, and inventory materials present in the room.

So, there has been a revision in the Swedish fire code to compute the fire load energy density, not at the standard value, but is dependent on realistic parameters as you see here. The standard fire curve only indicates the growth phase, but does not talk about the cooling phase. Whereas, a parametric fire curve used in euro code talks about the cooling phase as well.

(Refer Slide Time: 38:05)

1st step To compute FLED

$$q_{f,d} = q_{f,k}(m) \delta_{q1} \delta_{q2} \delta_{qn} \quad (3)$$

m : combustion factor ≈ 0.8
 δ_{q1} - fire activation risk factor (shape, size)
 δ_{q2} - type of occupancy
 δ_{qn} - combined effect of the above factors

$q_{f,d}$ - design FLED $q_{f,k}$ - characteristic fire load density per area of flow
 (MJ/m²)

So, therefore, friends in fire resistance design, the 1st step is to compute fire load energy density, which is given by

$$q_{f,d} = q_{f,k}(m) \delta_{q1} \delta_{q2} \delta_{qn}$$

Call this equation number 3 where m is the combustion factor, which is approximately 0.8. δ_{q1} is a fire activation risk which depends on the shape and size.

δ_{q2} depends on the type of occupancy. And δ_{qn} is a combined effect of the above factors.

Now, $q_{f,d}$ is called the design FLED, $q_{f,k}$ is called the characteristic fire load density per area of flow which will be expressed in megajoules per square meter.

(Refer Slide Time: 40:25)

for example in NBC (India)
 $\approx 25 \text{ kg/m}^2$ wood equivalent
 $= (25 \times 17) = 425 \text{ MJ/m}^2$

For example, in national building code of Indian practice, it is said as 25 kg per square meter of wood, equivalent of wood. So, we now say, wood equivalent we can say, which is 25 into; the calorific value of wood which is giving me 425 megajoules per square meter.

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Compartment (area, A1 (m ²))	Risk factors (size of compartment (δ _{q1}), Type of occupancy (δ _{q2}))		Examples of occupancies
25	1.10	0.78	Art gallery, museum, swimming pool
250	1.50	1.00	Office, residence, hotels, paper industry
7500	1.90	1.22	Manufacturing heavy machinery and engines
5000	2.00	1.44	Chemical labs, painting workshops
10000	2.13	1.66	Manufacturing fire-works or paints

Now, the other factors δ_{q1} and δ_{q2} are given here depending upon the type of occupancy and the size and shape. If the compartment area is about 25 square meters δ_{q1} is about 1.1 and for art gallery museum etcetera is 0.78, whereas manufacturing fireworks is about 1.66. So, the


example of occupancy is also listed here which helps me to compute the δ_{q1} and δ_{q2} factors required to compute the FLED of the design value.

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Description	Nomenclature	Value
Water extinguisher systems	δ_{s1}	0.61
Automatic fire suppression	δ_{s2}	1.0
Independent water supply system	δ_{s3}	0.87
	δ_{s4}	0.70
Automatic fire detection & alarm	By smoke	δ_{s5}
	By heat	δ_{s6}
Auto alarm transmitters to fire brigade	δ_{s7}	0.87
Fire brigade at site	δ_{s8}	0.61
Fire brigade at off-site	δ_{s9}	0.78
Manual fire suppression	Safe access routes available	δ_{s10} 0.5, 1.0 or 1.5
	Fire fighting devices available	δ_{s11} 1.0 or 1.5
	Smoke exhaust system available	δ_{s12} 1.0 or 1.5

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δ_n



If you have firefighting systems which is useful for suppressing fire with water extinguisher systems, independent water supply system, fire brigade located off site, or firefighting devices available, then the del n value is also varied. So, it is a combined effect which is useful to compute the FLED for the design.


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Occupancy	Average value	80% Fractile Recommended for design
Dwelling	780	948
Hospital room	230	280
Hotel room	310	377
Library	1500	1834
Office	420	511
Classroom of school	285	347
Shopping center	600	730
Theatre hall	300	365
Public place	100	122

NPTEL

$q_{1k} (MJ/m^2)$

$(q_{1k})_{Dwelling} = 948 MJ/m^2$



The table what you see on the screen is an average value of $q_{f,k}$ in megajoules per square meter is $q_{f,k}$. So, for example, $q_{f,k}$ for dwelling units is about 948 megajoules per square meter which is equivalent value of wood. So, it is available for different kinds of public spaces as well as private spaces which is used for the design, which is the characteristic value. Now, with the help of this one can compute the FLED.

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NPTEL

2nd step heat phase calculation

$$\theta_g = 20 + 1325 \left[1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \right]$$

θ_g - gas temp ($^{\circ}\text{C}$) - time delay
 t^* - expressed in hours

- opening factor (ventilation)
- area of vertical opening in walls
- total area of the compartment

Now, the second step involved in fires resistant design or the fire load estimate is heat phase calculation.


$$\theta_g = 20 + 1325 \left[1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \right]$$

(Refer Time: 44:17) equation number 5.

Where θ_g is expresses the gas temperature in degree Celsius which is based upon the time delay. t^* is expressed in hours. t^* depends on opening factors that is the ventilation then area of the vertical opening in walls. Total area of the compartment for which fires resistant design is attempted.

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$t^* = t \cdot r \quad (6)$
 $t = \text{actual time (hr)}$
 $\gamma = \frac{\left(\frac{\text{Opening area}}{b}\right)^2}{\left(\frac{0.04}{1160}\right)^2}$




$$t^* = t \cdot r$$

where t is the actual time in hours and γ is opening factor by breadth b square. Let me write down here. γ is opening area by breadth square which is 0.04 by 1160 square. Let us not.

(Refer Slide Time: 46:27)

$t^* = t \cdot r \quad (6)$
 $t = \text{actual time (hr)}$
 $\gamma = \text{based on the ratio of opening to the whole area - other factor}$
 $\gamma = \left(\frac{O}{b}\right)^2 \quad (7)$
 $0.02 < O < 0.2 \quad (8)$
 $O = \frac{A_v \cdot \sqrt{h_{sp}}}{A_t}$
 $A_v = \text{vertical opening area}$
 $A_t = \text{total area of enclosure}$
 $h_s = \text{av height of window in opening}$



$$\gamma = \left(\frac{O}{b}\right)^2$$

So, gamma is based on the ratio of opening to the whole area. This is referred as other factors that influence the design. Now, gamma is O by b square, where O is called as the opening factor which is

$$O = \frac{A_v \sqrt{h_{req}}}{A_t}$$

$$0.02 < O < 0.2$$

where A v is ventilated opening, A t is the total area of enclosure, and O lies between 0.02 to 0.2. h equivalent is the average height of windows in the openings.

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b- depends on the material property

$$b = \sqrt{\rho c \lambda} \quad (100 \leq \rho c \leq 2200 \text{ J/m}^2\text{K})$$

(ρ, c, λ) density
specific heat of the material
Thermal Conduct

(ρcλ) - thermal inertia of the compartment
Γ = With - standard T-t curve

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In this expression, b depends on the material property;

$$b = \sqrt{\rho c \lambda}$$

for 100 and 2200 joules as square meter per root s k where ρ, c, λ are density, specific heat, and thermal conductivity of the material. ρ, c, λ product is called thermal inertia of the compartment. Gamma, if it is unity, which is referred to which will refer to the standard time temperature curve. We have got seen two curves, right, standard and actual the equation 8.

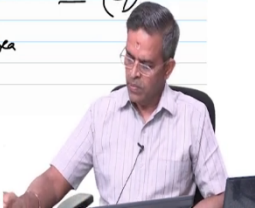
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Opening factor also governs the fire behavior

- in general, all fire are ventilation controlled
- fuel-controlled — offshore platform
- fire intensity depends on the fuel

$$t_{max}^* = \text{Max} \left(0.2 \times 10^{-3} \frac{q_{t,a}}{O}; t_{lim} \right) \quad \text{--- (9)}$$

fuel-controlled or ventilation controlled
opening area



Opening factor also depends on or also governs the fire behavior. In general, all fire are ventilation controlled. Few of them could be fuel controlled. For example, in offshore platforms, you have got lot of ventilation around. So, there is no problem of ventilation, but inventory of fuel will control the fire.


$$t_{max}^* = \text{Max} \left(0.2 \times 10^{-3} \frac{q_{t,a}}{O}; t_{lim} \right)$$

Fire intensity depends on the fuel. where O is the opening area and t limit depends on whether it is fuel controlled or ventilation controlled - equation 9.

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$$q_{t,d} = q_{f,d} \frac{A_f}{A_t} \quad 50 \leq q_{t,d} \leq 1000 \text{ MJ/m}^2$$

$q_{f,d}$. design value of fire load density
 which is computed based on total area
 of ventilation (A_t)



$$q_{t,d} = q_{f,d} \frac{A_f}{A_t}$$

Now, for 50 less than or equal to $q_{t,d}$ less than or equal to 1000 megajoules as square meter, where $q_{f,d}$ is called the design value for fire load density, which is computed based on the total area of ventilation which is A_t .


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III step . cooling phase

$$q_c = Q_{max} - 625(t^* - t_{min}^*, x) \quad \text{for } t_{min}^* \leq 0.5 \text{ hr}$$

$$= Q_{max} - 250(3 - t_{min}^*) (t^* - t_{min}^*, x) \quad 0.5 \leq t_{min}^* \leq 2$$

$$\gamma = \begin{cases} 1.0 & \text{if } t_{min}^* > t_{in} \\ \frac{t_{in}}{t_{min}^*} & \text{if } t_{min}^* = t_{in} \end{cases}$$

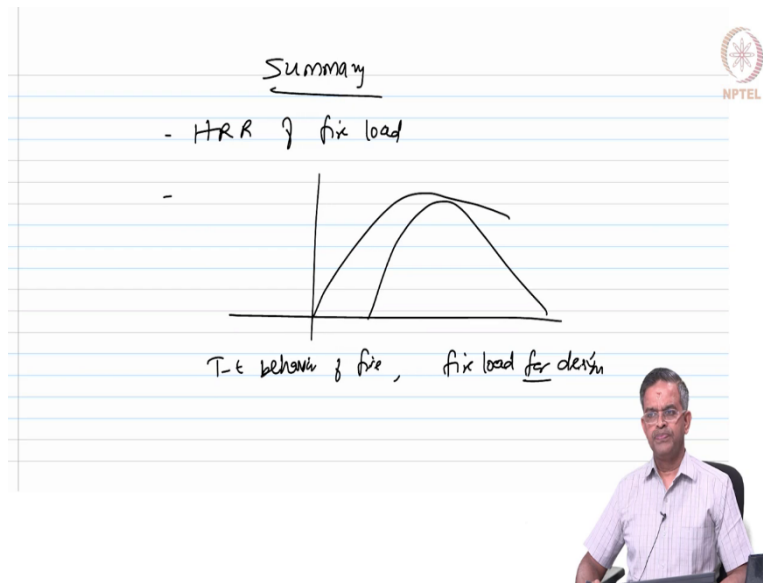


The 3rd step is the cooling phase. Now,

$$\theta_g = \theta_{max} - 625(t^* - t_{max}^*, x) \text{ for } t_{max}^* \leq 0.5 \text{ hrs}$$

$$\theta_g = \theta_{max} - 250(3 - t_{max}^*)(t^* - t_{max}^*, x) \text{ for } 0.5 \text{ hrs} \leq t_{max}^* \leq 2 \text{ hrs}$$

(Refer Slide Time: 54:21)



So, friends, in this lecture, we learnt about the heat release rate of fire load. We also learnt about the standard fire curve and the cooling phase of the fire curve. We understood the time, temperature, behavior of fire, and understood how to compute the fire load for design.

So, more details of this fire-resistant design part can be seen in a separate course of NPTEL conducted by IIT, Madras by me on Offshore Structures under Special Loads including Fire Resistant Design. So, design examples are available. And I also authored a book on fire resistant design which can be useful to you for working out more examples on this. Please refer to them. And try to also refer the DNB code and the European code for learning more about the parametric fire curves.

Thank you very much. And have a good day. Bye.