Fire Protection, Services and Maintenance Management of Building
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Lecture – 08
Design for Fire Resistance: Steel

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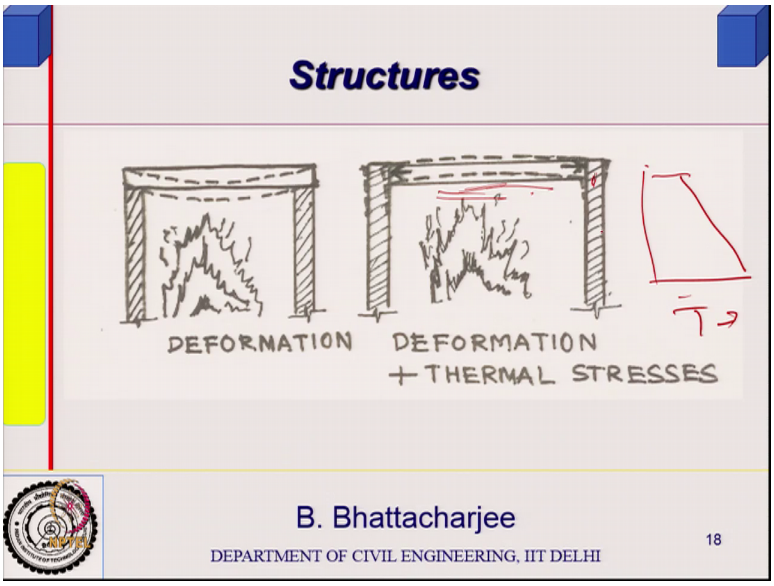

So, if you look at the structure you see one thing is effect of temperature on the material, but structural behaviour the material loses its strength all right, but structural behaviour sometime you know as you can see the support condition. So, when you look and structural element, its deformation properties right, or load carrying capacity is not only the function of material properties, but it is also function of it support condition, because your bending moment or you know forces, if I may call it in generals axial forces, or bending moment etcetera etcetera.

They would depend upon how the load is transferred to that structures from surrounding elements. So, they are n conditions are important. Now, is an example considered, this if I have no fire before fire the load deformation will have been something like this right and, during the fire it by nullify the burning action, because here the expansion would now occur here and it is restrained here.

So, if here is an expansion of the bottom and top is expanding layers, because temperature differential would be something like this high temperature here, temperature high temperature here low temperature here. So, it you will have a kind of an, it will try to expand here and if you have restrained. Then there is a compression in at the bottom because higher expansion in tendency but you are holding it.

So, therefore your compressing at the bottom while top is restrained, but expansion is less. So, net effect is as if you are pushing from both the side right at the bottom mode. So, it is like your you know it is like applying an eccentric load, applying the eccentric load with the eccentricity or the load is being applied below the neutral axis.

So, you apply in axial force below the neutral axis it will be the tendency to depend. So, it will nullify the effect of flexure which was there earlier also it will induce a kind of push phases to the supporting structure you know it will. So, structural behavior deformation plus thermal stresses if you see, net effect has to be seen of this of both. Now, simple cases earlier people who are designing for fire resistance, or understanding of fire resistance is only related to material.

For example I said if you take steel the moment it reaches 550 degree centigrade, you say the system is you know it was it reached its fire resistance, but that is extremely conservative because that is not taking account of the n conditions of the element. So, element by element one should do thorough analysis, or may be the whole structure.

So, structural fire design today it looks into the structure as a whole, its behaviour under the simulated fire under simulated fire, you know could be I mean theoretically if it is then it is simulated fire, or might put standard time temperature curve, its temperature and time you know is curve is known. So, that condition you take inside the room and, then try to find out how each member would be affected due to this because both the effect of the properties, as well as n condition changes modulus of elasticity bending moment everything you do one can see.

In our case class we are not looking into this, because structural fire design would be a subject will be a subject some they, because till they you know still in good lot of research stage.

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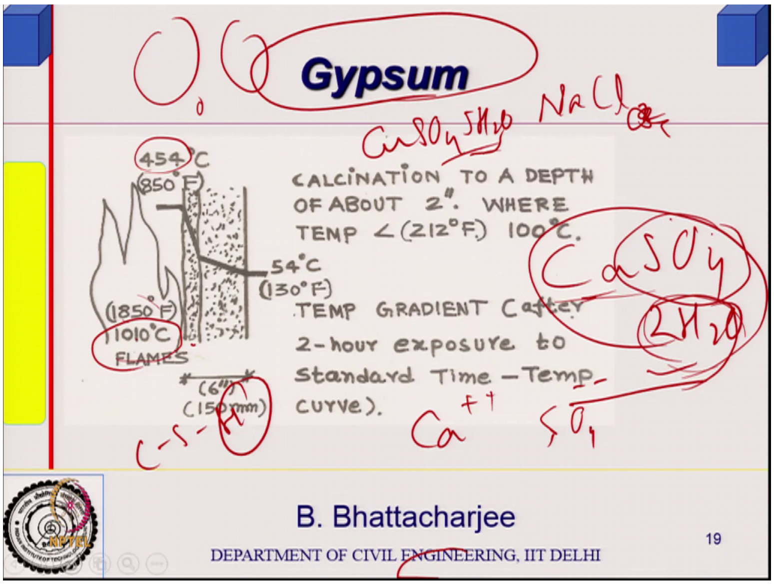

So, that is they it is one more material I want to say that is related to structural materials, one more material I would like to you know introduce to you is Gypsum. Gypsum is used often as a protection for steel why, we see what is gypsum chemically gypsum is calcium sulphate, 2 H 2 O right, calcium sulphate an hydrides calcium sulphate. And then when 2 H 2 O it form crystalline structure and, that is gypsum. Now, this is you know this crystalline structure this goes chemical combination it is chemically combined water.

As I said crystal formation only occurs, when you have appropriate packing density. Now, you see sulphate is an anion and it sizes very large you know its calcium plus plus 2 calcium and SO 4 minus 2 minus right. So, you have radical SO 4 and calcium, they try to arrange themselves in some regular order, when they try to do that the volume occupied by this is much larger, because SO 4 large molecule is large.

This does not happen in case of you know many other sodium chloride for example, it crystal by sorry its crystal by itself does not require water, the molecules are I mean atoms are of the similar sizes, where the sizes of this is very large compared to this cation. So, they would be occupying you know like something like this right the word space in between is too large for crystal to become stable.

So, what it does it actually takes water from outside, wherever it is available and then puts water also into the system, water molecule also into the system chemically combined H 2 O, chemically and combined H 2 O system and this crystal is stable. So, this copper sulphate 5 H 2 O and you remember why I brought in proper sulphate is you would have studied in school chemistry, that you cannot remove this water very easily, because they are chemically combined like say it as calcium silicate hydrates this H is chemically combined.

So, what you do you can remove some water at lower heat, lower temperature I mean less heat and to remove all the water you need lot of heat, shows a case of calcium gypsum when you want to remove first you have to remove the water out of it. And this absorbs a lot of heat. So, it can take a lot of heat to become anhydrous calcium sulphate, gypsum will take a lot of heat.

So, if you have fire on this side let us say 1010 degree centigrade in flame, or 1800 and 15 Fahrenheit, or 450 you know. So, you will find that if you have a thickness small thickness of gypsum, it itself we will get first calcine it itself we will get calcine to a depth of about 2 inch right, or 50 mm you can say where the temperature will be 100 degree centigrade or so, because this solid gypsum as observed on the water, I mean all the heat to liberate the H 2 O.

And then this so, (Refer Time: 07:47) I can it heat absorber heat sink that is why gypsum is very good. So, you would see many of the buildings you will see gyp boards gypsum boards, if there are steel they would be either covered with gypsum, or modern days there are other kind of like polymers as mentioning, polymers are they can be synthesized and thus you can design the material polymer composites.

So, for example, you know polytetrafluoroethylene PTFE you use it very often Teflon. So, you use Teflon coated frying pan, now you see it is also a polymer and polythene is also a polymer, now that which tend 1800 2200 degree centigrade while this one just does not. So, you can a variation so, there are fire retardant and coating polymer coating many of them are patented may be.

So, either those kind of thing or gypsum are used for applied, you know they are applied on top of the steel, in order to protect the steel from fire. So, gypsum is a good fire you know fire protection devices.

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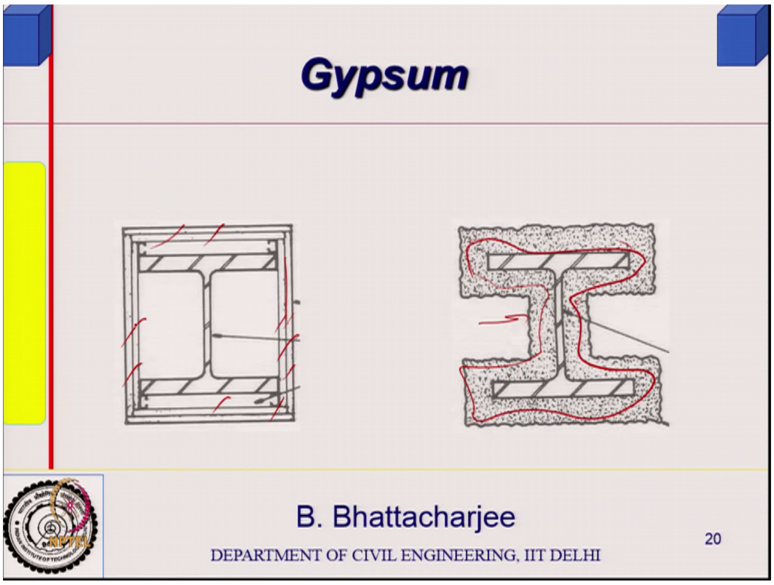

For example, this is what it is gypsum this is steel section and I have a kind of gypsum spray. So, this will ensure that this steel is protected, because steel is vulnerable steel is vulnerable steel is vulnerable.

And you know like localized heat generation and steel is a good conductor. So, localize heat generate the heat generated would get transmitted easily to other parts as well, while these are the this inorganic materials you know I inorganic I mean say particulate material like, ceramics and such systems that concrete and chemically combined ceramics or otherwise.

They are not good conductors they are insulators, they are insulators. So, as a result they do not transmit the heat. Now, steel it starts heating fire at one place it will easily go to other places as well other places as well. So, steel is protection and you can see that it is too much less temperature 550 degree centigrade, it we say that it collapse somewhere there might be a hinge formation, it will work plastic state hinge formation would occur and, if sufficient plastic hinges are formed the element may collapse also.

Normally that is unusual, because fire does not go to all places till the flash over occurs. And where it as actually locally all places, you know hinge formation will not occur. One place it as formed it might form a mechanism, or may not from a mechanism right. So, you have to analyze the whole thing, but suppose you have put in gypsum cupboard steel is vulnerable, I have put in gypsum cover or something of that kind of thing, if can withstand much longer period of time structural stability is better against fire.

So, gypsum spray or gypsum broad these are the gypsum board, used around steel in order to protect steel.

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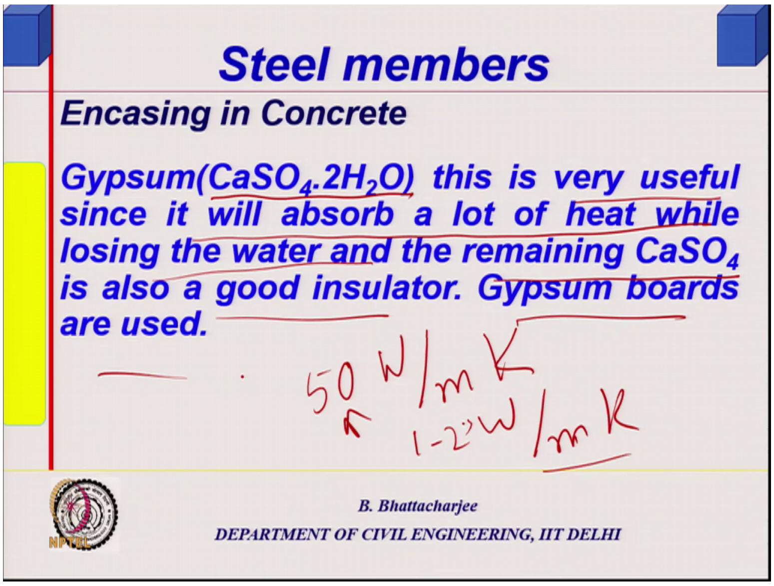

You know you will find gyp board fall ceiling all over the place, that is one of the reason is it will not spread fire, it they are very good against fire. So, steel also can be encased in concrete I can encase them in concrete.

Steel is either you know steel exposed steel is rarely used, I will either encased in gypsum board spread gypsum, or encased them in concrete. Because concrete is good insulator. Now, thermal conductivity of steel we shall see it again later on is 50 watt, concrete would be 1 to 2 watt so, 25 times more you know nearly 25 or 25 times more 25 or 250 times more, somewhere locally I say its 2.5 somewhere around 20 times more.

So, steel has got high conductivity concrete has got much less, gypsum this is the cases saying I very useful, since it will observe a lot of heat while losing water and the remaining calcium sulfate is also a good insulator. So, gypsum boards that is why we use it, right.

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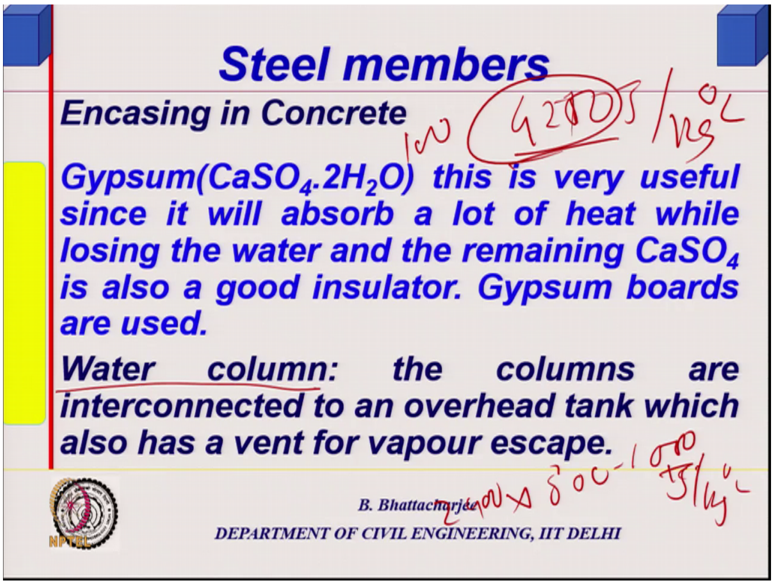

The other kind of thing which were used earlier days were called water column, water has got highest specific heat right, it is you know compared to compared to compare to let us say concrete it will be about 4 4 more than 4 times.

Concrete to you know thermal I mean specific heat, because it is around 4.270 something of this order 4 point you know order is this joules per kg rate 4.27 etcetera etcetera kg per degree centigrade, when concrete would be order of 1000 kg per joules per kg degree centigrade right, many of these materials that concrete brick will be 900 800 to 1800 to 1000.

So, specific heat of water is much higher density of course, so thermal capacity is multiplied by density. So, 2400 and this will be 1000 multiplied so, it will go accordingly, but water can absorb heat, but more importantly water is a fluid it as got high specific it can also convect, you know it can be by convection it can transmit the heat. So, water columns where used this columns are interconnected to an over head tank, which has a vent for vapor to escape.

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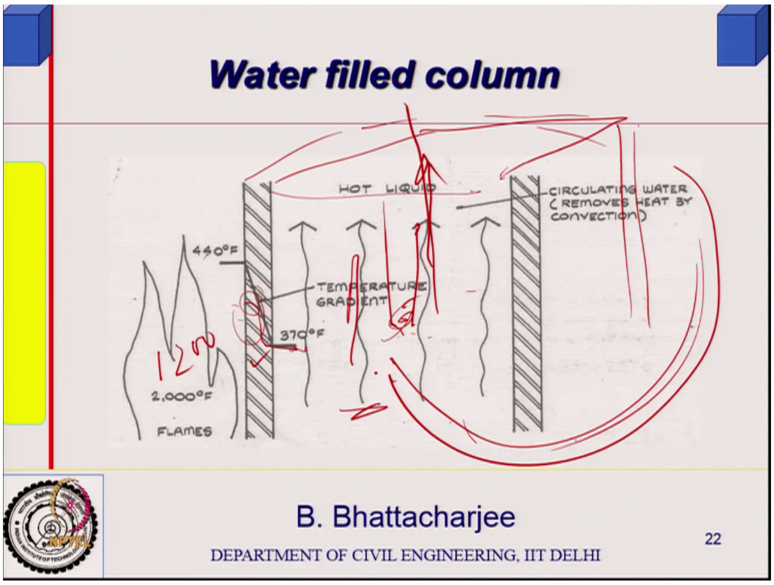

So, how it looks like? So, you have hot liquid sorry you have hot liquid water steel here so, the heat see for example, somewhere the flame is you know 1200 1000 degree centigrade, you will have so, this would come down significantly here, because liquid here the water can get will get heated up and it will transmit.

If all the column whole of the column is all effected by fire, then there is a different case, but the when fire starts the water in that particular column. So, this will be a rectangular column cross sections would be something like this, you know cross section, it is a closed column it has to be a closed columns filled with water.

So, when heat comes in this surface it will get heated up, the water we will go out and the it is connected to other columns as well by circulation, convection the fresh cool water, we will come in that we will take the heat. So, heat get is transmitted from here and this is how it actually maintains.

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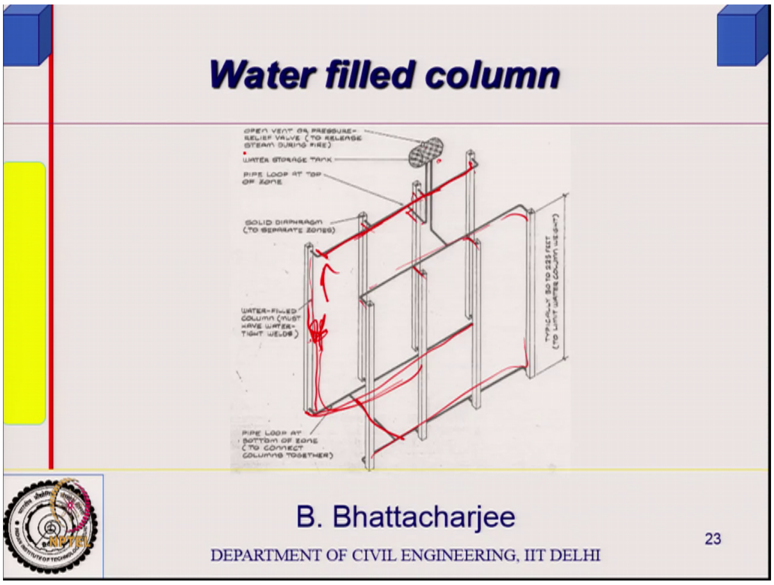

So, water field columns where used something like this should be there, you have a tank on top all the columns are connected, you know through this pipe system; all the columns are connected through this pipe system right. So, this all columns are connected here, all columns are connected here right, they are connected they are connected, they are connected and there is a bottom connection also and there is a connection here also.

So, all the columns are connected top and bottom right top and bottom. So, there is a tank up so, what will happen, if you have fire here the water we will move upward and cool air from the cool, water from other places will come, that is how it will remove the heat. And hot water will have a tendency to accumulate here, there is a vent here the vapor would actually called this was used, but it is not a very you know it is fairly combustion.

You have to also see that you protect the steel from corrosion process, metal you know moisture and water aqueous corrosion can occur. So, painting and of course, the lack of oxygen availability as to be their partially weight scenario were corrosion now occurs much faster. So, that is that is related to that is related to some of the material, material related properties some of the material related properties some of the material related properties, we can look into. Now, based on this concepts design for fire resistance, we can look from this based on this concept, we can consider you know we can design for fire resistance design for fire resistance we can design for fire resistance all right.

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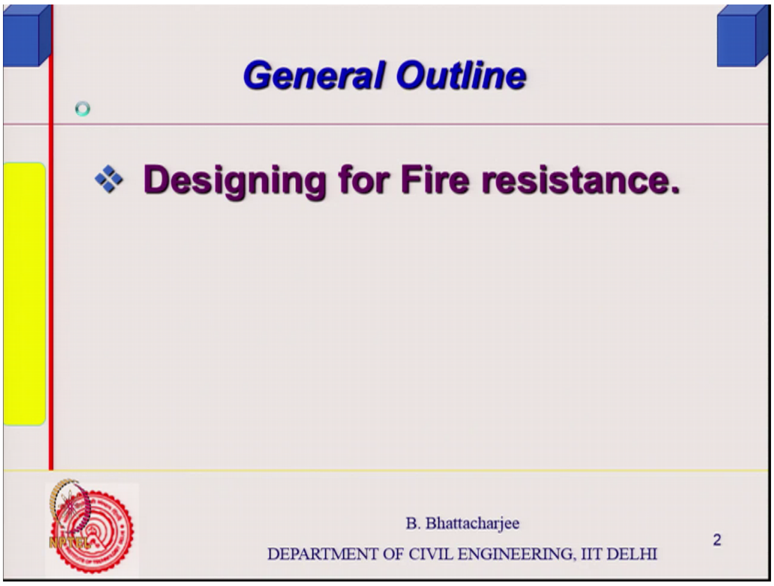

So, designing for fire resistance is what we look into designing for fire resistance is what we look into simply cases. Actually today if you want to look at full structure simulate the fire and as I said software's can do that like abacus does, or you know like fire simulation we will be done by CFD models and all, but in the class we are looking at simple cases of fire design, for steel which is simple.

So, that you understand the principle that would be their but that is design of an element irrespective its n condition, support condition or structural behavior that is what we will do in the class, that is very conservative. In actual structure the n conditions and behavior of the whole beam, or column must be looked into we are.

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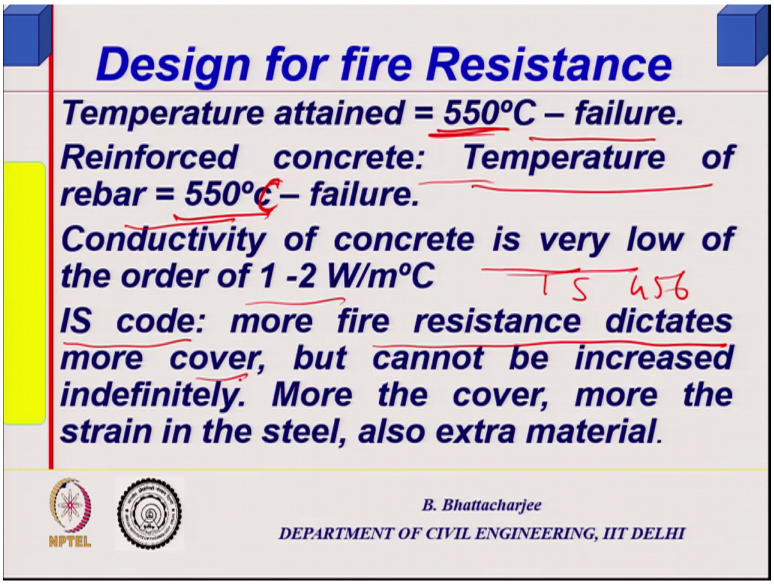

Now, look into that all criteria that we are using is that 550 degree is the, 550 degree is a this is the criteria, we are using for fire resistance. So, as soon as the steel reaches 550 degree centigrade, we say that, that is the time of it is fire resistance.

So, that is only a thermal design really the structural part, we are not look into we have simplified it here actually. So, that is very conservative that is very conservative. So, reinforced concrete what is the what is the criteria temperature of the rebar should reach only 550 degree centigrade, you know because concrete is not as vulnerable it is an insulator it protects, that reinforcement rebar but reinforcement rebar is what provides tensile capacity to concrete.

So, if the reinforcement rebar is not effective in carrying the load the crack should develop in concrete and it will eventually call up that is again the concept. So, this is also fairly conservative we are looking into it right. Now, as I said conductivity of concrete is very low of the order of 1 to 2 meter watt meter degree centigrade and, if you look at Indian Standard Code; IS 456, IS 456 more fire resistance means, you want higher fire resistance you require more cover.

So, it gives you a table where cover depth for fire resistance against fire resistance is given. So, if you want one hour fire resistance cover depth required is relatively less 2 hours more and so on so forth. So, cover depth now in 2000 code, or now modern all codes is governed by not only by your durability you know prescription attack from aggressive environment, but it also depends on fire.

So, sometime we will find for fire resistance we require higher cover. So, that is what they have done that, but you cannot go on increasingly infinitely increasing the cover depth although concrete is cheaper than steel, because then you got to restrain you will have to restrict the strain level at the steel, otherwise concrete will crack you have a section like this is your RCC section.

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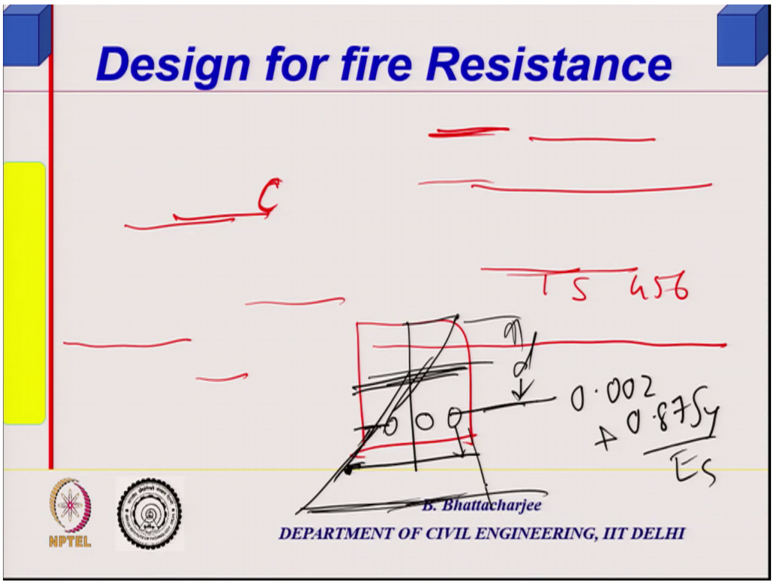

If you have steel, if you have steel somewhere their steels here right, you know effective depth is somethings d you call it effective depth the steel is somewhere here. Now, supposing I increase the cover depth, now at this level the you remember the you know the strain is fixed at 0.002 plus 0.84 f y divided by you know E of the steel, that is what it is you remember that that is what we do right. So, that is the strain.

Now, if this is the strain the strain diagram will be something like this, strain diagram will be you know is the neutral axis is somewhere, their strain diagram will be something like this. So, if I maintain this strength if the cover depth is more the strain will be more, at the bottom of the concrete phase cracks will appear, because tensile strain capacity of concrete is generally low.

So, if I increase go on you know make it something like this the strain is very higher very high on to the cover concrete. So, it will crack so, that is not it is not. So, increasing you cannot go on increasing the cover just like that so, but cannot increase infinitely more the cover more the strain of the steel also extra material right. Otherwise you will not be and if you do not want to increase the strain in the you know, we say that bottom fiber of the concrete will be restrict the strain there.

The steel may not yield at failure at ultimate load and therefore, it might be a brittle failure so, the consequences are that way. So, we just cannot go on increasing right. So, that is the idea, but then minimal cover is specified for given fire resistance.

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So, we will look into design of simple steel section for fire resistance. Let us say l is the thickness of the material, this is the temperature according to standard fire T a plus 345 log 8 t plus 1 that is what formula I have given you earlier. So, we can we assume that steel section is engulfed in fire fully right, steel section is engulfed in fire fully ok.

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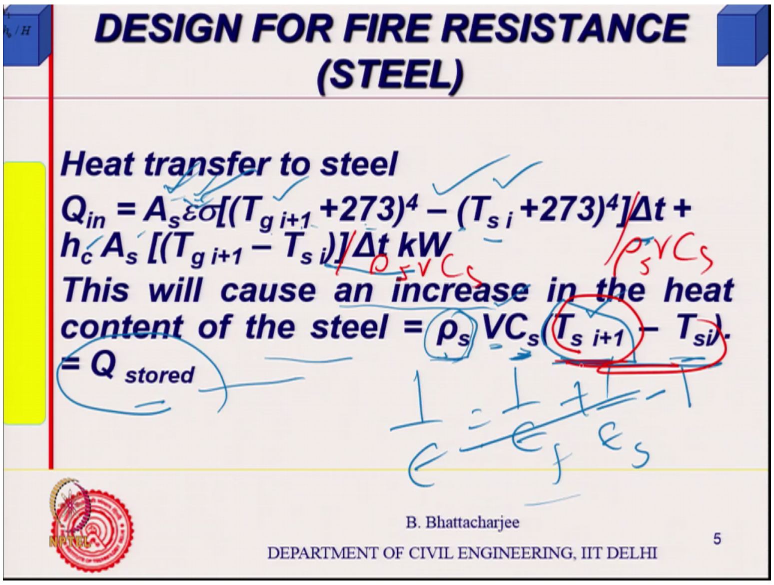

So, if that is the case heat transfer to the steel we will occur for, let us have a let me draw this for you, if this is my this is my fire this is my fire this is the all side both sides all sides, I have I think fire is there and my steel section is something like this let us say, a rectangular steel section simple case I am taking let us say, it is a fabricated engineered structure made from plates just simple. Although real system will be either i or two channels it could be two channels in fact, it is engulfed by fire from all direction engulfed by fire from all direction right.

Now, how will be the heat be transferred, heat transfer will occur heat transfer will occur you know from this to this steel, what mode radiation because this is all flame. So, flame is hot from hot flame by radiation plus hot gases are here by convection. So, steel if it is cold hot gases will come in contact with the steel pass on the heat and you know more hot gas will try to tend to I mean, they try to you know, we will try to it will try to move cold gases, we will tend to move downward hot gases we will move from.

So, radiation plus convection and we assume the steel is a very good conductor therefore, steel temperature is a uniform in all this places, temperature is uniform in all this places. Since it is flame is a gas phase phenomena, it is a fluid phase phenomena only radiation and convection will be mode will be you know the heat will be transferred to the steel section by radiation and convection mode all right.

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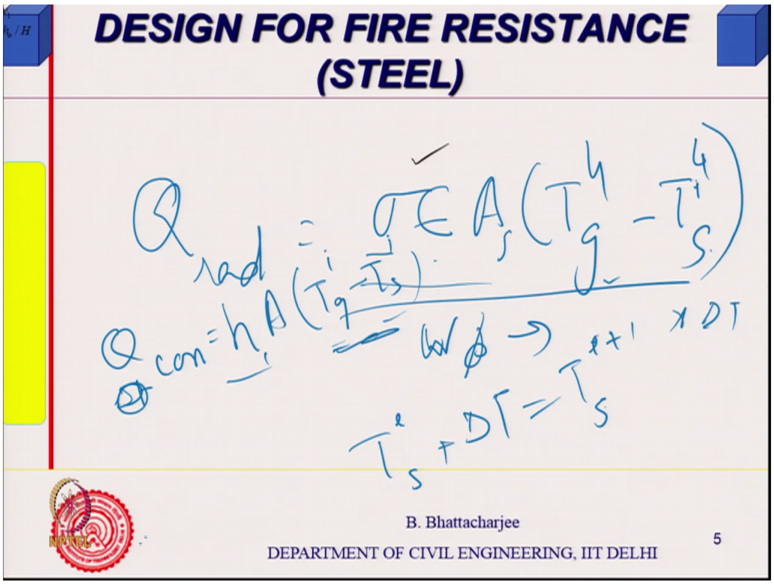

So, you look at that heat transfer so, you remember we talked in terms of radiation heat transfer was Q rad. We said that it is governed by stiffens Boltzmann law, which will be sigma epsilon area, area multiplied by T gas to the power 4 minus T steel to the power 4 that is a formula, you know radiation heat transfer is this formula right.

Now, here area will be steel surface which is engulfed in flowing from all its direction, sigma is the stiffens Boltzmann constant T g is the fire temperature and T s is the so, this is how per unit time you know watt per watt would this much watt, or joules per second it will go, now what we do is we assume a small time step of delta t.

During this period of time, there are heat that would be transferred will be this multiplied by this is per unit multiplied by delta t right. And this will go on raising the temperature of the steel from T s to T s plus some delta temperature, which I call as T you know s T s i plus 1 so, T s i plus 1. So, T s i T s i plus 1.

So, I can assume small delta t time step during which heat would be transferred from the flame to the steel section and, it will go on storing that heat, or its temperature will be raised. So, initial temperature next step temperature in this manner I can go on calculating. Now, I have only taken radiation convection heat transfer is relatively simpler the Q convection is; Q convection is h, convective heat transfer coefficient multiplied by same area, multiplied by T g minus T s this is ith temperature this is ith time step ith time step, because it is linearly related. So, you know so, this is how you can find out.

So, this is this formula is here now for you this formula so, heat transfer, this is the radiation part, because this is in absolute it is in Kelvin. So, T g i plus 1th time 273 to ith time into delta t, because this was the rate of heat transfer per unit time area of the steel epsilon is emissivity you know, what we call equivalent you know it is basically given by 1 by epsilon is given by 1 by epsilon of the flame plus 1 by epsilon of the steel minus 1 I think minus 1 that is how it is.

You know 1 calculates this out effective emissivity for the two exchange surfaces, using this kind of formula anyway you are not going to calculate from basics, but this is known to us this is convective part, this is also known to us this is the area of the steel and that is how I can find out. Now, this causes an increase in the heat content of the steel.

So, C s is the specific heat of steel V is the volume of the steel, if I take 1 meter height, or 1 meter length of the steel density is rho s this is the temperature difference this is the amount of heat store. So, heat coming in time step during delta t time is this much, this must go on increasing the temperature it is basically a explicit finite difference formulation, you know explicit finite difference formulation.

Everything else is known to you, because this will be known to you from the formula. This is the previous time temperature of the steel right, this properties are known to you area of the steel is known to you, this density of steel is known to you we will do an calculation actually. Volume of the steel we can we know, specific heat of steel is known and this is the unknown temperature at the you know after this time step this is known. So, we can find out explicitly find out T s i, when we equate this 2, because Q stored must be equals to Q coming in right.

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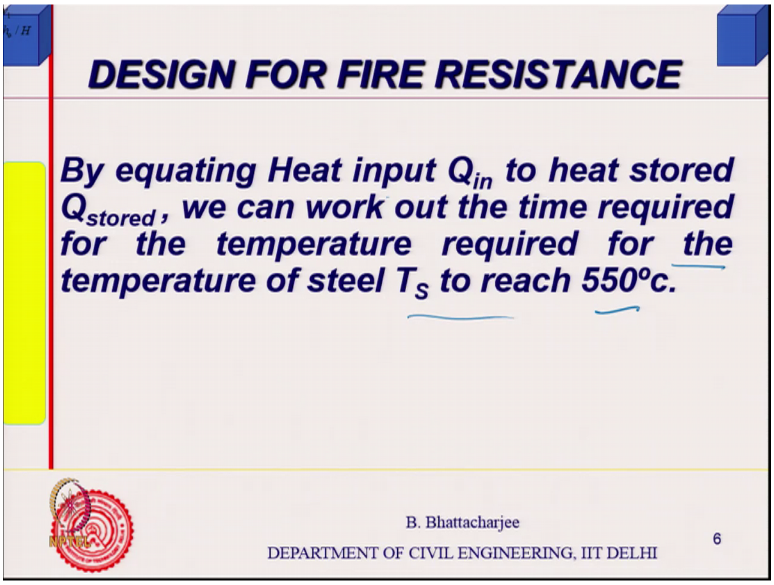

So, Q in must be equals to by equating heat input into the heat stored, we can work out the time required for the temperature to you know delta t to go to 550 degree centigrade. So, by equating this heat coming in heat to the heat stored, I can find out temperature change in every time step, go on repeating this till the temperature of the steel becomes 550 degree centigrade total sum of the total time step, that gives you the fire resistance, that gives you the fire resistance right.

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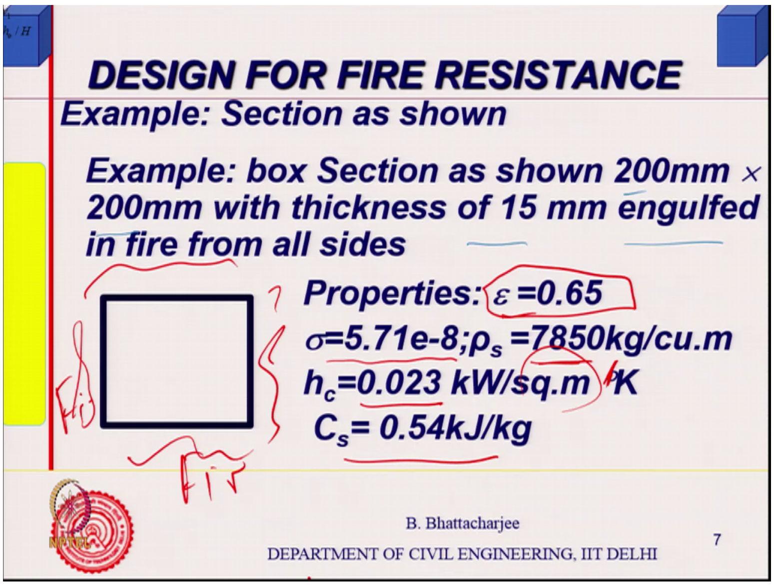

So, we do it in a tabular form for example, consider this section box section let us say I have got 200 mm and 200 mm with thickness of 15 mm engulfed in fire from all sides right. So, this is my steel section engulfed in fire from all sides. So, I have got fire from all sides fire, there is a vertical section let us say it is a column, let us say it is a column I consider 1 meter height.

So, its column fire, fire on this sides all sides fire right. This property is equivalent emissivity of flame and steel is generally taken to be 0.65 and stiffen Boltzmann constant is 5.71 into 10 to the power minus 8. Density of steel is 7850 and convective heat transfer is 0.023 kilo watt per square meter Kelvin, specific heat of steel is 0.54 kilo joules per kg. So, this properties are known.

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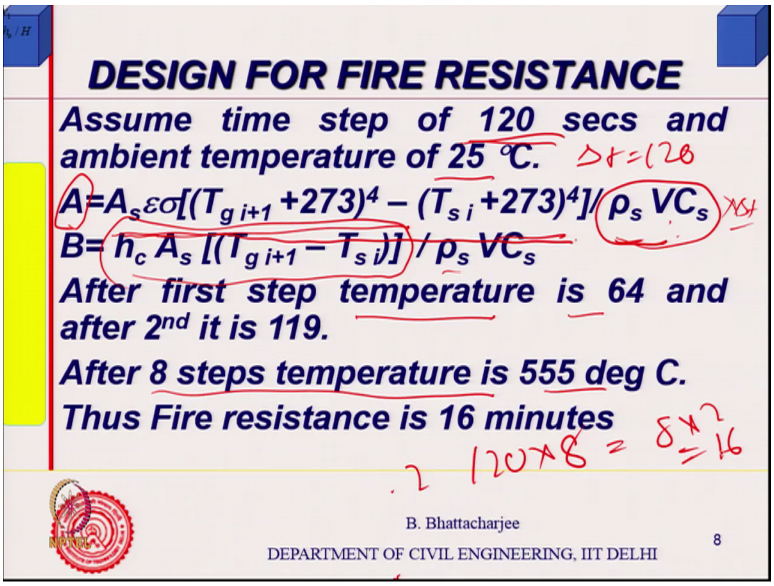

I can sit said this equation time step let us say in I am taking a larger time step you can take smaller, but it makes not much a way difference take 120 second time step delta t, delta t is goes to 120 and ambient temperature is 25, I first find out A a constant which covers the radiation heat transfer divided by rho s V s VC s.

You know if I equate this two equations earlier that I was showing, earlier equation this two equations if I equate, then I will get this part will be obtained by simply dividing this by rho s VC s, you know this will be divided by rho s VC s. So, T s 1 I want to find out explicitly I will be simply doing this dividing by this and then add T s i at the next step.

So, that is what we do in tabular form tabular form exactly we do the same right 7850. So, this is given and this is what I find as a divided by rho s VC s you know this part the radiation heat transfer component VC s, this would be multiplied by delta t that is 120 and this is the convective heat transfer part divided by rho s VC s.

After first time step temperature is 64 one can calculate this out for this particular case and, this 109. After 8 step temperature becomes 550 degree 55 degree centigrade, thus fire resistance is 120 into 8 seconds right so; that means, 8 into 216 minutes 16 minutes 16 minutes that is what it is.

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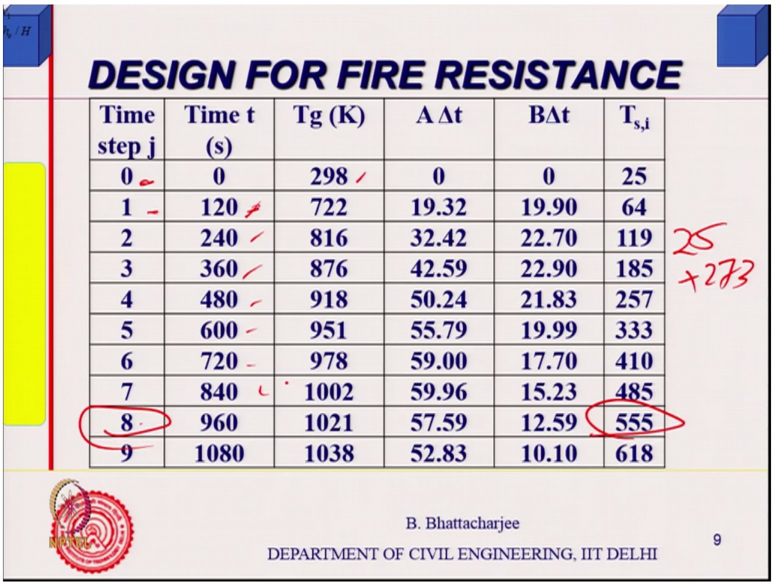

DESIGN FOR FIRE RESISTANCE

Time step j	Time t (s)	Tg (K)	A Δt	B Δt	$T_{s,i}$
0	0	298	0	0	25
1	120	722	19.32	19.90	64
2	240	816	32.42	22.70	119
3	360	876	42.59	22.90	185
4	480	918	50.24	21.83	257
5	600	951	55.79	19.99	333
6	720	978	59.00	17.70	410
7	840	1002	59.96	15.23	485
8	960	1021	57.59	12.59	555
9	1080	1038	52.83	10.10	618

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This is done in tabular form, you can you know I will since I will be uploading this you can find it out. To start with T g is 25 plus 273 in Kelvin 298 right to start at time step 0, time step this is delta t is goes to 120. And we will calculate some of this in the next class. And we can flame make this kind of table and, you can see that this temperature goes to 555 after 8 minutes. Therefore fire resistance is you know 8 time step 2 minutes 4 minutes 6 minutes 8 minutes 16 minutes that is how, we will stop at this point.