Fire Protection, Services and Maintenance Management of Building
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Lecture - 09
Design for Fire Resistance: Steel

So, we continue from you know continue with what we have doing in the last class that is Fire Resistance Design, Thermal Design for Fire Resistance I will call it, you know; so, thermal design for fire resistance.

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Now, basically if you will consider a section like this or you know for any section like this consider, any section like this, say steel member we are looking at steel member at the movement, ok.

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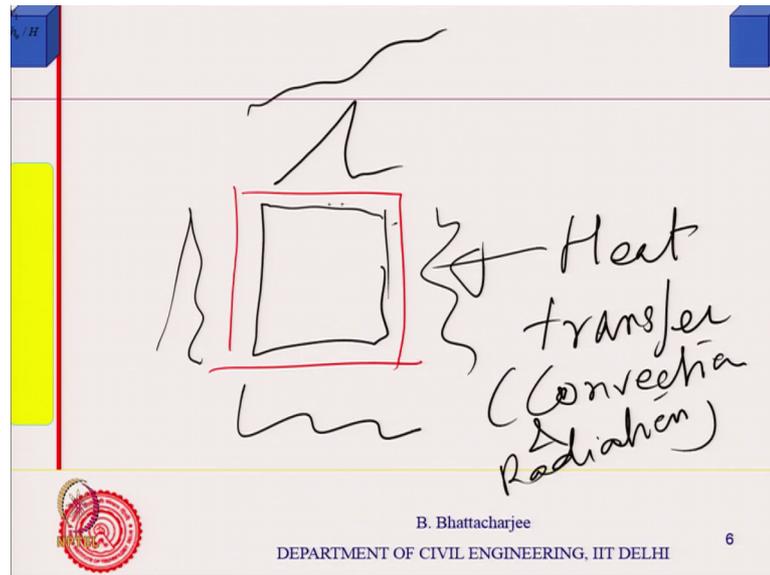
And which is angled by fire from all sides fire from all sides all sides you know there is fire from all sides. So, what will happen? Heat transfer takes place, heat transfer last class we just discuss this I want to give you the an example by convection and radiation; convection and radiation and this heat goes on raising the temperature of the section. And for steel we assume that it is all uniform temperature because its conductivity is very high. So, wherever you know whenever I mean the heat is being received by the section which is section could be something like this it received this. So, uniform temperature we assume.

So, therefore, look into Q input that is, Q input is this component is a radiation component, this component is a radiation component right, last class we are looking at it.

Student: (Refer Time: 02:03).

This component is a radiation component, over a period of time delta t, where this is the area surface area of the steel, this is the surface area of the steal right, this is the surface area of the steel this is the surface area of the steel, this one. This is equivalent emissivity Stephen Boltzmann's constant, Stephen Boltzmann's constant. This is the gas temperature at i plus 1th time step and this is the.

So, what you assume is that gas temperature increases and the steel is still at the original temperature. So, there is a radiation with transfer taking place T s i plus 273 to the power

4 into delta t plus this is the convective heat transfer, this is the convective heat transfer coefficient; surface area of the steel into delta t during the delta t period of time.

Now, this heat we will actually go on increasing the temperature of the steel section during this period of time. So, T s i you know from ith time step to i plus 1th time step. Rho is the density, V is the volume of the steel and C s is the heat capacity. So, Q stored, so Q in is equals to Q stored. And you go T g is, T g at any time you can find out and you know only thing in this kind of an expressive formulation only unknown is this if you equate this you can find out. So, every step you can find out the temperature increase in steel and finally, whenever this steel temperature reaches 550 degree centigrade that you assume as the fire resistance. So, that is what last class we discussed when we were solving a problem right. So, we are solving a problem.

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So, this is the box section 200 mm, 200 mm thick, 15 centimetre angled in fire from all sides. It could be from 3 sides one side insulation and all that but simple case is example this all angled from fire in all sides you know.

And properties of course, equivalent emissivity coefficient is 0.65 right, and Stephen Boltzmann constant is this, density of steel is being taken as this, and this is the conductivity heat transfer coefficient. So, this is for fire this value and these values are taken actually for fire case these values are taken like this, right. So, first approach would be to calculate out the you know at time we have gas temperature.

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So, because assume the time step of 120 seconds in our case we are doing it that way to make it simple and ambient temperature is 25.

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So, if I calculate out the gas temperature at i plus you know say 1, two step or one step because first one was T, T g 0 was 25 only 25 degree centigrade, and then this would be 25 plus 345.

Student: (Refer Time: 05:21).

Log of 18 to 2 minutes because it is in minutes because 120 seconds plus 1; so, we will get 25 plus 345 log 17 which will be 1.8 something or whatever it is and this can be calculated in tabular form.

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So, you calculate this out and you will get this value, you know at words this temperature will be plus 273 added it will be 722. 25 plus 25 plus 273 is 298. So, T g gas temperature in Kelvin is 298 and after first time step which we will calculate out as T g 1 is equals to 25 plus you know 345 log 17 plus 273 and we have because then we will get 722. You can calculate this out and find out.

And this we want to find out the heat input. What we do is we write A is this to find out heat input. So, this is the radiation component right, this is the radiation component; also divided by density of the steel, also divided by density of the steel and volume of the steel. Now, what is the volume of the steel? What is the surface area of the steel? Surface area is perimeter multiplied by 1 because we take we are saying the whole column is angle will fire, right.

So, we take 1 meter height we take, you know 1 meter height of the column, 1 meter height of the steel column, 1 meter height of the steel column. So, we take 1 meter height, 1 meter height right, 1 meter height of the column, 1 meter height of the column and this section as we have seen already. So, surface area when I am finding out it will be the perimeter you know this surface area right this surface area and volume when I am finding out volume is the whole volume section volume of the section.

So, area of the surface is the perimeter average perimeter because what I will do is, I will take it the centre point right centre point. So, thickness as we know as your thickness are known.

Student: 15 mm.

15 mm. So, 200 mm and 200 mm is a diameter. So, 15 mm is the thickness. So, surface area it can average surface area I can find out through which one dimensional heat transfer is taken place. So, that is how we calculate out A s, that is how the we calculate out A s and A s into epsilon is 0.65, sigma is 5.7 into 10 to the power minus 8 and all that.

And this is I have already calculated as 722 to the power 4, this is 298 to the power 4, rho s is 7850, V would be volume of the steel because 1 meter high so column steel column 200 by you know 200 column with 15 centimetre thickness you can calculate out

the volume and C s is all these remember this is given in kilo Joules per you know the properties were given in kilo Joules. So, compare them into Joules that is 540 Joules per kg. This is 780 kg per cubic meter, this is 23 watt fire meter square degree, Kelvin I mean meter square Kelvin.

So, that is how we can calculate out, that is how you can calculate out A. And similarly you can calculate out B this is given its point 0 you know 23 in watt meter square Kelvin and area surface area is as I have told you. So, you can calculate out in this manner. So, after first step you find out A into 120 seconds, A multiplied comes out to be 19.32. B delta t that is convective component divided by rho s v you know C s gives is this.

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So, then you know if you recollect A B was this and that must be equals to, A plus B must be equals to t s i plus 1 minus T s i. So, this is known to us, this is 25 degree centigrade. This sum total we can find out which comes out to be 19 plus something like 38 so 38 plus 25 38 you know, so 38 this comes out to be 38. So, 39 let us say, so 39 plus 25; so 39 plus 25 is 64. So, this is in degree centigrade T s i in degree centigrade 64 after first time interval.

Now, you take this as the next time and then calculate out A and you know, A this would be T g would be simply calculated as 3 4 20; you know 25 plus 345. Now, log off 8 into 4, so log of 8 into 4 sorry; this is let me clear this up.

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345 log of 8 into 4 is 32 plus 1 plus 25. So, that will come out to be 860. And similarly A into delta t, A is the radiative component, this delta t is now you know multiplied by 120. So, this is T g is A into this comes out, and if you sum this up together you get 32 plus you get 32 plus 23 you can say something like approximately 55, 55 plus 64. So, 55 plus 64 gives you 119.

Student: (Refer Time: 11:12).

So, and this is how you can go on calculating and find the at 8 minutes you find that it is 555, which means it is exceeded the criteria thermal criteria of 550 degree centigrade. So, therefore, fire resistance of this steel section when it is when the fire is there from all the direction is simply you know 16 minutes because every time step is 120 seconds it as it 8, 8 into 120 that many seconds would be there or 8 into 2, 16 minutes.

So, fire resistance of this section therefore, is 16 minutes you know. So, fire resistance of this one is then 16 minutes that is what you see fire resistance of this one is 16 minutes. So, this is 16 minutes that is how you can calculate out in tabular form. It is a little bit of time consuming, but if you do it in excel it is pretty simple. So, that is how you can calculate it out, right. Now, let us see if I provide an insulation why we use some insulation gypsum board or something like that, that would increase the fire resistance significantly. Let us see what is it.

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So, if you have if you have encased steel now the heat transfer completely changes. Because I have got an this is this is my steel, this is my steel section, right, this is my steel section, same section let us say and then I have just put in some sort of encasement here, right. This was the steel section an output and in this steel section still is still an output and encasement.

Now, heat transfer will take place and again it is angled in fire from all sides. So, fire is there from all sides, this side this side. Now, what will happen? The heat transfer will now first must takes place to the insulation and then it will reached the steel. Now, once assumption which is conservative anyway, we are assuming the gas temperature is at this point is same as the temperature of the solid insulation, right. How you are doing? Basically why you are doing because this insulation; so it will not transfer the it will take long time to transfer the heat it is not very good conductor.

So, whatever heat is received here it goes on increasing the causes, so we assume the approximately this surface temperature is a gas temperature. Now, how does the heat comes inside? By simple conduction, because there is no gas now, no fluid, so no radiation and conduction heat transfer is simply k you know k A.

Student: (Refer Time: 14:01).

Delta t right, divided by l thickness; so, k by l into A s into T g minus A into delta t. So, input now heat input is given by this, where k is the thermal conductivity of insulation, thermal conductivity because heat will be now transfer to the steel because we are interested in the steel temperature.

So, heat will be transfer to the steel through the insulation only. So, this is the heat transfer you know heat received by the steel, area of the steel and etcetera etcetera, and it will go on raising the steel temperature in this manner. So, if you the calculation, if you calculate now conductivity of this one are very small you know if you quite small actually it is a gypsum board or something similar.

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So, if you calculate out take care for the, you know k for the k for the k for the insulation was 0.5 watt meter degree centigrade you know. It will be of this order, many of this metal. In fact, it could be less also, if it is gypsum board as I said it will observe lot of fit. So, it will because of consignation because of removing that to H 2 O an equivalent conductivity will be still less.

But some insulation we say is 0.5 watt meter degree centigrade. Then you can calculate out you can you can calculate out the heat coming in Q in it will be much less much same principle is same heat stored and one can work out the time required for temperature to reach to 550.

So, this is the now, this will be very very small very very small in the sense that 0.5 divided by thickness let us say again 20 mm. So, 0.02 Q in is equals to 0.5 divided by point 0 to k by l into same A s into T g minus. So, fist time step we will have 722 minus 298, right, 722 a same case as before into time step 120. Now, you can see it is it will be much less compare to much less input will be much and this is stored this is equals to 7850 kg per meter cube, volume of the steel which you can find out depending upon its perimeter, size, right.

And then which was the specific it is 540 into right, this is a into delta t temperature increased right which will be temperature increased or T s i or you know T s 1 minus 25 something like this. So, T s 1 I can calculated delta t is equals to is equals to this. Now, we can see that this factor is very very small compare to what you have seen earlier. Earlier it was to the power 4, to the power 4. So, this value becomes very large this A s remains same, but this term was you know epsilon, sigma etcetera etcetera and also a convective term. So, Q input is much higher, now Q input is much less because this the insulation will not allow all the heat to go.

So, what happens is 16 minutes fire resistance might go to couple of hours. So, it increase a significantly although I am not doing an calculation here given in the outline on the outline on the calculation you can try it out you will see that which was 16 minutes earlier might go to few hours you know 1 or 2 hours basically.

So, that is what that is what it is. So, you know in case significantly that is what it is. So, you can see that 50 millimetre insulation we have taken the 50 millimetre insulation means quite thick in fact. I would it, so it will be 0.5 by 50 mm. So, heat that will go in is much much less and time will increase by its significantly. That is why around the steel input are insulating here. Either we encase it in concrete or put in some gypsum plaster or gypsum board or whatever it is which will actually save the steel time increases significantly, right, ok. So, that is it.

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Now, let us look into properties of steel something more, right. Some details on the steel I have given you briefly and thermal design of steel you have looked into. As I told you earlier the enforcement bars this days use the thermo mechanically treated bars. And cold twisted deformed bars were what you used earlier. Fire resistance of some of the spray primary pray which are used as fire retardant coatings can be toxic. So, one has to be careful about that. So, you know, so fire resistance of steel if you have provided adequate duration it can be send higher temperature without compromising which is ductility and.

Student: Weldability

Weldability which I discussed earlier, that it loses the ductility, alright.

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Now, how do you improve this if I want to there are better steels fire resistance steel. So, TMT with molybdenum, chromium, and addition of nickel, vanadium and titanium improves the temperature sustenance properties.

See so far we discussed that ordinary steel mile steel section or properties we have discussed of high strength steel you know height tensile strength steel earlier and mile steel which was the conventional steel. But then people develop fire resistance steel with other kind of allowing. Fire resistance does not mean it will be fully resistant but its loss of strength with temperature will be much less compare to mile steel CTD bars or TMT bars you know it will be much less.

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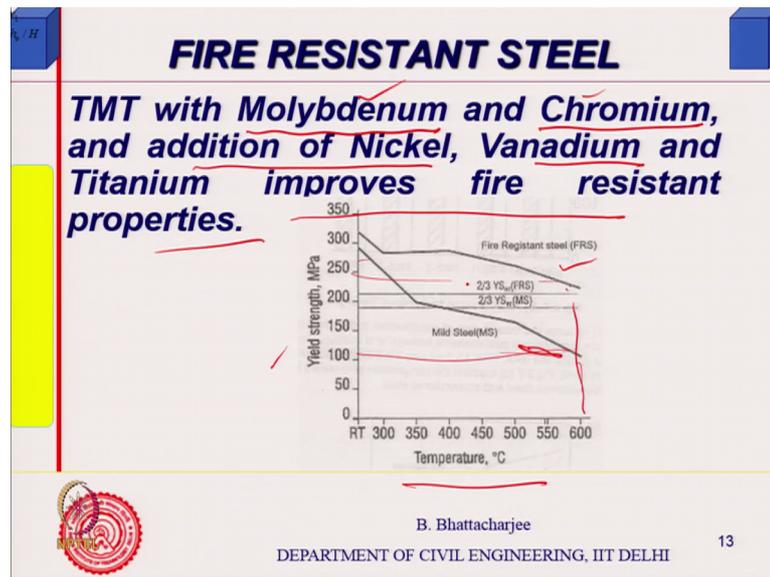
So, this is typically what it is temperature versus yield strength this is for mile steel this is for fire resistance steel right. So, fire resistance steel does not lose its strength so easily. It remains say for example, this is 250 or somewhere around 200 degree centigrade, you know to 250 or so will be the mile steel yield strength but this steel. And then it comes to somewhere around 100 reduced to 40 percent reduced to 40 percent that is what I showed you earlier several test results.

Here this reduce to that will reduce so significantly. So, one can you know they are improved steels again fires are also there. So, as I have very proven to fire one may used it will be costlier, it will be surely costlier, right, ok.
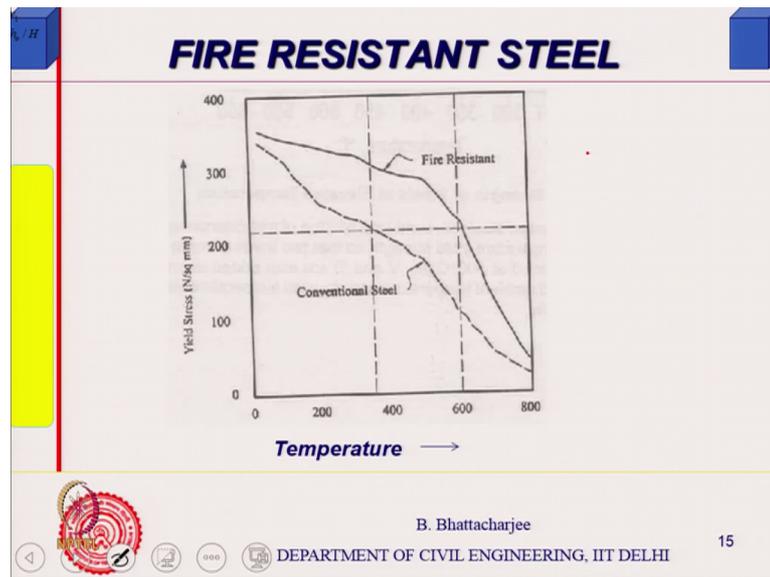
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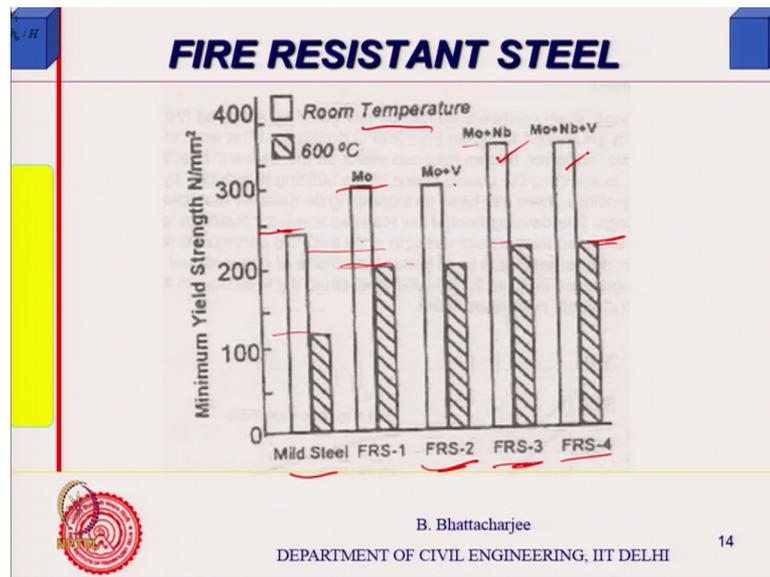
So, there are several fire resistance steel developed now mile steel for example, yield strength is 250 at room temperature 600 you get somewhere like this. If you have molybdenum you get at 600 also you get 200. There are some reduction much less. Fire resistance steel to molybdenum and vanadium similar, and 3 molybdenum niobium somewhere there molybdenum niobium, vanadium somewhere there.

So, you can you can you know you have there room temperature strength is also increased. So, properties can be enhanced by alloying modern steels some of them are capable of doing that. So, I just wanted to interest that right, ok.

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See this is the fire resistance steel that is what I was saying that up to 600 degree now it can be strength better up to 600 degree centigrade. So, that is it. This is conventional steel some more experimental (Refer Time: 22:00), right.

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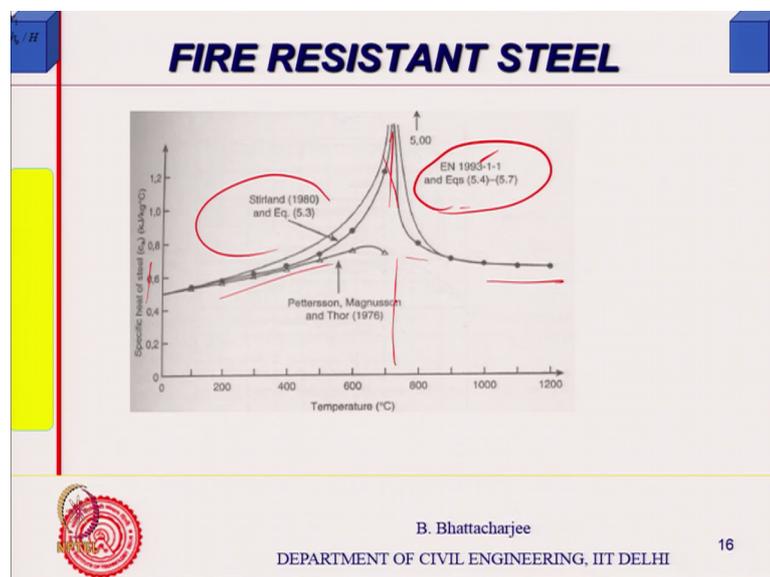
Now, this is not fire resistance but some of those other properties specific heat of steel. Just as a qualitative idea European standard 1993 etcetera etcetera and so on. Now, specific heat of the steel suddenly increases around 700 degree centigrade significantly,

and then again it becomes constant. So, it increases a little bit and then so several experiments have been there.

So, from steel specific heat also changes with temperature. It increases and then goes to a very high value somewhere around 700 and something because face the new the you know the when your heating is the change in face is there. So, around this temperature we will find that there is a increase in specific heat of steel.

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Thermal properties of Steel

$0 \leq T \leq 650^0 C \quad \rho_s C_s = (0.004T + 3.3) \times 10^6 \, J \, m^{-3}\,{}^0 C^{-1}$

$650^0 C < T \leq 725^0 C$

$\rho_s C_s = (0.068T + 38.3) \times 10^6 \, J \, m^{-3}\,{}^0 C^{-1}$

$725^0 C < T \leq 800^0 C$
$\rho_s C_s = (-0.086T + 73.35) \times 10^6 \, J \, m^{-3}\,{}^0 C^{-1}$

$T > 800^0 C \quad \rho_s C_s = 4.55 \times 10^6 \, J \, m^{-3}\,{}^0 C^{-1}$

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And thermal properties some ideas are there I do not want to you to remember this formally, but if you want to use you can use the slides and use this formally. So, you can see that rho C rho s 7850 into specific heat of steel is given by this formula which is a function of temperature.

So, as temperature increases this increases as I have shown here, right up to 650 degree centigrade and at 650 to the 725 something like this. Beyond that it will become constant, beyond that you know it in fact, it there is a reduction with temperature as we have seen. And at some point it becomes constant independent of the.

So, typical behaviour of steel in thermal capacity is given by this sort of formula increases with steel, increases more stiff manner with steel determine the temperature. And then reduces and then it becomes constant. So, this is how the behaviour is, you know it increases stiffly from here then reduces and then there is a constant. So, this is a

typical variation of steal specific heat properties, all right. So, you can you can actually use them, these are available in literature actually I think it is by book by Lie, Margaret Margaret Lie and she is I think (Refer Time: 24:18) of this data.
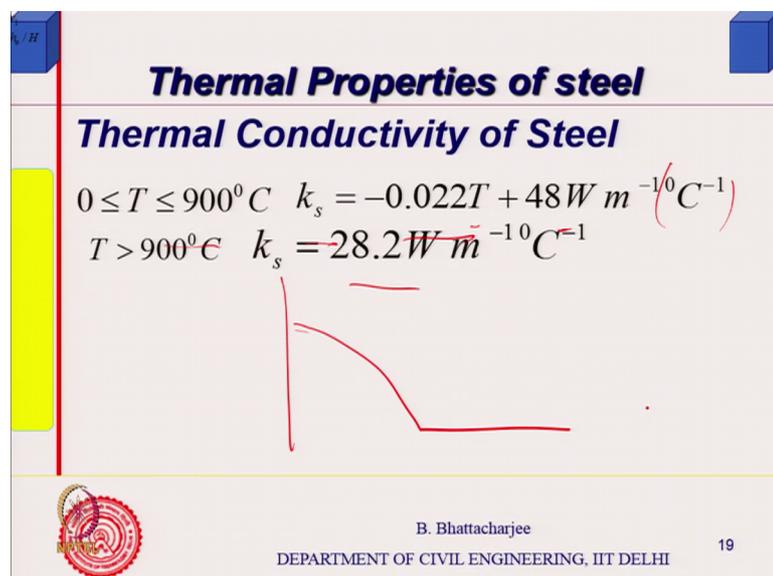
American (Refer Time: 24:19) trust see materials or obligation is mostly must be from North American research. But similar results are available elsewhere also.

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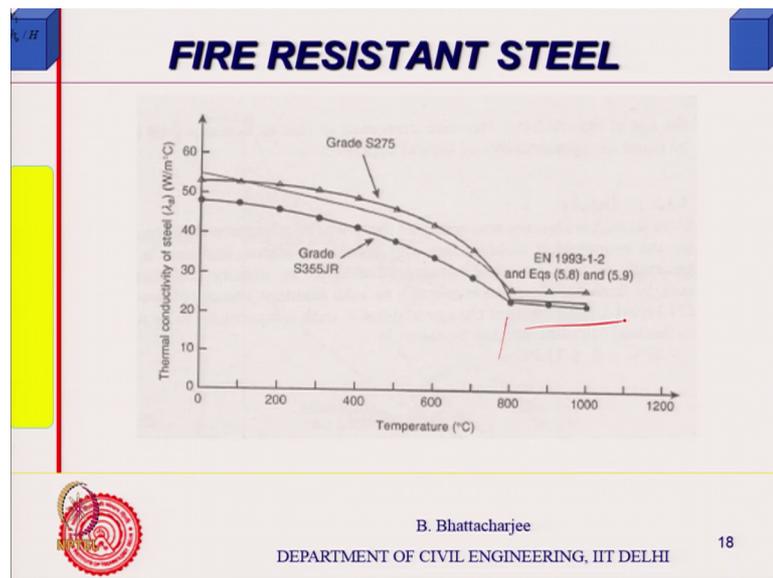
Then if you see a thermal conductivity, thermal conductivities are still reduces and then again it becomes constant.

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So, again similar formula is there, up to 900 degree centigrade it reduces with temperature, at temperature let us say 0 48 watt meter degree centigrade you know minus 1 this here, this. So, it reduces and beyond this is constant value is taken. It reduces curve is something like this curve is approximated to something like this. So, if you have modelling actually.

Heat transfer modelling which is you will take properties varying with the temperature, which means that you know first if you use the properties are constant and you know the property then determined, that a next step temperature. But it will do not know what is a next time step temperature and do not know also the properties then it becomes a non linier problem. So, I treat you solutions is used to do that. Coefficient of thermal expansion is given by this. It increases with temperature in this manner, right.

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Thermal Properties of steel

Thermal Conductivity of Steel

$0 \leq T \leq 900^0 C \quad k_s = -0.022T + 48 W\ m^{-1\,0}C^{-1}$

$T > 900^0 C \quad k_s = 28.2 W\ m^{-1\,0}C^{-1}$

Coefficient of Thermal Expansion

$T < 1000^0 C \quad \alpha_s = (0.004T + 12) \times 10^{-6\,0}C^{-1}$

$T \geq 1000^0 C \quad \alpha_s = 16 \times 10^{-6\,0}C^{-1}$

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So, nature of the curve I have just trying to explain to you, values you do not have to remember because this is this is from sort of experiments done then inside variation here and there from another code or something that kind that mature is similar. Above 1000 degree it is 16 into 10 to the power minus 6 per degree centigrade right. So, when temperature 0 it is around 12, that we know 11 12 in ambient temperature.

Yield strengths again there are formula available. So, yield strength there is again formula available, right f y T, T to 600 it varies in this manner. 600 to 1000 it varies in this manner. So, some formula is available because you said it reduces with temperature and you can see that yield strength reduces with temperature in all cases.

Similarly, elastic modulus also varies. So, formula is available to calculate out, elastic modulus as well as strength of steel. Now, you know residual strength of steel can be found out from some simple formula which are give you later on, because post fire if you

want to find out how much is the damage, what is our capacity of the structure then we need residual strength. Similarly 600 to 1000 degree centigrade this is the for modulus of elasticity E 0 is at ambient temperature.

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So, this is as far as the steel and their properties are concerned, right steel and some. I do not expect to you to remember this formula no way you can remember them. But if you want you use them you can use them the reference books are also available. So, you can make use of them anywhere a new calculations you want to do, but there are simpler formula also which I will give you sometimes later.

Now, let us look at concrete; concrete is relatively complex. Why? You know the complexity of the concrete calculation procedure would be because still we assume what, it is a good conductor. So, I will have uniform temperature throughout first specimen. You know the column way element or beam element or whatever it is, right. But if I take if I take concrete if I take concrete if I take concrete you know say slab, concrete slab, reinforce concrete slab, right.

And heat transfer I am looking or a or even a column solid column concrete column beam whatever it is. Heat transfer now would be taking place from all sides let us say here the bottom is subjected to fire. What will happen is if you the heat transfer through this will has to take place through concrete and steel has to reach 550 that is the criteria. Thermal design for fire resistance criteria is at still has to reach.

Student: 550.

550. So, if it is bear steel then also in the same case and if it is you know from mile steel if you are using fire resistant steel then it can be higher, right. So, heat transfer will takes place to concrete and concrete is an insulator concrete is an insulator right. So, even if it is 50 mm cover heat transfer 50 mm cover you go to consider, and this temperate across this 50 mm also will vary. So, if this one this point is 800 degree centigrade here it may be 300 or 400 degree centigrade because concrete itself is an insulation. And therefore, the properties here also will vary.

So, a complex heat transfer calculation has to be done, in that case you cannot use simply the all concrete temperature is constant that is not valid, and relatively complex heat transfer calculation. So, one can do by finite element or finite differencing difference numerical method because it is again and only new problem.

So, divide the cover concrete or this concrete into small small element, and do the heat transfer solve the heat transfer equation. So, the conduction heat transfer equations of that, heat conduction equation of that, ok.

But I do not thing I am going to do it in the class. I will do, I will give you some simple empirical formula which gives you the idea that what are the properties which governs the fire resistance, thermal fire resistance you know this is all thermal we have doing. Structural would mean then you have to take care of the support conditions as well which you are not taking, we are only talking of thermal.

So, I think we will break here and then again restart.