Maintenance and Repair of Concrete Structures
Prof. Sripriya Rengaraju
Prof. Radhakrishna G. Pillai
Department of Civil Engineering
Indian Institute of Technology – Madras

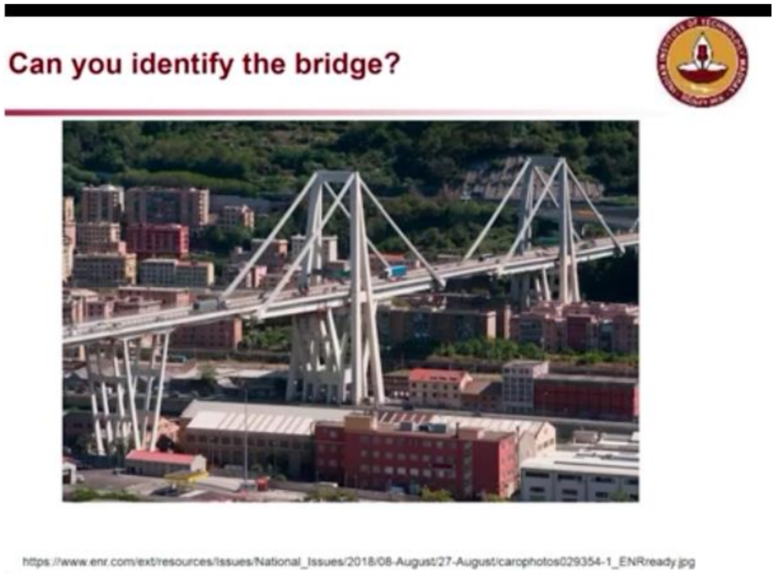
Lecture - 34
Residual Service Life Estimation of Reinforced Concrete Structures

Hello everyone. Welcome to the lecture on maintenance and repair of concrete structures. I am Sripriya. I have recently completed my Ph. D. Today, I am going to discuss about the residual service life estimation of reinforced concrete structures.

(Refer Slide Time: 00:27)

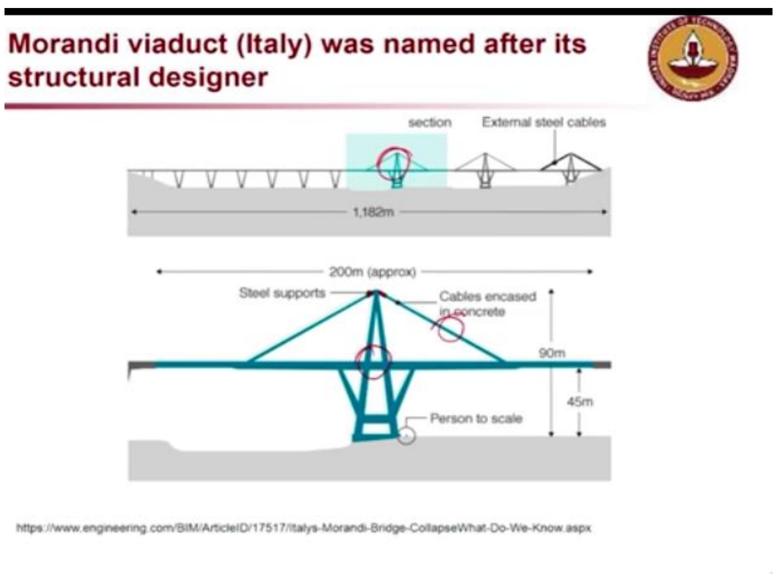
What we see here is the brief outline of the presentation. First, I will be discussing the principles of service life design, various models available and how to do the residual service life estimation, what are the approaches that need to be taken in case of chloride induced corrosion and carbonation induced corrosion.

(Refer Slide Time: 00:49)



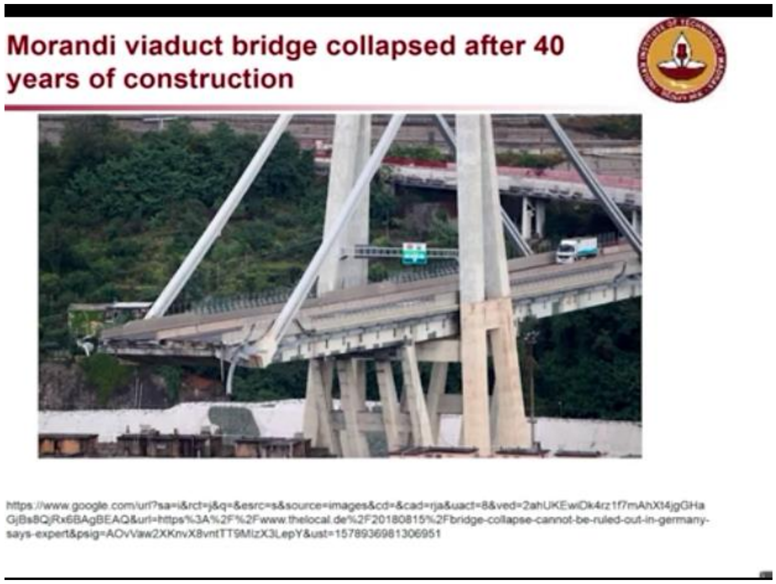
Can you identify this bridge? See carefully.

(Refer Slide Time: 01:00)



This is the famous Morandi viaduct bridge in Italy. It is an iconic structure, named after a structural designer. It is a cable stayed bridge with two cables on each side of the pylon. If you go in to the structural details, it is approximately about 200 meter span and the cables are encapsulated by prestressed concrete; instead of usual metally oven cables. This is an innovative design and it has obtained many applauds for its light weight and new type of design.

(Refer Slide Time: 01:44)



But what happened to this structure after 40 years of constructions? You can see here the deck has fallen down. The bridge collapsed.

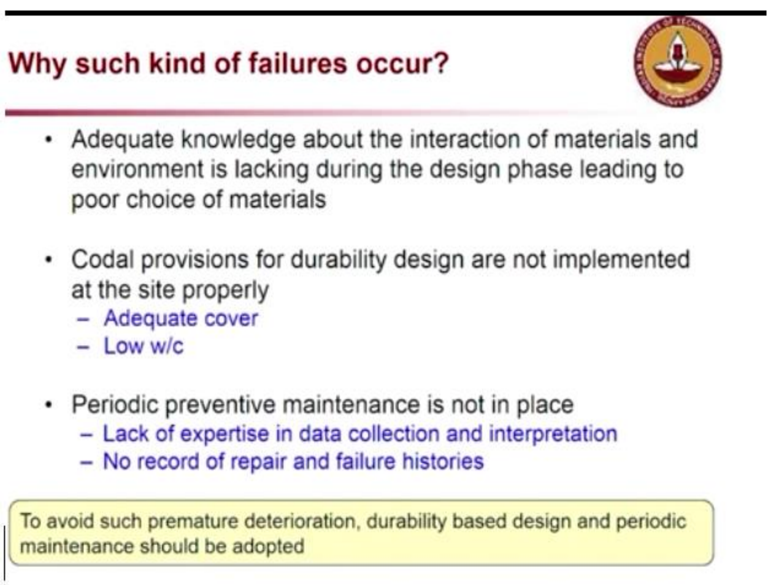
(Refer Slide Time: 01:56)

Then the condition of bridge was assessed. Here you can see at the top, top of the pylon, a lot of corrosion happened, which led to the reduction in the structural capacity. The corrosion of the cables and lack of maintenance were identified as the major cause of collapse. This is not only the case in other countries.

(Refer Slide Time: 02:22)

We have similar kind of bridge collapses in India too. These are recent bridge collapses that happened in 2018 and 2019. The Andheri pedestrian bridge collapse, Siliguri bridge collapse in West Bengal, Junagadh bridge collapse in Gujarat, Kolkata bridge collapse, all these bridge collapses claiming lot of lives and huge economic loss. So why such kind of failures occur? It is high time to introspect such kind of failures and learn from these failures.

(Refer Slide Time: 02:53)

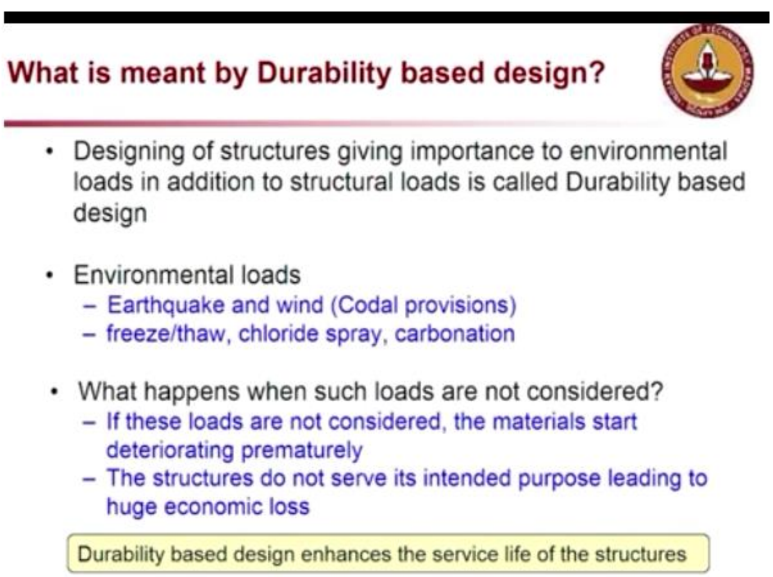


What will we learn from these failures? Adequate knowledge about the interaction of materials and environment is lacking during the design phase leading to the poor choice of materials. Even in the case of Morandi bridge, you can see that the designer has chosen prestressed concrete to avoid premature corrosion, but the interaction of the concrete the environment was not considered sufficiently.

This led to the poor choice of material and led to final collapse of the structure. Second is the codal provision for durability designs are not implemented at site properly. For example, if some cover has to be given according to the code, the minimum cover is only provided. In case of structural loads, we are giving sufficient factor safety and then consider that for design, but in case of materials, if you are giving the factor of safety for durability based design, then these kind of cover and low water cement ratio are not implemented at site due to poor site practices.

The third and foremost important thing is periodic preventive maintenance. This is not in place in many of the structures. Lack of expertise in data collection and interpretation is also prevalent. If you go to any kind of field, the data interpretation is very difficult, because of the lack of expertise and there is no record for repair and failure histories. So, to avoid such kind of premature deterioration, durability-based design and periodic maintenance should be adopted. To understand more, what is meant by durability-based design, we will dig deeper.

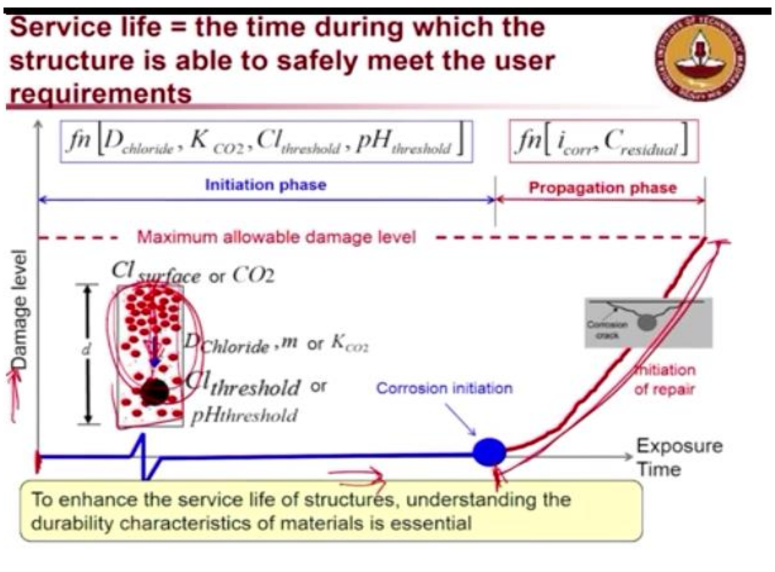
(Refer Slide Time: 04:44)



Designing the structures giving importance to environmental loads in addition to structural loads is called durability-based design. So now the question arises, what is mean by environmental loads? For example, if you have earthquake and wind, then these are called environmental loads and they are adequately taken care by codal provisions with the probability of occurrence, once in 50 years or once in 100 years, but if we take chloride spray, carbonation, etc., which are daily changes.

And freeze and thaw-like seasonal variation, these environment loads are not considered adequately and these are also subjected to huge variation, because of change in climate conditions, example global warming. So, what happens when such loads are not considered? If these loads are not considered, then the material start deteriorating prematurely. If this continue to happen, then the structures do not serve its intended, leading to huge economic loss. So, the durability-based design enhances the service life of structures. Now we will see what is meant by service life?

(Refer Slide Time: 05:59)

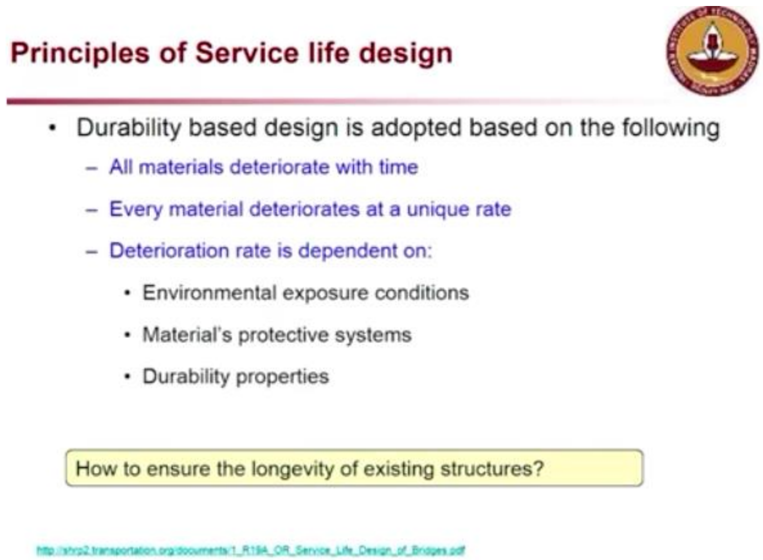


Service life is the time during which the structure is able to meet the requirements of the user safely without any repair or any intervention. For example, this is the age of structure and this is the damage level (see the graph). This is the structural element considered. So from the construction to the initiation of corrosion, this is called corrosion initiation phase and once the corrosion starts, this is called propagation phase.

Chlorides or carbonation from outer surface enter through the cover concrete and reaches the surface of steel and leading to the initiation of corrosion. So, in case of corrosion, there are only two major types that are being considered. One is chloride-induced corrosion and another one is carbonation induced corrosion. So, chlorides or carbonation enter from the cover concrete and reaches the steel and we are talking about the cover concrete of 2 inches.

So, if you have to design a structure for 100 years, then you have consider the ingress of chloride or carbonation for the 2-inch cover with 100 years, so that is the challenge that exist in the service life. So to enhance the service life, understanding the durability characteristics of the materials is essential.

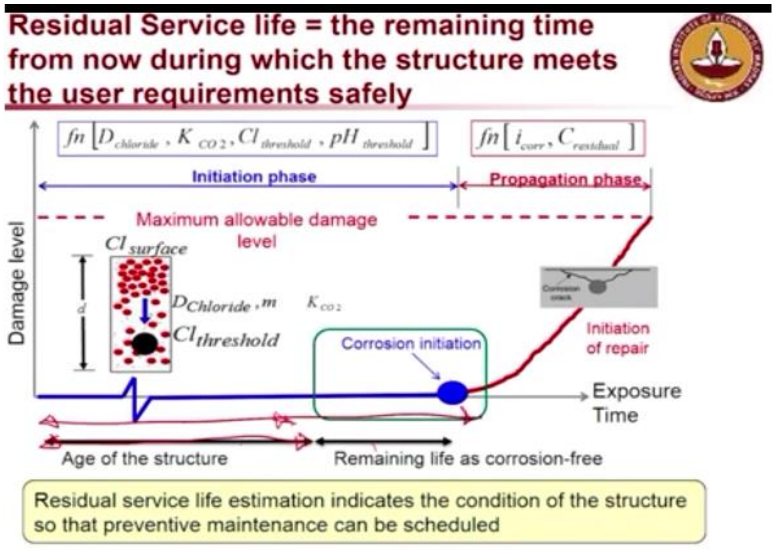
(Refer Slide Time: 07:30)



So the first and foremost principle of durability based design is all materials deteriorate with time. Every material deteriorates at a unique rate. For example, if you take concrete. Concrete reacts with environmental exposure in a different way than that of steel. So, each material deteriorates at a unique rate and the deterioration rate also depends on the environmental exposure condition, material protective systems.

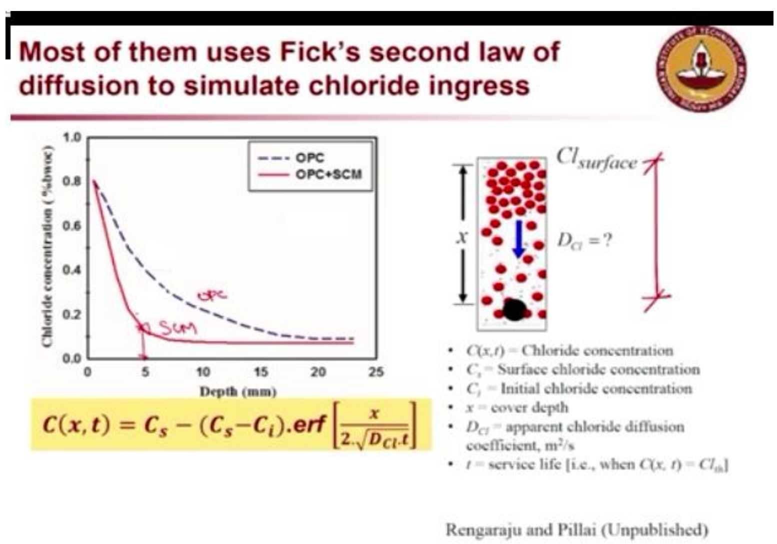
For example, if you want to prevent carbonation from happening in concrete, you can have an anti-carbonation coating and if you use supplementary cementitious based concrete, then there will be a greater resistance towards the ingress of deleterious agents than the normal concrete. So all these impact the service life. So these systems can be considered for designing the new structure. But we have lot of existing structures, so how to ensure the longevity of the such existing structures.

(Refer Slide Time: 08:41)



For that, we have to calculate the residual service life. The residual service life is the remaining time from now to the corrosion initiation. For example, if this is the age of structure that is being considered and this is the initiation time that is being estimated, then the remaining life, which is the corrosion-free life can be estimated from the initiation by subtracting the initiation years from the age of structure. So why this is important? Because this will help us to schedule the preventive maintenance.

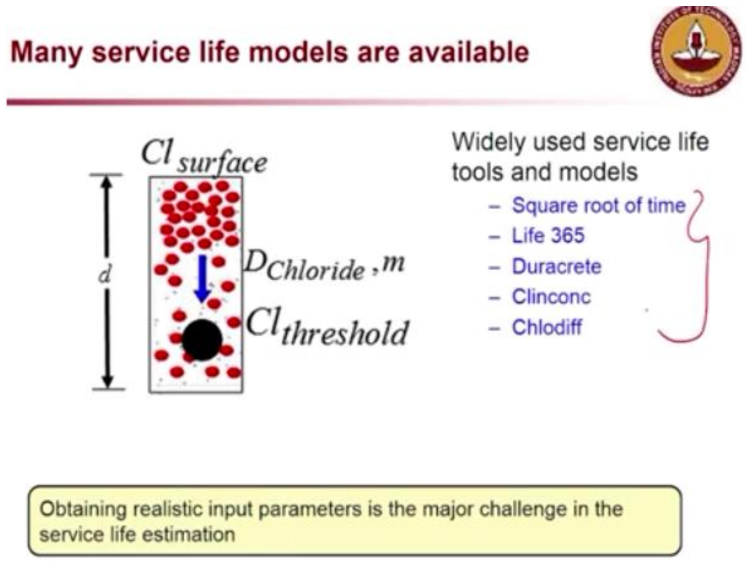
(Refer Slide Time: 09:25)



Now we will move on to chloride induced corrosion. So, if you have to model the ingress of chlorides in this cover depth, then we can use Fick's second law of diffusion to simulate the chloride ingress. You can see here that this is OPC and this is SCM based concrete. So once you have to SCM based concrete for the same depth the chloride amount differs hugely. So this is because of the resistance that is being developed.

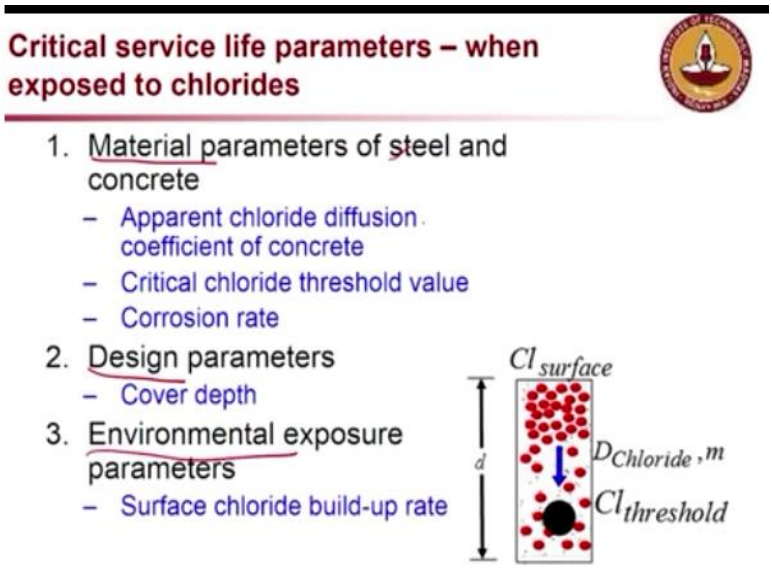
Also you have note that with the SCM based concretes, concrete hydrates in a slower rate leading to a value called M, that is the ageing factor. So for all the SCM based concretes, there will be a greater M than that of the control mix. That is the OPC concrete. So these parameters should be considered in this equation before estimating the service life.

(Refer Slide Time: 10:32)



So many models are available, which uses Fick's second law of diffusion and here you can see that there are plenty of models available, square root of time, Life 365, Duracrete, Clinconc, Chlodiff, etc. But obtaining realistic input parameters is the major challenge.

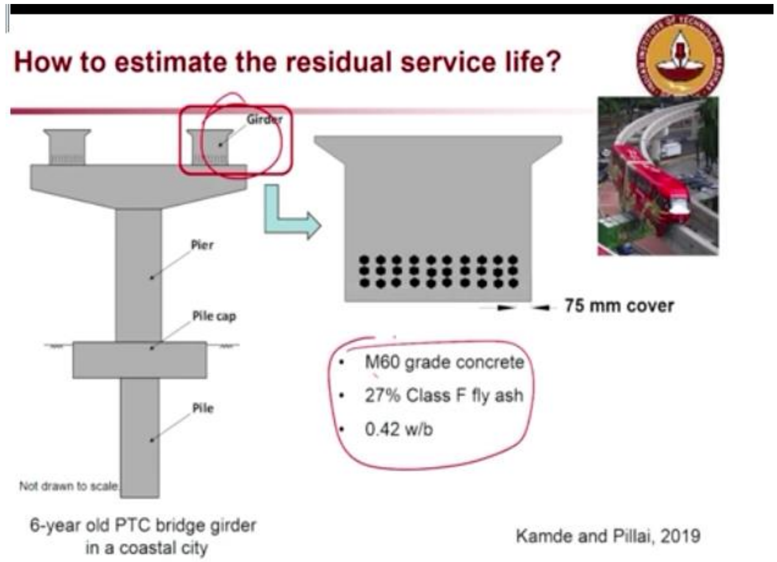
(Refer Slide Time: 10:58)



So these are the different parameters that has to be considered in case of chloride-induced corrosion. There are three major parameters. One is related to materials. Second one is related to design and third is related to environment exposure condition. In case of material parameters that is apparent diffusion coefficient that is rate at which the chloride is ingressing, critical chloride threshold value is amount of chlorides that are required at the steel interface to initiate corrosion.

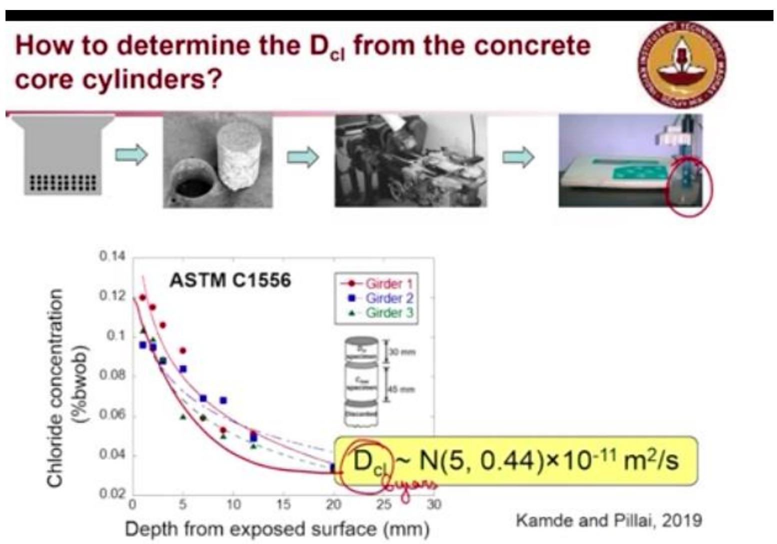
This depends on the combination of steel and binder and the corrosion rate if we are considering the propagation phase also. In case of design parameter, we will majorly consider the cover depth. In case of environmental exposure condition, the surface chloride and the build-up rate are important.

(Refer Slide Time: 11:56)



Once you have these parameters, you can estimate the residual service life. Here, I have taken a 6-year-old bridge. I have taken the girder. So this is the background information of the girder. It has the M60 concrete with 27% class F fly ash and 0.42 water binder ratio.

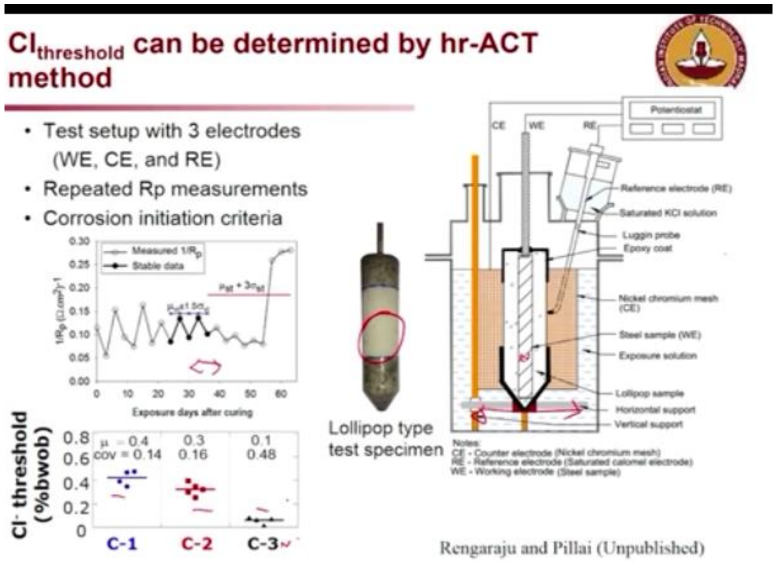
(Refer Slide Time: 12:19)



If you take the core of the concrete, we can layer the core and take the chloride concentration by doing the chloride analysis. Once you get these points, you can fit a curve and with this, you can get the D_{cl}. This D_{cl} will be the D_{cl} at the age of structure. In this case, we have taken 6-year-old bridge, so this is D_{cl} at 6 years, but all the service life estimation considers D_{cl} at age of 28 days. So we have some equations and we can back calculate D_{cl} 28 from D_{cl} 6 years.

Similarly, with this speed, you can also do calculation for M, that is the aging coefficient. So, the first top most layer you can consider for surface chloride concentration and then the exposure condition for the chloride build-up rate.

(Refer Slide Time: 13:20)



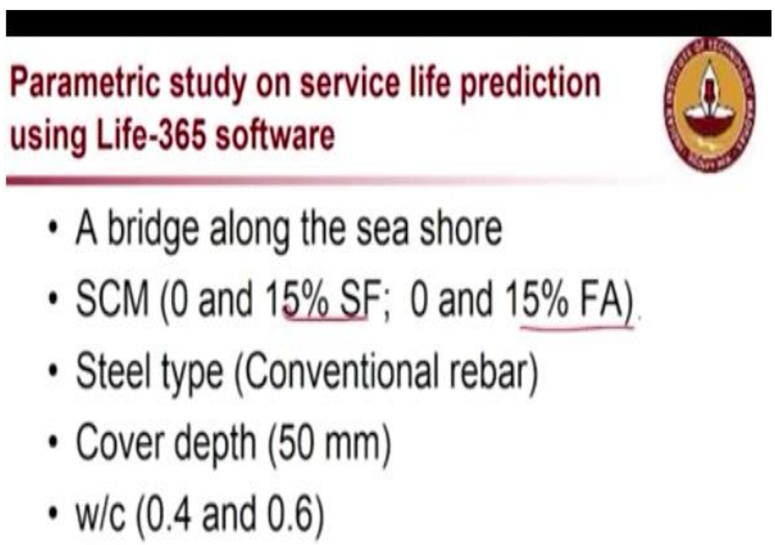
So the next parameter we need know is chloride threshold. This can be determined by hr-ACT method. Here you can see this lollipop specimen. This is the rebar that has been used with the mortar specimen, which is similar to the composition at that of the binder in the concrete. So you can do a repeated R_p measurement with this three electrode system and then with the corrosion initiation criteria, you can find the chloride threshold for different types of concrete.

You can see that the different type of concrete has different values for chloride threshold, even though the steel is same. You can get the further details of this experiment in the previous lecture.

(Refer Slide Time: 14:07)

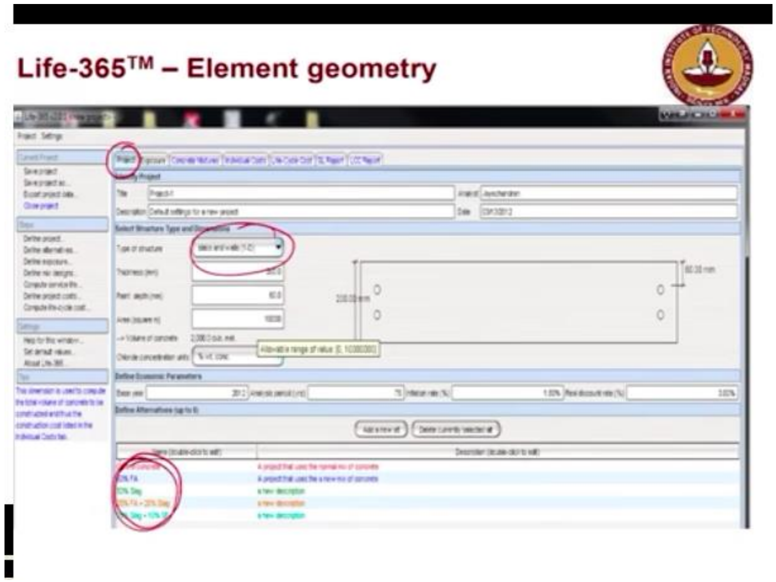
So now you have all the parameters required for service life estimation. Now you need a tool. So, this is Life-365 tool, which is easily available in internet and easily downloadable. This is user interface of Life-365.

(Refer Slide Time: 14:27)



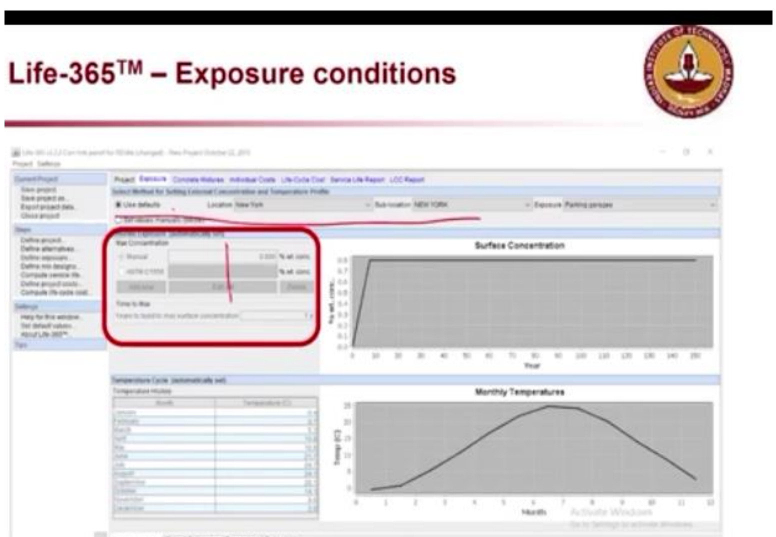
Now we can take case studies with a consideration that a bridge is along the seashore with SCM based concrete, 15% of silica fume and 15% fly ash and then we can consider a conventional steel cover depth 50 mm and water cement ratio 0.4 and 0.6.

(Refer Slide Time: 14:47)



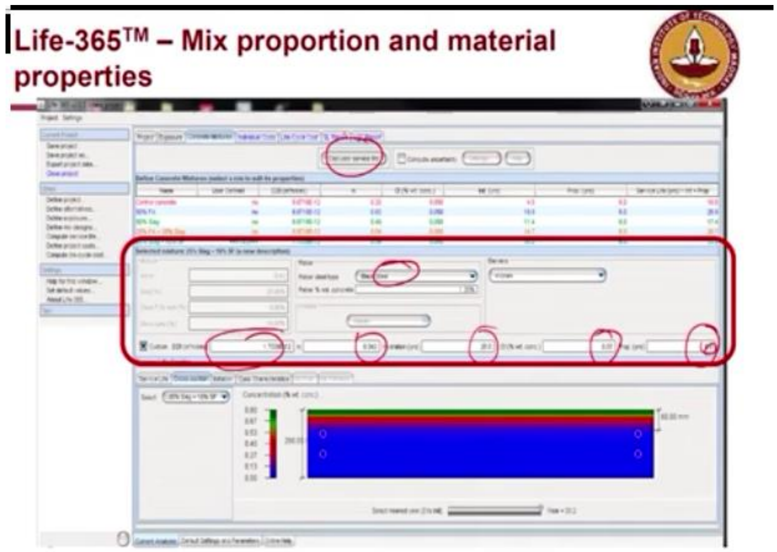
This is first tab. This is the project tab. Here you can do all the design parameters. You can choose the type of the structure whether it is a slab and wall. Slab or wall means, it is one dimensional exposure. You can also choose column, which will be a two-dimensional exposure, then you can also choose different types of concrete that is being fed. If you have three different choices, you can feed all the information about the concrete in this.

(Refer Slide Time: 15:21)



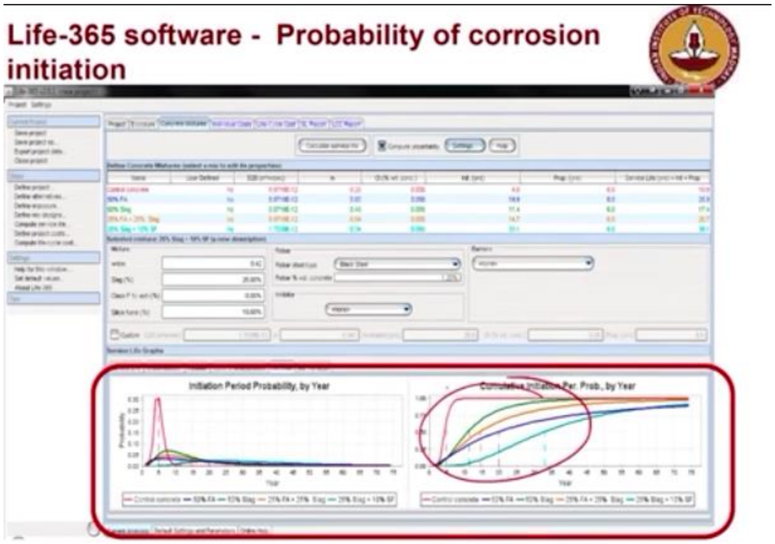
Second is the exposure tab. So, this Life-365 is based mainly for chloride-induced corrosion. So, you can directly choose the location of the structure, from that it will automatically calculate the surface chloride concentration and chloride build up rate, etc. or if you have a structure that is already in place, from that you can set the values here. Similarly, the temperature history also you can either fit the temperature, based on the exposure condition or it will take automatically from the location chosen.

(Refer Slide Time: 16:01)



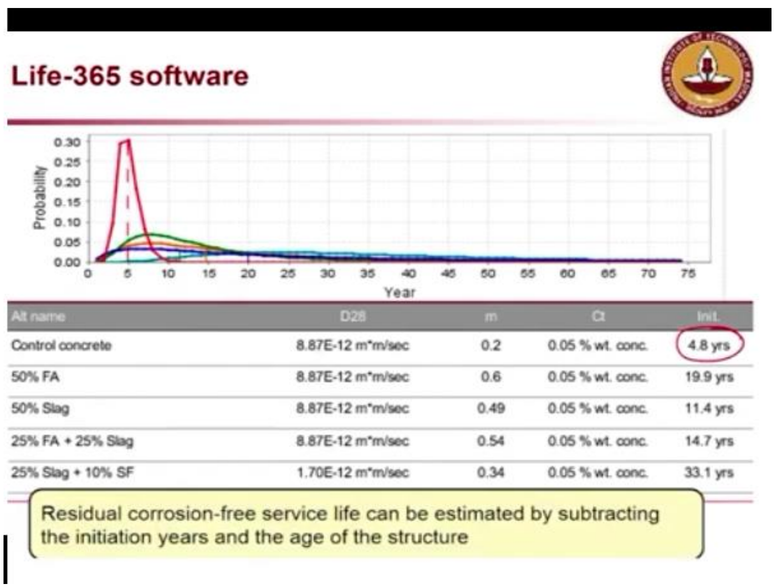
The third is the material characteristics. Here you can input what is type of the steel, what is the D_{cl} at 28 days, M, hydration years; it is usually taken as 25 and then chloride threshold, which we found by hr-ACT and propagation years. Life-365 by default takes 6 years as propagation years. So if you want to calculate corrosion-free life, then you can make this as 0 and if you have to calculate M, there is formula given in Life-365 manual. That is also easily downloadable from internet. So, from that formula, you calculate the M value and then when you click calculate service life, it will estimate the service life.

(Refer Slide Time: 16:51)



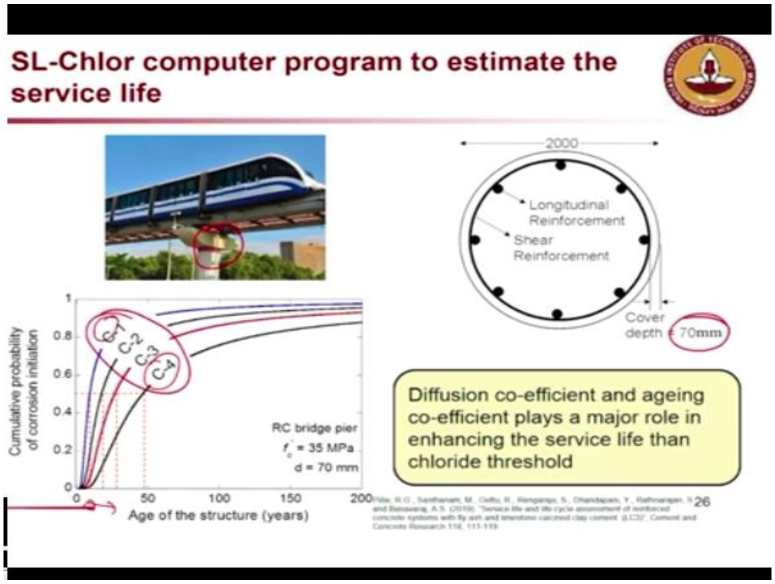
And give us a cumulative density function. From here, you can see there for 50% probability, it has given for different types of concrete the initiation years.

(Refer Slide Time: 17:03)



If you see closely, the control concrete has given only 4.8 years and other type of concretes has given at least 2-3 times increase. So this emphasizes the idea of using SCM based concrete in sites and also lower water binder ratio. From this you can calculate the residual service life by subtracting the initiation years and the age of structure.

(Refer Slide Time: 17:36)

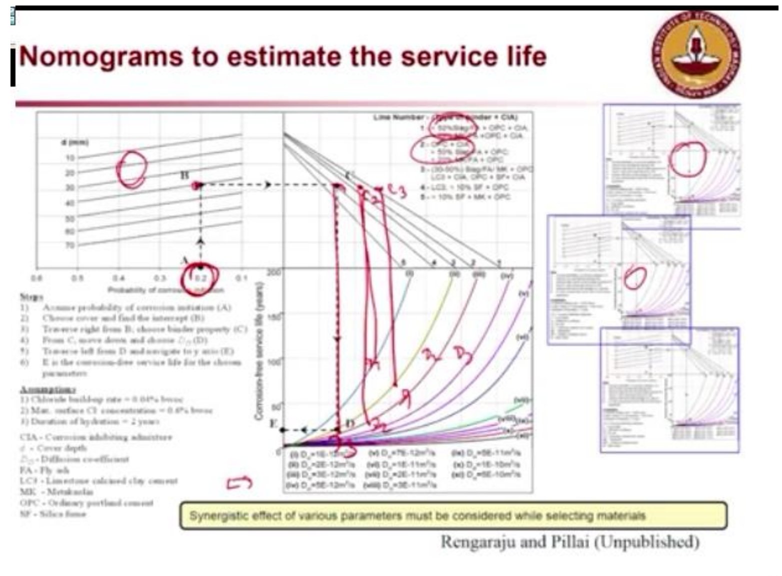


But Life-365 has some limitations like the calculation of M is very much dependent on the composition and it restricts the usage of M to only 0.6. So nowadays, we have lot of materials, new materials, which are having slower hydration. So maybe you have to relook at the calculation of M, so that cannot be accommodated in Life-365, also the standard deviation by default is taken as 25%, but in case of field structures, the variation will be huge.

So, to accommodate these kinds of small variations, we have developed a program called SL-Chlor to estimate the service life. So this is also based on Fick’s second law of diffusion. Here we have taken an example of bridge pier with 70 mm cover depth. So, we have taken 4 different types of concrete and we have estimated the service life. So here you can see for C-1 and C-4, even though it is of same grade, it is showing that the age is increased by four times.

So, this again and again emphasizes that the type of concrete and water cement ratio that has been used in the concrete plays a major role. So, the diffusion coefficient and the ageing coefficient, which indirectly plays a role for type of concrete and water binder ratio that place in a major role in enhancing the service life than chloride threshold. So, if you are deciding authority and if you are not of materials background, how will you choose the materials? For that, you need to have user friendly tool, which is readily available like a design chart.

(Refer Slide Time: 19:47)



We developed similar kind of thing called nomogram to estimate the service life. Here you can see the first quadrant, it is composed of probability of failure. Here the probability of failure means the corrosion initiation. So, this is called probability of corrosion initiation and then the cover depth. So, if you say what is the probability of corrosion initiation? If you have a tender document, which specifies the service life as 100 years, the probability of corrosion to occur in 100 years is 20%.

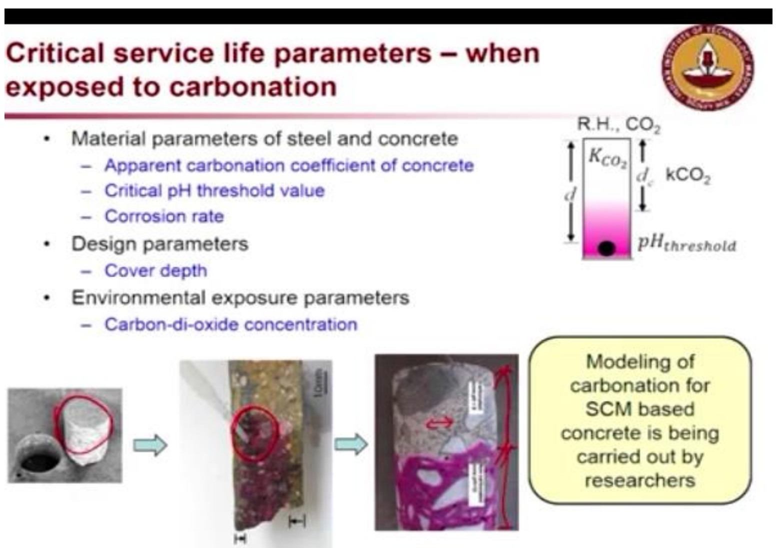
That means it is 0.2. So, if you have, in this example, I have taken as 0.2 and the cover depth as 40. So, this will be specified in the code for exposure condition minimum cover depth will be given. So, I have taken that cover depth and then if you have a choice of material. For example, you can take OPC concrete. So, the OPC concrete is given and then you have another that choice of material. For example, 50% slag and fly ash or OPC with corrosion inhibiter that is 2.

So you can have 3 choices that is OPC C-1 and then OPC with inhibiter that is C-2 and then slag that is C3. For these 3 different types of materials, you can make a concrete and find the respective diffusion coefficient. So that will be given as D1, D2 and D3. So, once you hit D1, D2, D3, you can go to the left and find out the service life. So, you can choose the materials based on the optimal cost and the service life it is rendering.

So, you have ability to choose the materials based on its performance. You can use nomogram in a reversal way also. If you want to have 100 years of service life, then you can from here you can have a diffusion coefficient. So you have D1, D2, D3 and then from that you can know what are the different types of materials used. So you know the C-1, C-2, C-3 and from that you have to go left to understand, what is the type of cover depth you want.

Then, from that you will understand the probability of failure. So, these kinds of nomograms are also developed for different exposure conditions. For example, the one I explained is for 800 meter away from sea. Similar nomograms were constructed for structures, which are exposed in the splash zone, spray zone and then 1500 meter away from the sea. So synergistic effect of various parameters must be considered while selecting materials and these nomograms help us to do that effectively.

(Refer Slide Time: 23:03)

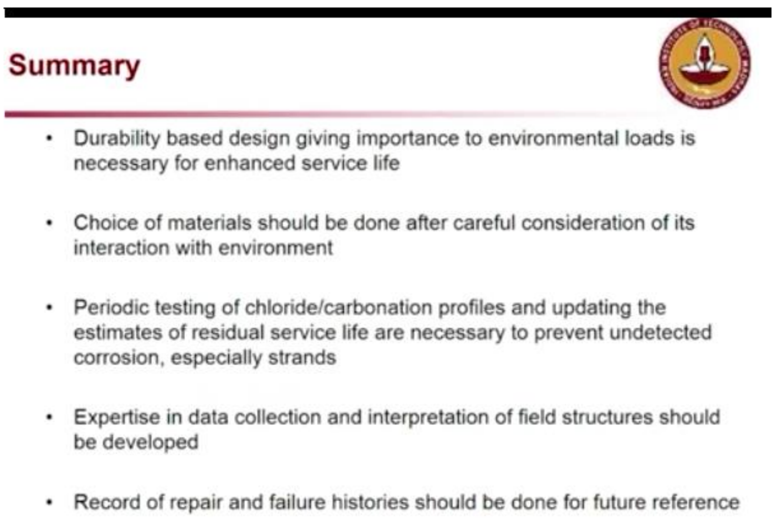


Now we will come to carbonation. In case of carbonation also, there are different parameters that need to be considered. Here, I have categorized in to 3 parameters that is material parameters, design parameters and environmental exposure parameter. In the material parameters, we have apparent carbonation coefficient critical pH value and corrosion rate in case of propagation phase and design parameter that is cover depth and environmental exposure condition that is carbon dioxide concentration.

So, if you take a core from the existing structure and spray phenolphthalein indicator, because of phenolphthalein, the concrete will change its colour. So if it is carbonated, that is if the pH is less than 9, then it will turn as colourless. This carbonation is being researched throughout by various researchers, especially for SCM based concrete.

Because the carbon dioxide concentration is varying from place to place. For example, if CO2 concentration in Madras will be different from Delhi and if you compare these two, the carbonation rate will be different. Similarly, if you compare India with Singapore, the carbonation rate will be different. So, we have to model such kind of variation in the climatic conditions and generate similar nomograms. So in IIT Madras, we are researching this and we can expect similar nomograms soon.

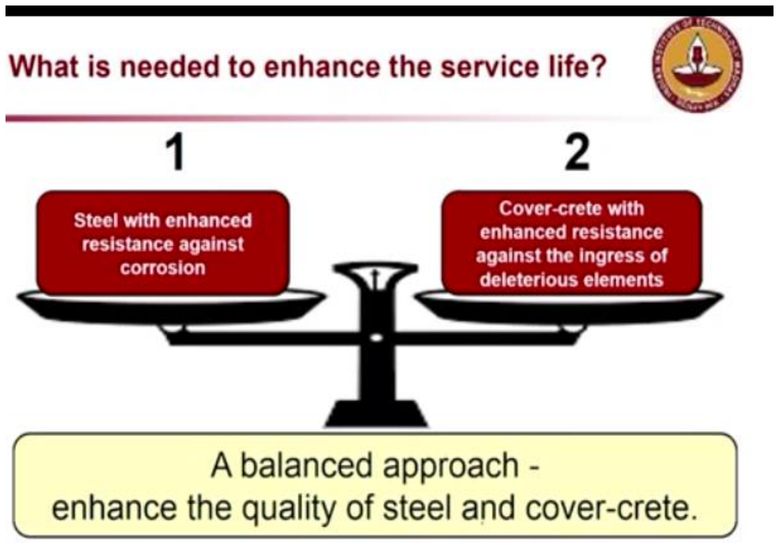
(Refer Slide Time: 24:57)



So, to summarize, the durability-based design giving importance to environmental loads is necessary for enhanced service life. The choice of material should be done after careful consideration of its interaction with environment. Periodic testing of chloride and carbonation profiles and updating the estimates of residual service life are necessary to prevent and detect a corrosion, especially in case of strands, which has happened in Morandi duct.

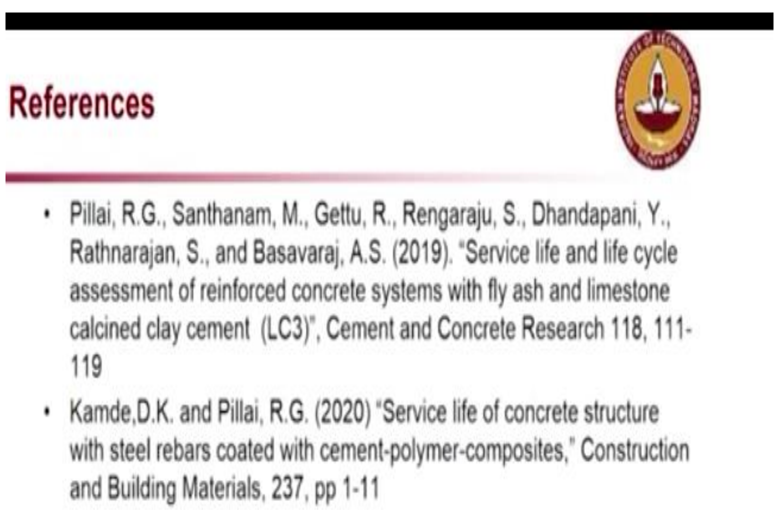
And expertise and data collection and interpretation of field structures should be developed and we should encourage the young researches to go to this research carrier. Record of repair and failure history should be done for future reference.

(Refer Slide Time: 25:48)



In short, a balance between steel and concrete should be achieved. That is quality of both steel and concrete should be given appropriate care for enhancing the service life.

(Refer Slide Time: 26:03)



Thank you.