Advanced Design of Steel Structures
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Lecture - 33
Critical buckling load - Numerical examples

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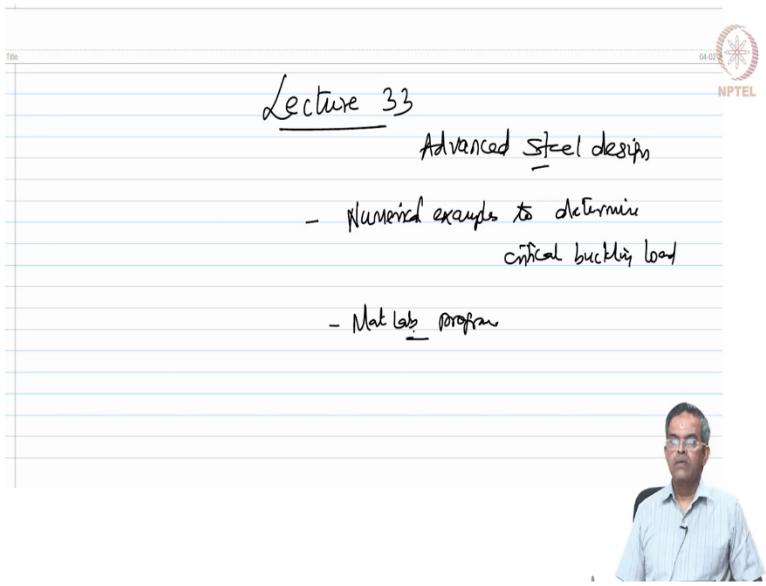

Friends, welcome to the 33rd lecture of the course Advanced Steel Design. In this lecture we are going to do some numerical examples to determine Critical Buckling load we are going to use MATLAB programs for doing this.

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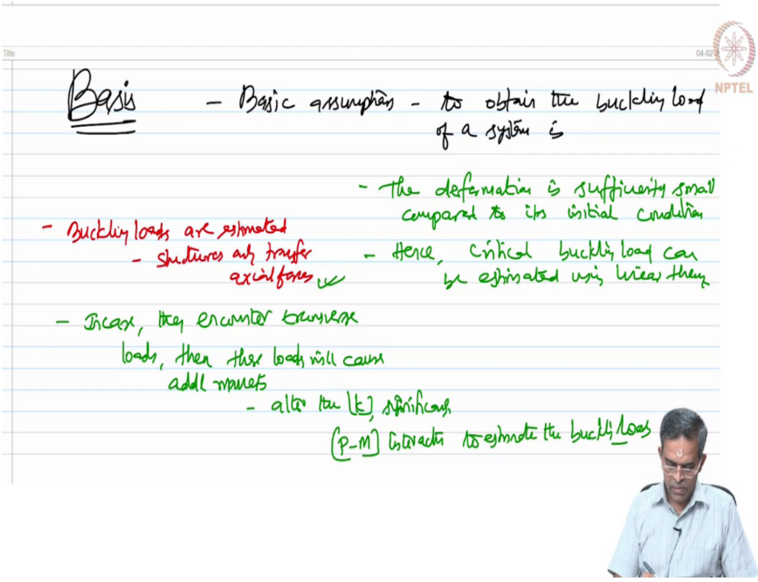

So, let us first see the basis of doing this analysis. Friends, one of the basic assumptions which we made to obtain the buckling load of a structural system is the deformation is sufficiently small compared to its initial condition that is it undergoes small deformation. And hence critical buckling load can be estimated using linear theory. Furthermore, friends it is also important that buckling loads are estimated under the assumption that structures only transfer axial forces.

In case they encounter transverse loads then these loads will cause additional moments which will alter the stiffness significantly. Therefore, in such situation one must use continuous P-M interaction curve to estimate the buckling load we must remember this. So, we are under the assumption the structure will undergo only or will encounter only axial forces.

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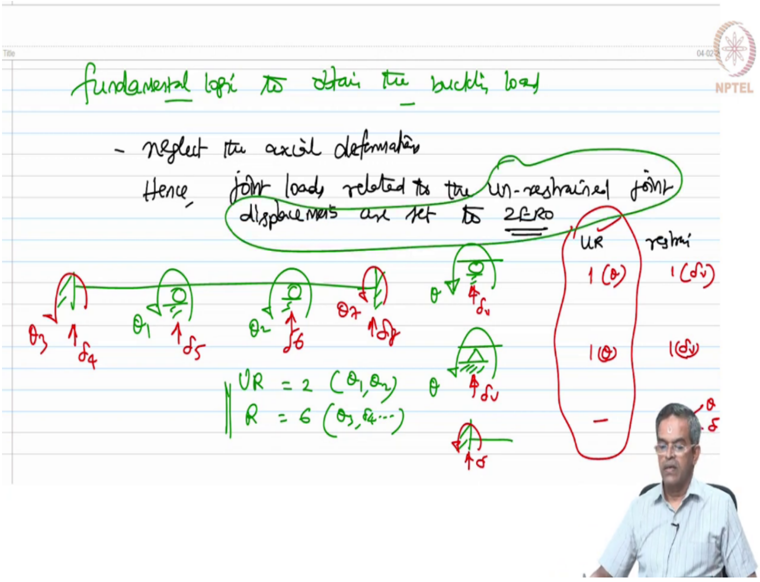

Now, let us see what the basis fundamental logic is to obtain the buckling load. Friends, we already said we are taking a basic module we are neglecting the axial deformations. Therefore, joint loads related to the unrestrained joint displacements are set to 0. You may be wondering how to identify an unrestrained joint displacement we will give some examples.

Let us say I take here three span continuous beam like this let me mark the unrestrained displacements for all the type of supports first. So, if it is a roller support, the roller can undergo rotation, but roller cannot undergo vertical displacement. So, I will make a table unrestrained and restrained let me call this as θ and this as δv. So, I showed a table unrestrained as 1 which is θ and restrained as 1 which is δ v.

If I have a hinged support this can undergo rotation, but again vertical displacement is restrained. So, one rotation unrestrained one vertical displacement restrained. If you have a fixed support rotation as well as restraints alright, so this 0 this is 2 1 is θ1 is δta. So, these are unrestrained displacements of varieties of supports learning this we can now mark the unrestrained displacements in green.

So, as θ1, θ2 and restrained degrees of freedom in red θ3, δ4, δ5, δ6, θ7 δ8 by neglecting axial deformation. I can say this beam has got unrestrained joint displacements as 2 which is θ1 and θ2 restrained displacements are 1, 2, 3, 4, 5, 6 which is θ3 δ4 and so, on. So, what we are now saying is unrestrained joint displacements are set to 0.

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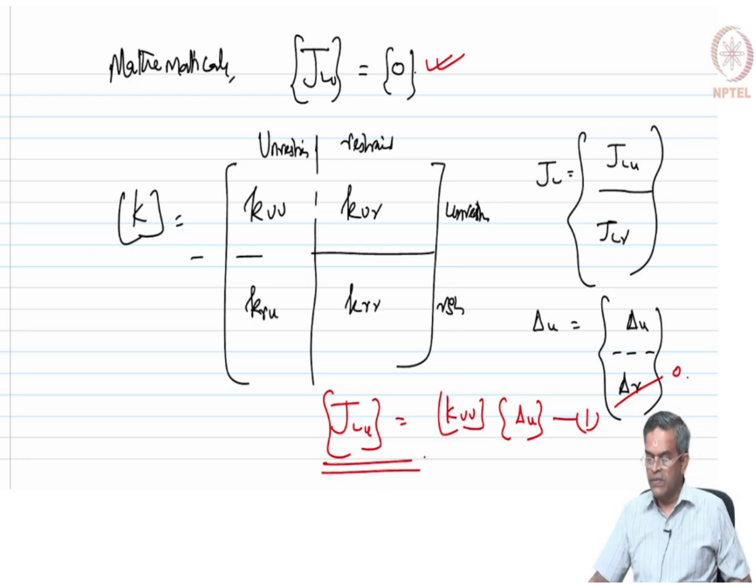

So, mathematically the joint load unrestrained should be set to 0. We know for a given matrix k if we partition this matrix as unrestrained and restrained unrestrained and restrained. So, this is k uu, this is k ur, this is k ru, this is k rr we also know the joint load can also be partitioned as J Lu and J Lr u stands for unrestrained and the displacements can also be partitioned unrestrained displacements and restrained displacements restrained displacements anyway will be equal to 0.

We have an equation now force is stiffness multiplied by displacement is it not. So, we already said this should be set to 0. So, look at this equation now.

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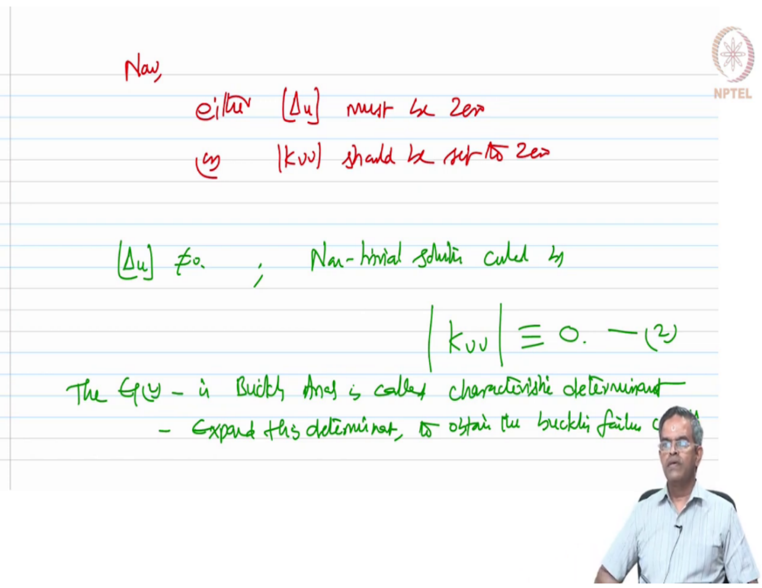

This equation left hand side is 0 which implies the fact. Now this implies a fact that either δ u must be 0 or kuu should be set to 0. Now friends you please see δ u cannot be 0 is under it undergoes displacement is it not? Because unrestrained joint displacements are not zero. So, the nontrivial solution could be determinant of this k u u matrix should be set to 0. The equation 2 in stability analysis is called not stability I will say buckling analysis is called characteristic determinant. Now when you expand the determinant to obtain the buckling failure condition.

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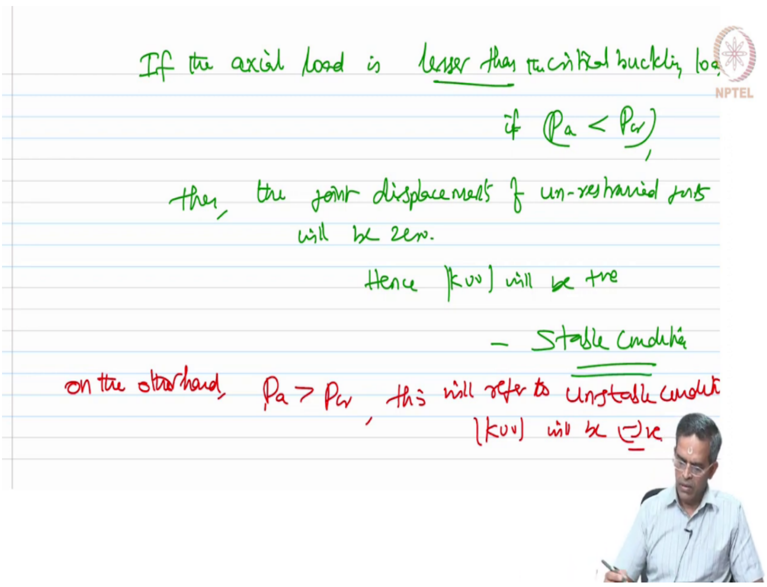

Friends, we should also remember if the axial load if the axial load is lesser than the critical buckling load that is if axial load is lesser than critical buckling load then the joint displacements of unrestrained joints will be 0. Because for buckling failure you must impose this displacement hence determinant k_{uu} will be positive which corresponds to a stable condition.

On the other hand, if the applied load exceeds buckling load critical buckling load this will refer to unstable condition because we already said buckling is a mode of consequence of instability. So, in this case k_{uu} determinant will be negative that is an important point which we have to remember.

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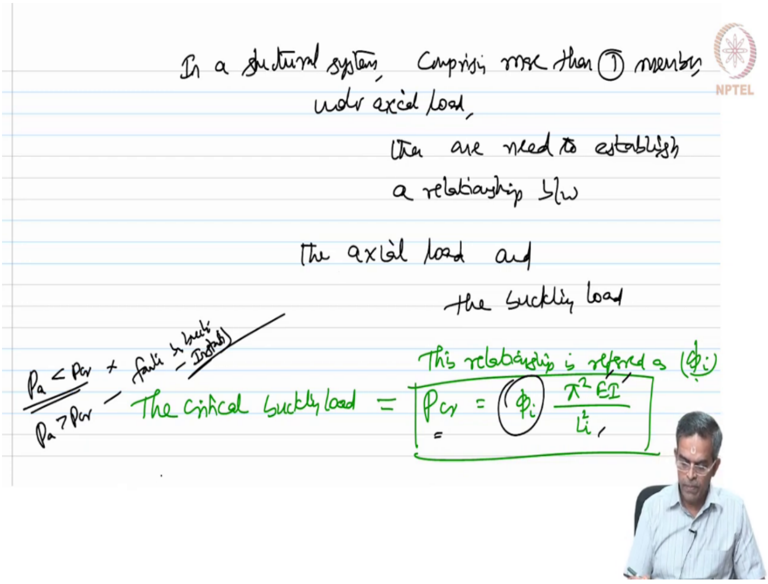

Furthermore friends, in a structural system comprising more than one member under axial load then one need to establish a relationship between the axial load and the buckling load. This relationship is referred as ϕi which we have used in the derivation. Therefore, the critical buckling load can be given by the relationship P c r is ϕi of πsquare EI by l I square.

So, if you know ϕ if you know ϕi know E I know cross sectional moment of inertia I know the length of the member I can find the critical buckling load and if P a is lesser than P c r applied load we do not have to bother if P a exceeds P c r we can say it is failing by buckling which is causing instability. So, with this background let us start doing a numerical example of estimating the critical load we will see this example 1.

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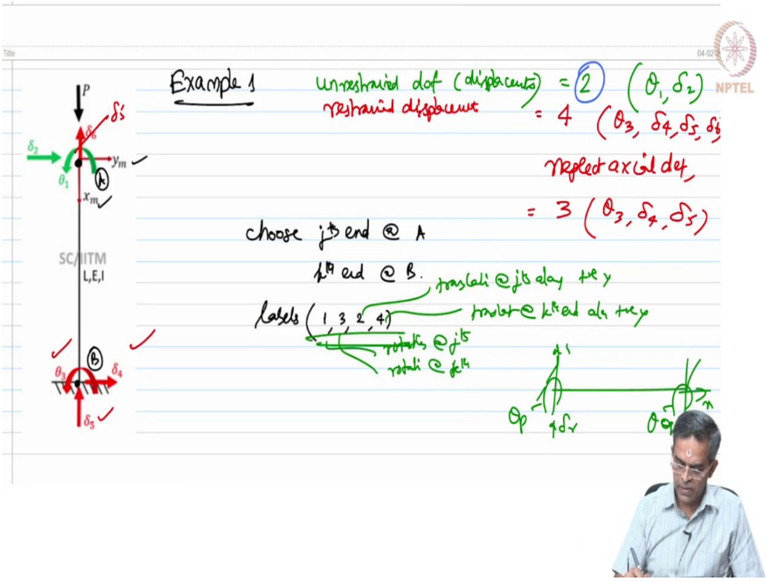

So, on the screen you see a column subjected to axial compressive load the degrees of freedom are marked. So, unrestrained degrees are marked in green that is displacements. Displacements include both rotation and translation remember that are marked in green color and restrained displacements are marked in red color. So, now we can see very well here this problem has got 2 unrestrained degrees displacements that is θ 1 and δ 2 and this has got 6 well 4 restrained degrees namely $\theta 3$ $\delta 4$, 5 and 6.

Suppose if we neglect axial deformation then restrained degree will be 3 which will be θ 3, δ 4 and δ ϕ because this will also become δ ϕ this will also become δ ϕ I am neglecting axial deformation. So, now we have chosen j th end at here which is marked as A and this is kth end which is B at A and kth end at B. So, this is my x m and y m. Now I can write the stiffness matrix for stability functions for this problem we can recollect that equation which we wrote.

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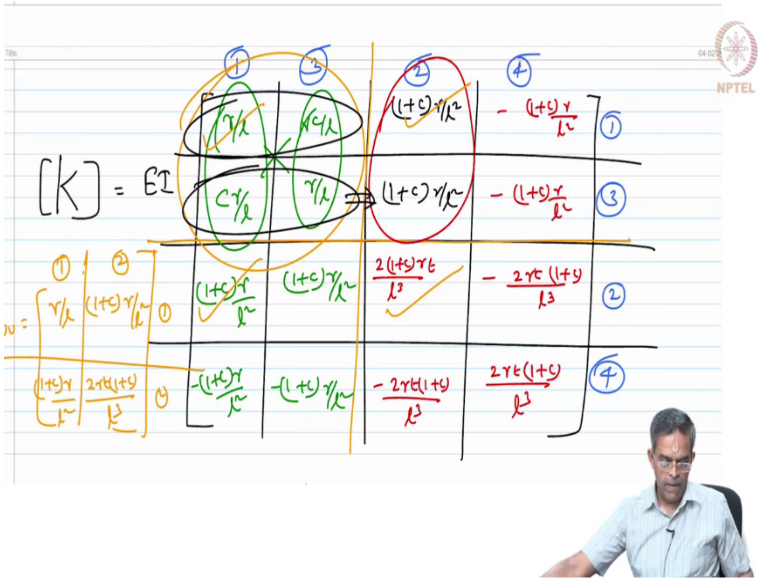

So, the stability function which will be EI times of let us mark the labels of this problem. So, rotation at j. So, label is going to be rotation at j now rotation at k then translation along positive m positive y at j translation along positive y at k. So, 1, 3, 2, 4 are the labels. How do you do that? I repeat again rotation at j th end rotation at k th end translation at j th end along positive y translation at k th end along positive y that is standard know see look at the fixed beam this is x m this is y m θ p θ q δ r and δ s is it not.

So, p corresponds to rotation at j th end q corresponds rotation at k th end r corresponds to translation at j th end along positive y and s is at the k th end, so same logic here. So, let me write down this matrix. We already know this is r by l this is C r by l this is 1 plus c of r by l is minus of this in the next column I just interchange this. So, this is r by l this is c by l and sum of these two this is r c by l.

So, 1 plus c r by l minus 1 plus c r by l and the third column sum of these two by l. So, 1 plus c r by l sum of these two 1 plus c r by l then sum of these two by l, but I have to use my l square right this is l square by l square again. So, this is l square this is l square this is l square because it is sum of these two by l is it not? Again, this is l square sum of these two by l. So, now, this value k 3 3 will be sum of these 2 read by l. So, let me write that.

So, twice of 1 plus c r by l cube and I also say t translation function is it not. So, minus 2 r t 1 plus c by l cube. Fourth column is minus of third. So, minus of 1 plus c r by l square minus of 1 plus c r by l square minus of 2 r t 1 plus c l cube 2 r t 1 plus c l cube. So, this is what my matrix is. Let me enter the labels we already marked the labels 1 3 2 4. So, 1 3 2 4now friends please note this problem has two unrestrained degrees is it not.

So, therefore, I must partition this matrix at 2 by 2 to get my kuu. So, let me partition this matrix at 2 by 2 and this becomes my k uu is it not. So, I can now write kuu as r by l, c r by l sorry 1 2 sorry. So, not partitioning I think we can pick up the first and second. So, I must pick up k 1 1 k 1 2 and then k 2 1 and k 2. So, let me write kuu as k11 k12 1 plus c r by l square then k 2 1 1 plus c r by l square then k 2 2 which is 2 times of r t 1 plus c by l cube am I right. So, I have kuu now. So, let me copy this and put it here. I have kuu.

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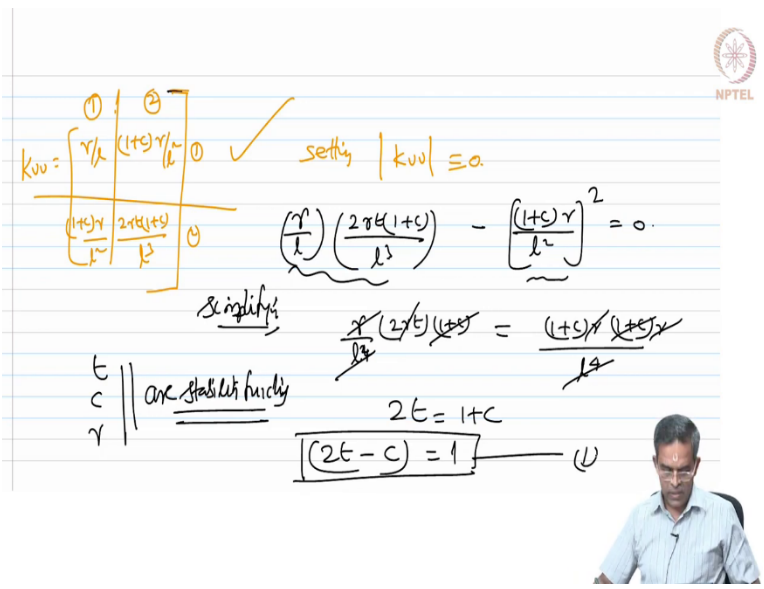

Let me that is kuu matrix as we just now discussed I must set determinant of this to 0. So, setting determinant of kuu to 0. So, if I do that. So, it is going to be r by l into 2 r t 1 plus c by l cube minus 1 plus c r by l square the whole square is it not? Should be set to 0. Simplifying you can simplify this very easily because you know l 4 l 4 here1 plus c into r 1 plus c into r here in the left-hand side. So, if I say r by l square of 2 r t 1 plus c is equal to 1 plus c into r 1 plus c into r by l 4l 4 goes away 1 plus c goes away r goes away and one more r goes away.

So, I can now say 2 t is equal to 1 plus c or 2 t minus c will be 1 this is my control equation. These are all stability functions t c and r are stability functions friends which we derived in the previous lectures under axial compression axial tension we have these values. So, the equation 1 on the screen is called characteristic equation which is 2 t minus c is 1 is called characteristic equation.

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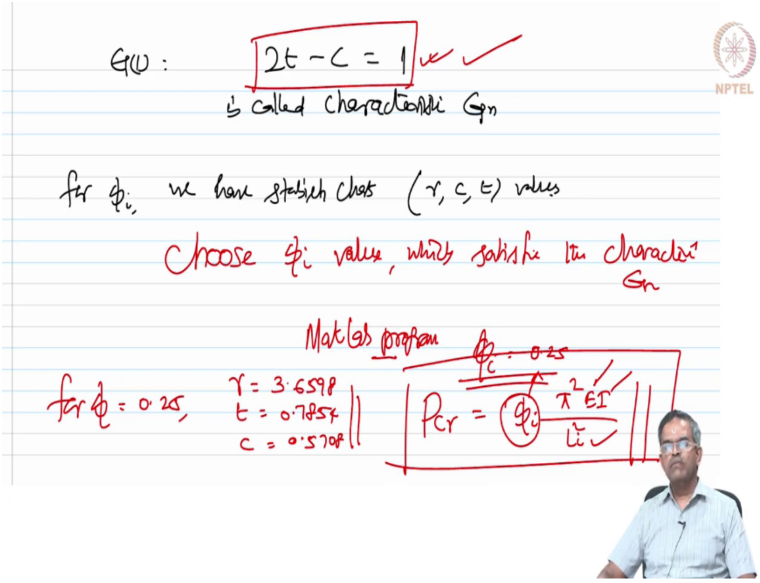

So, now, for different values of ϕi we have the stability charts is it not which indicates r, c and t values. So, what I should do I should go to the table choose ϕi value which satisfies the characteristic equation. I will show you typically how the stability chart looks like give me a minute.

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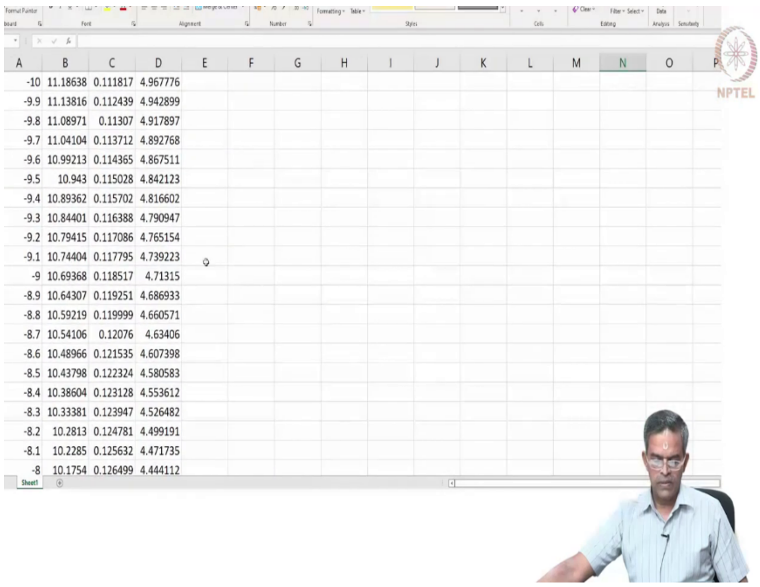

Friends, I will just enlarge this it is a typical stability chart friends for different values of ϕminus indicates tension and positive indicates compression.

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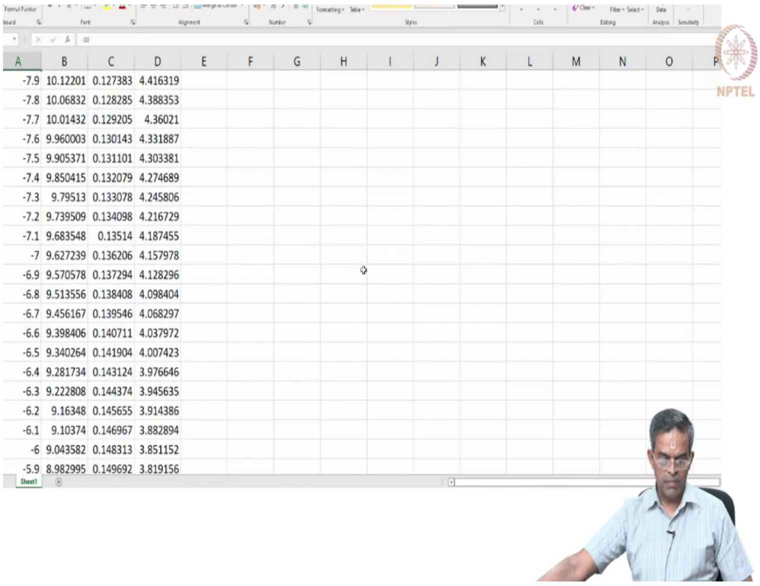

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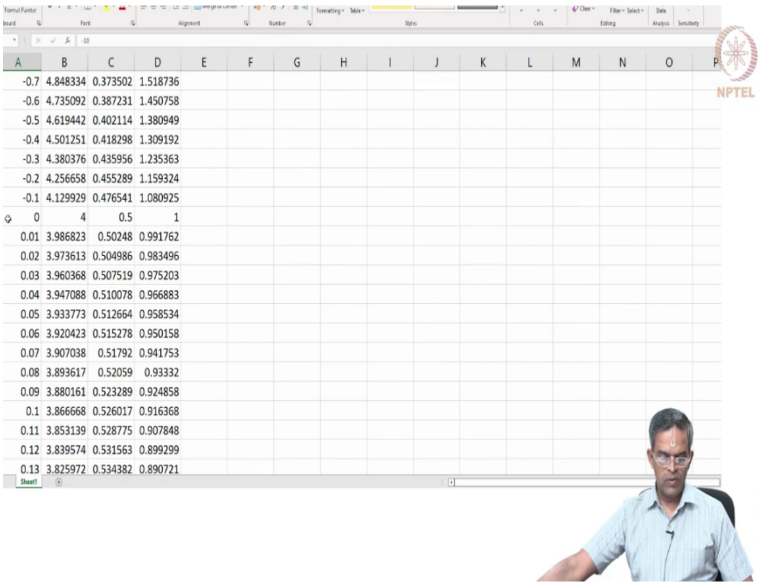

It goes to 0 the 0 value is here then it goes positive.

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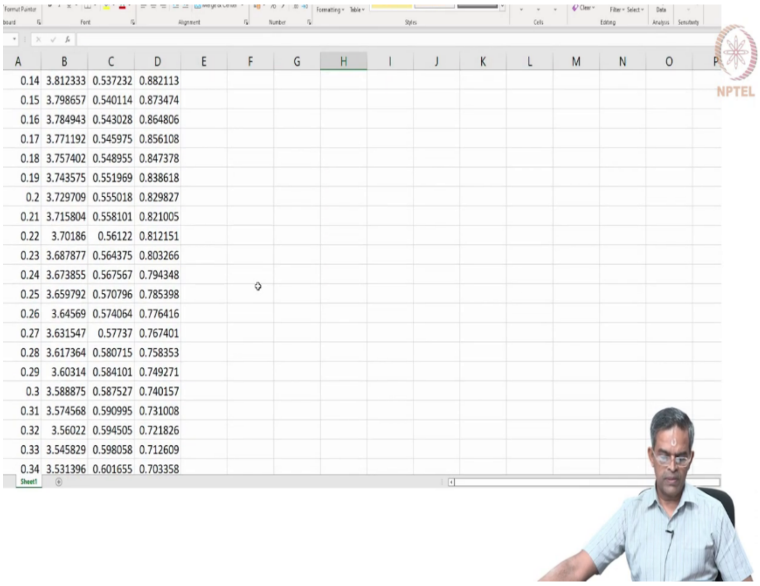

A	B	C	D
0.14	3.812333	0.537232	0.882113
0.15	3.798657	0.540114	0.873474
0.16	3.784943	0.543028	0.864806
0.17	3.771192	0.545975	0.856108
0.18	3.757402	0.548955	0.847378
0.19	3.743575	0.551969	0.838618
0.2	3.729709	0.555018	0.829827
0.21	3.715804	0.558101	0.821005
0.22	3.70186	0.56122	0.812151
0.23	3.687877	0.564375	0.803266
0.24	3.673855	0.567567	0.794348
0.25	3.659792	0.570796	0.785398
0.26	3.64569	0.574064	0.776416
0.27	3.631547	0.57737	0.767401
0.28	3.617364	0.580715	0.758353
0.29	3.60314	0.584101	0.749271
0.3	3.588875	0.587527	0.740157
0.31	3.574568	0.590995	0.731008
0.32	3.56022	0.594505	0.721826
0.33	3.545829	0.598058	0.712609
0.34	3.531396	0.601655	0.703358

So, positive compression. So, it is varying from minus 10 ϕi value to plus 4we can see that plus 4.

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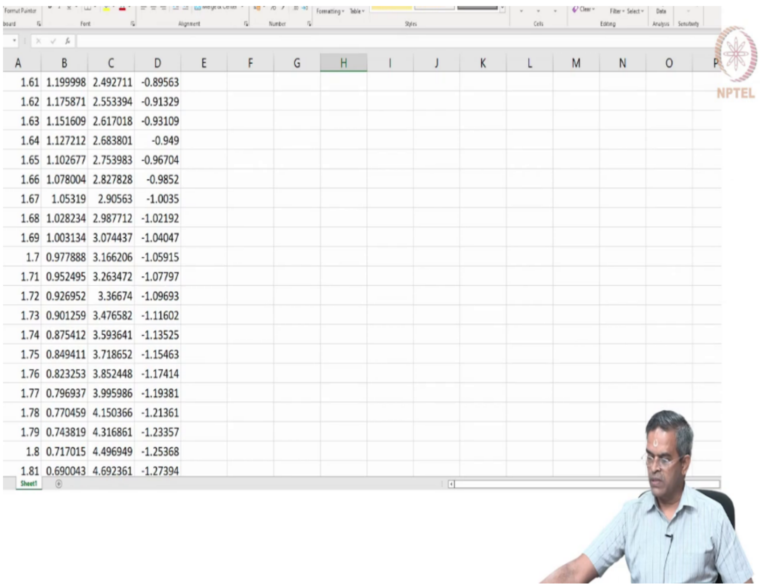

A	B	C	D
1.61	1.199998	2.492711	-0.89563
1.62	1.175871	2.553394	-0.91329
1.63	1.151609	2.617018	-0.93109
1.64	1.127212	2.683801	-0.949
1.65	1.102677	2.753983	-0.96704
1.66	1.078004	2.827828	-0.9852
1.67	1.05319	2.90563	-1.0035
1.68	1.028234	2.987712	-1.02192
1.69	1.003134	3.074437	-1.04047
1.7	0.977888	3.166206	-1.05915
1.71	0.952495	3.263472	-1.07797
1.72	0.926952	3.36674	-1.09693
1.73	0.901259	3.476582	-1.11602
1.74	0.875412	3.593641	-1.13525
1.75	0.849411	3.718652	-1.15463
1.76	0.823253	3.852448	-1.17414
1.77	0.796937	3.995986	-1.19381
1.78	0.770459	4.150366	-1.21361
1.79	0.743819	4.316861	-1.23357
1.8	0.717015	4.496949	-1.25368
1.81	0.690043	4.692361	-1.27394

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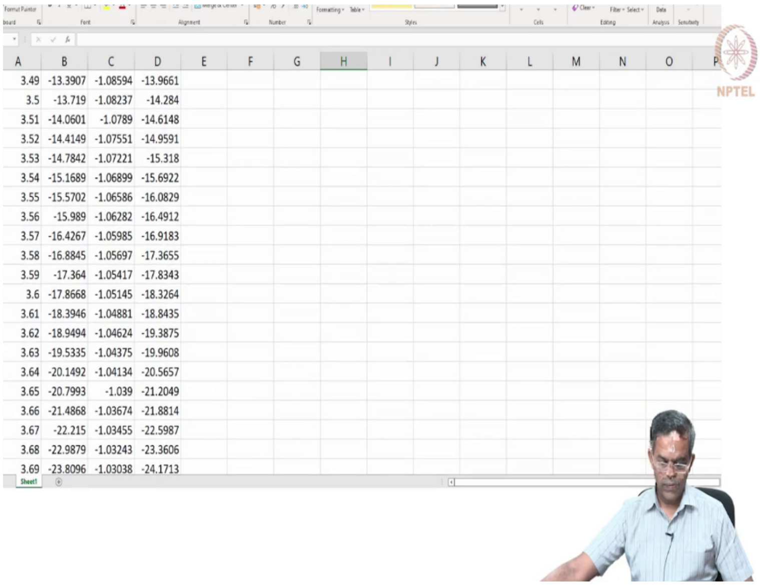

A	B	C	D
3.49	-13.3907	-1.08594	-13.9661
3.5	-13.719	-1.08237	-14.284
3.51	-14.0601	-1.0789	-14.6148
3.52	-14.4149	-1.07551	-14.9591
3.53	-14.7842	-1.07221	-15.318
3.54	-15.1689	-1.06899	-15.6922
3.55	-15.5702	-1.06586	-16.0829
3.56	-15.989	-1.06282	-16.4912
3.57	-16.4267	-1.05985	-16.9183
3.58	-16.8845	-1.05697	-17.3655
3.59	-17.364	-1.05417	-17.8343
3.6	-17.8668	-1.05145	-18.3264
3.61	-18.3946	-1.04881	-18.8435
3.62	-18.9494	-1.04624	-19.3875
3.63	-19.5335	-1.04375	-19.9608
3.64	-20.1492	-1.04134	-20.5657
3.65	-20.7993	-1.039	-21.2049
3.66	-21.4868	-1.03674	-21.8814
3.67	-22.215	-1.03455	-22.5987
3.68	-22.9879	-1.03243	-23.3606
3.69	-23.8096	-1.03038	-24.1713

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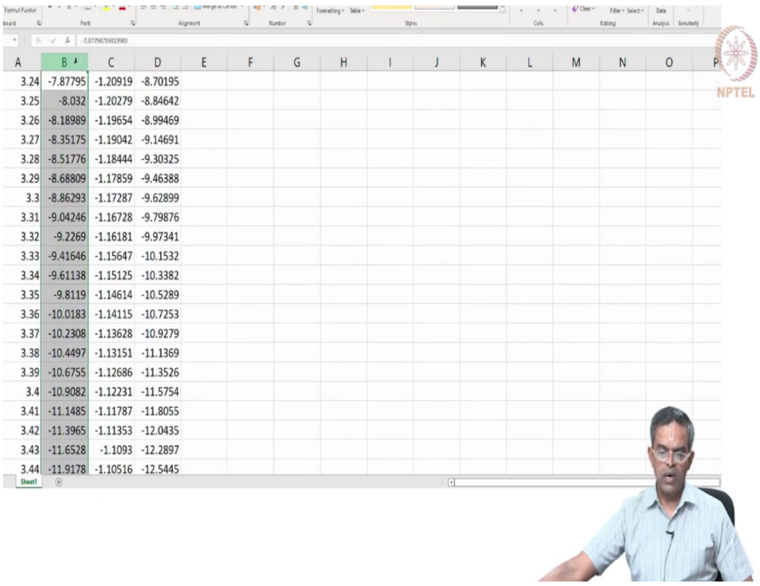

A	B	C	D
3.24	-7.87795	-1.20919	-8.70195
3.25	-8.032	-1.20279	-8.84642
3.26	-8.18989	-1.19654	-8.99469
3.27	-8.35175	-1.19042	-9.14691
3.28	-8.51776	-1.18444	-9.30325
3.29	-8.68809	-1.17859	-9.46388
3.3	-8.86293	-1.17287	-9.62899
3.31	-9.04246	-1.16728	-9.79876
3.32	-9.2269	-1.16181	-9.97341
3.33	-9.41646	-1.15647	-10.1532
3.34	-9.61138	-1.15125	-10.3382
3.35	-9.8119	-1.14614	-10.5289
3.36	-10.0183	-1.14115	-10.7253
3.37	-10.2308	-1.13628	-10.9279
3.38	-10.4497	-1.13151	-11.1369
3.39	-10.6755	-1.12686	-11.3526
3.4	-10.9082	-1.12231	-11.5754
3.41	-11.1485	-1.11787	-11.8055
3.42	-11.3965	-1.11353	-12.0435
3.43	-11.6528	-1.1093	-12.2897
3.44	-11.9178	-1.10516	-12.5445

So, the first column refers to r t and c. So, these are the values. So, what I should do for this control equation; for this control equation to be satisfied I must choose a ϕ value it is very difficult know it is very difficult to undergo and scan all entire table to satisfy this equation. So, to solve this problem we use the MATLAB program. So, I will show you. So, we are now using a MATLAB program, the program is available in the textbook referred in this course you can download the program easily MATLAB support is also extended for NPTEL students through IIT Madras link.

You can also undo a free tutorial student MATLAB program is given to you and it does not require a sophisticated laptop or an desktop to run a MATLAB software. A normal laptop should be able to run the problem what I am discussing about MATLAB has got many facilities which requires a high-end computational facility. However, the problem what I am discussing now can be run in an ordinary conventional laptop do not worry about that. So, now, I will show you the MATLAB program.

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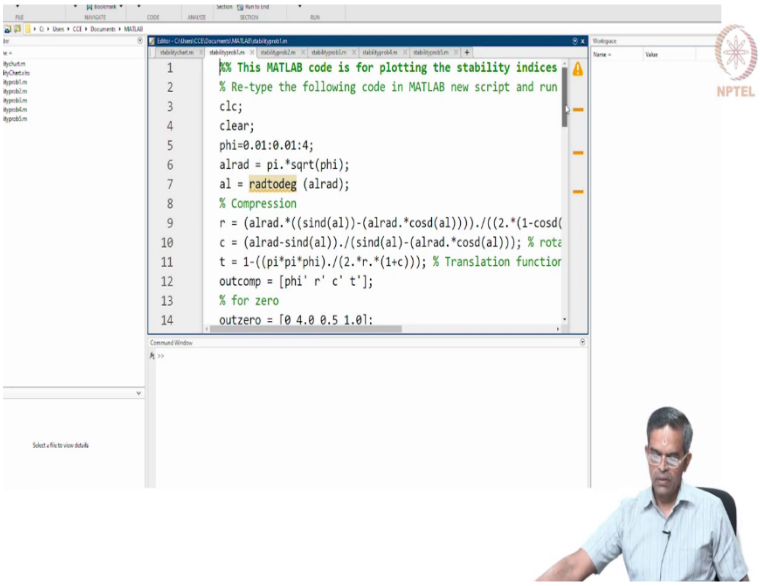

So, friends what you see on the screen is the MATLAB program.

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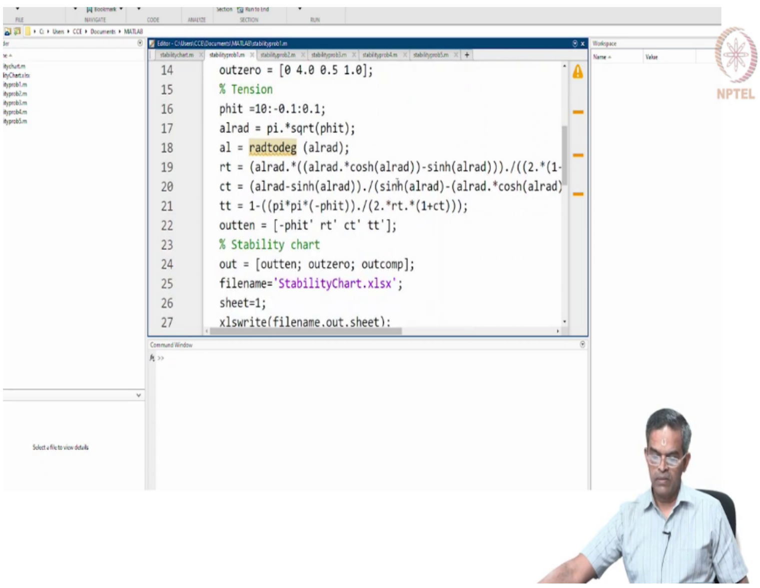

So, this is a program written for compression you can say from 0.01 to 4 we saw the value just now on the table and for tension it plots up to 10, tension is minus. There is minus right and then for 0 also we have plotted.

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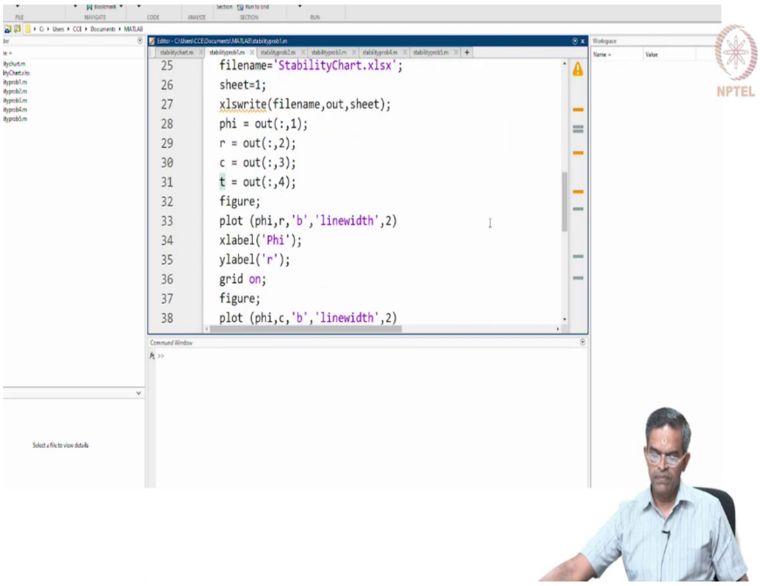

It is a program it gives you a stability functions r c and t this is an equation what we already have derived you know this. So, we can easily, and chart is also prepared.

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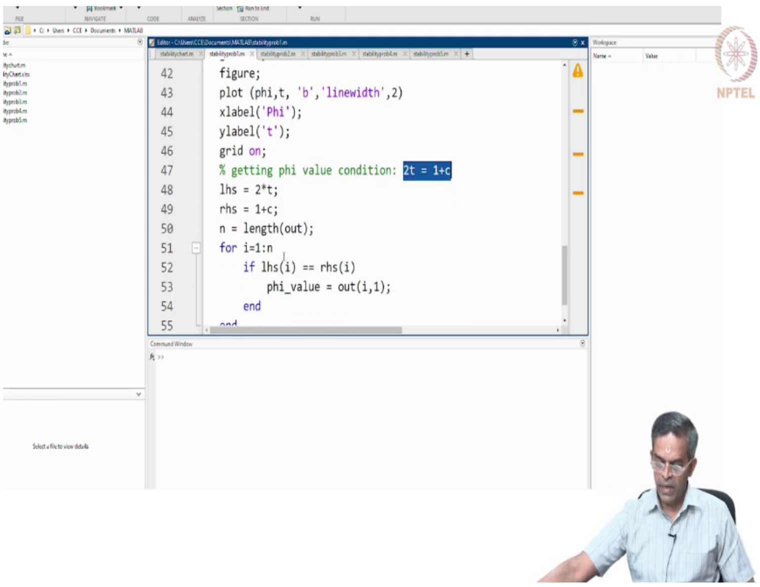

Then further friends we have a control equation which is the characteristic equation for this problem 2t minus c is 1. So, a program is written to equate and find a specific ϕ value from the output file which is generated from here.

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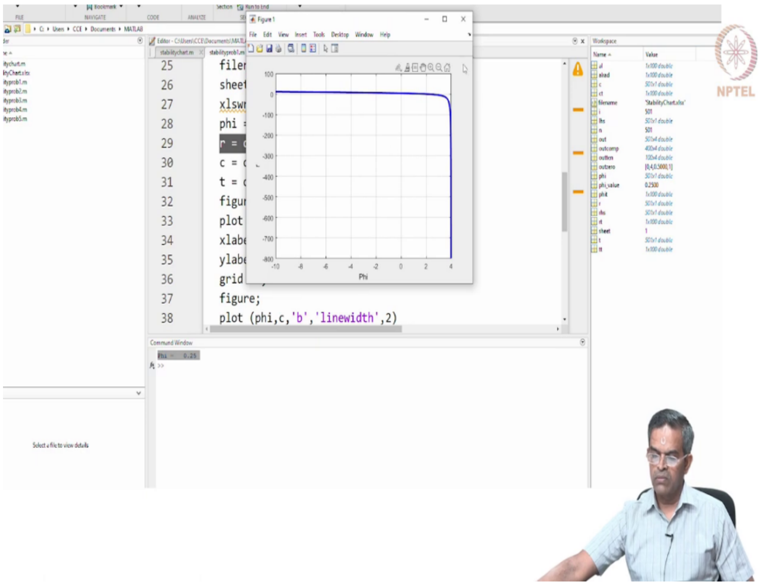

Satisfy this equation. So, this program is now run. So, it gives me the ϕ value please see on the screen 0.25, it also shows me the chart for your learning this is my r value variation, and this is my c variation with respect to ϕ and this is variation of t with respect to ϕit is a chart.

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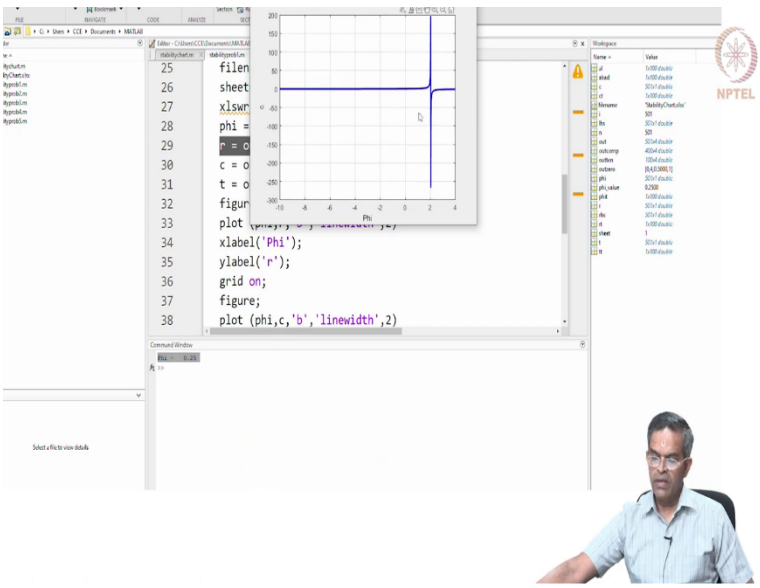

So, it gives me after searching in the table or the chart gives me a ϕ value as 0.25. So, now, I got ϕ value as 0.25 from the MATLAB. So, I will go to the screen now. So, I have got ϕ value as 0.25 now how do we get the buckling load that is the question is it not. So, now, for ϕ value of 0.25, from the chart or table you can refer r will be 3.6598, t will be 0.7854 and c is 0.5708 which satisfies the characteristic equation.

So, now, what I do, I substitute P c r as ϕ i of π square E I by L i square where ϕ is 0.25 if you know the material constant if you know the second moment of area or moment of inertia of the cross section if I know the length of the member, I can find the Euler's critical load. So, the problem is very simple stability functions help you to obtain the Euler's critical load which is going to help you to estimate the buckling load.

So, program is given, derivations are clear, application is being done and I think it is very easy for us to practice a greater number of problems is it not let us do one more problem.

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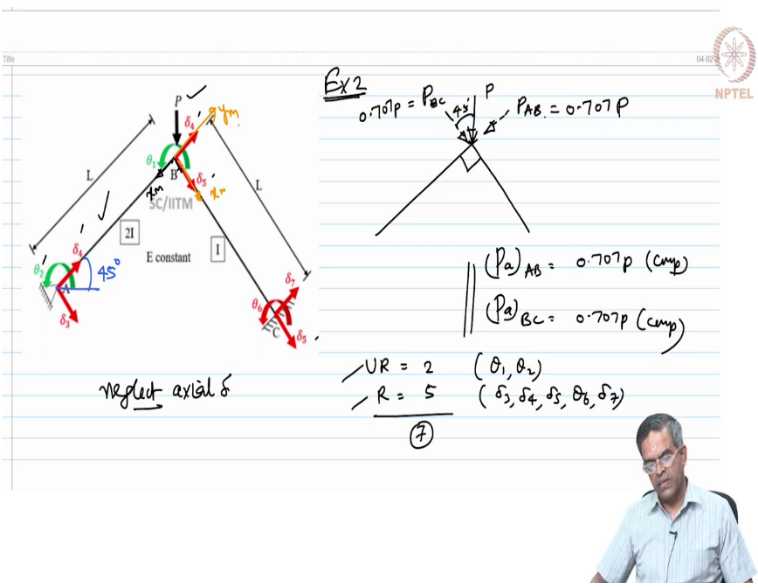

So, example 2we will do one more problem. So, this is an example 2 where one member is having 2 I other member has moment of inertia as I A B and C are the nodes. As the length of the member is same, I can interpret this angle has 45 degrees right. Now I can also find at node B; at node B if I have a load P applied here, I can find the component of this load which I am going to call as P B C and the component of this load which I am going to call as P AB or P B A as 0.707 P.

Now the angle is 45 degree right this angle is 90 and this angle is 45. So, now, I can say the axial load on the member AB is 0.707 P compressive the axial load on the member BC is 0.707 P compressive. Now, there are two members sharing this load P. So, we must carefully form the characteristic equation now let us mark the unrestrained degrees one can see here on the screen θ 1 and θ 2 are the rotations which are unrestrained remaining all are restrained and look at δ 4 same both places indicating we are neglecting axial deformation.

Similarly, δ ϕ and δ ϕ neglect axial deformation along the member BC. So, I can say this member has unrestrained degrees 2 which are θ 1 and θ 2 restrained degrees as 1 2 3 1 3 4 5 6 and 7. So, 5 which are δ 3, δ 4, δ 5, θ 6 and δ 7. So, the total kinematic degree of freedom is 7 neglecting axial deformation restrained is 5 and unrestrained is 2as usual I must now derive the stiffness matrix using rotational stability functions for the member AB and for the member BC.

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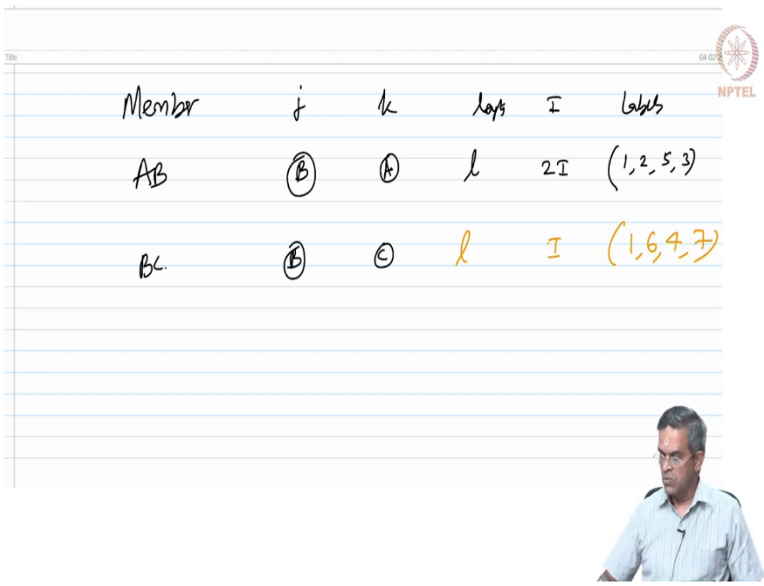

So, for the member AB I will make a table for the member j and k and l I and labels. Let us say for the member AB I am going to say the jth end is at B and kth end is at A. So, that is here. So, this is my x m and this is my y m for the member AB length of the member AB is l and moment of inertia is 2 I is it not let me mark the labels for the member AB. So, rotation at j rotation at k displacement along positive y at j and at k is it not. So, rotation is 1 rotation is then 2 then 5 and 3. So, the label should be strictly speaking 1, 2, 5 and 3. So, let us say the labels are 1, 2, 5 and 3.

Now, for the member BC for the member BC we will take the j th end at B and this at C. So, the j th end is here. So, this becomes my x m and y m for the member BC the labels are going to be 1, 6, 4 and 7 is it not. So, labels are 1, 64 and 7 right the length of the member is again l, but the moment of inertia is only I. So, I do not think there is any confusion for you people to write this table. Once this table is done let us now write the matrix for the member AB and the matrix for the member BC4 by 4.

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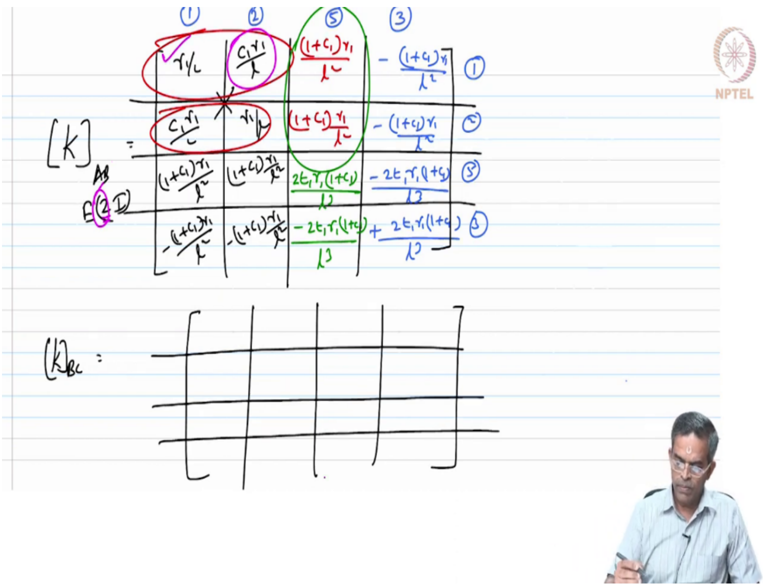

So, E into 2 I for the member AB right. So, I should say it is r 1 by l, c 1 r 1 by l, 1 plus c 1 of r 1 by l square minus 1 plus c 1 r 1 by l square. So, then I cross this is c 1 r 1 by l, this is r 1 by l, this is 1 plus c 1 of r 1 by l, 1 plus c 1 of r 1 by l. Then we add these two and divide by l. So, 1 plus c 1 r 1 by l square, 1 plus c 1 r 1 by l square that is adding these two by l then adding these two by l, but t along with that.

So, that is going to be 2 t 1 r 1 1 plus c 1 by l cube right minus 2 t 1 r 1, 1 plus c 1 by l cube the fourth column is negative of 3. So, minus of 1 plus c 1 r 1 by l square minus of 1 plus c 1 r 1 by l square minus of 2 t 1 r 1 1 plus c 1 by l cube plus of 2 t 1 r 1 1 plus c 1 by l cube right. Let us mark the labels for the member AB is 1, 2, 5, 31, 2, 5 and 3 similarly here 1, 2, 5 and 3.

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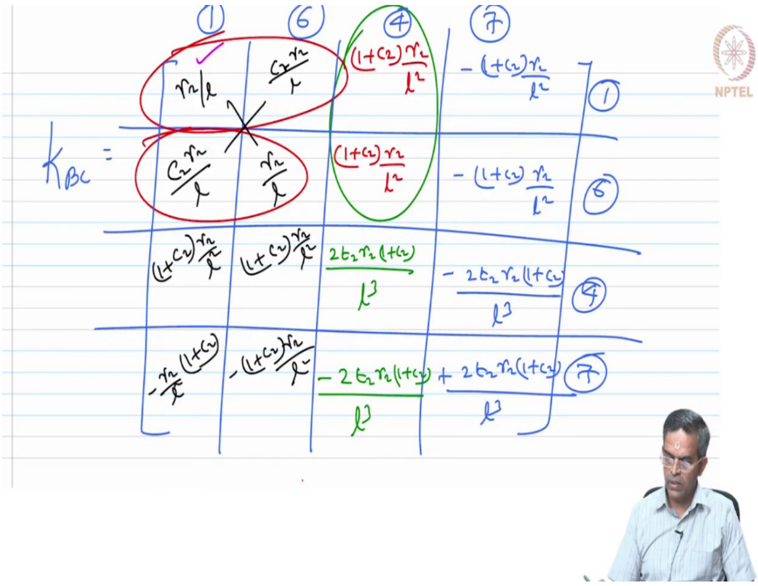

Then for the member BC let me do it to the next page. k BC r 2 by l 2 l that is the length of the member c 2 r 2 by l 1 plus c 2 r 2 by l minus 1 plus c then it is crossed, so c 2 r 2 by l r 2 by l 1 plus c 2 r 2 by l minus of. Then sum of these two by l this is l square right there will be l square here the previous case also l square that is right. It l square here then sum of these two by l then sum of these two by l again. So, 2 t 2 r 2 1 plus c 2 by l cube minus of 2 t 2 r 2 1 plus c 2 by l cube the fourth column is minus of this. We also know the labels of this is 1, 6, 4, 7. So, let us enter the labels 1, 6, 4, 7.

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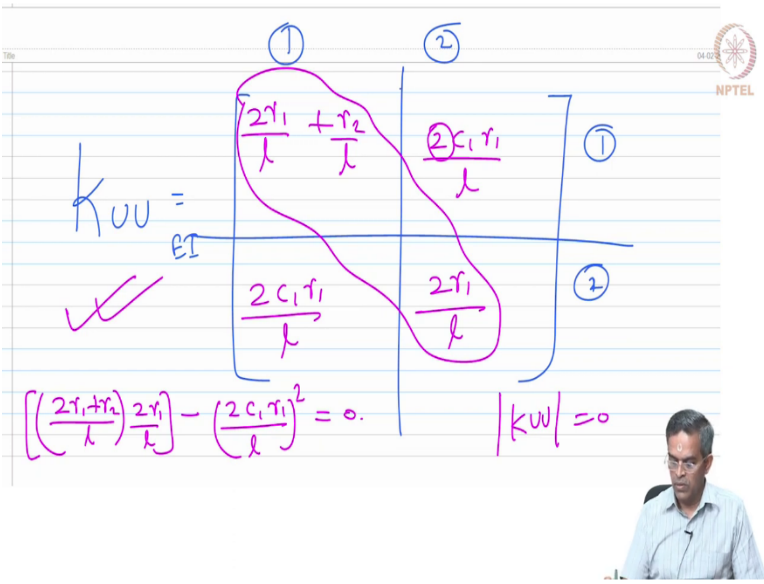

Now, friends, let us form k uu. Let us form k uu how many unrestrained degrees are there? We have got two unrestrained degrees in this problem see here 1 and 2. So, I must get E I common 1 and 2. So, I must find k 1 1. Let us look at this k 1 1 is this I am just indicating with maybe the pink color k 1 1 is this from here. So, k 1 1plus the other one is k 1. So, now, please note there is a two multiplier here. So, 2 r 1 by l 1 2 r 1 by l l 1 and is same. So, then for the second member it is r 2 by l then let us go to 1 2 from here 1 2 is this value.

So, 2 c 1 r 1 by l right 2 c 1 r 1 by l why this 2 has come? This 2 has come because of this 2 has come because of this. Now, I must get 2 1 go here 2 1 is this value. So, 2 c 1 r 1 by l correct then let us go to 2 2. 2 2 is this value we also have 2 2 here, we also have 2 2 here no we do not have it only this. So, 2 2s r 1 by l there is a 2 here. So, I should say 2 r 1 by l friends we have got kuu matrix now.

Now, I must set this determinant of k uu to 0. So, this diagonal multiply minus this diagonal and set it to 0. So, I should say 2 r 1 plus r 2 by l into 2 r 1 by l minus 2 c 1 r 1 by l the whole square should be 0 am I right.

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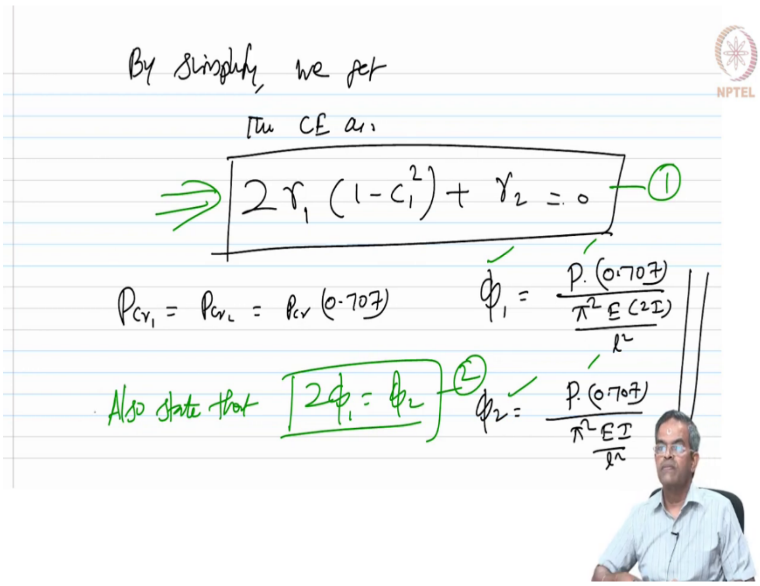

This is what I must get set it to 0 when I set this to 0 and expand and simplify we get the characteristic equation as 2 r 1 of 1 minus c 1 square plus r 2 is u this my characteristic equation. Further, we know P c r 1 is P c r 2 which is P c r of 0.707 is it not? Well, that is the load which is being applied therefore, friends we have 1 more relationship ϕ 1 will be P times of 0.707 π square E to I by l square ϕ 2 will be P of 0.707 by π square E I by l square.

So, comparing these two equations we can now also say 2 ϕ 1 is ϕ 2 you can see easily from here2 ϕ 1 will be 5 2 right. So, I have to satisfy two equations while selecting ϕ. So, I must find ϕ 1 and ϕ 2 because ϕ 1 and ϕ 2 will be helpful to get P and the characteristics equation should be satisfied. So, I can refer to the chart or the table and try to get.

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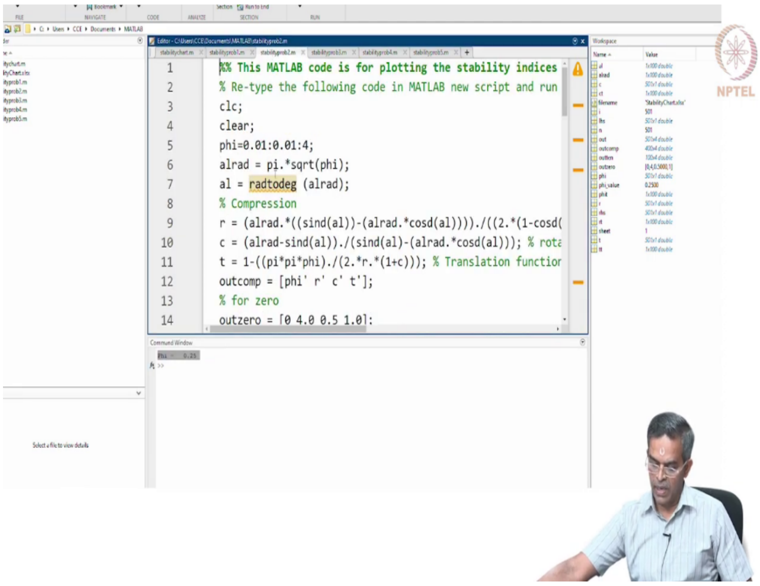

So, I am going to use MATLAB again, so using MATLAB.

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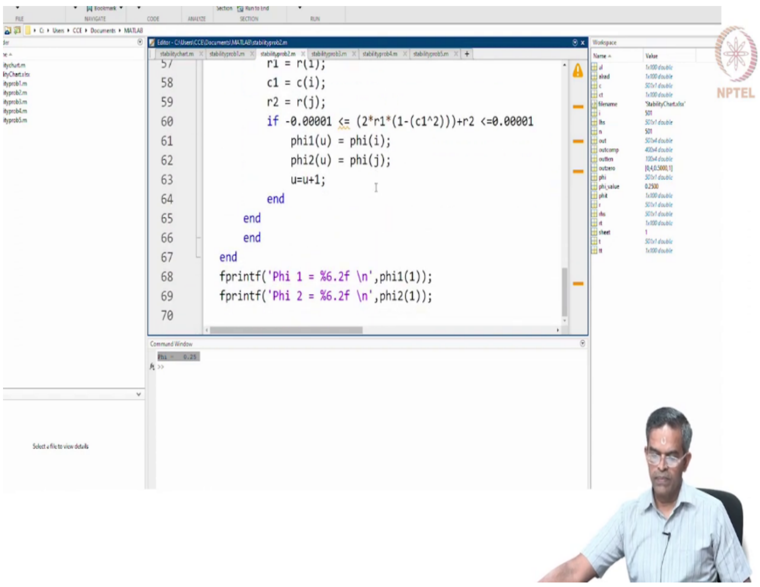

So, again the same plot, but I am going to show you the control equation.

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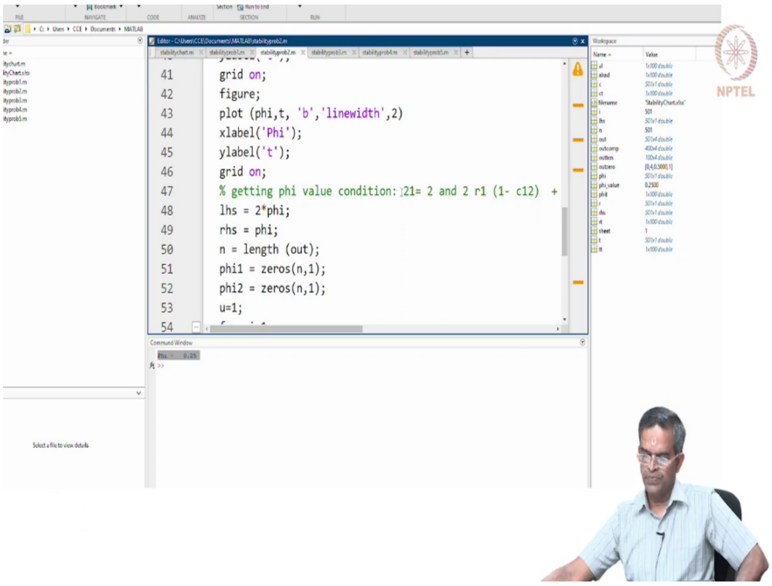

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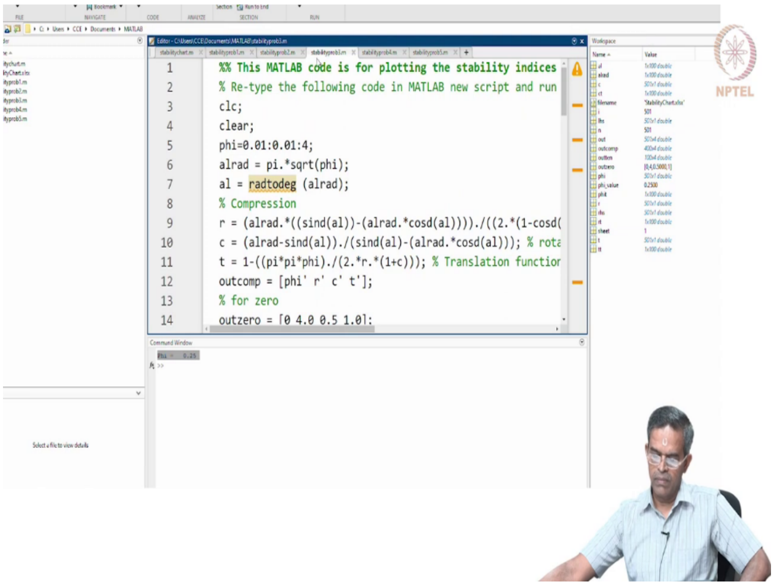

The control equation what we had is 2 r 1 1 minus e 1 square plus r 2 is 0 is it not this is the control equation here.

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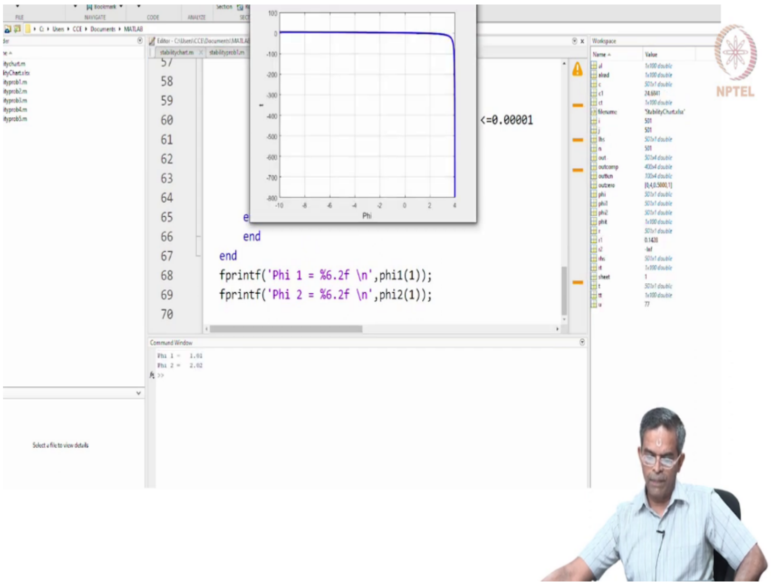

So, we have developed this control equation apply this and wrote an algorithm and then we run this program. So, forget about these plots, we get ϕ 1 as 1.01 and ϕ 2 as 2.02. So, I will write it here I will close this minimize this, these are charts being plotted I will minimize this.

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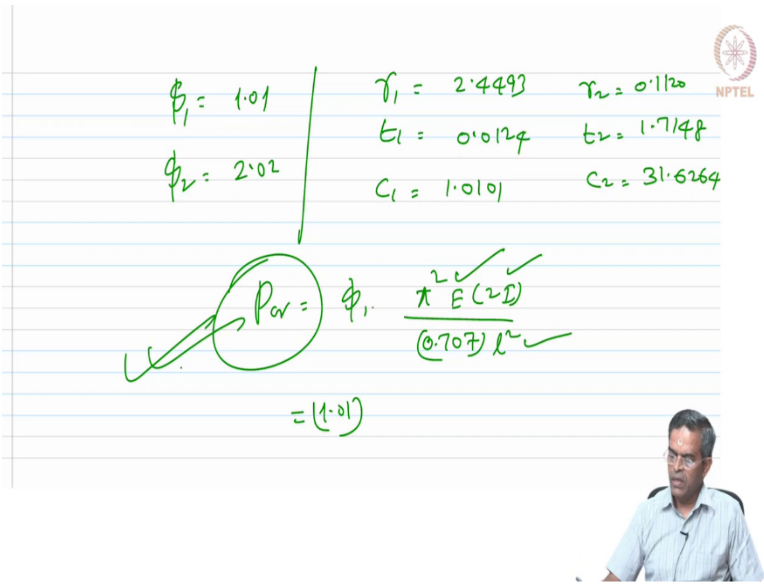

So, now I can write ϕ 1 is 1.01 and ϕ 2 is 2.02 for these values we got r 1 as 2.4493, t 1 as 0.0124 and c 1 as 1.0101 and r 2 as 0.1120, t 2 as 1.7148 and c 2 as 31.6264. So, now I have got p critical is ϕ 1 times of π square E of 2 I by 0.707 of l square. So, ϕ 1 I already have, which is 1.01. So, if you know E if you know I if you know l I can find.

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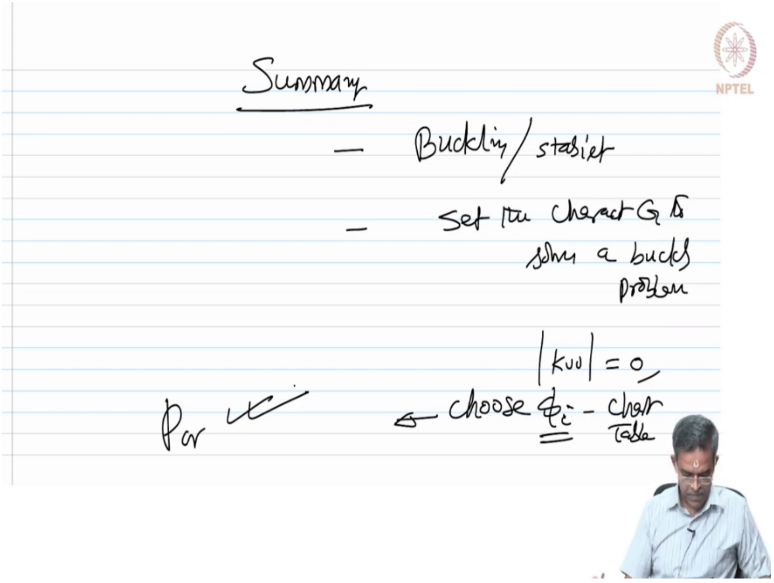

So, friends in this lecture we learnt the difference between buckling and stability analysis. We also learnt how to set the characteristic equation to solve a buckling problem for a frame subject to axial loads. So, we said that set the k uu determinant to 0 for non-trivial solution and try to get the control equation and then choose the ϕ values from the chart or the table and try to find the ϕ.

Once I know the ϕ value I can find p critical. So, I wish you should do more examples to solve more problems and try to learn more about this. So, friends stability analysis is not difficult it is easy please practice more problems and use the MATLAB program given.

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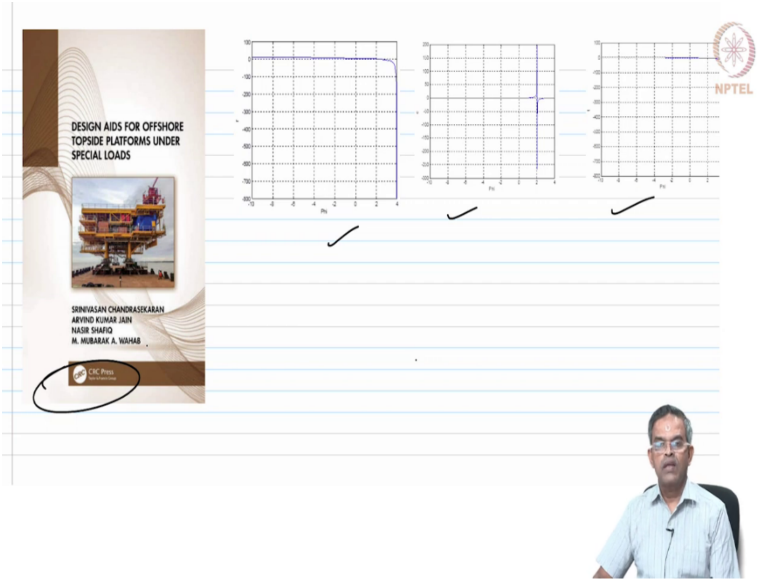

And also this book will be very helpful for you which is being used as a reference. So, please refer to this book Design Aids for Offshore Structures Topside Platforms under Special Loads which has got the stability charts and the table and also the MATLAB program. This is a CRC press release this book is available in public domain please access to this book through your institute library subscribe this to a library recommend this to your resource scholars and friends and faculty colleagues and I hope you will find an extremely useful contributions from this book for your additional learning on this course.

Thank you very much and have a good day bye.