Aircraft Structures - I

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Module – 1
Lecture – 1
Introduction

Welcome to aircraft structures one course. Myself professor Anup Ghosh from the aerospace engineering department of IIT Kharagpur. This is the first lecture in that series to introduce with you the aircraft structures, better we look into some video. **(Video Starts: 00:46)** video options like this though it may not look good to bring the detail of aircraft structure at the first slide, but this is the other way I feel better because it gives us the insight of the structure.

In a general sense, if we talk about structures, this is an assembly of elements which has load externally applied loads or and a self-load of weight also or the weight which it is having on its own. This particular example if we look at, this example is actually a double-decker aircraft fuselage cross-section. This may not match exactly with any commercial aircraft, but these aircraft fuselage section has been created in CAD software and it is created to give a better feeling before we start the aircraft structures course.

If you look at it, the most predominant thing is that the structure is no way solid in nature. This is build up thin sections and there are two decks. Below portion, if you look at, this portion where generally cargo goods those things are placed. This portion and as well as this portion if you look at, this and this usually really passengers are carried, that is why windows are provided here, even doors are also provided here and this is the normal way it is done. **(Video Ends: 02:43)**

So another video I would like to show you in this regard that is again a representative wing structure. In this, we will see different sections of the wing like the ribs, the spars. **(Video Starts: 03:04)** In this, what we see is that these shapes which are we say airfoil shape, these maintain the shape of the wing. These sections are known as spars and that way, these are all built from thin work sections.

These are the aim of our study how each and every part is designed or analyzed. **(Video**

Ends: 03:33) But before we start into that analysis and design, we would like to go to the basics of the solids mechanics.

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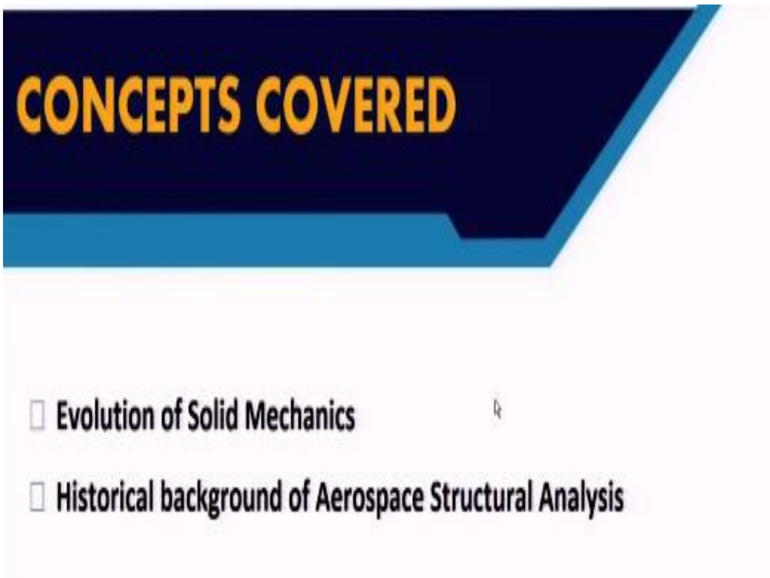

So in that concern to go through the basics of solid mechanics, it is better to go through the evolution of solid mechanics on the other way we may say that it is the history of solid mechanics and since we cannot disassociate aircraft structure from solid mechanics, so it is also the history of aircraft structures as well.

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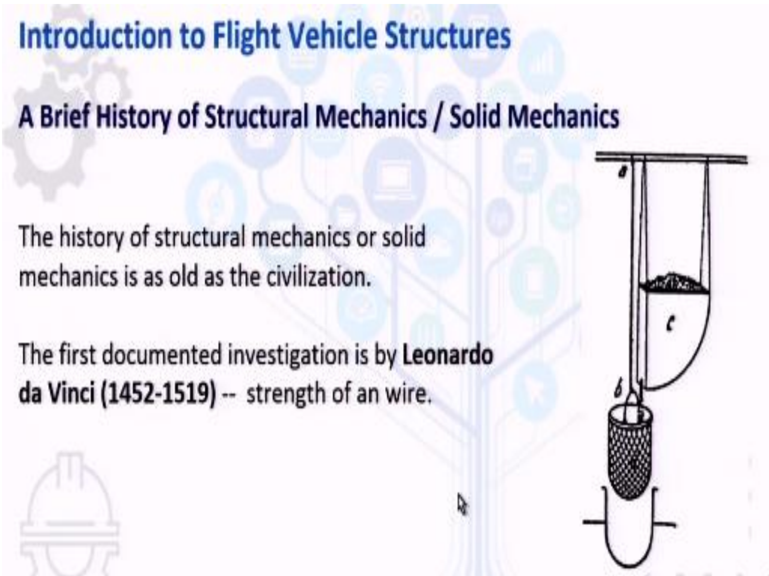

This is a very interesting one. I really feel encouraged looking at this one. This may be the first point or noted point in the history while someone did some experiment to find out properties of a material. So if you look at the slide, this is an introduction to flight vehicle structures. Definitely, it is a common title for this portion, but basically now what we will do we will consider a brief history of structural mechanics and or solid mechanics as we said.

The history of structural mechanics or solid mechanics is as old as civilization. So this statement I have put at first because you know anything we do even if we sleep on a cot that is a structure. So whatever we do, even if we think of the invention of the wheel that is also a structure, anything, we can imagine anything. If we think of an axe that axe is also a structure, that handle of the axe has somebody thought of its strength, somebody thought of its size, and then he designed it.

So if you think of a spear that is also a structure, so looking at that point of view, it is really as old as the civilization is but the similar way if we look at the noted down history or the fast documented investigation that is done by Leonardo da Vinci though Leonardo da Vinci is much more famous with arts and sculptures and paintings all those things, we are familiar with Mona Lisa, but see he is the person who did experiments with these things also.

If we look at the setup, this is a very nice interesting setup. This is a bag c, c is a bag full of sand, b is a bucket and the string ab which is connected or from the horizontal bar is going to be tested. So what is happening? From the bucket c, sands are coming to the bucket b and at some point of time slowly as the load will increase as the amount of sand will increase, it will exert more force on the string and we can find out, we can estimate a measure of how much is the strength of the string ab.

So this may be considered that the string or wire whatever, we say the wire ab how much is the strength. So this is the first noted point. We can say that this is the first tensile testing of material. So this is a really notable thing, we should honour him with giving him credit, but after this, we will go to the other portions, other portions like the history how we have come across all these analysis design and other aspects of solid mechanics and analysis of aircraft structures.

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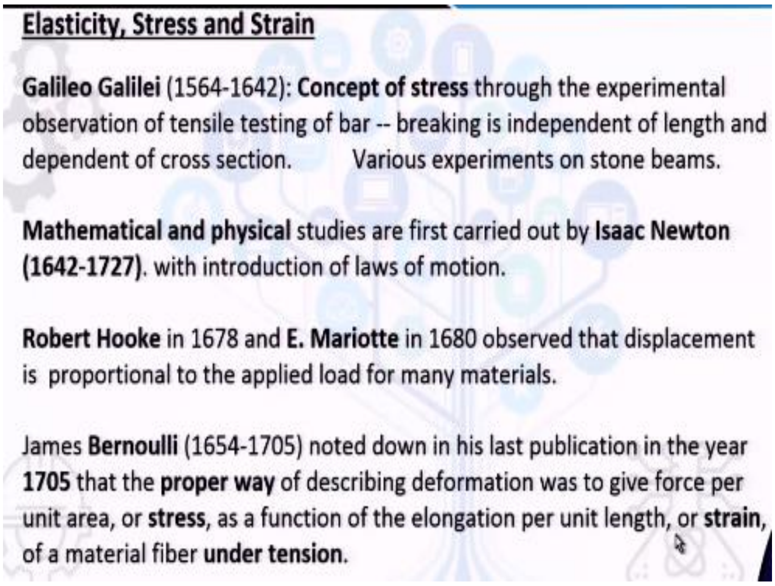

So we have segmented this lecture. I have planned the lecture in 3 segments. We were first considering the elasticity, stress and strain. So if we look at it if you go to the previous slide, please note the time it is something in the mid of or late of 15th century. Then what happens, we denoted scientist or physicist, when we say that time everyone was physicists, so Galileo Galilei may introduce the concept of stress.

Concept of stress through the experimental observation of tensile testing of bar breaking is independent of length and dependent on the cross section. So it is something considered that Galileo Galilei is the person who first established the correlation between the length and cross section with respect to their breaking load. So he concluded that breaking is independent of length and it is dependent on the cross section.

Various experiments on stone beams also he did. He did a lot of experiments on stone beams. Next, if we look at it is say maybe in the 17th century, mathematical and physical studies are first carried out by Isaac Newton with the introduction of laws of motion. This is very famous, we have heard anyways, three famous laws, we would not spend much time on that. These are quite available in books, and we are very aware of it. Next, if we look at Robert Hooke, now we always say it is Hook's law.

So what did Robert Hooke said? Robert Hooke and E Mariotte in 1680 observed that displacement is proportional to the applied load for many materials. So this is a very very common observation for us nowadays, but they first noted down this observation. About James Bernoulli, he is one of the famous Bernoulli family physicists. James Bernoulli noted down in his last publication in the year 1705 that proper way of describing deformation was to give force per unit area or stress.

As a function of the elongation per unit length or strain of a material fiber under tension. It is something he is the person first said that there might be two terms or two way we can define, one is with respect to the force per unit area, and the other is with respect to the material fiber under tension, so elongation per unit length.

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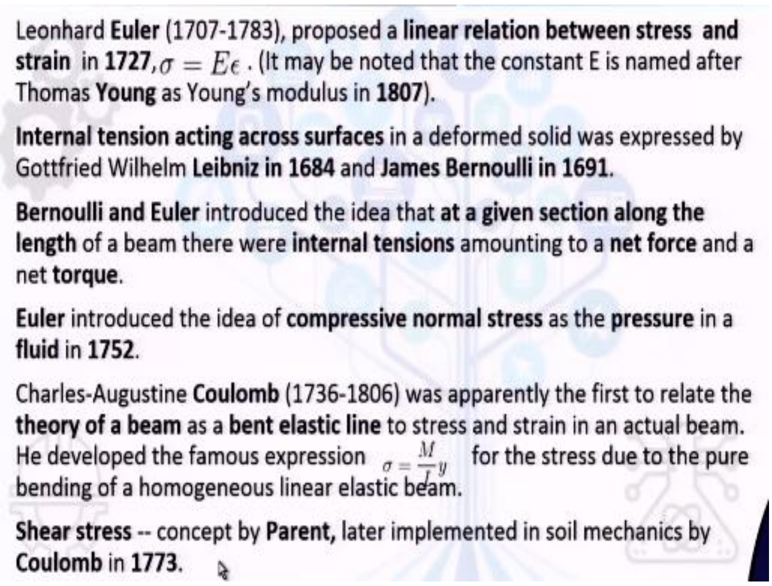

Then it comes about Leonhard Euler, proposed the linear relationship between stress and strain in 1727 sigma is equal to E epsilon ($\sigma = E\varepsilon$)and this may be noted at this point of time that it may be noted that constant E is named after Thomas Young as Young's modulus in 1807. So if we see what we generally say stress-strain relation sigma is equal to E epsilon for that only there is the contribution of Leonhard Euler, there is the contribution of Bernoulli, there are contributions from Robert Hooke and Mariotte.

So later if we look at the internal tension acting across surfaces in a deformed solid was expressed by Gottfried Wilhelm Leibniz in 1684 and James Bernoulli in 1691. Now with probably you have come across the mechanics course in your first year, maybe in your first or second semester this is quite familiar to us that there are something internal stresses, internal tension acting across the surface, there are stresses which acts internally within a body but see that was first noted down by Leibniz Ian Bernoulli in 1691.

Bernoulli and Euler introduced the idea that at a given section along the length of a beam there were internal tensions amounting to a net force and a net torque. So, they tried to make some correlation between the net force and torque and internal tensions. Euler introduced the idea of compressive normal stress as the pressure in a fluid. He again did further calculations for that proposition and he said that there is something compressive normal stresses also.

It is compressive in nature and that may be considered may be said as the pressure in case of fluid. Charles-Augustine Coulomb more popularly known as Coulomb was apparently the first to relate the theory of beam as a bent elastic line to stress and strain in an actual beam. So he is the person who first assumed that, he proposed that the bent elastic line has a relation with the stress-strain of the actual beam.

He developed the famous expression sigma is equal to M cross y by I ($\sigma = \frac{M\,y}{I}$). This expression is really very very good and we use it, you have done in your mechanics course all problems with this but it got introduced sometime in the late 18th century. He developed the famous expression sigma equals to M by I multiplied by y for the stress due to pure bending of a homogeneous linear elastic beam.

So this formula holds for pure bending and he established this. Shear stress, the concept of shear stress probably you have now but it was a say concept by Parent, later implemented in soil mechanics by Coulomb in 1773.

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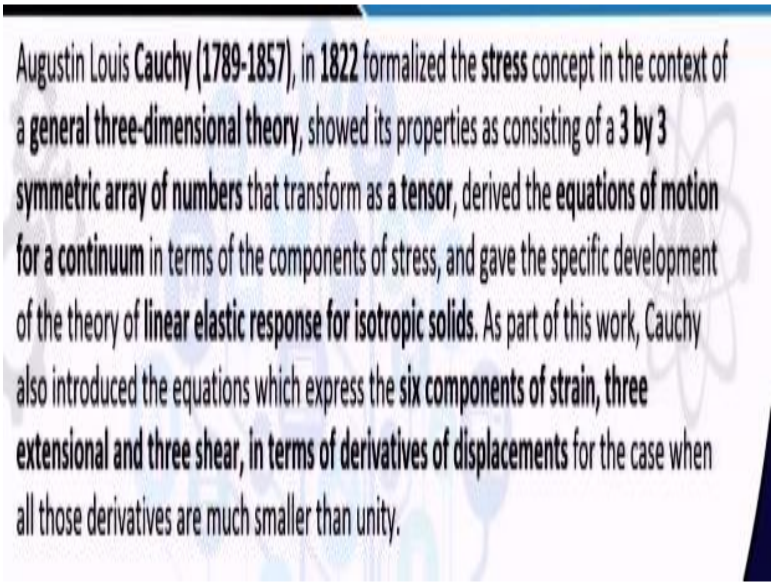

Then we say a lot of contribution is done from Augustin Cauchy. Augustin Louis **cost**

Cauchy in 1822 formalized the stress concept in the context of a general 3-dimensional theory, and he showed that its properties as consisting of 3 by 3 symmetric array of numbers that transform as a tensor, derived the equation of motion for continuum in terms of components of stresses and gave the specific development of the theory of linear elastic response for isotropic solids. This is really a big sentence for us to study now.

There are terms which are probably we are not familiar with like the continuum, equation of motion for a continuum, 3 by 3, symmetric area of numbers which is actually a tensor, so but see it is better to get introduced with these things because we will be using in our later courses or maybe in a very brief way in this present course. As part of this work, Cauchy also introduced the equation which expresses the six components of strain, three extensional and three shear.

In terms of derivatives of displacements for the case when all these derivatives are much smaller than unity. So this is del u del x equals to ε of x that is what he said.

He is in the year 1822 or in the close year he proposed that and it was continuing. So this is something we will come back again about the further development of this continuum equation, who did what, but before that, we better get introduced with these things which are related to the beams, columns, plates and shells development.

Development in the sense analysis development, how those analyses were being slowly developed by the famous physicist.

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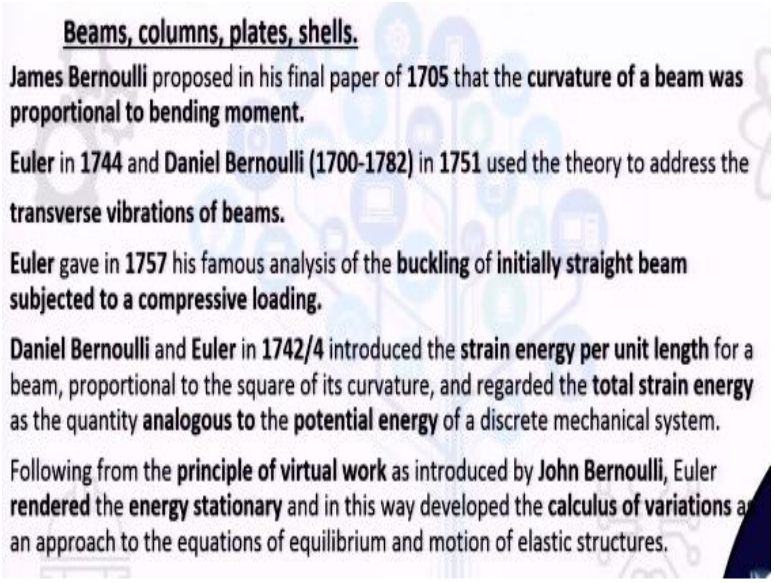

James Bernoulli if you look at proposed in his final paper in the year 1705 that curvature of a beam is proportional to the bending moment. This we know that M by EI is equalled to 1 by rho and we can also see that Euler in 1744 and Daniel Bernoulli, he is also from that Bernoulli family in 1751 used the theory to address the transverse vibration of beam. Transverse vibration of beam is if we have in interest to look at the response of a vibrating structure.

The first thing we generally study is a single degree freedom system, but invariably it goes to the beam vibration. That means if it is under dynamic load or it is vibrating because of its inertia how the response is, all those things were first introduced in 1751. Euler gave in 1757 his famous analysis of buckling or buckling of an initially straight beam subjected to compressive loading. This Euler buckling formula already we are introduced with.

Buckling is a kind of instability and we need to understand it, we need to find out the critical load so that structure does not go to any unstable region and it serves its purpose of carrying a load. Daniel Bernoulli and Euler in 1742 and in 44 introduced the strain energy per unit length for a beam proportional to the square of its curvature and regarded the total strain energy as the quantity analogous to the potential energy of a discrete mechanical system.

So if we look at this statement, this is a very important development, this may be the fundamental of today's numerical analysis. He said that the strain energy per unit length is analogous to the potential energy. So this may be considered as the first statement for the analysis with respect to the energy we will see, many more other things are also developed and that slowly has invented the process of numerical methods like finite element methods.

Following from the principle of virtual work as introduced by John Bernoulli, Euler rendered the energy stationary and in this way developed the calculus of variations as an approach to the equations of equilibrium and motion of elastic structures. So this energy stationary and the calculus of variation, these are the two fundamental mathematical tools which further laid down the process of invention of finite element analysis or other numerical methods and approximate methods what we generally learn.

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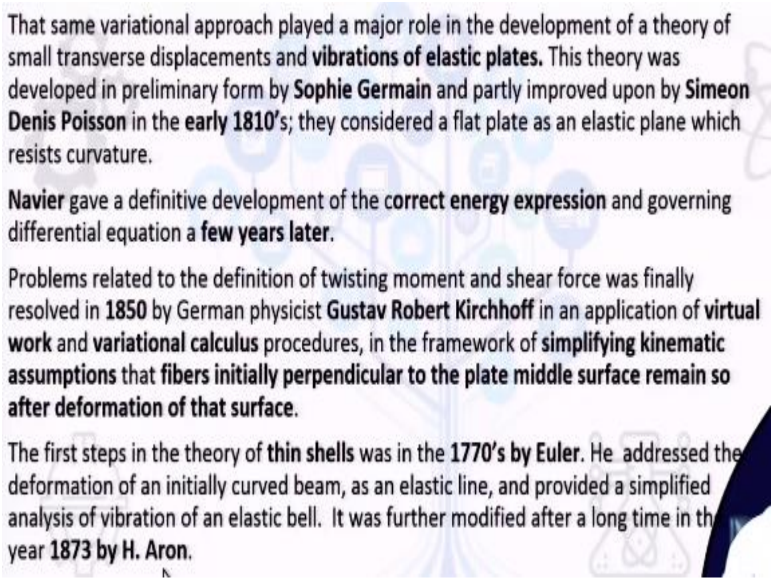

So we were talking about the variational approach. Variational approach played really a major role in the development of the theory of small transverse displacements and variations of elastic plates and this point of time it is better to get introduced with the plates in structural analysis or in structures, and we generally call a structure plate while the anyone of the dimension is very very thin compared to its other two-dimension.

So if we see if we consider a rectangle like this and say if the thickness of this rectangle is very small with respect to its other two dimensions, say this is a this is b, we call this as a plate and curvature we say it is of an infinite radius of curvature, while it is having some curvature that case we call that structure as a shell. So predominantly, we have much use of plates and shells in our aircraft structures, so this is an important structure in our case and we will see how we will analyze those things slowly.

So this theory was developed in preliminary form by Sophie Germain and partly improved upon by Simeon Daniel Poisson in the year 1810. They considered a flat plate as an elastic plate which resists curvature, that means probably they try to mean the bending. Navier gave a definitive development of correct energy expression and governing differential equation a few years later.

So if you see already, we have come across with respect to the energy, with respect to the variational calculus, many names like Navier, like Poisson, like that name Sophie Germain. Before that, we have already heard about Bernoulli, Euler and many more. So let us go further. Problems related to the definition of twisting moment and shear force was finally resolved in 1850 by German physicist Gustav Robert Kirchhoff.

Kirchhoff also has done many works in relation to plate in some advanced stage, we generally say Kirchhoff's plate, but those things are much later stage, but he first did a distinguished work in relation to the twisting moment and shear force. So the application of virtual work he did and variational calculus procedures also he established for that, in the framework of simplifying kinematic assumptions, fibers initially perpendicular to the plate middle surface remains so after deformation of that surface.

This statement has become very famous with respect to Kirchhoff and this has led down the analysis of many more bigger structures, simplified way of analysis this assumption in your later stage of study you will understand and you will learn. The first step in the theory of thin shell was in the year 1770's by Euler. As we have just now got introduced what is the shell and what is the plate, the shell is a structure where the third dimension is very small compared to the other two dimensions and it is having a curvature.

Also analysis wise, shells are also in two different ways it is generally categorized deep shell and shallow cell, but we would not go into those details at present. So for a thin shell, it was first introduced by Euler. He addressed the deformation of an initially curved beam as an elastic line and provided a simplified analysis of vibration of an elastic bell. This is related to a famous for his analysis of a big charge bell. It was further modified after a long time in the year 1873 by H. Aaron.

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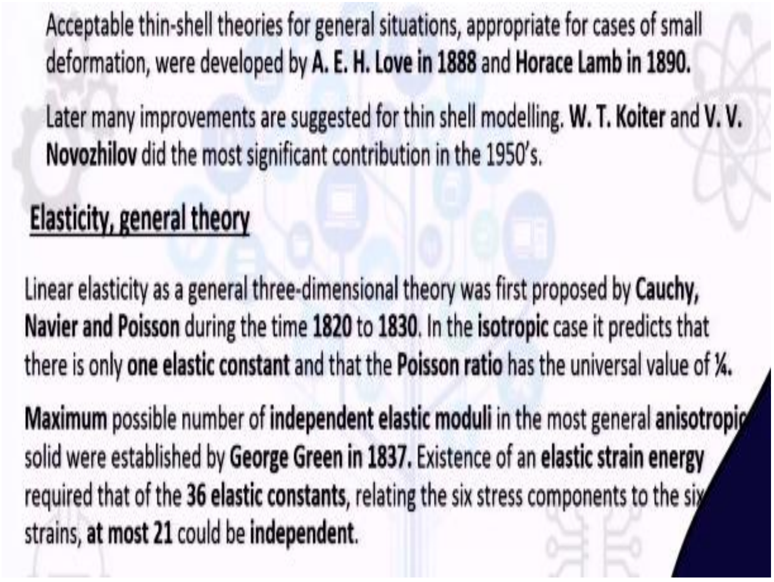

Acceptable thin--shell theories for general situations, appropriate for cases of small deformations were developed by A. E. H. Love. He also did a lot of work for thin shell formulation and later it got further extended by Lamb in 1890. Later many improvements are suggested for thin shell modelling by W. T. Koiter and Novozhilov made the most significant contribution in the year 1950's. With this, let us try to conclude this part of the introduction.

More elastic general theories in relation to the detailed description in tensor were formed by Cauchy and then later by Poisson, by Wilhelm Leibniz descriptions, Green described in more detailed way anisotropy, those things may be considered later and it may be noted that it is not much earlier this history ends, it is something around 1950. If we look at this slide, the linear elasticity as a general 3-dimensional theory was first proposed by Cauchy, Navier and Poisson.

These term in this sentence linear elasticity is very important, and our discussion will be related to linear elasticity only. There is a huge domain of nonlinear elasticity also, we would not go into that. General 3-dimensional theory, this general 3-dimensional theory will get introduced in this course at some advanced stage, maybe in the last few lectures and these things were introduced in the year 1820 to 1830.

In the isotropic case, it predicts that there is only one elastic constant and that the Poisson's ratio has the universal value of one-fourth. See this is we know now it is not true, but at that point of time it got proved and people started believing that and later it was changed and got introduced in a different way. Now, this is related to some introduction with the non-isotropic material which has a predominant use in aircraft structural analysis.

In case of laminated composite we have many application related to that, so a maximum possible number of independent elastic moduli in the most general anisotropic solid was established by George Green in 1837. Existence of elastic strain energy required that the 36 elastic constants relating the 6 stress components to the 6 strains, at most 21 could be independent. So this is a famous conclusion drawn by Green, 36 to 21.

Then we will see later for orthotropic it reduces much more and use considering orthotropic material we can analyze many of the applications in the aerospace industry, for example, the composite structures. With this history, let us conclude today's lecture, the first session of the lecture.

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Leonardo da Vinci	Italy	1452	1519
Galileo Galilei	Italy	1564	1642
E. Mariotte	France	1620	1684
Robert Hooke	England	1635	1703
Isaac Newton	England	1642	1727
Gottfried Wilhelm Leibniz	Germany	1646	1716
James Bernoulli	Switzerland	1654	1705
John Bernoulli	Switzerland	1667	1748
Daniel Bernoulli	Switzerland	1700	1782
Leonhard Euler	Switzerland	1707	1783
Charles-Augustine Coulomb	France	1736	1806
George Green	England	1773	1841
Thomas Young	England	1773	1829
Sophie Germain	France	1776	1831
Simeon Denis Poisson	France	1781	1840

Claude-Louis Navier	France	1785	1836
Augustin Louis Cauchy	France	1789	1857
G. Piola	Italy	1794	1850
Barre de Saint-Venant	France	1797	1886
Lord Kelvin	Scotland	1824	1907
Gustav Kirchhoff	Germany	1824	1887
L. Pochhammer	Germany	1841	1902
J. V. Bousinesq	France	1842	1929
Horace Lamb	England	1849	1934
V. Cerruti	Italy	1850	1909
Heinrich Rudolph Hertz	Germany	1857	1894
A. E. H. Love	England	1863	1940
V. V. Novozhilov	Soviet	1892	1970
W. T. Koiter	Netherland	1914	1997

We will start further in our forthcoming session, but before we finish it, it is better to pay our gratitude to these famous scientists. I have tabulated with their birth and year and the duration they were on the earth to facilitate human civilization and without their contribution probably we cannot imagine anything under the earth. So it starts with Leonardo da Vinci and I have noted here as the last person has W. T. Koiter, but it is not that there it ends, history is a continuing process and goes further.

So you may also look at that contribution is not from any one region of the earth, it is from various places like Italy, France, England, Switzerland, France, Scotland, Germany and Soviet Union and Netherland also. So to show them the gratitude, to end with let me name them for once Leonardo da Vinci from Italy, Galileo Galilei from Italy, E. Mariotte from France, Robert Hooke from England, Isaac Newton from England, G Wilhelm Leibniz from Germany.

James Bernoulli from Switzerland, John Bernoulli from Switzerland, Daniel Bernoulli from Switzerland, they are of the same family, and this is very surprising. Leonardo Euler from Switzerland, Charles-Augustin Coulomb from France, George Green from England, Thomas Young from England, Sophie Germain from France, S. D. Poisson from France, Claude-Louis Navier from France, Augustin Louie Cauchy from France, G. Piola from Italy, Barre de Saint-Venant from France, Lord Kelvin from Scotland.

Gustav Kirchhoff from Germany, L. Pochhammer from Germany, J. V. Boussinesq from France, H. Lamb from England, V. Cerruti from Italy, H. R. Hertz on whose name the frequency Hertz unit is there from Germany, he also gave theories related to impact. Love, he is A. E. H. Love, his books are also there nowadays on publication, you can find out, we call he is the father of shell theory, he is from England, Novozhilov from the Soviet Union, and Koiter from Netherland. So with that, let us end today's session. Thank you.