Engineering Mechanics
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Module-01
Statics
Lecture -11
Beams - II

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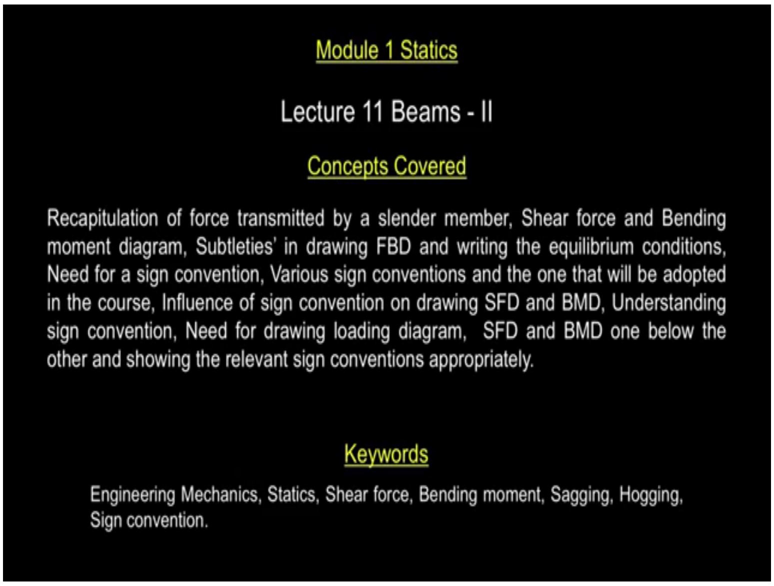

Let us continue our discussion on Beams.

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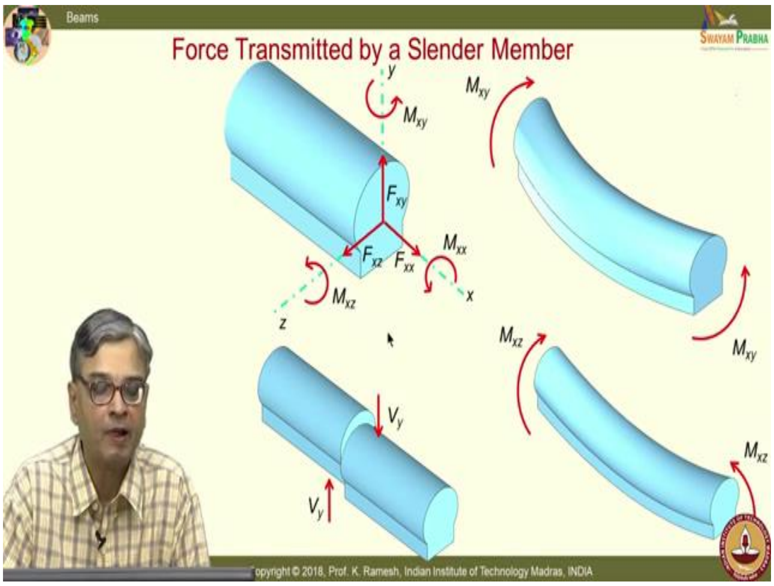
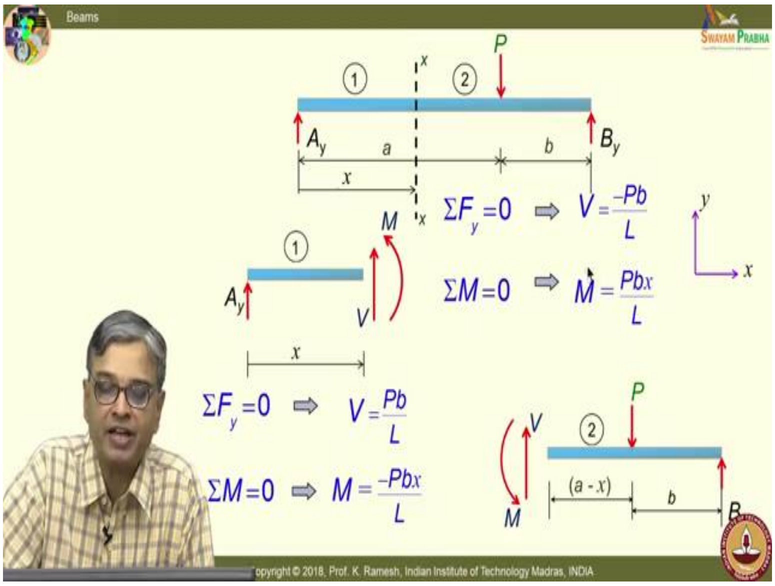


See, in the last class I had mentioned that we are essentially analyzing a slender member. It is a very long member; a portion of it is shown. The cross-sectional dimensions are much smaller than the length. In general, it can transmit three forces and three moments and what you see here is a shear force. This is a symbolism is used in higher studies, but in this course, we would simply indicate it by the symbol V.

You can also have a bending moment transmitted. So, it would bend in the plane xy like this. It can also have a bending moment M_{xy}. So, it would bend in the plane xz like this and you can also have a shear in the z direction no sketch is separately shown for this. You also have an axial force and you have a twisting moment. See, in the case of a truss, the members are also slender members.

It was essentially transmitting in axial force. In general, a slender member can transmit three forces and three moments. In the contest of bending, we would be interested if my loading is in the plane xy I would have the shear force F_{xy} or V_y or simply V and the bending moment M_{xz}.

And the idea is I have to decide on the cross-sectional dimensions. See, I said you are not going to get all answers for the problem related to bending in this course; whatever the information you get is the starting point for your next course to calculate the resistance offered by the member. There you will consider the beam as deformable. Whatever the forces you determine; it helps you to calculate the resistance on that basis you go and decide the cross-sectional dimensions.



So, one of the requirements is, how these forces vary along the length of the beam? That would help you to determine the critical load and design the structure or the cross-sectional dimension based on the critical load.

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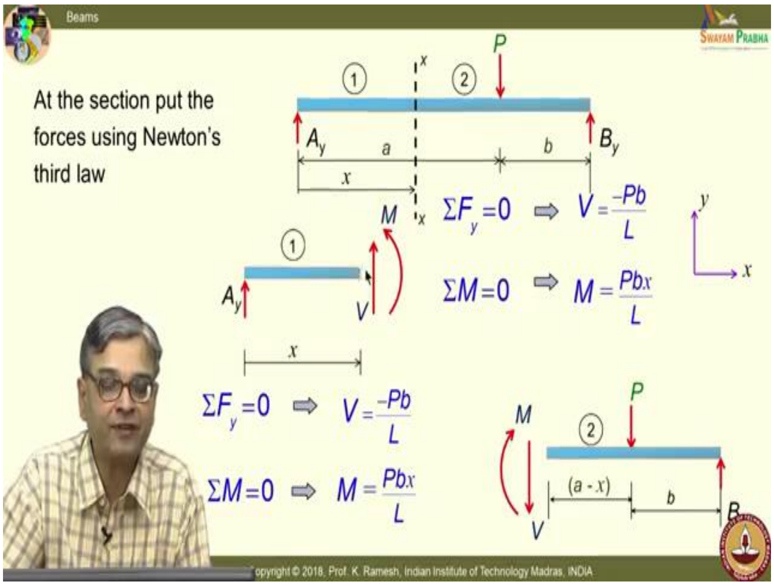
And we had also taken as simple beam like this; a simply supported beam. We have already learnt how to isolate a body. And if I have forces interacting here, when you draw the free body you can start with any direction. If our ultimate objective is to know whether it is tension or compression in the case of trusses, we have dealt it, how to put the forces? We had an elaborate discussion on this.

A similar exercise we should also do for the beams. Let me put the forces like this; individually this is quite all right. I do not know the value of *V*, I do not know the value of *M*, I put it on the positive direction to start with. And if I do this, I get the value of *V* as -*Pb/L* and if I put *M* = 0, I get M as Pbx/L; no issues about it.

This only indicates my original direction of *V* is not correct, it should be reversed because I said the mathematics will help you whether your direction is correct or wrong. On the other hand, I could also analyze this beam by taking this cross section. I am not going from this cross section to this cross section; I independently analyze this. The recommendation when you analyze it independently is put the unknown forces in the positive direction.

So, one would naturally start with putting them in the positive direction. When you do this, I would see the magnitudes are all right, but the sign, there is a difference. I get *V* as Pb/L, M as -Pbx/L. Suppose, I go and correct this free body diagram based on this and I correct this free body diagram based on this. The resulting free body will be only one; there will not be any change, we will see that also. Now, the idea is I have to plot the variation of *V*, plot the variation of *M* along the length of the beam. So, I should get one unique sign; whichever, way I cut the beam and do the analysis.



You cut the beam and analyze the left portion or the right portion whichever is having minimum number of mathematical steps. So, you would like to have a luxury to analyze a left segment or the right segment depending on the problem context. Ultimately, when I plot shear force or the bending moment; I should not have confusion on the sign.

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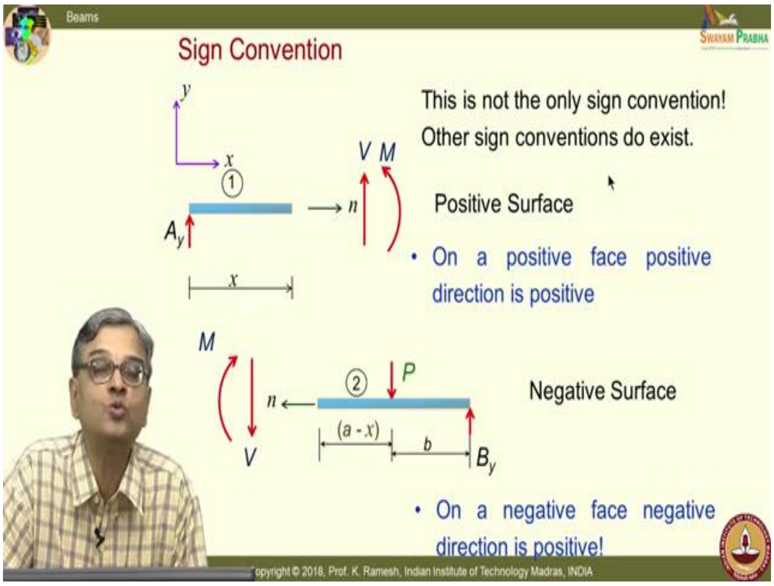
Suppose, we look back the problem again and when we studied inter connected rigid bodies. We had a recommendation; if I have assumed on this, how would I assume the forces here? If I, have assumed it I have to necessarily use Newton’s third law and put it in the opposite direction. Only then, it is consistent. See, in an inter connected body you go from one body to another body.

Here the body is continuous; in this example because we have time, we analyze the left portion and right portion and see, what kind of contradictions that can come up. When you really solve a problem, you will do only the left portion or you will do the right portion and go ahead with solving the problem. So, when I reverse the sign like this based on Newton’s third law, I do get the values of *V* and values of *M* including the sign as identical, there is no change fine.

So, you have to know a priori; when I have a surface like this, how do I assume the unknown forces to start with? On the other hand, if I use the right section, how do I assume the forces to start with? So, that whichever way I cut the beam and evaluate I have one unique sign of *V* as well as *M*. For that you need a sign convention. Can you see, what is the way that you can mathematically represent this surface and mathematically represent this surface? Surface is denoted by the outward normal fine. So, I would level them as positive and negative surfaces.



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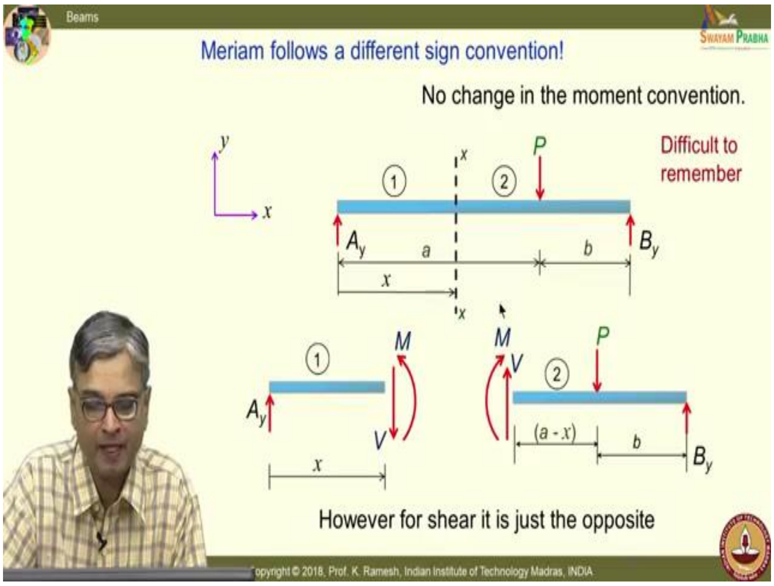
So, you need a sign convention; for you to analyze the left portion of the beam or the right portion of the beam and I said that you have to put the normal and this normal is in the positive direction of the coordinate axis. So, I call this as a positive surface. Please take a note listening will be like a story, these are all very subtle things and none of the books explain it in detail; they all rush through this subtilities. We spend more time on this subtilities so that you can solve problem from any book, any sign convention you should be comfortable with. And if I look at this portion of the beam and when I put the outward normal, I could recognize that this is on the negative direction of the co-ordinate axis. So, I will call this as a negative surface.

So, while solving a real-life problem you may choose a section of your choice to analyze either the left portion or the right portion. When you analyze a left portion, you are essentially doing the positive surface; when you are analyzing the right portion, you are essentially handling a negative surface. So, I must follow a convention to put the forces on this free body to start with.

On a positive surface, positive direction is positive to start with. So, I would indicate the unknown force as V, coinciding with the positive direction of the y axis and we have always been saying anticlockwise moment is positive. So, I put an anticlockwise moment, as the moment at this section. After putting this, you know when I want to analyze the free body I will go with the standard approach. I have the co-ordinate axis; I verify with this. No confusion comes, when you are handling this.

On the other hand, when I want to analyze the negative surface you have to follow the convention negative direction is positive, two negatives make it as positive. So, I would put unknown force as in the negative direction, unknown moment as clockwise. So, you have to follow a convention. See, you can have keep left or keep right. You cannot mix up this in the road in between then, you will end up in accidents. So, you need to follow a convention.

So, I should identify a positive surface, I should identify a negative surface to start with I put this. Suppose, I analyze this free body in my summation of sigma $F_y = 0$. How would I put V? V is in the negative direction; I will put it as $-V$; please understand that ok. When you start writing the free body because I; this is the continues member I need to follow a convention no matter whether I analyze the left portion or the right portion. I should get one unique fine answer including the sign on the shear force and bending moment that is a focus. I have shown you one sign convention and you should recognize other sign conventions do exists.



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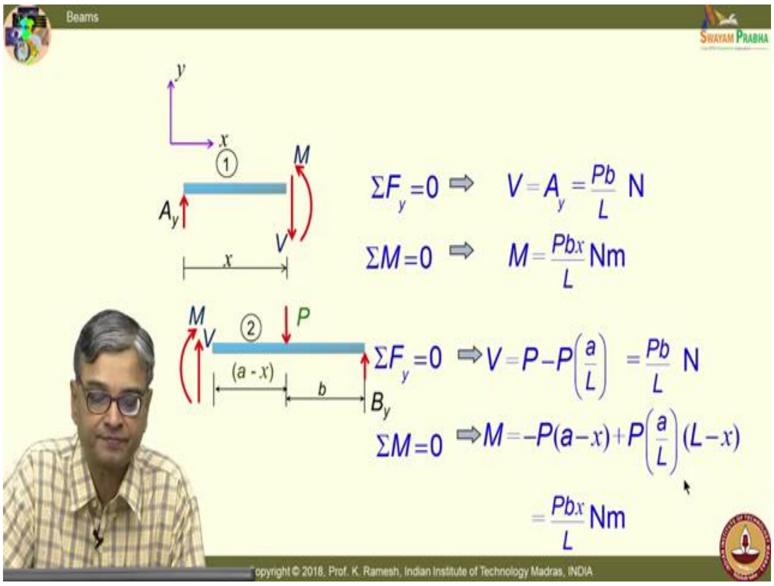
Let me revisit this again and you have to know that Meriam is the book that we have adopted for this course IIT Madras and this follows a different sign convention. We would also see that sign convention and when I cut the left portion; no problem in the moment convention, moment anticlockwise is taken as positive; clockwise is taken as negative. On a negative surface, negative direction is positive, this is how you indicate.



But for the shear force, you take exactly the opposite. You take this as positive to start with. This is the convention you have in the book by Meriam. We would also evaluate the forces based on this convention and find out what is the difference? There is no change in the moment convention for shear it is just the opposite.

Suppose, I solve the forces and it is also interesting to note it is difficult to remember because, you have the contradiction; one is positive, one is negative and higher level of studies people follow what I have shown, but since we have adopted Meriam, I should solve problems using the Meriam sign convention.

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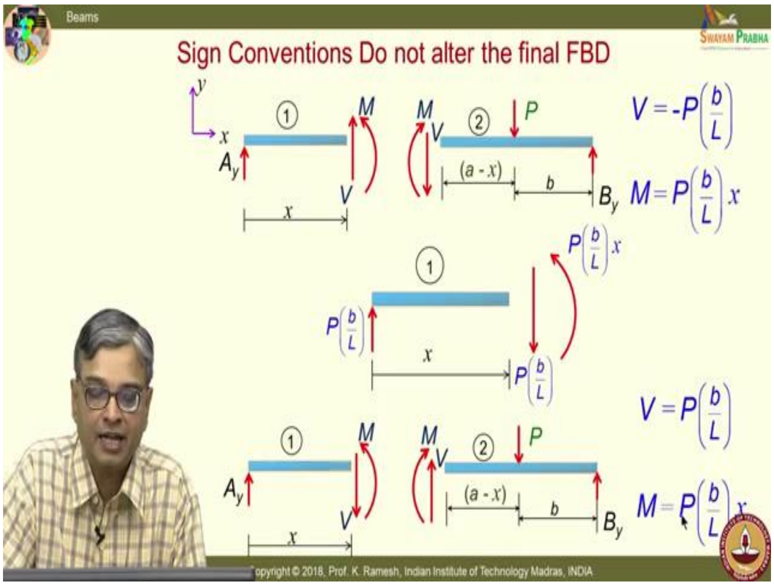
And we would also calculate the forces; we have already determined, what is A_y? A_y is I think it is *Pb/L* and I have M as *Pbx/L* and I have this; since, we have to verify whether I analyze the left portion or the right portion; I get the same answer there is no difference.



You choose which portion to do that has minimum number of mathematical steps and also visualize, what is the moment? This force gives and what is the moment this force gives. You should indicate it correctly in your equation and I get this as *Pbx / L* because I have taken the sign convention properly. I do get V and M, no matter I analyze the left one or the right one I get the same identical answer. Now, let me compare these two sign conventions for clarity.

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First, let me take the sign convention by Crandall and Dahl and I have V as minus P b by L and M as P b by L into x and if I apply this to this and indicate the final free body, how would I put the forces? Originally, I assume this is in this direction my mathematics has given the answer as negative. So, I would put it down. This is what I would put it in the final free body; *Pb / L* and this as *Pbx/L*.

Now, let us look at the sign convention by Meriam to start with in the free body we have assumed this as the direction V and what is the answer that we have got; $V = P\ b\ /\ L$. So, if I want to write the final free body, I do not have to change this direction and I have $M = P\ b\ x\ /\ L$. So, this will not change. So, the idea is no matter which sign convention you use the final free body when you correct the forces as indicated by your mathematical sign; it is identical. Free body should not change that is the idea of it. The moment you take the free body sign convention is only a via media, for you to have communication properly.

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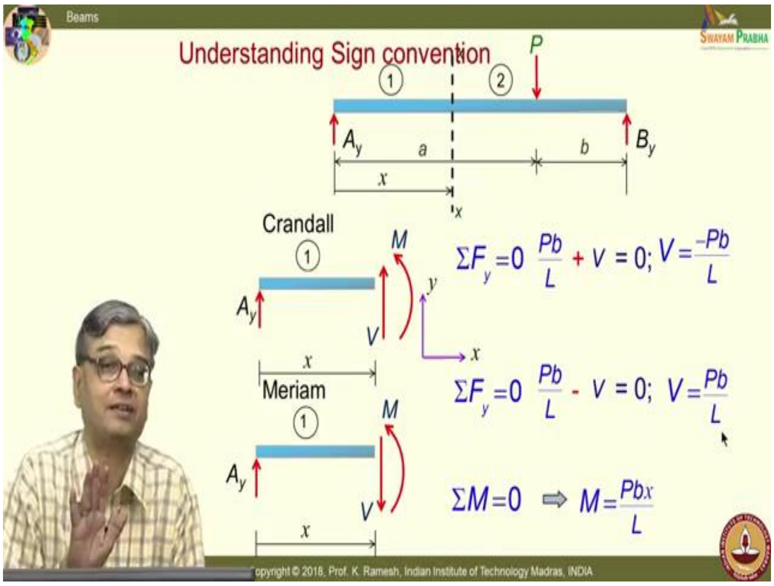

Though, the free body does not change, sign conventions do affect the plotting of shear force diagram and bending moment diagram. There would definitely be a difference, if I follow Crandall and Dahl sign convention, I would get one SFD. I will get another SFD, when I do the Meriam sign convention. But the beam experiences a same force, which you have identified that there is no two opinion about it.

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For me to draw the SFD and BMD; I have not determine the variation for the entire length I have to get it for the other section also, but before I do that we will again understand the sign convention because I want to caution you, there could be a possible confusion when you draw the free body, how do you start writing the equations. And here, I have taken the Crandall and Dahl sign convention. I put the force like this and when I write the equation, I would put it as $+V$ because this coincides with the positive direction of the coordinate axis.

And when I write the moment this is already in the positive direction. So, I am going to write this as $M = Pbx / L$. Now, let me take the Meriam sign convention; I would have the force acting downwards, when I write sigma $F_y = 0$, should I put V as positive or negative? This confusion can come. See, whatever you write here is for you to extrapolate it for your final sign convention. The moment you have indicated forces like this; when I want to solve this free body my reference point is the coordinate axis whichever is in the positive direction of the coordinate axis, put it as positive whichever is the negative direction, put it as negative.

So, you should understand this distinction clearly. So, when I write this $\sum F_y = 0$; I will have to write this as $Pb / L - V$. This would give me $V = Pb / L$. It might appear trivial, but you will get confused when you start thinking at the examination hall. It will be very crystal clear now because, you understand the subject better when, you prepare for the examination. Then you suddenly start thinking and get thoroughly confused and write the bending moment shear force topsy-turvy ok. Please, have a clarity on how we are doing it. When I isolate a body, when I want to put the forces, I follow a convention to put the forces.

Moment I put the forces, when I solve for this forces my reference point is coordinate axis. You should understand this distinction clearly.

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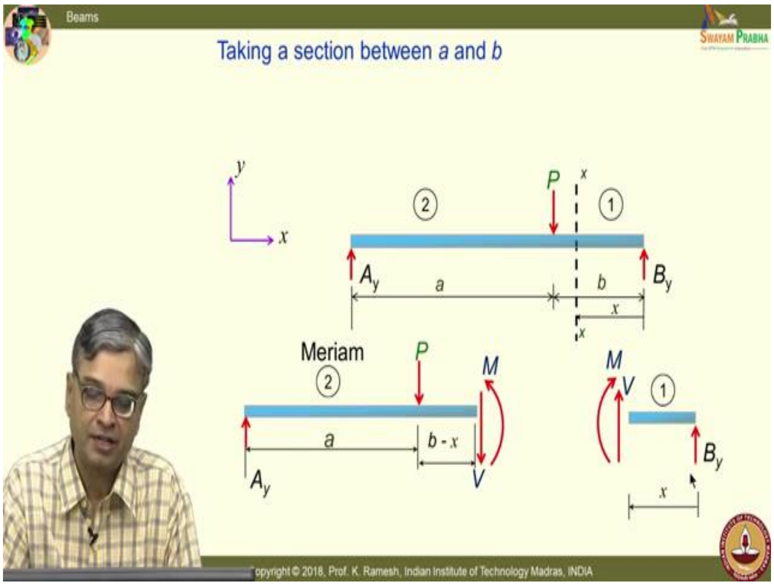
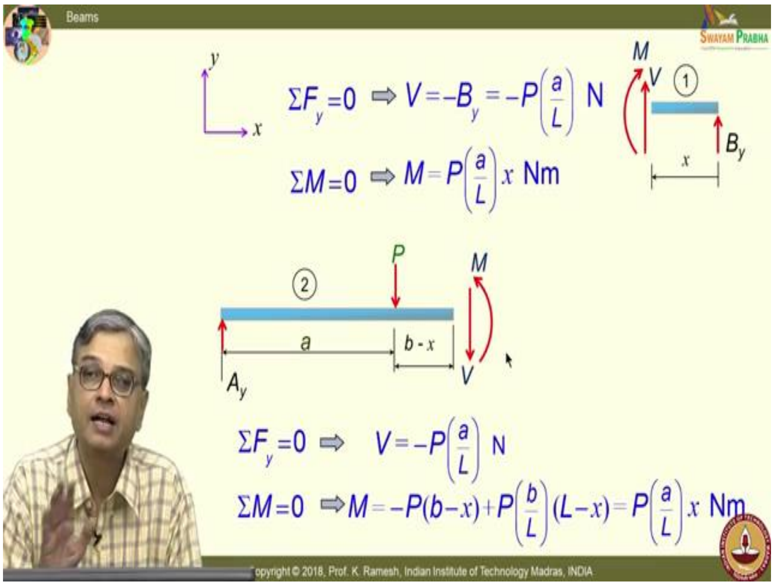
So, I said that we have not completely got the variation over the length of the beam. So, we should also find out what happens in this segment and I can separate it as two segments, segment one and segment two. Can you tell me, what is the sign convention I have put? You have to be; you have to be very clear; you have to be very clear, what is the sign convention I have put. I have put it as Meriam because on a negative surface, I think I have put it wrong did I this should be Crandall only, I should put, I think I have put this differently ok.



No, this is Meriam only. Because, Meriam on the negative surface, he will have his positive negative; these are different. So, this is a convention followed by Meriam fine. It is a convention followed by Meriam and obviously, when I have to find out the forces, if you have these two choices you would definitely choose this. The idea is depending on the problem context, I must have a flexibility to analyze a left portion or the right portion at will; that is where the sign convention helps.



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But since, we are learning it for the first time to make our self-convinced. We will get the results from analyzing segment one as well as segment two. So, that we make sure that you take the free body whether you do it by the long winding route or the shortest route the results are same.

So, when I put

$$\Sigma F_y = 0 \Rightarrow V = -B_y = -P\left(\frac{a}{L}\right) \text{ N}$$

I get the moment as

$$\Sigma M = 0 \Rightarrow M = P\left(\frac{a}{L}\right) x \text{ Nm}$$

Now let me analyze this; I would like you to put the equations. Please, write the equations and visualize whether the moment is giving you clockwise rotation or anticlockwise rotation, you associate the sign; if it is anticlockwise positive, if it is clockwise negative visualize that. You have the luxury to visualize only in the class because we develop the subject slowly you also develop the practice of visualization and write down these expressions.

I put F y equal to 0. So, I get V equal to minus P a by L Newtons and

$$\Sigma F_y = 0 \Rightarrow V = -P\left(\frac{a}{L}\right) \text{ N}$$

I write this moment I have this

$$\Sigma M = 0 \Rightarrow M = -P(b-x) + P\left(\frac{b}{L}\right)(L-x) = P\left(\frac{a}{L}\right) x \text{ Nm}$$

and if I compare this whether I use this free body or this free body I get identical answer, no problem ok.

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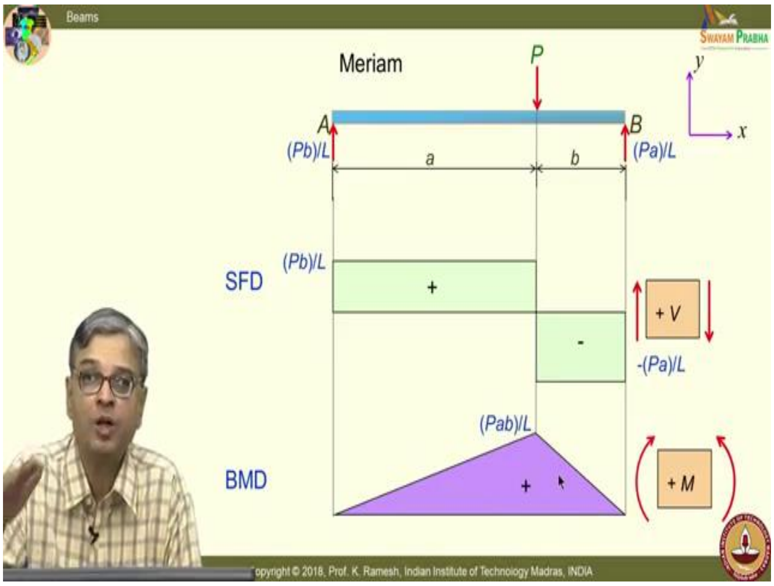
So, it is always better when you are writing the shear force diagram and bending moment diagram first indicate the sign convention; without the sign convention interpreting the shear force diagram and bending moment diagram will be difficult; if you are not trained.



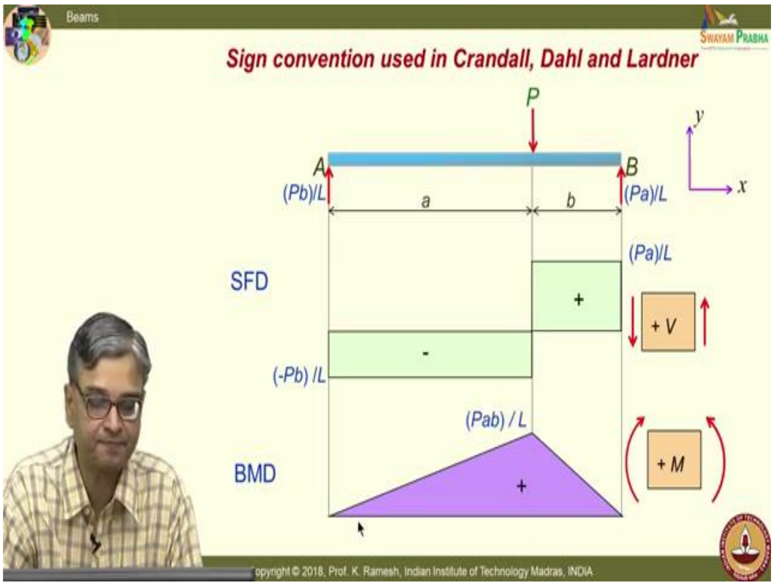
What is this sign convention? When I have a box like this, I would say that this is the positive surface and this is the negative surface. I have indicated what I would put on the positive surface, what I put in the negative surface. Similarly, I put the moment on the positive surface, I put anticlockwise as positive and clockwise as negative. So, this is the convention followed by Meriam and I also draw the shear force diagram in a particular fashion from left to right; you would see the reason a little while later.

It remains constant in this segment and it remain constant in this segment and it switches from positive to negative it crosses 0 here and you should label the key points you should label the values. And let me draw the bending moment diagram, I am drawing it from right to left. And what are the striking features you get in the bending moment diagram? If I compare the shear force diagram and the bending moment diagram. The first striking feature is when I have this as constant, I have this as a linear variation.

That is first observation; second observation is, when it crosses 0, I have the peak value here; you would see that as an extremum value. There is some kind of interrelationship between the shear force diagram and bending moment diagram, which we would formalize it as part of series of lectures on beams.

And this is one of the reasons I would always recommend you to draw the loading diagram, shear force diagram and bending moment diagram one below the other. And I have also instructed my TAs, when they correct your tutorials and also when I correct your exams, you would get 0 because that is the language you understand, when you want to learn; if you do not follow this practice. The idea is if you have made some calculations, mistakes it will be visible to you if these are not calculated properly because you can use the property of shear force diagram and bending moment diagram to verify.

See, as engineers you should be confident of what is the answer that you are reporting. Even if there is a mistake that you have done; you do not have time to identify the mistake; if you declare something has gone wrong somewhere that shows that you are thinking. I would give credits for your answer, but you will get 0, if you do not plan your answer sheet, where you do not put the loading diagram, shear force diagram and bending moment diagram one below the other; that is one aspect you should do.



Another very important aspect is you should always associate the shear force diagram with its sign convention and bending moment diagram with its sign convention. Do not put shear force diagram and bending moment diagram without any sign convention, it is meaningless.

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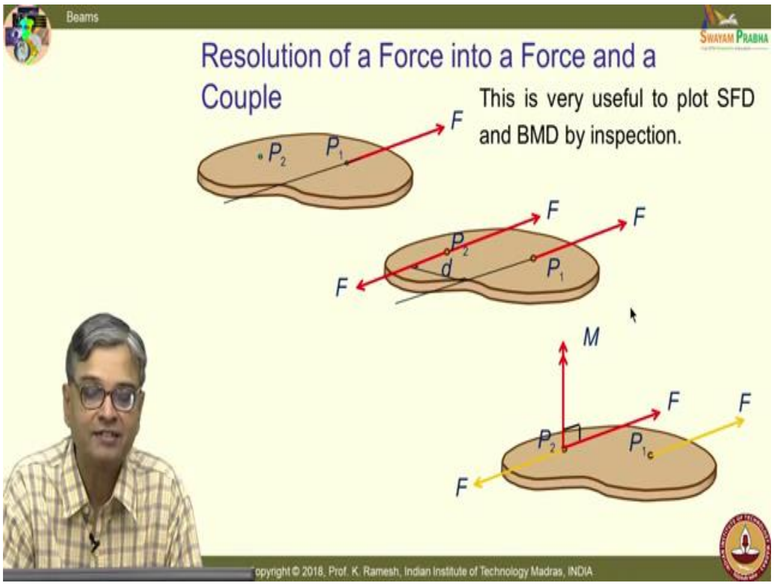
So, we go back and draw the shear force and bending moment diagram, based on Crandall, Dahl and Lardner, which could easily identify here. This is the sign convention used in Crandall and that is how it is used in higher studies very simple to remember and I could draw the shear force diagram I would deliberately draw it from right to left.

So, here you what you find is that shear force diagram is different than what you had seen in the Meriam sign convention, the sign changes. But I have already told you earlier whether in bending moment or shear force from the point of view of finding out the resistance with the cross-section sign does not really play a role, that apart when you draw the shear force variation along the length of the beam. I should get one unique answer whether I analyze left portion of the beam or right portion of the beam.

That is where your sign convention helps you to do that and your bending moment diagram will be precisely the same. See, you are learning the course for the first time, where you are learning the drawing of shear force and bending moment diagram. You should always cut an imaginary section, isolate the free body, calculate the bending moment and shear force using the free body. That is what I would recommend and you would also be given credit for it in your final answer scripts.



But nevertheless, you must also develop certain quick methods to verify at least that selected points whether your answer is correct. If you go back and see what you have done earlier in your force systems. You can extend that idea and quickly get the value of shear force and bending moment at any point of interest without drawing a free body just by inspection.

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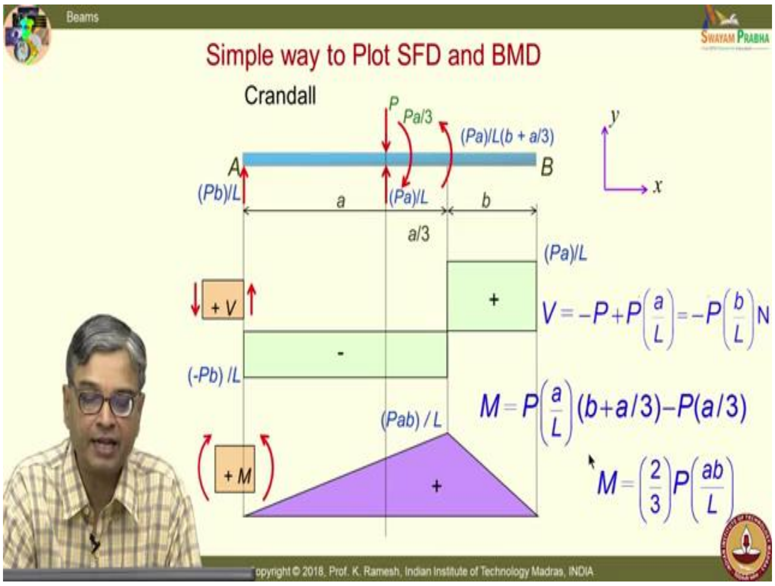
We will learn the trick now. To learn the trick, you should go back to your resolution of a force into a force and a couple. Let me revisit it again, I have a force acting at point $P1$. When we developed the concept of force, I said force is a sliding vector. Sliding vector means I can slide it along its line of action. That is what I meant it as a sliding vector. You cannot simply put this force at point $P2$ and said that you said it is a sliding vector; instead of sliding it along the line of action, I slide the vector on the left side or the right side. That is totally wrong and this is where we learn if I want to know, what is the effect of the force F acting at point $P1$ to point $P2$ I put a force parallel to this and cancel this force at point $P2$; so that I have the same external effect. So, when I put the force like this, the external effect is not altered.

Now, I would visualize this from a fresh perspective and you have the perpendicular distance as d and I have shown this as forces in yellow. So that I could visualize these two forces forming a couple. This force system is same as this force system. So, when I reduce this force system here, I would visualize what is written is red is the final one. These are like intermediate steps.



I have a force as well as a couple. What you write is shear force and bending moment? It is nothing, but effect of the force acting at some distance as force and momentum. That is what you are writing it. Let me explain it. So, this is very useful to plot SFD and BMD by inspection and this is where the sign convention of Crandall is very useful.

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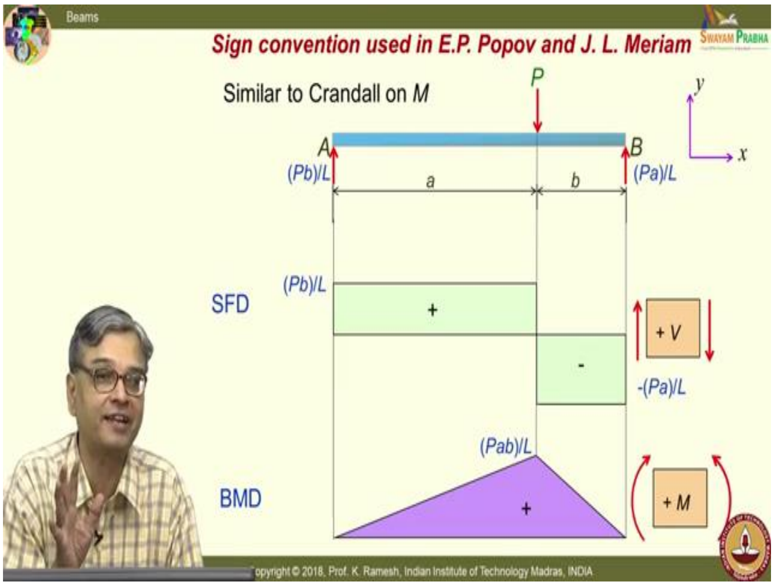
And we have already seen the shear force diagram and bending moment diagram. And I have also mentioned that I am drawing it from right to left. For example, I want to find out what is the value of shear force and bending moment at this point? Just for illustration I am analyzing the right side of the beam.

So, if I have to find out what is the shear force? It is nothing, but effect of these two forces at this point; that means, I have to translate these forces to the point of interest. When I translate these forces to the point of interest, I will have a force as well as a couple. The couple will be the bending moment at that point the force summation would give you the shear force.

You do not have to worry about the sign convention and all that. Crandall and Dahl sign convention will work without cutting the beam I can draw the shear force and bending moment. In fact, many teachers would do like that. They would just see the problem and start writing the shear force and bending moment diagram. How do they do it? You have to know the trick behind it ok.

Now, let me translate this force. So, I am translating this force, I cannot simply translate this force. I should also have a couple that is *Pa* / 3. We mind you that these are all acting at this point for clarity I have put them on this. Do not take that this is acting at a distance. These are all acting, at the selected section. So, this force has given me the couple *Pa* / 3 and this force has given me the couple *Pa* /*L* × (*b* + *a*/3). So, now I take the summation of it. I get shear force as *P b* / *L* that is what you get it here and then I get moment as (2/3) P (ab / L) which you could visualize from this.



So, I have no difficulty in finding out this, just by translating the force. So, if I move from right to left, I can keep plotting the shear force and bending moment diagram conveniently. Use this as a verification to verify your final drawing of shear force and bending moment. As far as you find out these expressions, isolate the free body, draw the forces and then, draw the shear force and bending moment diagram.

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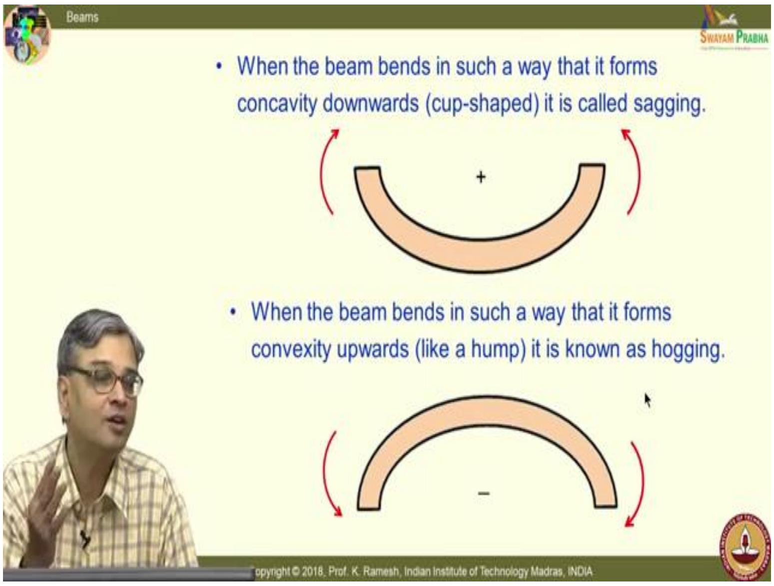
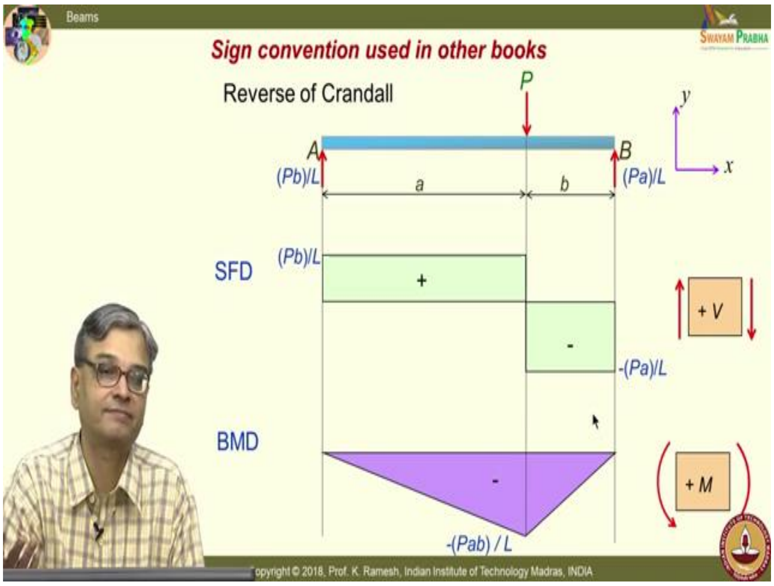
Now, we revisit the sign convention by Meriam and Meriam also has another partner. The book by Popov is a civil engineer, they share the same sign convention. And if I follow the same trick you know, you have to note down that on the bending moment the sign convention is similar to what is used by Crandall and I have drawn this from right to left and this is from left to right and from this is from right to left.



So, it is like I have Pb by L, I go up remain constant, come down and then remain constant and go up. This is how teachers draw the SFD and BMD quickly. We will not cut the section, draw the free body and get all this. You can also get that fast writings SFD and BMD, if you understand the concepts clearly and if I do the bending moment, I will do from right to left for this and you should always put the sign convention. That is very important.



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And in civil engineering, they also associate and anticlockwise moment to produce what is called sagging of the beam this is cup shaped. They call it as positive and if I have a hump, they call it as hogging. This is nothing, but this is anticlockwise bending moment, this is clockwise bending moment. Can I have one more sign convention possible? We have seen two sign conventions. The sign convention by Meriam and Popov was intermediate, I could have another sign convention, which is totally opposite to what is Crandall and Dahl.

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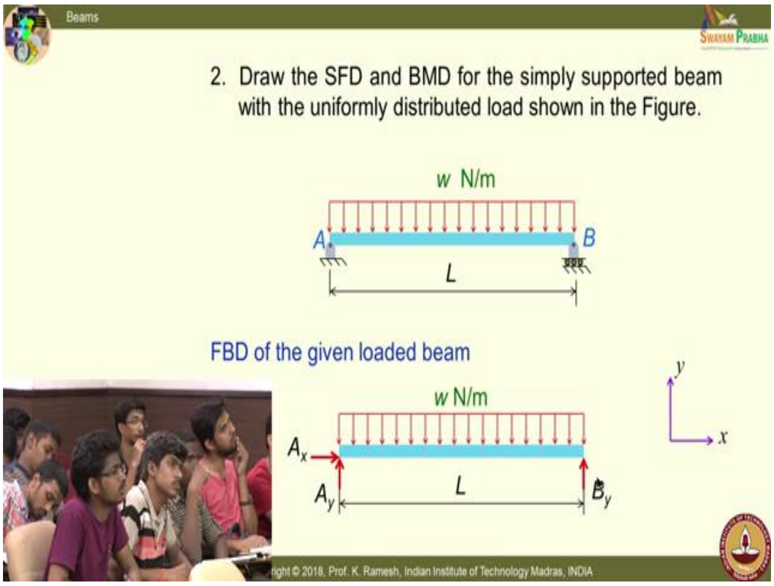
So, the third sign convention, what you can think of is I can have shear force like, what is there in Meriam? And I also change the bending moment; clockwise is positive and anticlockwise is negative and when I draw the shear force and bending moment diagram, how do they appear? They will appear differently.

See, you have to check this. These are all drawn at different points in time. Just go by this Pb by L and Pa by L. The heights are you know not strictly followed that is what I find in the diagrams, but you get this as positive and negative and you get the bending moment totally reverse. So, do not get confused if you see for the same problem different shear force and bending moment diagram. This depends on the sign convention used in a book.



After having learnt beams under me you should be able to solve any problem, from any book and interpret the sign convention appropriately. You should not have fear in handling any of those problems and what is the key? Whenever you solve a problem always put the sign convention.

You cannot come back and say you have declared in the class we are following Meriam sign convention. Because we follow Meriam sign convention, I have not indicated; no. You have to indicate a Meriam sign convention in your answers. If you do not indicate that answer you will never get that practice. That is one important aspect for you to learn and always put the bending moment and shear force diagram, below the loading diagram.

So, that if you have made any mistake there is a chance for you to reflect and go back and redo the calculation or at least mention something has gone wrong somewhere. You should be alert both doctors and engineers have to be definite in their answers they should not be ambiguous.

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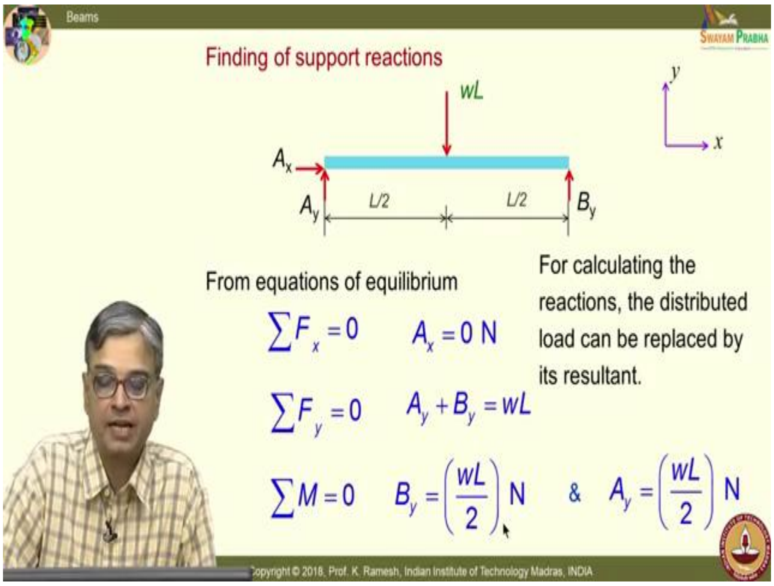
Let us take one more, simple example problem. I said it in all civil engineering constructions, you have the beam is so heavy and if I have to incorporate the way. One best way of incorporating in my analysis, used to consider that as uniformly distributed weight. And it is enough that I take one section and find out the expressions for this problem and it should again recognize that this is the pin joint and this is the roller support and in order to draw the shear force and bending moment diagram I have to first calculate the reactions. Let me not bypass any of the steps.

So, the FBD of the given loaded beam; see, I follow your discipline. I put the reference axis, I expect you to put the reference axis in your free bodies and when I put the body, I completely remove it from the supports and you have here the hinged joint. That is replaced by two forces, *A*x and *A*y, on the other side, you have a roller support, which is replaced by a single vertical force *B*y.



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Let us find out the support reactions. For calculating the reactions, the distributed load can be replaced by its resultant. So, I replace the force; it is easy for you to find out the centroid. That is at the center of the rectangle and you have the resultant force as *wL*. From equations of equilibrium, you get

$$\sum F_x = 0 \qquad A_x = 0 \text{ N}$$

$$\sum F_y = 0 \qquad A_y + B_y = wL$$

$$\sum M = 0 \quad B_y = \left(\frac{wL}{2}\right) \text{N} \quad \& \quad A_y = \left(\frac{wL}{2}\right)$$

In fact, the problem is symmetric and if you have solved many problems some of these results you could even write it by inspection.

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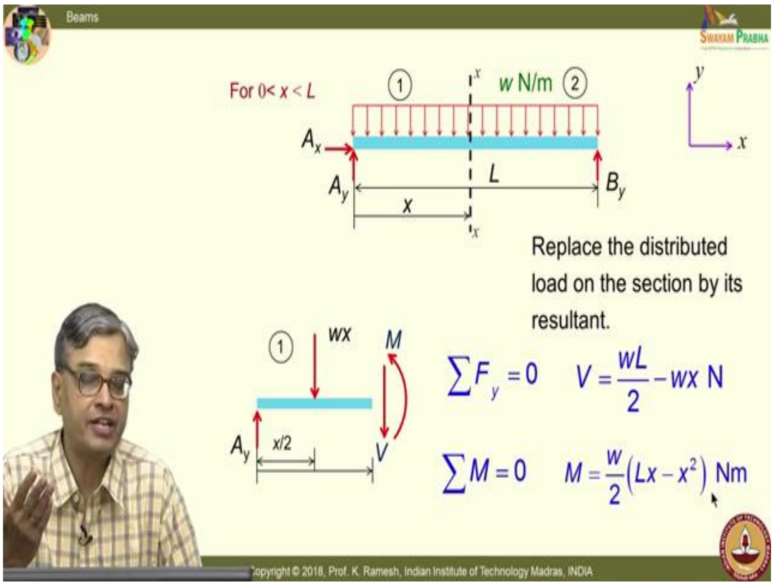
You should develop that kind of flexibility in solving a problem and suppose, I want to find out, what happens at a section of distance x from one of the ends. I take out this section and for this section, again if I have to find out the forces, I could replace this distributed force by its resultant and that is what I have done it here. And I put the unknown forces as per the sign convention of Meriam and what you will have to note down is while finding out the support reactions, we have replaced the original distributed force as a resultant force, that we have used it for finding out the support reactions.

But I cannot cut that beam, where you had one concentrated force for me to find out the variation of what is the bending moment and shear force when I cut a section at x. I have cut the section at x with distributed load and once I have drawn the free body within that free body, I replace that distributed force by its resultant *wx*. This is a settle point which will have to note and use it properly and when I do this equilibrium condition,



$$\sum F_y = 0 \quad V = \frac{wL}{2} - wx \text{ N}$$

$$\sum M = 0 \quad M = \frac{w}{2}\left(Lx - x^2\right) \text{ Nm}$$

So, you could see here, shear force is a linear variation and bending moment I get the second-degree curve. So, there is some kind of inter dependence between shear force and bending moment.

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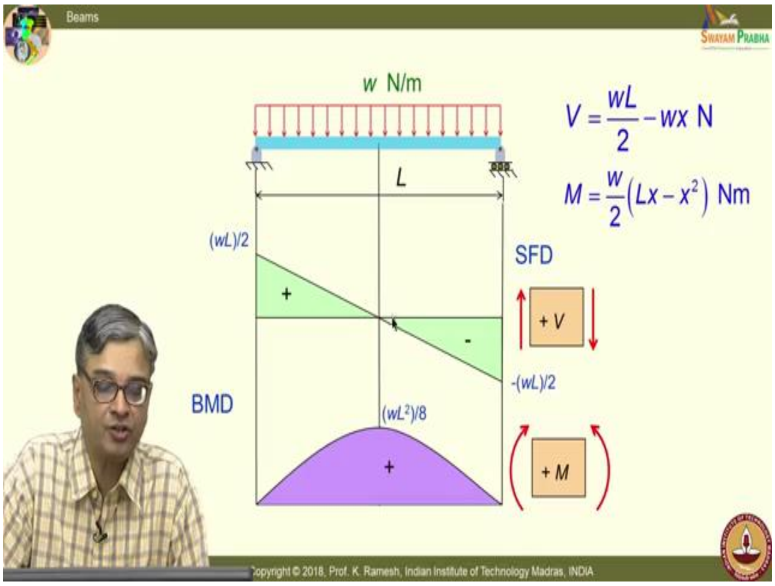

Let me go on and plot the shear force and bending moment diagram. And as I told you earlier you will have to plan your answer script in such a manner, below the loading diagram draw the shear force and below the shear force draw the bending moment diagram. And shear is varying linearly, so, I have a linear variation like this and it crosses 0 at this point.

And a sign convention is also indicated for the shear force. Then I have the bending moment. It is a second-degree curve. So, when I plot it, the variation is like this and I get the peak value as wL^2 / 8. This is the sign convention for bending moment and when I draw the line through the shear force at 0, I find that I have the maximum value of the bending moment. So, even before we develop an inter relationship between shear force and bending moment, you could gather some basic idea when shear force is varying linearly bending moment varies in a parabolic fashion and when shear crosses 0, in this case I have a maximum bending moment in general I would have extremum value.

So, in this lecture we have looked at a great length, what is a sign convention? How does the sign convention influence the free body of the isolated section of the beam? We have seen very clearly the final free body remains the same, when the forces are indicated after the mathematical calculation correctly. However, plotting of shear force diagram and bending moment diagram depends on the sign convention available. There are multiple sign conventions available and it is always a good practice, when you draw the shear force and bending moment diagram, put the sign convention side by side for the shear force diagram as well as bending moment diagram and it is also recommended that, you draw the loading diagram, shear force diagram and bending moment diagram one below the other. I said that we have adopted the book by Meriam and you cannot come back and say I have followed the Meriam sign convention. I expect you to specify the sign convention that you have adopted, for each one of your problems on bending moment and shear force.

Thank you.