Design of Connections in Steel Structures
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Module - 1
Lecture - 1
Basic Principles of Bolted Connections

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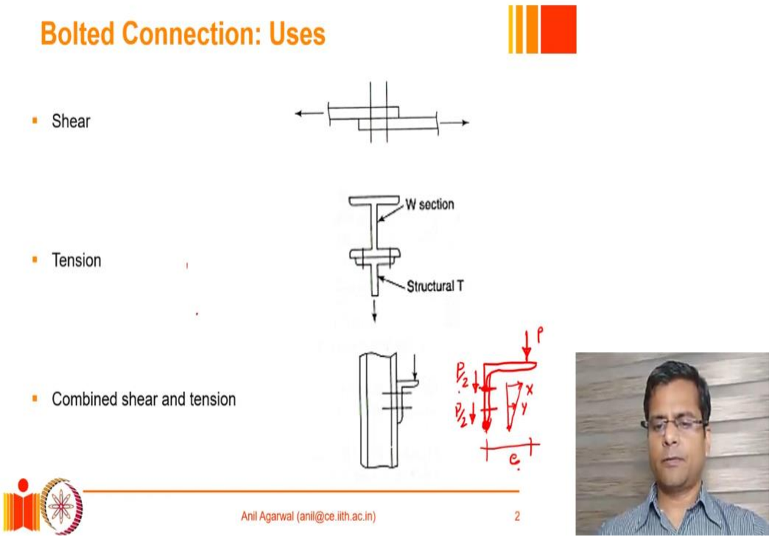

We will start with the first session which is on the Basic Principles of Bolted Connection Design. You might be aware that bolts can be used in various configurations. Idea behind using bolts is basically to join 2 plates. So, these plates could be a part of hot-rolled section or just a plate. For example, the first example that is shown here is basically a single plate that was spliced here at this location.

And because of this splicing, we had to provide a connection between the 2 parts. And since this plate is being pulled in tension, the bolts that are connecting these two plates would be subjected to shear. If I may draw the deformed shape for example; if let us say this plate is fixed and the bottom plate is being actually pulled when it is moving. So, if this plate moves to this new configuration, these bolts will actually also move to this new configuration.

Therefore, these bolts if I see, if the bolt diameter is not ignored, then this is the original shank size of the bolt. And once it is undergoing shear, it is actually deforming into this shape, which is basically primarily shear failure mode. So, this kind of bolted connections would be called the ones where the bolt is subjected to shear force demand. Also, there can be situations where the bolt is subjected to tension force demand.

One example is shown here, wherein a structural T section is being pulled from a wide flange or I section as shown here. And because of this tension force that is shown here in the form of an arrow, these bolts which are connecting the T section with the W section, these bolts will be subjected to tension force demand. So, in this particular case, if the structure is symmetric, if the total tension force is T, the tension demand in each bolt will be T/2.

Similarly, there can be situations where bolts are provided to resist a combination of tension and shear force. One such example is shown here. So, in this particular case, this angle is being used as a bracket to resist a vertical load at an offset from the support. So, in this situation, whatever force P is acting for forced equilibrium, you will see that there are 2 bolts provided.

In all these diagrams, the line that is representing the bolt actually is the length of the bolt, and diameter is not shown here explicitly. So, these two bolts basically are going to resist this force. So, this force has 2 components. One component would be direct shear component on each bolt. So, if the stiffness of this angle is quite large in comparison to the stiffness of the angles, we can approximate the total force demand on each bolt as P/ 2

Now, the force equilibrium is satisfied. However, the moment equilibrium is not satisfied, because there is an eccentricity between the location where the force is acting and where the support is. And because of this eccentricity, essentially what would happen is that some kind of a heel or some kind of pivoting point will form somewhere near the bottom edge of this angle.

And these bolts, individual bolts will be subjected to a tension force demand which you can assume to be linearly varying with respect to pivoted around the point of pivot. And these forces, individual forces; let us call them X and Y. These individual forces in the horizontal direction will produce enough counter moment which will balance the total force, total moment of e x e. So, this way, we can see that these bolts are not only subjected to a shear force of P/2 but also an actual force of X or Y respectively.

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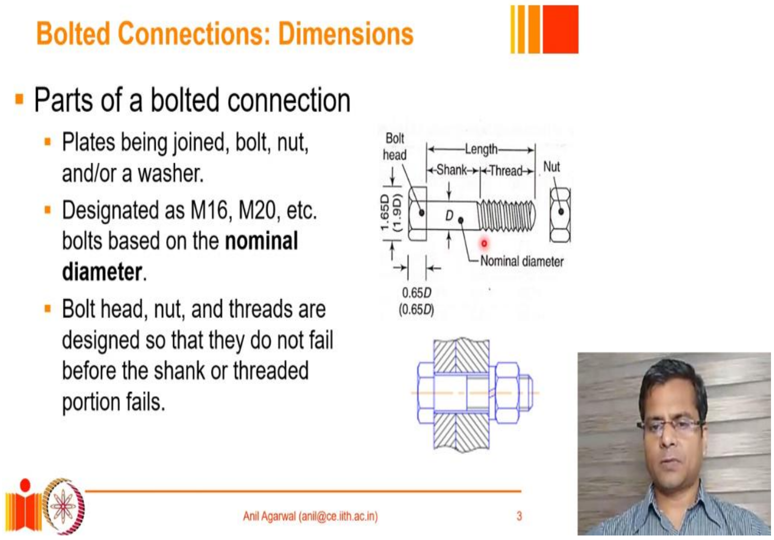

Now, in order to understand bolts, first we have to understand what are the dimensions, how to classify bolts, etcetera. So, this is basically an introductory lecture. A bolted connection consists of several components. The components include the plates that are being joined together. So, for example, in this diagram, there is a plate here, there is a plate here. There is a hole in both these plates and those plates are aligned together.

Then there is a bolt that has to pass through the hole. There is a nut that is used to tighten and clamp the bolt. And also there is a washer; washer is required to be able to uniformly distribute the stresses over that surface and also to keep the bolt from loosening. Now bolts are typically designated based on the diameter of their shank. So, typically bolts are known as M16 bolt, M20 bolt, M24 bolt and so on.

So, basically, this number 16, 20, etcetera is basically the diameter of the shank of bolt. The bolt itself has 3 or 4 major components. The first major component is the bolt head. The bolt head basically provides the bearing. Once it is clamped towards the bearing, the bearing resistance against the plate and keeps the bolt tight; the shank and then the threaded portion of the bolt.

So, in addition to that, there is a nut, the nut in geometry is very similar to the bolt head. The dimensions of all these parts, individual parts are given in various international and Indian codes; we will discuss about those. First we will talk about what is the relationship between the diameter at the root of the thread and the diameter of the shank.

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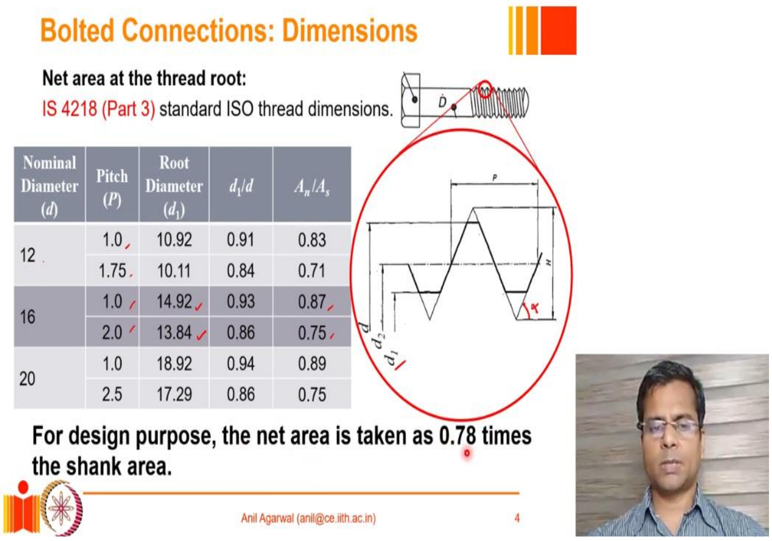

Nominal Diameter (d)	Pitch (P)	Root Diameter (d_1)	d_1/d	A_n/A_s
12	1.0	10.92	0.91	0.83
	1.75	10.11	0.84	0.71
16	1.0	14.92	0.93	0.87
	2.0	13.84	0.86	0.75
20	1.0	18.92	0.94	0.89
	2.5	17.29	0.86	0.75

So, in this diagram, what you see is basically a typical bolt, this much portion of the bolt is unthreaded. This is the thread, threaded portion of the bolt. If we go to IS 4218 Part 3, which is basically similar to the respective ISO code, this provides you various thread dimensions which are applicable or which are standardised in India. So, the thread dimensions basically are classified in terms of pitch.

Pitch is the distance between the two subsequent peaks. So, the bold black line here, this line for example, represents the thread. So, this is a peak and this is the trough of the thread. The pitch is the distance between 2 peaks or distance between 2 locations which are at the same elevation. Now, the way these threads are designed is such that, for standard threads, this angle does not change, the angle between, this angle remains constant.

However, the pitch can be changed and different values are possible. The different values or the extreme values of pitch which are allowed as per the standard IS 4218 Part 3 are listed here. So, for different bolt diameters, which is the d value here, the pitch distances in millimetres can be between these values. For example, for a 16 millimetre diameter bolt, the pitch can be at one extreme, 1 millimetre; at the other extreme, 2 millimetre.

Now, if this angle alpha is constant, it cannot change, but the pitch can change. What does that imply? I will give you a moment to think about it. If this alpha cannot change, but the P value, pitch can change, that means the distance or the change in diameter of the bolt will vary as you change the pitch value. So, d_1 represents the diameter of the root of the thread, and d represents the diameter of the peak of each thread.

So, d is same as the shank D, which is basically, in our case, let us say 16 millimetres. However, as the pitch value is changed from 1 millimetre to 2 millimetres, the d_1 value which is the root diameter is reduced to 14.92 or 13.84 millimetres. So, you can see that the pitch is making a difference or changing the root diameter. Now, if the root diameter is changed, we can calculate the ratio of the root diameters d_1 divided by d, and also we can calculate the net section that is available.

What is the net section? The net section is basically the cross-section that is available from root to the root on the other side. So, that net cross-section of the bolt which is the reduced cross-section, that is a smaller part of the total cross-section. So, depending on the pitch size, the ratio between the net cross-section and gross cross-section changes, which varies between 0.75 and 0.87 in case of 16 mm bolt, M16 bolt.

So, these are the possible values which you can use. However, for the design purposes, generally this net area is taken as approximately 78% times the shank area. So, if it is an M16 bolt, we will calculate the cross-section area of a 16 mm diameter rod, and then we will take 78% of that which will give us the cross-section area of the threaded portion.

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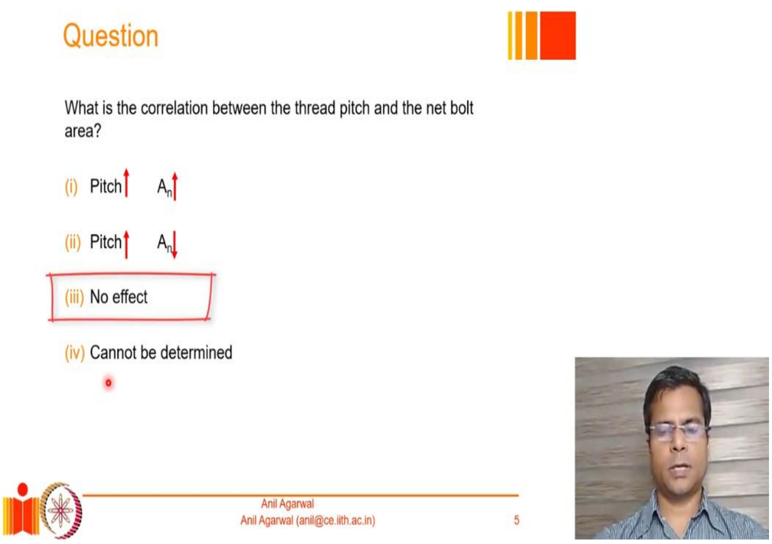

So, let us ask one question now. What is the correlation between the thread pitch P and the net bolt area A_n? Is it when that the pitch is increased, does the net cross-section area increases? When the pitch is increased, does the net cross-section area decrease? If there is no effect, please answer 3. If it cannot be determined, please answer 4. I will wait for you to answer. So, the correct answer is, as the pitch is increased, the net cross-section area decreases.

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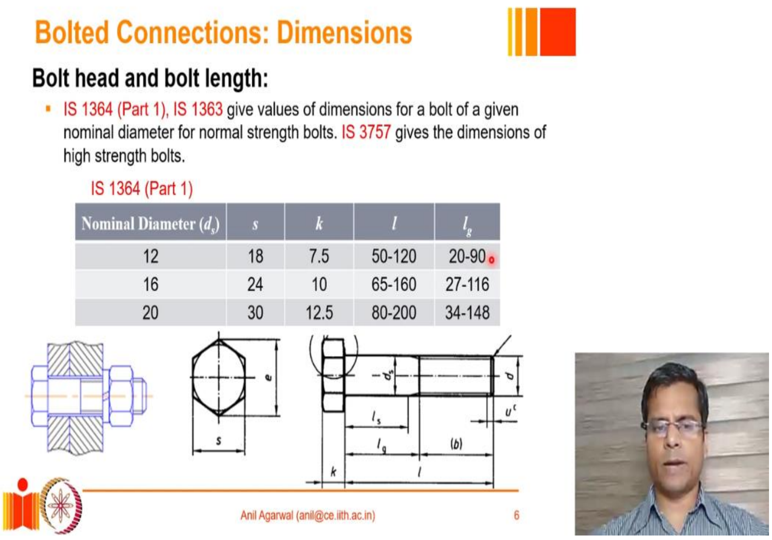

The other dimensions of a bolt are: Primarily consists of the length of the bolt, the length of the threaded portion of the bolt. So, for example, in this diagram, this is the length of the bolt, l; and length of the threaded portion of the bolt is given by l_s here; and l_g is the portion that is unthreaded. In addition to that, also the bolt head dimensions are relevant, because they are the ones that control how close the bolts can come together and how much space you need for tightening, etcetera.

Now, why is the length so critical? There is one obvious answer. If the length is not sufficient; let us say I want to connect these two plates and I need to put a bolt through this hole to connect these two plates. But if the length of the bolt is not sufficient to join these two plates, what would happen? I would not have sufficient length to grip with the nut here, why? Which will produce, either I will not be able to put any threads, or even if I am able to put a couple of threads, that is not sufficient, I need sufficient length on the grip side so that I can achieve the full strength of the bolt.

That is the limit on the minimum length requirement. How about the maximum length? Why cannot I just provide as long a bolt as I need? One is, sometimes it may make it difficult to fit in certain places where there may not be enough space to accommodate unnecessarily long bolt. Also, one needs to be mindful of this issue of threaded length. So, for different bolt lengths, there is a respective corresponding threaded length of the bolt.

So, if I go to IS 1364 Part 1 or IS 1363, they talk about the, all these dimensions they prescribe, all these dimensions for different diameter bolts of different types. So, for example 1363 and 1364 Part 1 talk about normal strength bolts, whereas IS 3757 gives all these dimensions for the higher strength bolts, which are known as high strength friction grip, HSFG bolts.

So, as you might see, for a given diameter, the ratio between the s or therefore e and the diameter is almost fixed. You can see these ratios between the different diameter bolts. Likewise, the k value with respect to the diameter of the bolt is also almost constant. For any given diameter, different lengths are available as standard lengths. And for a given length, there is a fixed length of threaded portion and unthreaded portion. And we have to be mindful, we have to be careful to pick the bolt so that we get sufficient threaded length.

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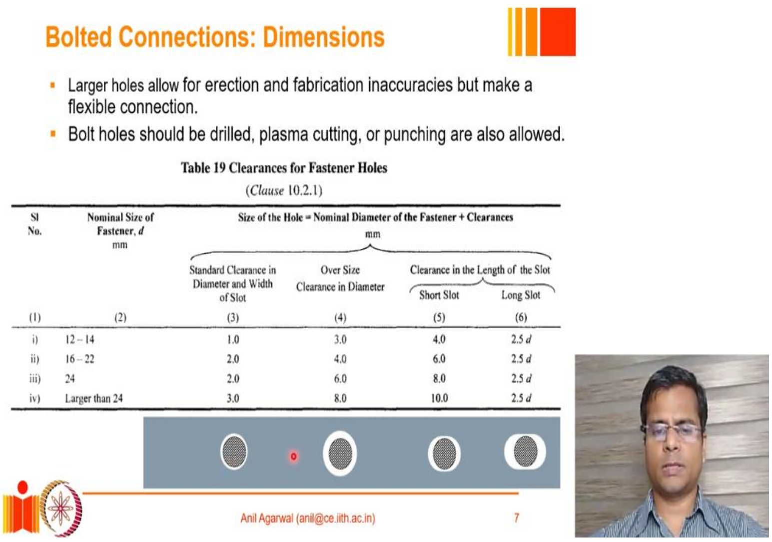

Sl No.	Nominal Size of Fastener, *d* mm	Size of the Hole = Nominal Diameter of the Fastener + Clearances mm			
		Standard Clearance in Diameter and Width of Slot	Over Size Clearance in Diameter	Clearance in the Length of the Slot	
				Short Slot	Long Slot
(1)	(2)	(3)	(4)	(5)	(6)
i)	12 – 14	1.0	3.0	4.0	2.5 *d*
ii)	16 – 22	2.0	4.0	6.0	2.5 *d*
iii)	24	2.0	6.0	8.0	2.5 *d*
iv)	Larger than 24	3.0	8.0	10.0	2.5 *d*

Another important dimension related parameter that we should pay attention to is the hole diameter, because we need holes of course, to be able to erect a structure using bolts. Now, we cannot provide a hole which is exactly the same diameter as the bolt, because we need some clearance in order to be able to slide the bolt into the hole. So, there can be some fabrication issues, there can be some inaccuracies.

So, because of all these reasons, there is a need of a clearance between the bolt and bolt hole. For the minimum clearance requirement, we are required to go with the standard clearance holes. This is table 19 given in our IS 800, which is the Indian Standard Code for steel design. So, for example, for a 16 mm diameter bolt, the standard clearance will be 2 millimetres.

That means, the hole diameter would be 16 + 2, that is 18 millimetres. In certain conditions where we are not so sure about our capabilities to fabricate accurately, we may decide to go for an oversize clearance in some of the bolt holes. The reason for that could be, because if we need more space to be able to fit the bolt or if we want to have some flexibility to accommodate some lateral movement or to accommodate some relative movement between the plates, we would want to go for an oversize clearance.

However, these kind of holes will lead to flexible bolted connections. Then there is an option of going with slotted holes. So, there are 2 options; one is a short slot, the other one is a long slot. And of course, they are less and less preferable, but sometimes we may be forced to, we may not have any other option but to provide these kind of arrangements. So, the dimensions of these are given. I am just going to give you an example.

So, we will take 16 mm diameter bolt as an example. So, for standard clearance hole, the hole diameter should be 18 mm. For the oversize clearance, the hole diameter should be 16 + 4, that is 20 millimetres. In short slot which will look like this, which is basically 2 semi circles and a rectangle in the middle, that is the whole shape. The length of the slot from this edge to this edge will be 16 + 6, that is 22 millimetres.

And in the other direction, the size will be same as what is required for a standard clearance, which is 18 millimetres. In case of this slot, the length between this edge to this edge of the slot will be equal to 2.5 times the diameter. So, the diameter is 16 millimetres; 2.5 times 16 will be 14. So, 14 millimetre will be the total slot length. And in the width direction, it will again follow the same standard, that is 16 + 2, 18 millimetres.

The holes can be provided by drilling, by punching or by plasma cutting. Out of these, drilling is the most preferable way, because it does not introduce any local imperfections or does not change the material characteristics in the neighbourhood; it creates a smooth surface. Punching is allowed only in relatively lower strength steel and the steel plates which are not very thick. Plasma cutting does affect the local property somewhat because of the heating effect, but that is also permissible in certain cases.

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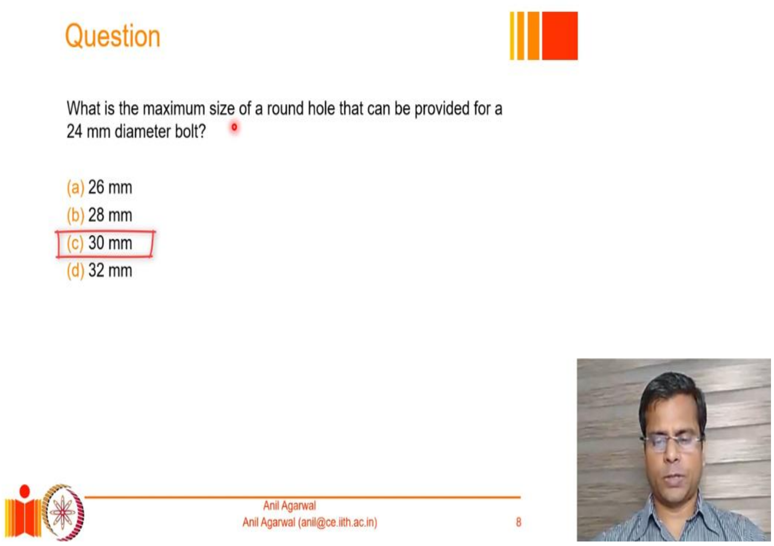

So, let us take one question; what is the maximum size of a round hole that can be provided for a 24 millimetre diameter bolt? You have 4 options: 26 millimetres, 28 millimetres, 30 millimetres, 32 millimetres. You can refer to the table 19 of IS 800. So, if the bolt diameter is 24 millimetres, we need to find out the maximum size. Maximum size should be the oversize clearance. That should be the enough clue.

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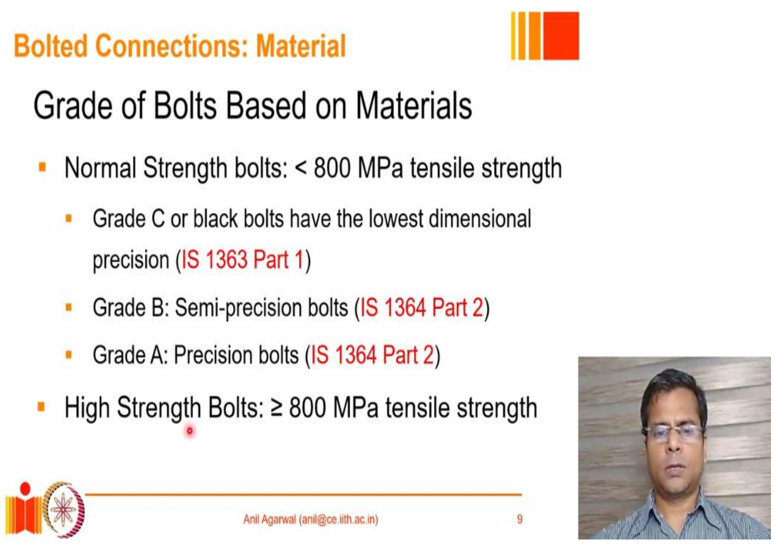

Now, in addition to the dimensions of bolts, also bolts can be made of different types of steels, and these steels primarily vary in terms of strength. There are 2 major classifications. One is normal strength steel or normal strength bolt or high strength bolt. The ones that have an ultimate stress of less than 800 MPa are classified as normal strength bolts. Within that, there are 3 classifications, A, B and C, which are based on the geometrical precision or geometrical accuracy of the dimensions. The high strength bolts, they are the ones that have greater than or equal to 800 MPa tensile strength.

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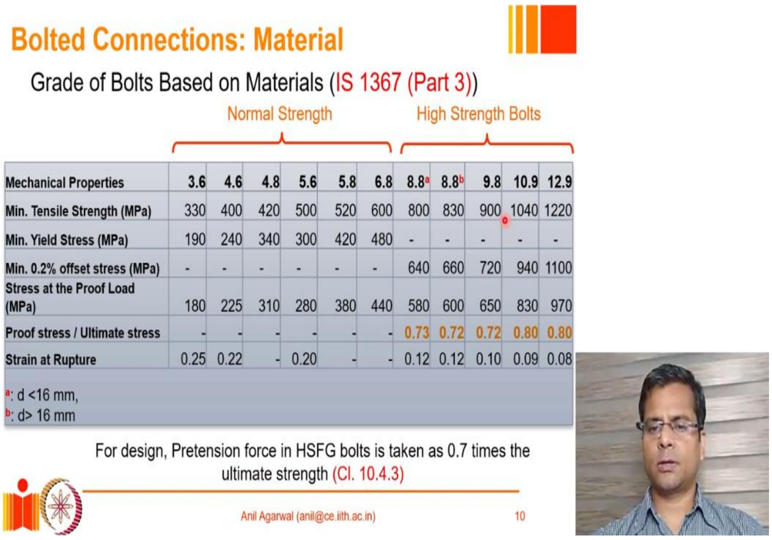

Typically, bolts are classified in terms of strength as these classes: Class 3.6, 4.6, 4.8 and so on. Now, the most critical mechanical property that is used to classify these bolts is the minimum tensile strength. So, actually, these numbers can be read to understand what is the approximate tensile strength and approximate yield strength of a bolt. For example, if a bolt has a classification of 4.8, it basically means that it has a tensile strength of almost 420 MPa, and it has a yield strength of 340.

And if we multiply 420 with 0.8, you will get 340. So, that is how this logic works. And that is how this classification works. In addition to these, when we go into the higher strength bolts, which is above or equal to 800 MPa strength, we will see that the yield point is not very clearly defined. And therefore, we do not use yield as a classifying criterion. We use the stress corresponding to 0.2% strain offset.

And those stress values are reported, which are written here. But again, the same logic stands. So, if the ultimate stress is for 800 MPa, the stress corresponding to 0.2% offset will be 800 multiplied by 0.8 which is 640 MPa. There is another interesting stress value of use, which is known as the stress at proof load. And these values actually are also provided by the code, which is basically, and the proof load is the load to which a bolt can be loaded or can be pretensioned.

Generally, the normal strength bolts are not pretensioned in a structure, but high strength bolts are often prestressed or pretensioned in a structure, and they provide a friction grip kind of a bolted connection. So, for such bolts, if we calculate the ratio between the proof stress and the ultimate stress, we will get these values. So, you can see the values vary between 0.72 to 0.8, about 72% to 80%.

That is, the proof stress, the stress pretension, the prestress level that will be existing in the bolt even without any external load will be about 70% to 80% of the ultimate strength of the bolt. Also another property of interest would be strain at rupture. So, as you may see, the minimum strain at rupture for low strength bolts such as 3.6 or 4.6 grade bolts is between 0.25, 0.22 and so on. However, higher strength bolts exhibit low strains at rupture.

The strain at rupture is basically a parameter that is used to quantify ductility of steel. And as you may understand, as the bolt strength increases, the ductility of the bolt decreases. The reason is quite obvious. The strength of a bolt is increased by one of the two methods. 1, either the carbon content in the steel is increased. If the carbon content is increased, it does increase the strength but it makes it more brittle.

Also, the other option is to use quenching which is basically a thermomechanical process. So, through quenching, the strength can be increased, but also at the same time, the ductility decreases. Now, as designers, we do not have to necessarily deal with the ductility properties of bolt, because, whatever bolts are classified, they have enough ductility so that they can be, the present guidelines can be used.

However, the parameters that are of relevance to us are tensile strength, yield strength and the proof stress. So, now for calculation of proof stress, we are not necessarily required to go to IS 1367 every time and calculate the proof stress only for a given bolt. Basically, the Indian code allows us to take the proof stress for HSFG bolts as 0.7 times the ultimate strength, because you can see the values are varying between 0.72 to 0.8. The code says you may simply take 0.7 times the ultimate stress and use that as proof stress instead of using these accurate values. So, let us take one more question.

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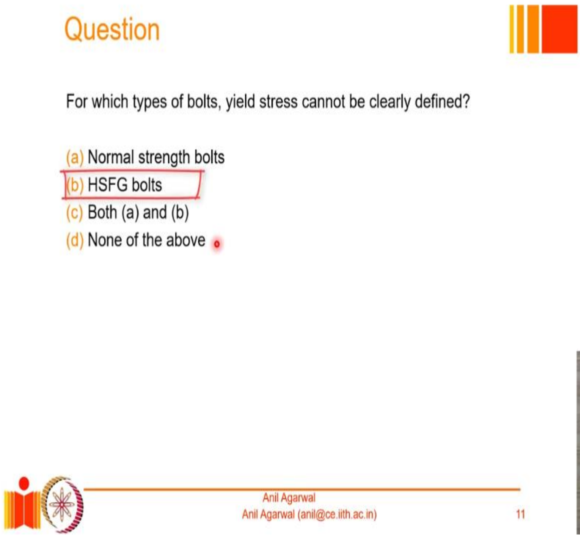

What do you think, for which type of bolts the yield stress cannot be clearly defined? Is it the normal strength bolts, the high strength friction grip bolts, for both of them you cannot define the yield stress, or both of them you can define the yield stress. What is your answer? Please give your answer.