Testing of Functional & Technical Textiles
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Lecture – 21
Testing of Ballistic Protective Clothing

Hello everyone. So, we will continue with the discussion on Testing of Functional and Technical Textiles. In this course till now what we have discussed first let us see; we have discussed the methods for testing of functional textiles, then we have started technical textiles.

So, in testing of technical textiles we have first discussed testing of fibre reinforced composite material, then filter fabrics, then testing of geotextiles. And today we will discuss Testing methods of Ballistic Protective Clothing. In ballistic protective clothing first let us try to understand what is ballistic protective clothing.

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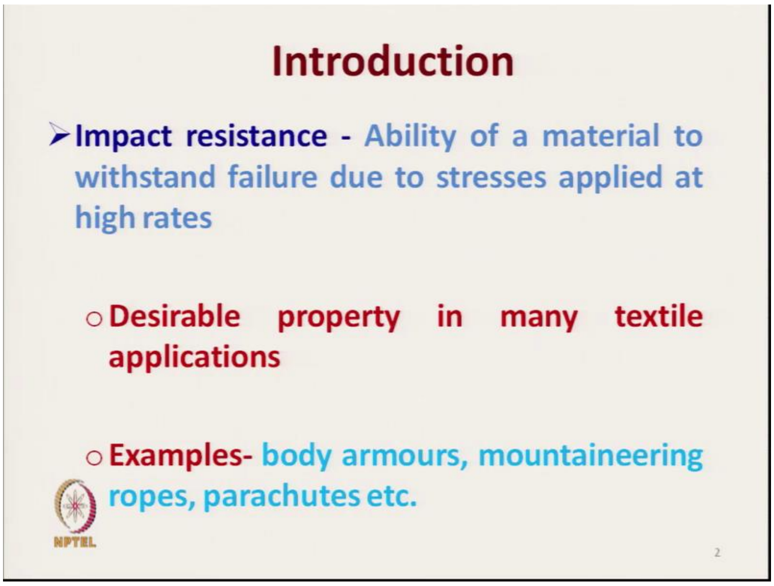

So, in any material where impact resistance is the prime importance so those are related to high stress application. So, these are basically coming under ballistic protection. So, ability of a material to withstand failure due to stress which is applied at very high rate so that is known as impact.

So, this impact resistance is very important for ballistic protective clothing. So, desirable property in many textile application this is not only for ballistic protection there are many other applications like; body armours that we will discuss in this segment. Then impact resistance is important in mountaineering ropes parachutes or many other areas.

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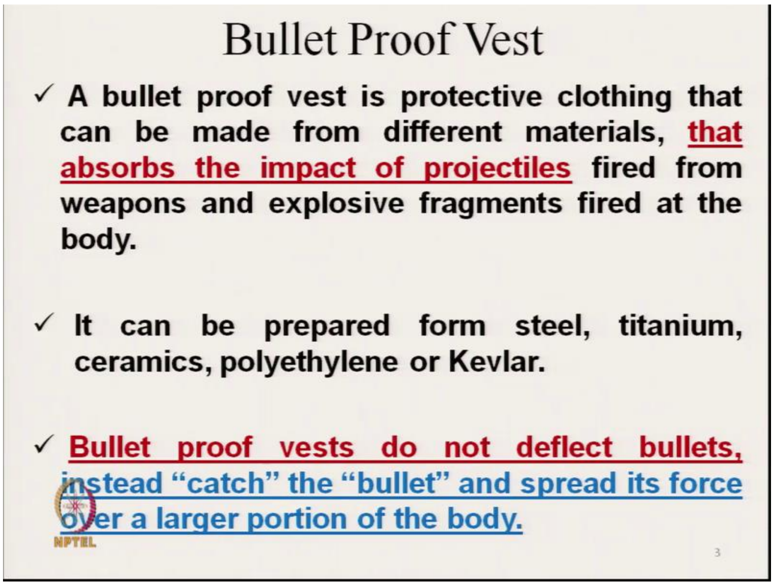

So, bulletproof vest which is coming under ballistic protective textiles is a protective clothing that can be made from different material which absorbs the impact of projectiles that is a bullet fire from weapons and explosive fragments fired at the body. So, this bulletproof vest has to protect us from all this impacts. So, this vests can be prepared from steel, titanium, ceramics, polyethylene or Kevlar.

So, this vests do not actually deflect the bullet. So, you should understand that bullet proof vest are not supposed to deflect the bullet instead it should catch the bullet and effectively it should spread the force over large area. So, that the impact on our body is minimized.

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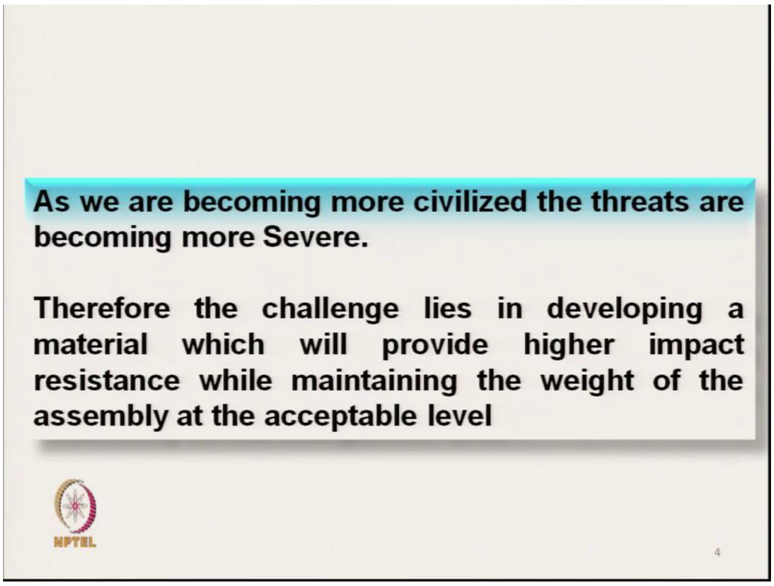

So, as we are becoming civilized the threats are becoming more and more severe. So, therefore, the challenges lie in developing a material which will provide higher impact resistance while maintaining the weight of the total assembly at lower level. So, that is the challenge. So, severity of threats have been increased, but at the same time we expect our bulletproof vest should be of lower mass.

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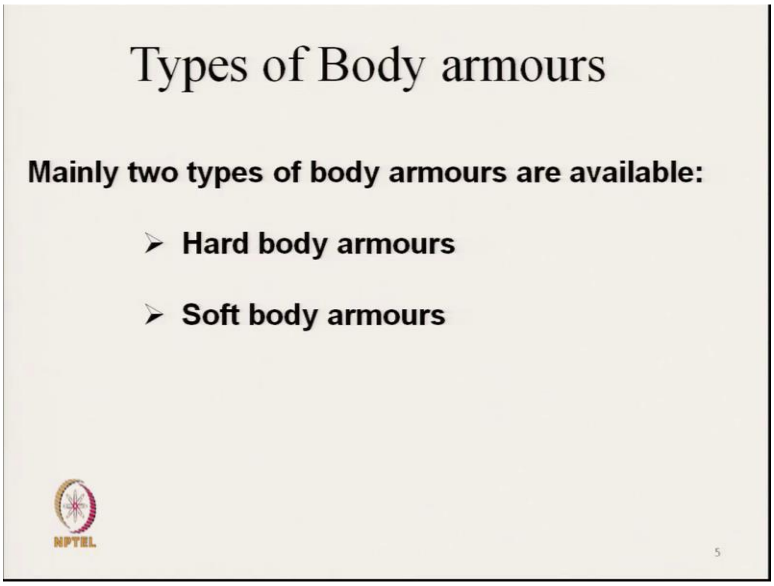

So, there are broadly two types of body armours; one is hard body armour and another is soft body armour. So, first let us try to understand what are the basic differences.

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The hard body armour are those where metals and ceramic plates are inserted within the structure. So, due to this metal and ceramic insertion they are becoming rigid, they are heavy. And all this hard body armours are used for military officers in the high risk region because this hard body armours are meant for the high threat.

So, these are basically used for protection against high velocity projectiles. So, in spite of all these advantages like protection from high threat the main disadvantages of this hard body armours are; they are hard, they are not flexible, they are heavy, it is difficult to handle, difficult to carry. So, they restrict the body movement. So, looking at all these disadvantages of hard body armour soft body armours have been developed.

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So, these are basically multilayered woven or laminated fabric structure. Typically they are supposed to be flexible and lighter in weight. So, they are relatively more flexible in nature than hard body armour lighter in mass. And they are used for routine wear of police officers and security personnel. The soft body armours normally do not use for high threat zone. So, they are providing protection against low velocity projectiles.

So, main disadvantages of this soft body armours are; we are looking at multilayered woven or laminated fabric which should be flexible, but 20 to 30 layers of this fabrics are required for sufficient protection. So, effectively this 20 to 30 layers makes the structure inflexible they can be used only for low velocity impacts. So, where there is high threat you cannot use this soft body armours.

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So, in soft body armours the impact resistance that is protection depends on the properties of fibres yarns and fabrics. So, we will see how fibres yarns and fabrics affect the impact resistance of soft body armours.

So, here generally multilayered woven Kevlar fabrics are used. So, as we have discussed 20 to 30 layers are required, this structures become heavy and they become thick and inflexible. So, effectively they are uncomfortable to use.

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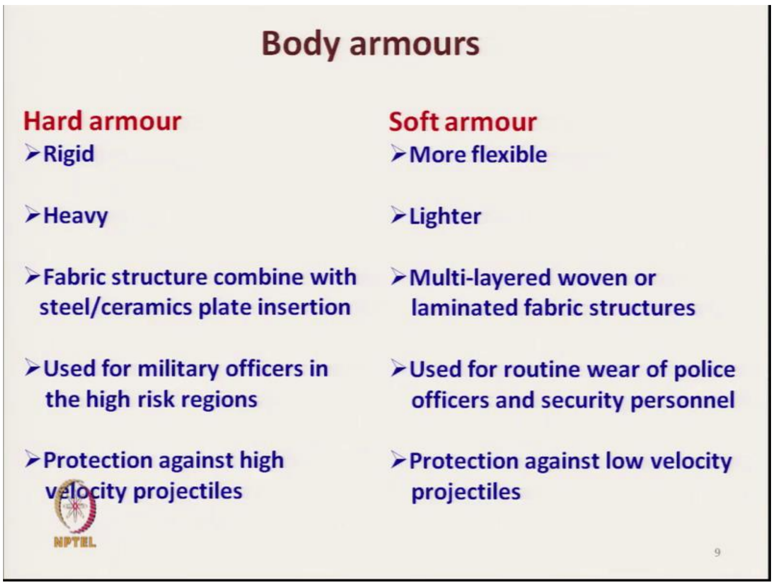

So, if you see broadly the difference between hard body armour and short soft body armours. The hard body armours are rigid whereas, soft body armour are relatively flexible. Hard body armours are heavy this soft body armours are lighter. Fabric structure combined with steel or ceramic plates insertion. Whereas, in case of soft body armour we do not need any insertion, but here multilayered woven or laminated fabric structures are used.

Hard body armours are used for military officers where high threats are there and soft body armours are used for police officers and security personnel. Hard body armours are meant for protection against high velocity projectiles and soft body armours are relatively low velocity projectiles.

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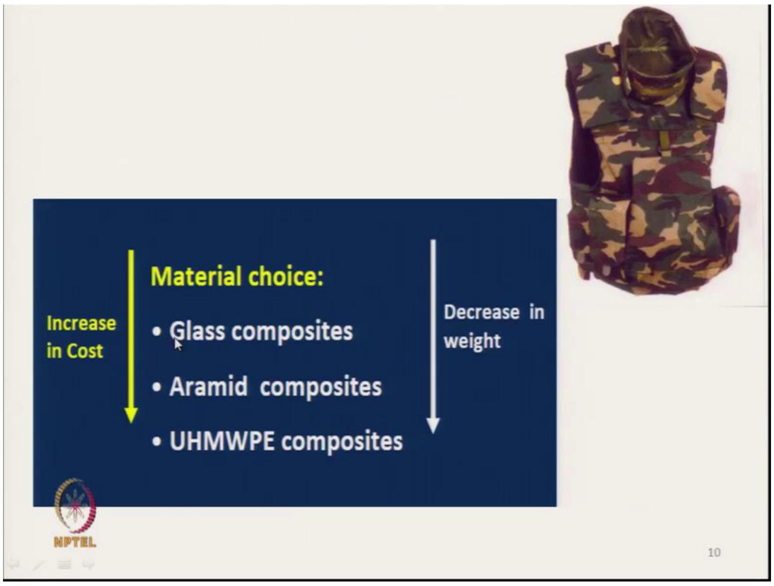

So, as the developments are going on the materials requirement towards decrease in weight we need lighter ballistic protective clothing at the same time the cost is increasing. So, materials choice are also changing initially we use the glass composite then aramid composite and then ultra high module molecular weight polyethylene composite.

So, gradually if we go towards glass to ultra high molecular weight polyethylene composites so weight is decreasing.

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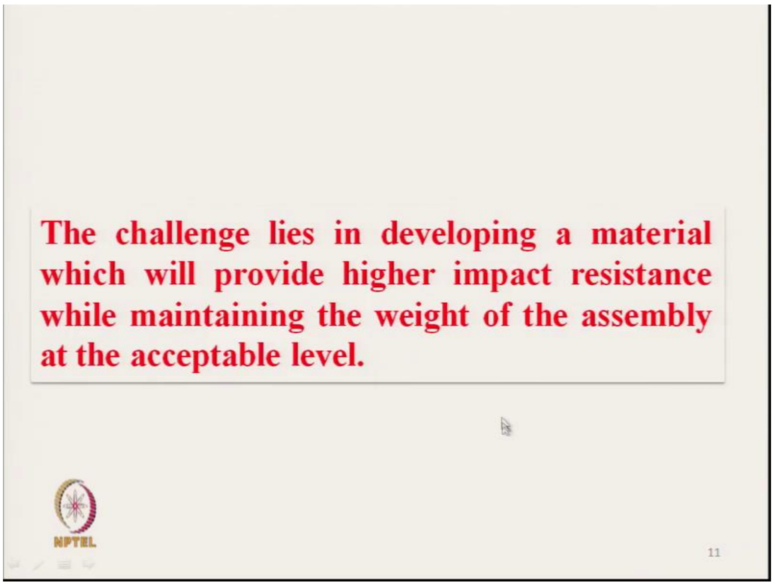

So, main challenge lies in the developing of material which will provide higher impact resistance while maintaining the weight of the assembly at the acceptable level. So, that is the basic requirement.

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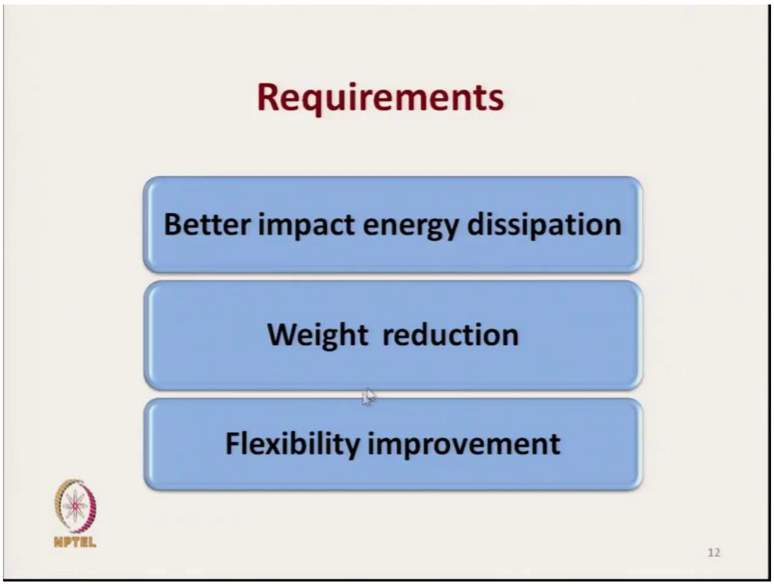

So, the requirements are in short better impact energy dissipation. So, the ballistic protective clothing should be able to dissipate the energy in a better way. The mass should be lower so weight reduction should be there and it should be flexible. So, that proper handle, proper comfort characteristics should be there.

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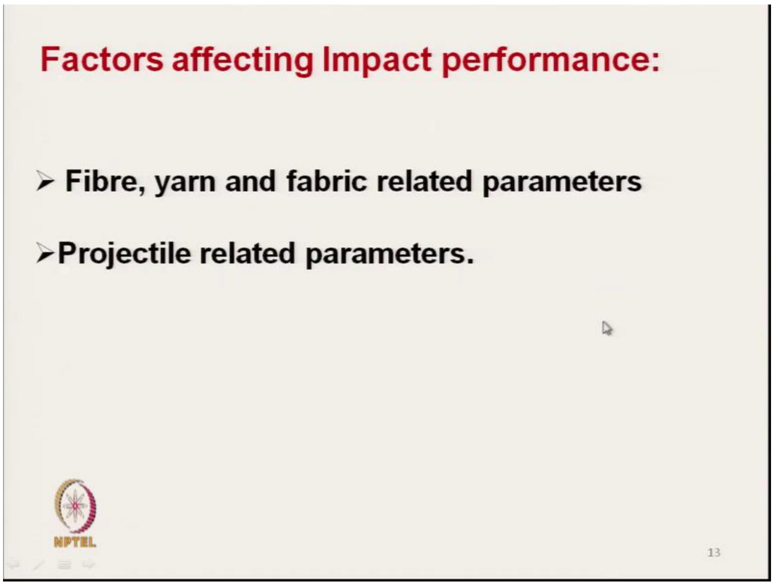

So, first let us see what are the factors effecting the impact performance of clothing. First factor is that it is a fibre yarn and fabric related parameters. So, we have select proper fibre, then we have to decide the yarn structure, what type of yarn, then fabric structure we have to decide to control the impact performance.

And then projectile related parameters what type of projectile what type of that tips are there. What is the angle of impact? So, this parameters also affect the impact performance of ballistic protective clothing.

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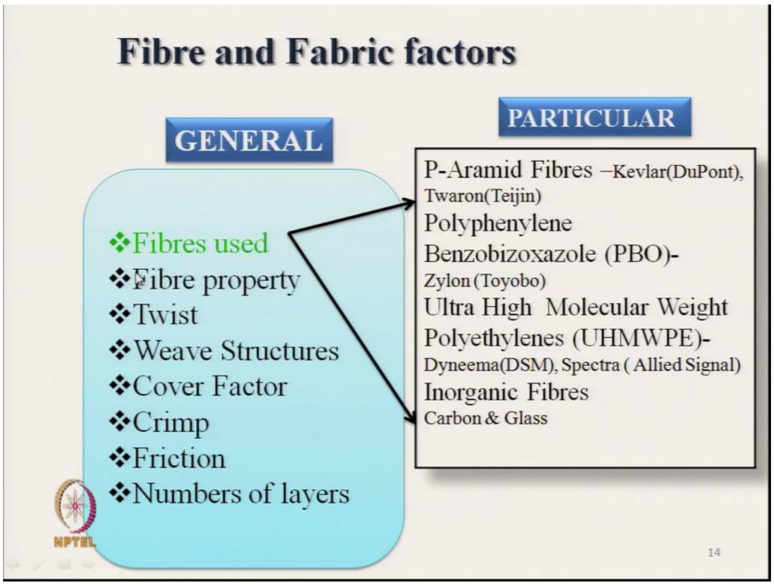

So, if we see the fibre and fabric parameters there are the parameters like what type of fibres we do we use. What is the fibre property what are the properties of fibre then twists in the yarn. What is the weave structure then cover factor of the fabric crimp level of yarns in the fabric friction between yarn in the fabric numbers of layers number of layers of fabrics used in the clothing assembly.

So, fibres used or there are different types of fibres like; para aramid fibres, a Kevlar polyphenylene fibre, PBO fibre, Ultra High Molecular Weight Polyethylene Fibre, Inorganic Fibres like carbon and glass fibres. So, these are in all this fibres which are used for making ballistic protective clothing. Then the properties of this fibres are all this properties which are extremely important for making the ballistic protective clothing effective.

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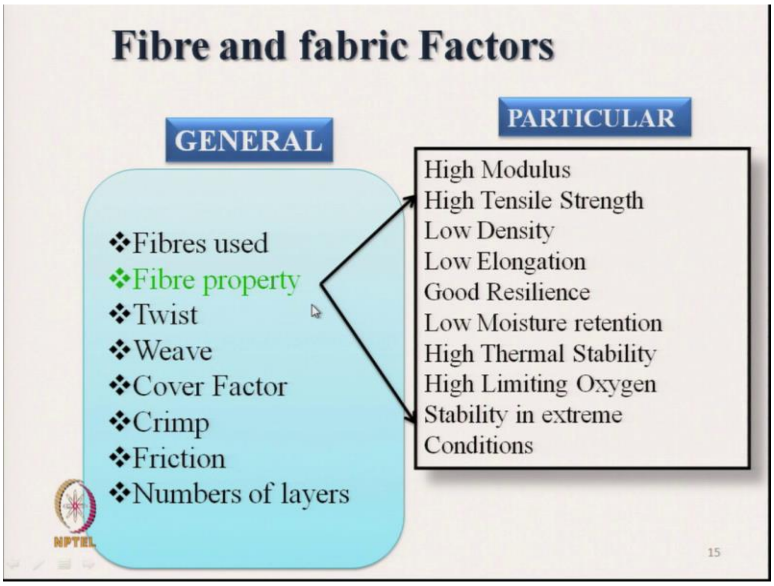

Like in fibre properties the fibre should have high modulus ok. Then high tensile strength low density because we need mass should be low it should be lighter low elongation if it elongates if it is elongation is very high then the impact performance impact resistance will be affected. Good resilience it should come back from the deformation. Low moisture retention so if the fibre retains moisture, then it is mechanical behaviour may get affected.

High thermal stability should be there because during impact there will be high temperature generation. And if the fibre is not stable at high temperature then the structure may get damaged and effectivity of the total clothing will deteriorate. Then high LOY value; that means, it is burning behaviour should be good stability in extreme condition. So, in case of extreme condition extreme heat or extreme cold condition the fibre should be stable.

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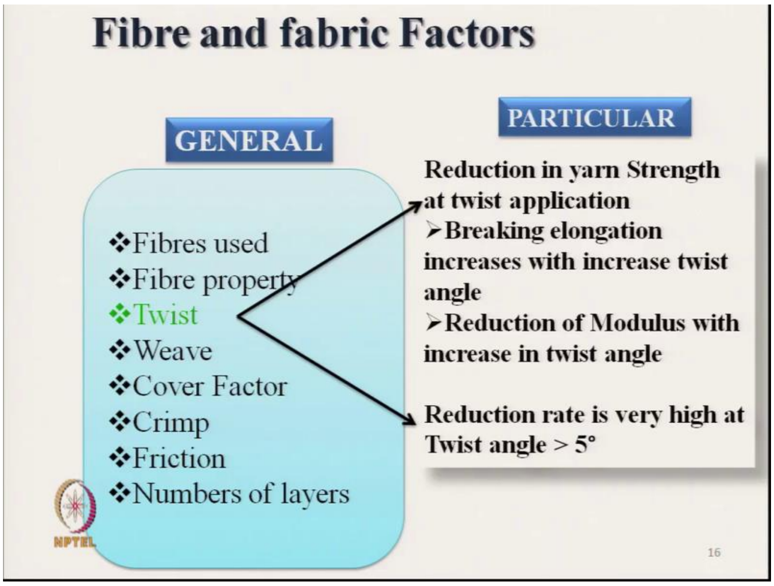

After the fibre property then yarn twist is a also very important reduction in yarn strength occurs when we apply twist that is very well known fact. And also with the increase in twist angle the breaking elongation also increases. So, we have to create yarn structure which has got high strength and low breaking elongation.

Also with the increase in twist the modulus of yarn reduces. So, effectively the yarn which we use should be of low twist. So, reduction rate is very high at twist angle more than 5 degree. So, the twist angle should be very low effectively it should be less than 5 degree.

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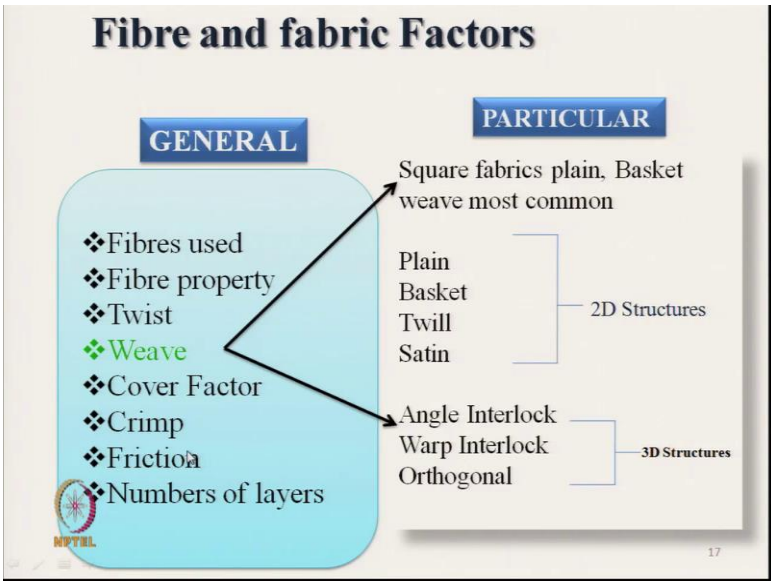

Then comes weave structure; so the structure of fabric, it should be square fabric plain structure or basket weave are most common. So, plain basket they are most commonly used with the square structure. And twill or satin sometime is being used all these structures are two dimensional structures in addition to two dimensional structure sometime we use 3D structures. Like angle interlock warp interlock orthogonal to enhance the impact performance of the clothing.

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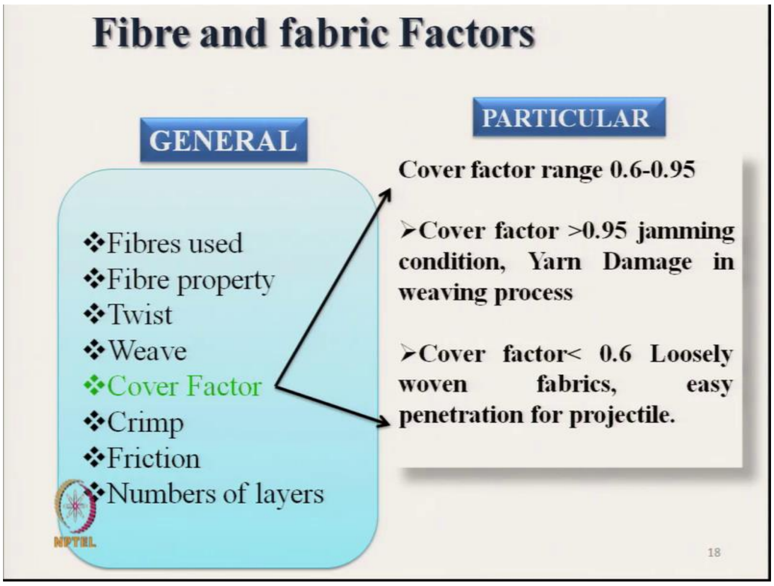

Cover factor is extremely important characteristics. So, it should range between 0.6 to 0.95, that is the range it should not be too high. If it is more than 0.95 then the jamming condition will be created and that will result yarn damage during weaving process and if yarn damages takes place during weaving.

So, that will effectively affect the impact characteristics. And at the same time if the clothing cover factor. Factor of the fabric is reduced if it is very low less than say 0.6 the fabric structure will be loose. And in that case the projectiles will penetrate easily and the effectivity of fabric as far as impact resistance is concerned will be dropped.

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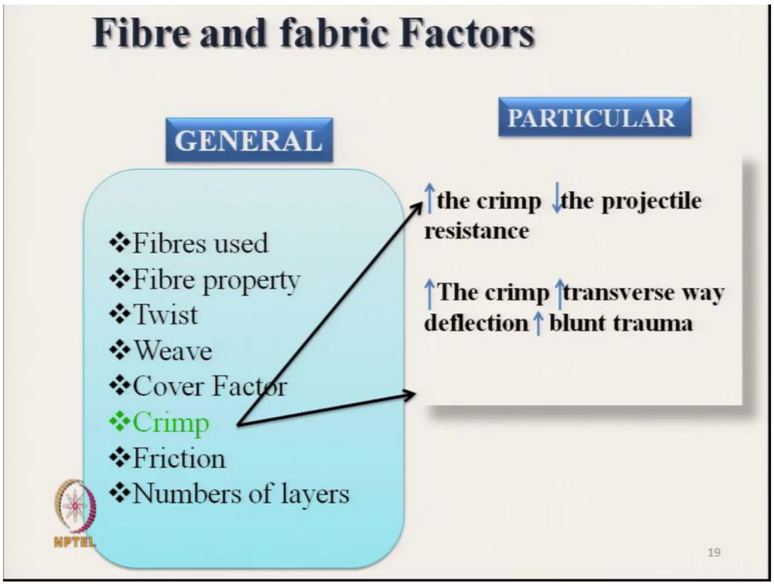

Next is crimp; which is very important for ballistic protective clothing we should have fabric with least crimp in yarn. So, if we increase the crimp so projectile resistance will be reduced. So, as the crimp increases transverse way deflection will increase which will result blunt trauma. This blunt trauma measurement process I will discuss later in this class.

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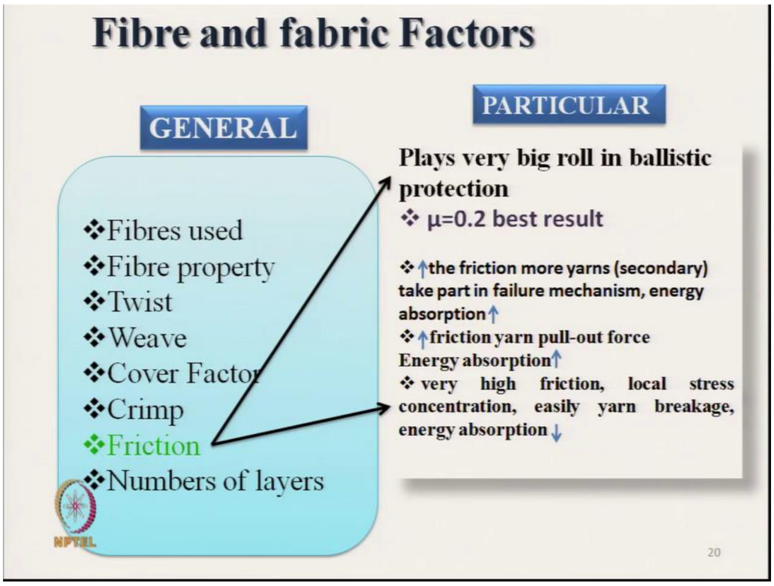

Next important characteristics is friction. Friction is also very important characteristics and typically the frictional coefficient of 0.2 is a optimum value. As the frictional coefficient increases the basic thing what happens due to increase in friction between yarn more and more secondary yarn will come into picture due to frictional contact. And those yarns will take part in the resistance and absorption of energy.

And if the yarn friction increases yarn pull out energy will also increase. So, as the pull out force increases the energy absorption will also increase. But if the friction becomes very high then the problem will be that the stress will be localized and that will result the yarn breakage ok. And energy absorption will drop immediately due to the localized stress concentration. And next factor is number of fabric layers.

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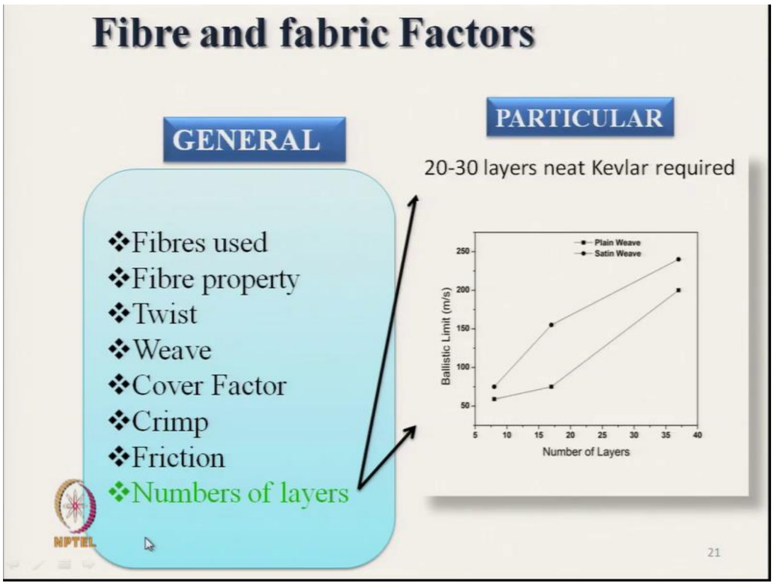

So, it is obvious if we increase the number of layer the ballistic limit will increase energy absorption will increase. But at the same time the mass of the total structure will increase which will result uncomfortable sensation.

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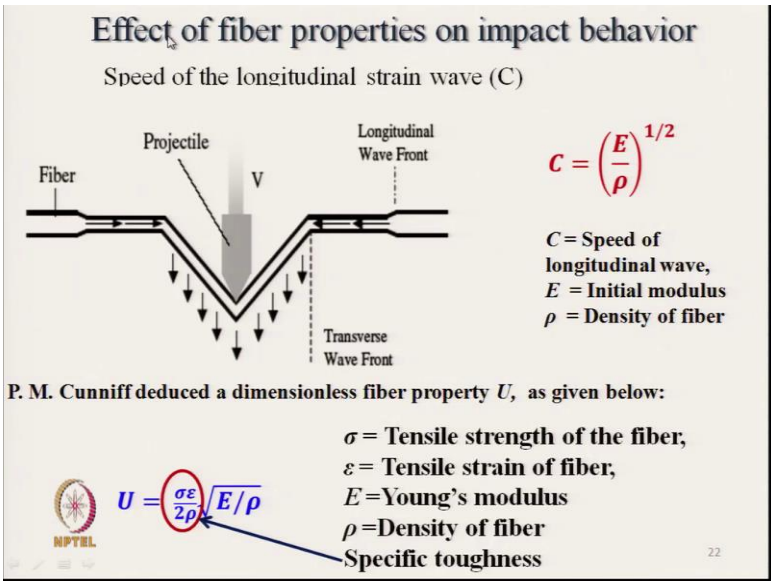

So, the fabric which we are making from a fibre with different characteristics that will affect the impact behaviour. So, effect of fibre properties on impact behaviour. This diagram shows here projectile is striking on the surface of the fabric and that will result the longitudinal wave. And the speed of this wave the longitudinal wave in the side way that way is expressed in terms of initial modulus of fibre and density of fibre which means that C equal to

$$C = \left(\frac{E}{\rho}\right)^{1/2}$$

***C* = Speed of longitudinal wave,**

***E* = Initial modulus**

***ρ* = Density of fiber**

So, under root E by P where E is initial modulus; that means, if the initial modulus of fibre is high that will result higher speed of longitudinal wave. And higher density of fibre will result lower speed of longitudinal wave. So, to have very high the transmission of wave we need high modulus fibre with low density. So, our target should be having high C value low that is high modulus fibre with lowest density.

Cunniff who deduced a dimensional less fibre property which is termed as U which is given by

$$U = \frac{\sigma\varepsilon}{2\rho}\sqrt{E/\rho}$$

***σ* = Tensile strength of the fiber,**

***ε* = Tensile strain of fiber,**

***E* =Young's modulus**

***ρ* =Density of fiber**

Specific toughness

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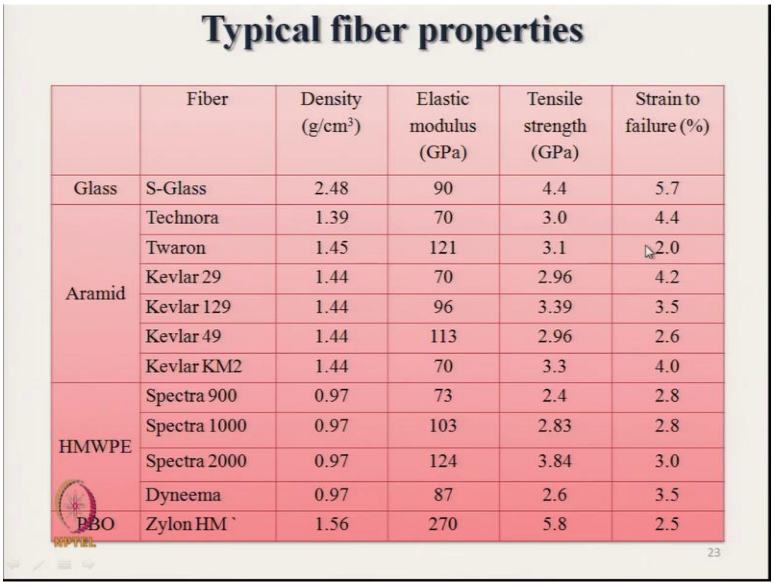

Typical fiber properties

	Fiber	Density (g/cm³)	Elastic modulus (GPa)	Tensile strength (GPa)	Strain to failure (%)
Glass	S-Glass	2.48	90	4.4	5.7
Aramid	Technora	1.39	70	3.0	4.4
	Twaron	1.45	121	3.1	2.0
	Kevlar 29	1.44	70	2.96	4.2
	Kevlar 129	1.44	96	3.39	3.5
	Kevlar 49	1.44	113	2.96	2.6
	Kevlar KM2	1.44	70	3.3	4.0
HMWPE	Spectra 900	0.97	73	2.4	2.8
	Spectra 1000	0.97	103	2.83	2.8
	Spectra 2000	0.97	124	3.84	3.0
	Dyneema	0.97	87	2.6	3.5
PBO	Zylon HM	1.56	270	5.8	2.5

So, these are the typical fibre properties we can get from the literature. And using this basic fibre properties that is density, elastic modulus, tensile strength strain to failure using this characteristics we can derive U value.

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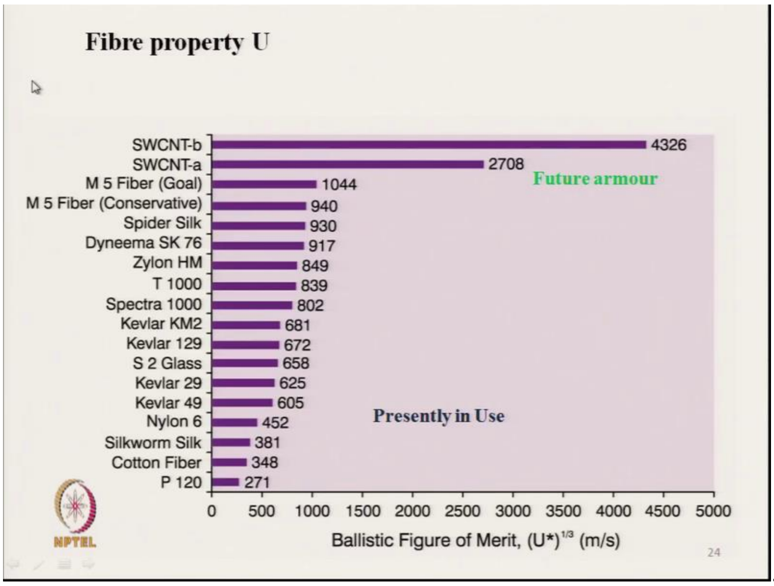

So, this is the fibre property, U value of different types of fibres. And here single wall carbon nano tube a and b which are actually for future armour with the very light high impact resistance fibres and higher U value indicates higher ballistic protection.

So, where Kevlar we can see Kevlar 129 its U value is 672. Whereas, single wall carbon nano tube b it has having 4326. So, if you compare it is typically 6 to 7 time 7 times more than the normal Kevlar. So, these are future armour.

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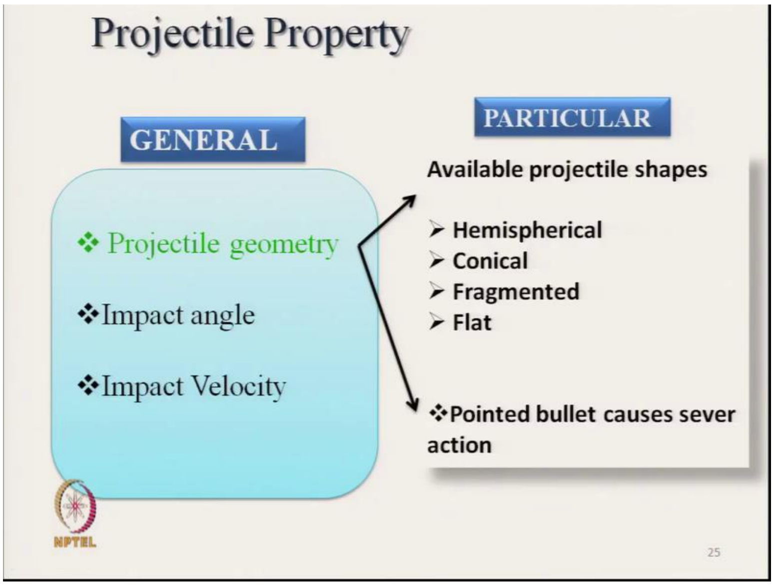

Now, let us see the factors related to projectile properties, which effect the impact resistance the projectile geometry is extremely important. So, there are different types of projectile shapes; hemispherical, conical, fragmented, or flat that is available projectile shape and pointed bullet causes severe action.

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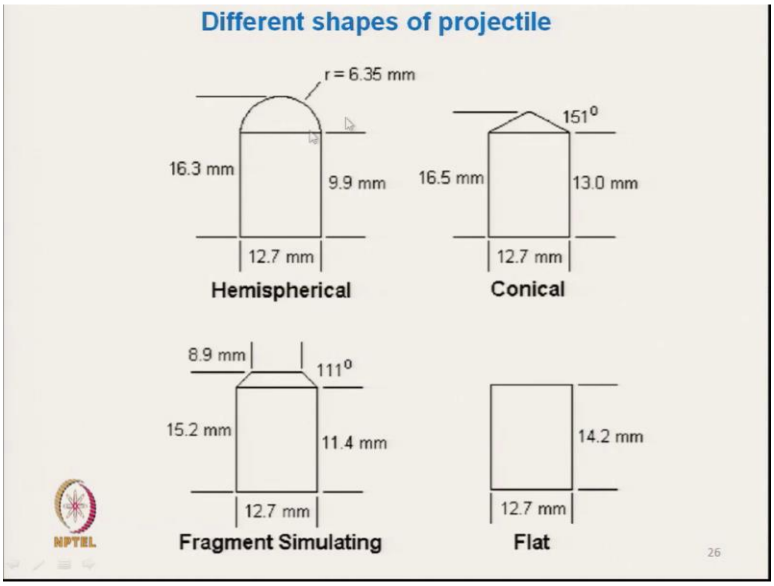

So, these are the different shapes hemispherical tip, conical tip, fragmented tip, and flat tip different types of shapes.

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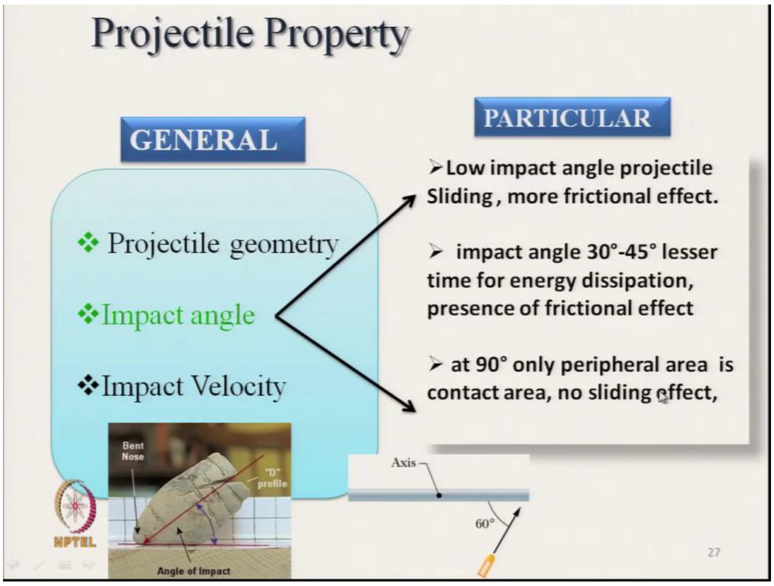

Then impact angle is also important low impact angle properties actually this is the angle with the surface and this is the projectile. So, low impact angle projectile it affect the sliding and more frictional effect. So, it if the angle is low the projectile instead of penetration it will slide

So, impact angle between 30 degree to 45 degree lesser time for energy dissipation, presence of frictional effect. And impact angle of 90 degree that there will be only peripheral area is under contact and no sliding will be there. If it is vertically is impacting there would not be any sliding impact velocity is also important.

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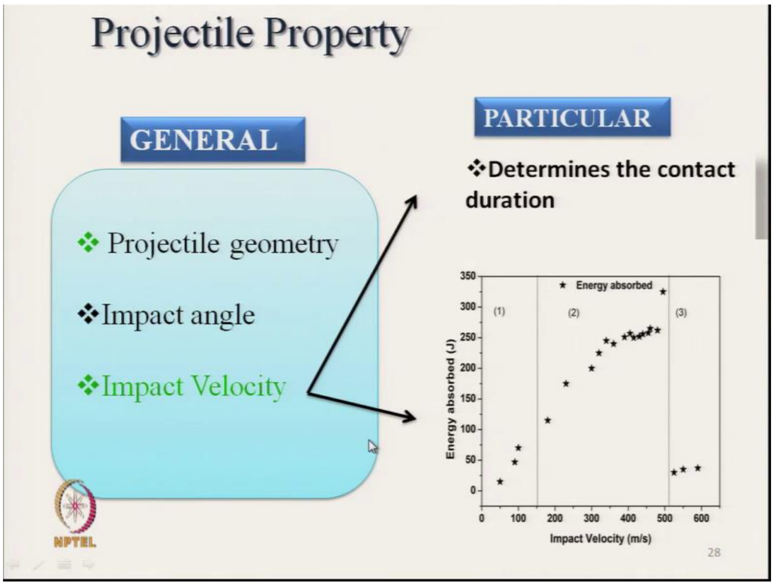

So, as the impact velocity is increasing here in the x axis it showing the impact velocity y axis it is showing the energy absorbed. As the impact velocity increases so initially the energy absorption will increase.

But at very high impact velocity it drops because the projectile simply penetrates through the fabric without much energy absorption. Now we will discuss the how to measure the performance of impact.

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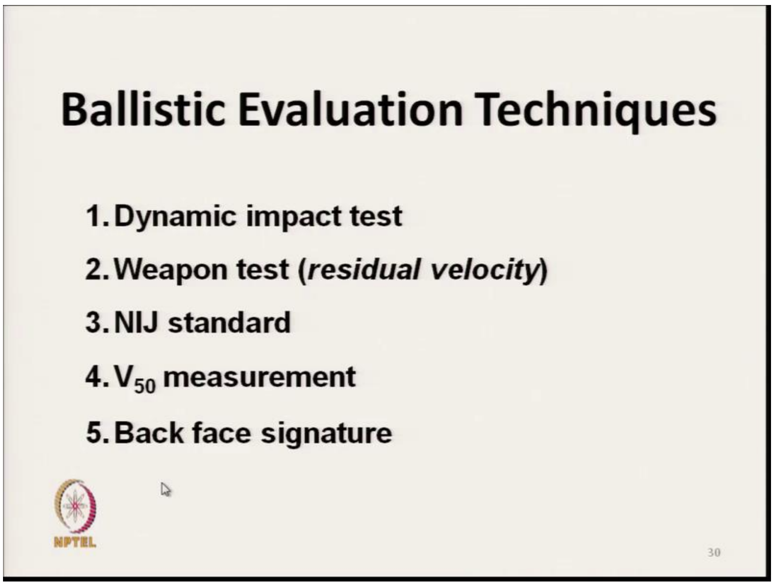

There are different methods so ballistic evaluation techniques are dynamic impact test weapon test which actually measures the residual velocity. So, after penetration what is the velocity remaining in the projectile that we measure.

So, we will see the NIJ standards. Then V_{50} measurement the concept of V_{50} measurement we will discuss and then back face signature. So, back face signature means the trauma level on the human body is assessed.

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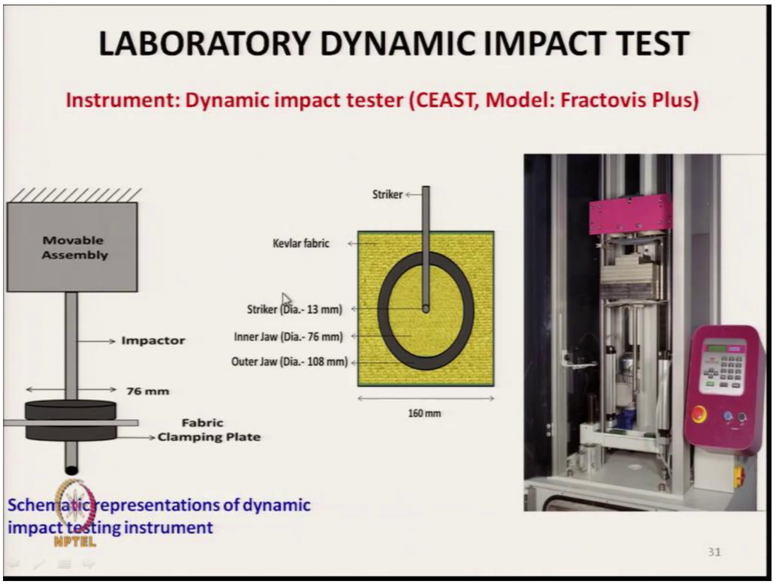

So, first we will see the dynamic impact tester. This is a diagram of the instrument ok. Here it is a schematic representation of dynamic impact test instrument where this is the impactor and tip of the impactor is here. And this is the impactor here the fabrics specimen is kept here and it is clamped, this is a clamp. And this is a impactor tip and from the top view.

We can see here this is a fabric specimen here striker and this is the clamp ok. So, outer jaw of 180 millimeter diameter, inner jaw of diameter 67 millimeter, striker diameter here it is a 30 millimeter. So, at the centre it will it is strikes at certain speed. And we measure the energy absorbed and also the diameter of the hole created that we can also measure.

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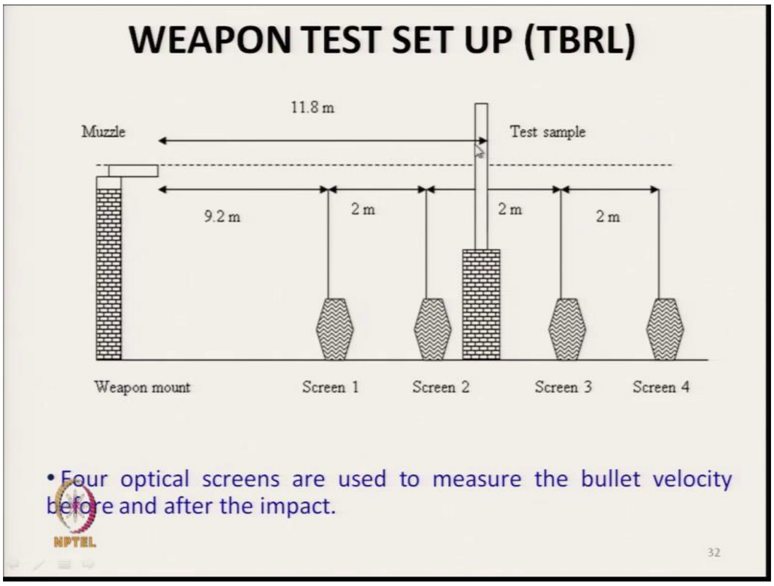

Another test is that weapon test setup, this is weapon test where there are different screens. Screen 1, screen 2, screen 3, screen 4 these are the different screen. So, four optical screens are used to measure the bullet velocity before and after the impact. So, different screens are used. So, we need to calculate the difference in speed for that we have to measure the speed of bullet before striking the fabric and the speed after it is penetrating through the fabric.

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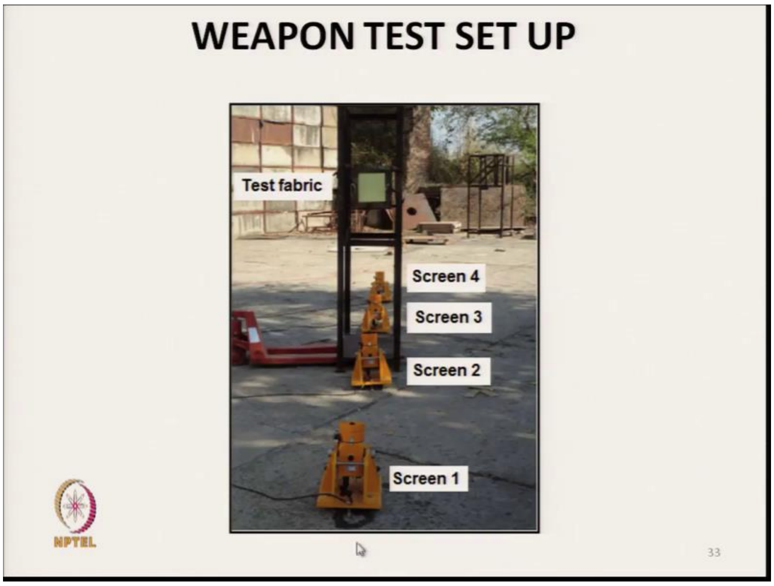

So, this is a test system where this is screen 1, screen 2, screen 3, and screen 4 are there and this is the fabric specimen. So, we can if we measure the speed between this before striking and after striking we can calculate the energy absorbed.

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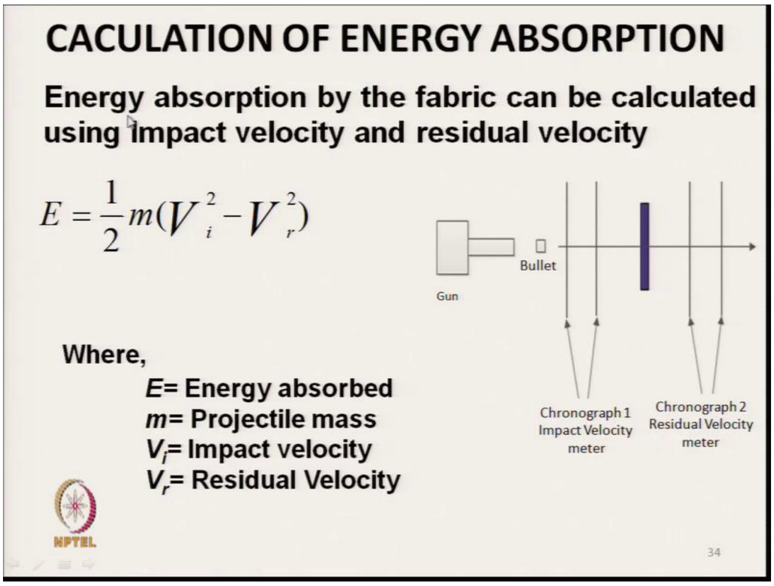

So, this is the energy absorption by fabric can be calculated using impact velocity and residual velocity. So, these are the different sensors here. So, energy absorbed E equal

$$E = \frac{1}{2} m (V_i^2 - V_r^2)$$

Where,

***E*= Energy absorbed**

***m*= Projectile mass**

V_i= Impact velocity

V_r**= Residual Velocity**

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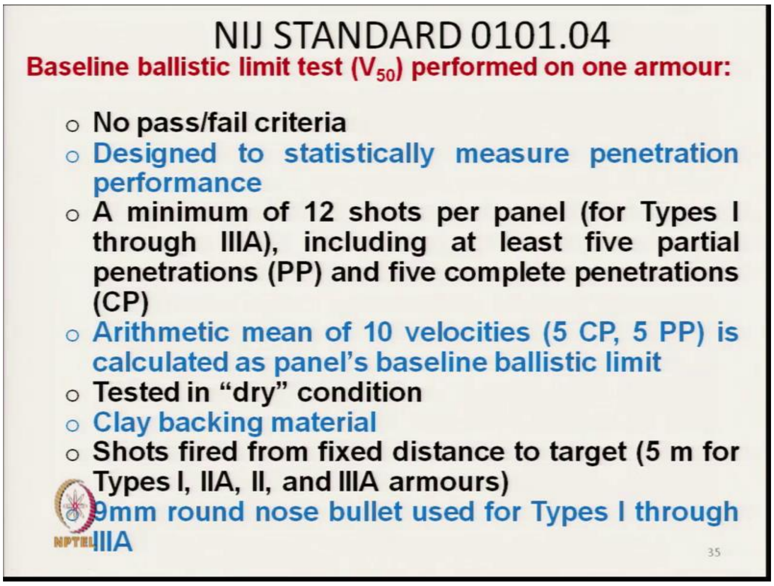

And as far as NIJ standard 0101.04, Ballistic baseline ballistic limit which is said as V_{50} which is performed on one armour. So, the method is here no pass fail criteria is decided only the velocity, which we try to find where the probability of penetration is 50 percent that is denoted as V_{50}. So, designed to statistically measure the penetration performance.

A minimum of 12 shots per panel for type I to type III A of this ballistic vests including at least five partial penetration, that is; PP and five complete penetration should be there. Out of 12 shots we have to have at least five complete penetration and five partial penetration then arithmetic mean of ten velocities. So, we all we will be changing the velocity from low velocity to high velocity to have five at least partial penetration and five complete penetration.

So, we will take the arithmetic mean of all 10 velocities. And the tested in dry condition so the specimen should be in dry. And clay backing should be there to measure the back face signature that we will see. Shots fired from fixed distance to the target that is the 5 meter from the armour. So, at fixed distance the shots are fired at different speed. So, that the there are at least five complete penetration and five partial penetration takes place and where the 9 millimeter round nose that is hemispherical bullet are used.

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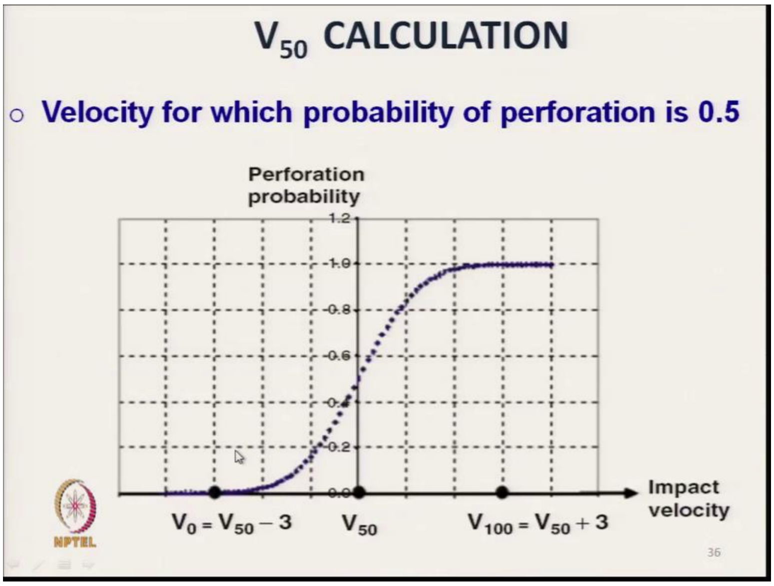

So, this is the velocity probability curve. So, as the velocity increases so where velocity say 0 so there is no penetration. And as we increase the velocity, the probability of penetration increases and when the velocity is say V_{100} at that velocity there will be 100 percent penetration.

So, if we plot the velocity versus probability of perforation so we will get this type of plot. And the velocity where the probability is 50 percent that velocity is known as V_{50}.

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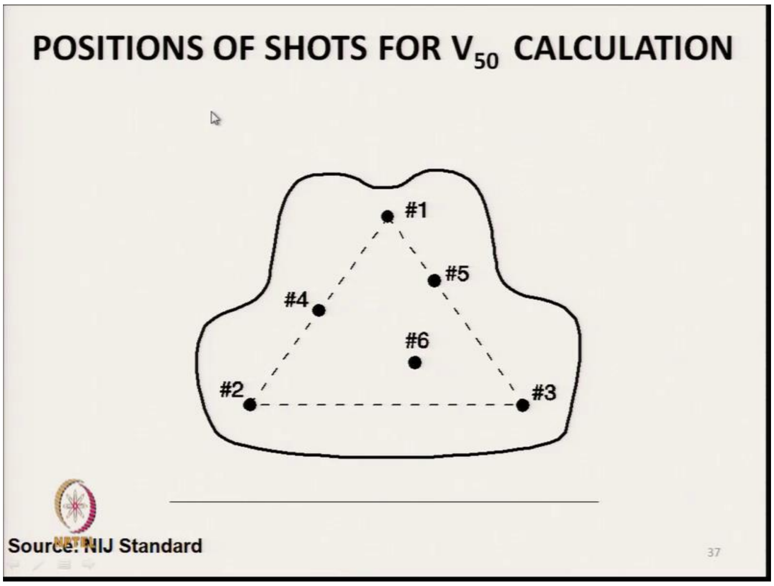

And positions shot for V 50 calculation these are the different positions where the bullets are being shot.

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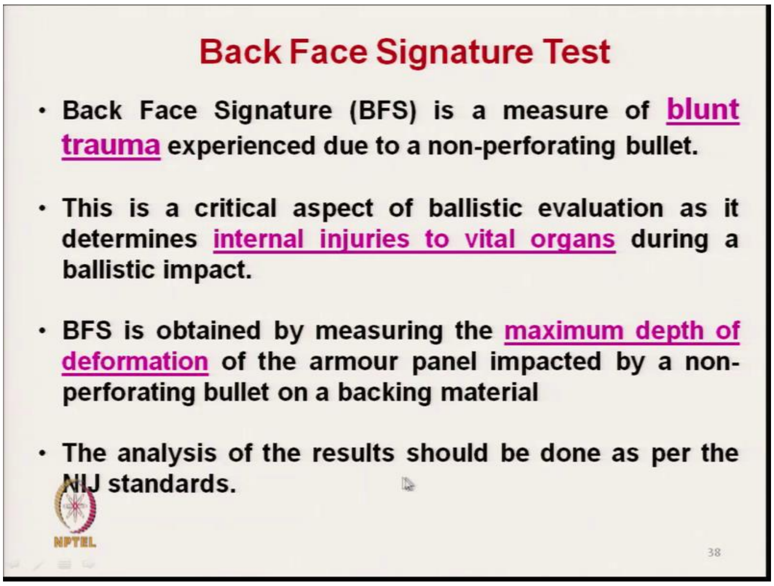

And the back face signature we can get this test is that the back face signature is measure of blunt trauma experience due to non perforating bullet. So, bullets are not being penetrating through the fabric structure. And that will create a blunt trauma at the backside. This is a critical aspect of ballistic evaluation as it determines the internal injury to vital organs during ballistic impact. So, that back face signature is extremely important to be evaluated BFS is obtained by measuring the maximum depth of deformation.

So, that if it our body at which depth up to which depth the bullet will have impact that can be measured. So, maximum depth of deformation of the armour panel impacted by non perforating bullet on the backing material. So, we will have a backing material so that the depth of deformation we can measure. The analysis of the result should be done as per the NIJ standards.

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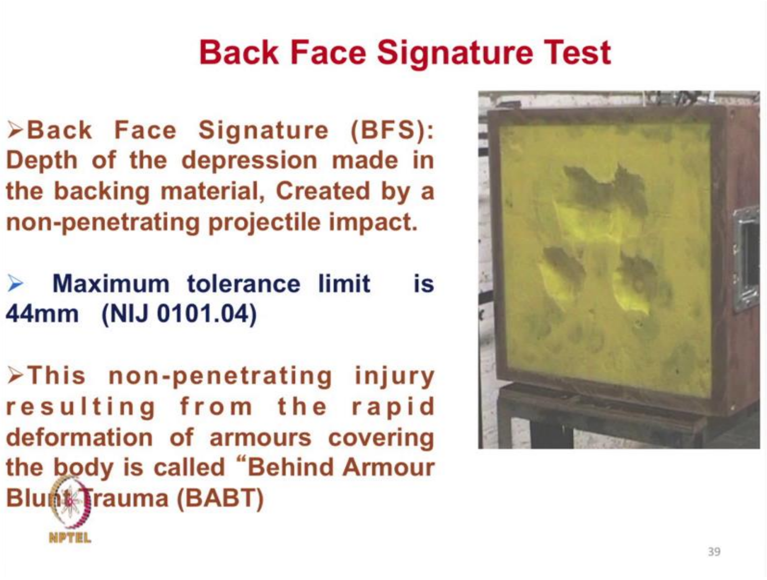

So, this is the back face so and the depth we can measure ok. Back face signature it is a depth of the depression made in the backing material. This yellow colour this is the backing material created by non perforating projectile impact ok. Maximum tolerance limit is 44 millimeter as per NIJ standards, this maximum depth should be 44 millimeter.

This non penetrating injury resulting from the rapid deformation of armours covering the body is called Behind Armour Blunt Trauma BABT. And that will indicate the level of injury which over the person who is wearing the vest will have will face. Now let us see the type of deformation which take place in hard body armour and soft body armour.

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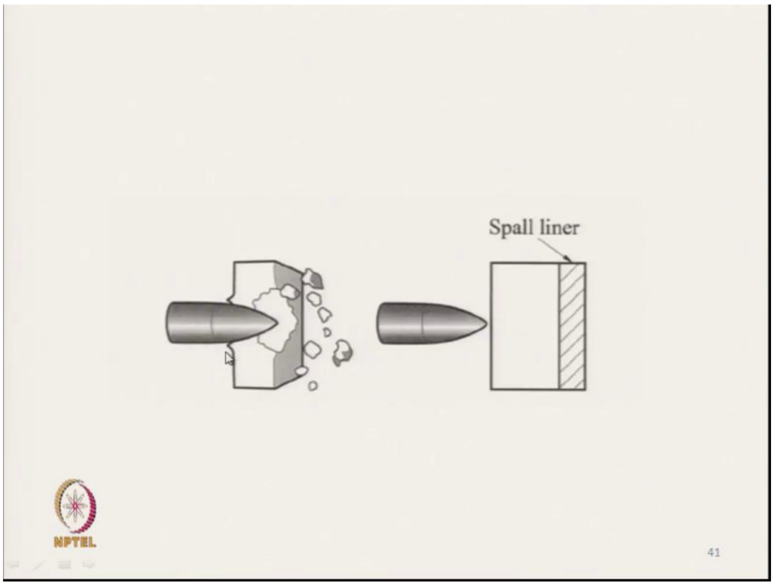

In hard body armours the deformation if it penetrates and the particles this particles will be coming out from the other side. That is why spall liner is provided so that it stops these particles to come out from the structure.

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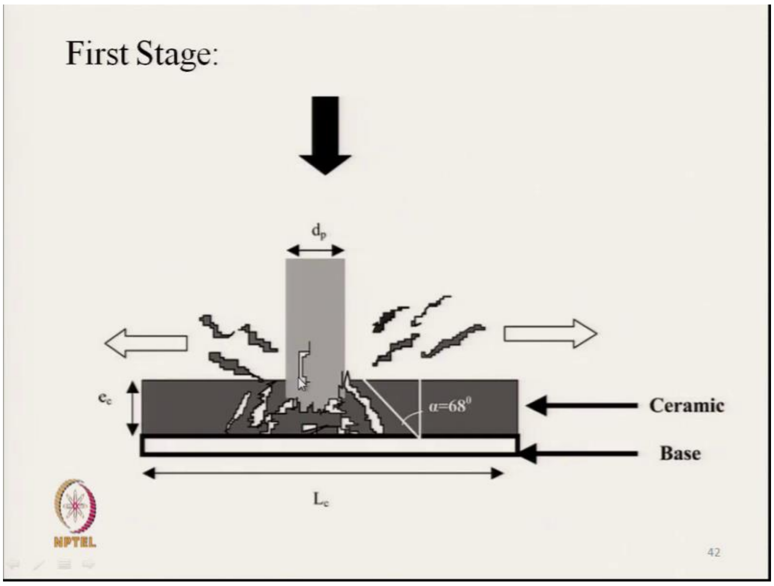

So, this is the first stage; once it is striking the particles are coming out this is a ceramic hard body armour and this is the base and after certain time.

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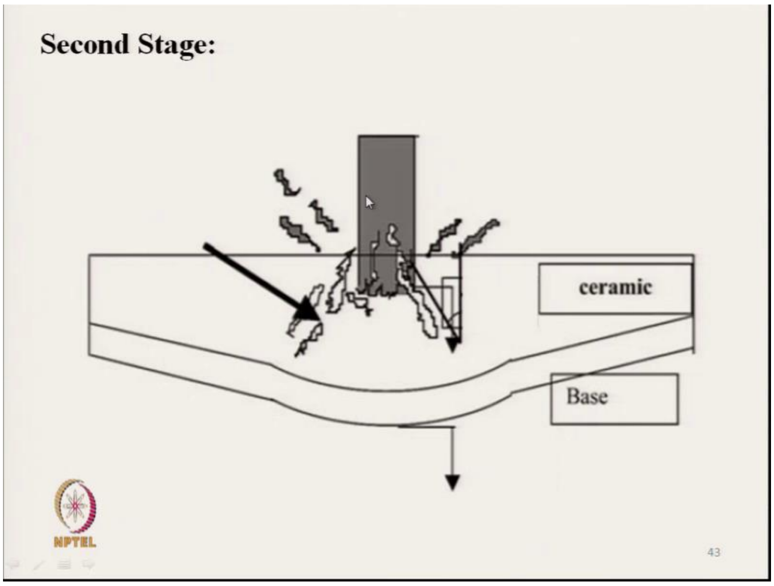

Next stage this is the state where the base will have deformation and there will be particles.

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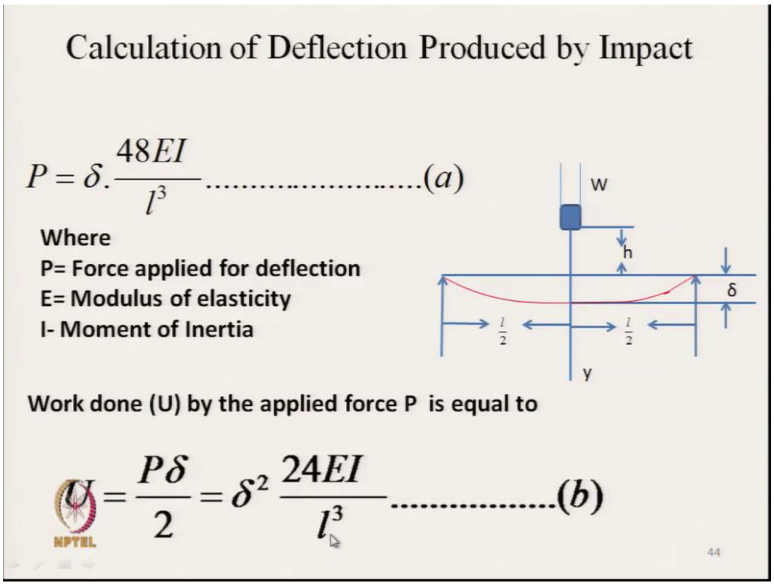
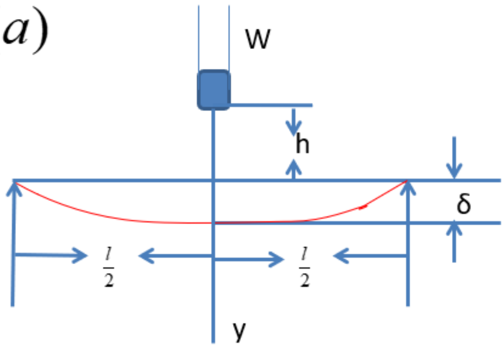


Now, if we calculate the deflection produced by the impact this is the actual deflection ok. This is the delta is the actual deflection.

$$P = \delta . \frac{48EI}{l^3} ....(a)$$



Where
P= Force applied for deflection
E= Modulus of elasticity
I- Moment of Inertia

Work done (U) by the applied force P is equal to

$$U = \frac{P\delta}{2} = \delta^2 \frac{24EI}{l^3} ....(b)$$

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If h denotes , as before, the distance fallen before impact, the equation for determining δ is

$$W(h+\delta) = \delta^2 \frac{24EI}{l^3} ....(C)$$

Where
W= Weight of the impactor,
h= the distance of the fallen before impact

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$$W(h+\delta) = \delta^2 \frac{24EI}{l^3} \ldots\ldots\ldots\ldots\ldots\ldots(C)$$

Where
W= Weight of the impactor,
h= the distance of the fallen before impact

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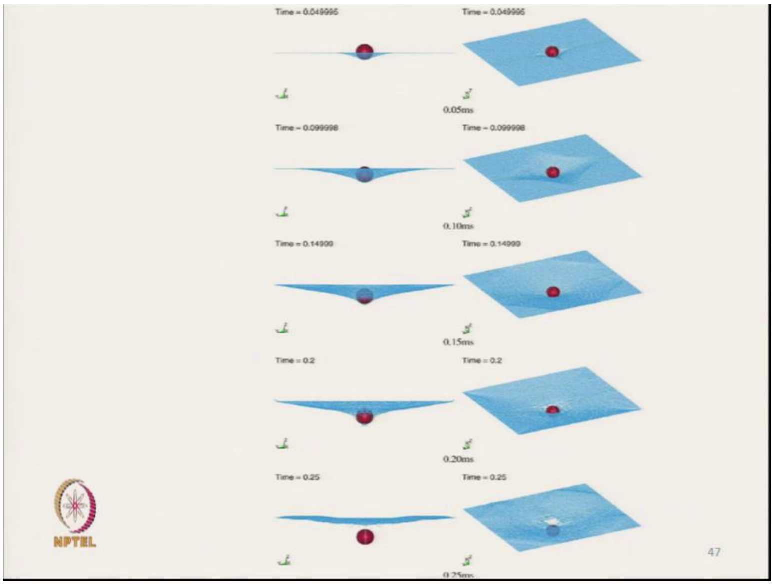

So, these are the schematic representation. So, gradually the impactor is impacting on the material and deflection is taking place. But if the velocity is very high it may sometime penetrate through the structure this is the only one layer we are talking about.

And during this penetration the speed of this impactor reduces and this at this speed it will strike the next layer. So, in this way after certain time the this impactor will be actually which will stop inside the structure.

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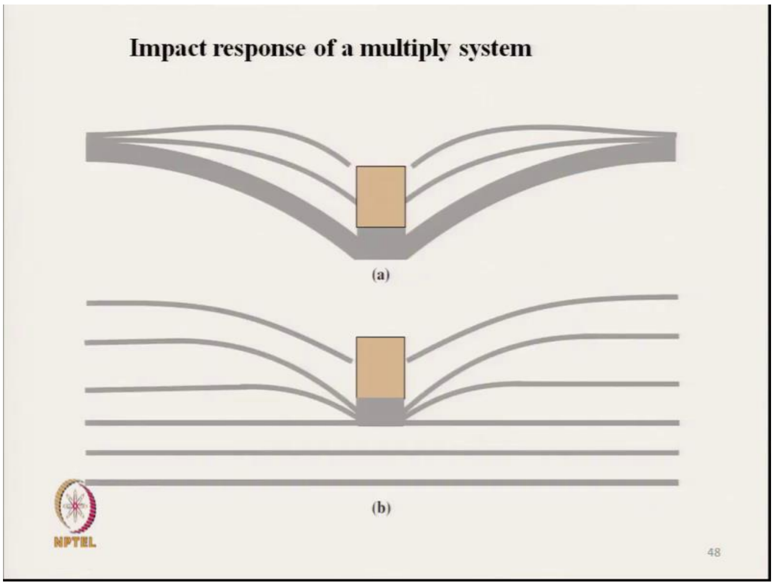

So, this is the type of representation first layer second layer third layer so there are different layers. So, it is penetrating through one layer, then second layer after second time there will be accumulation of layers next layers. So, it will ultimately stop in between this structures.

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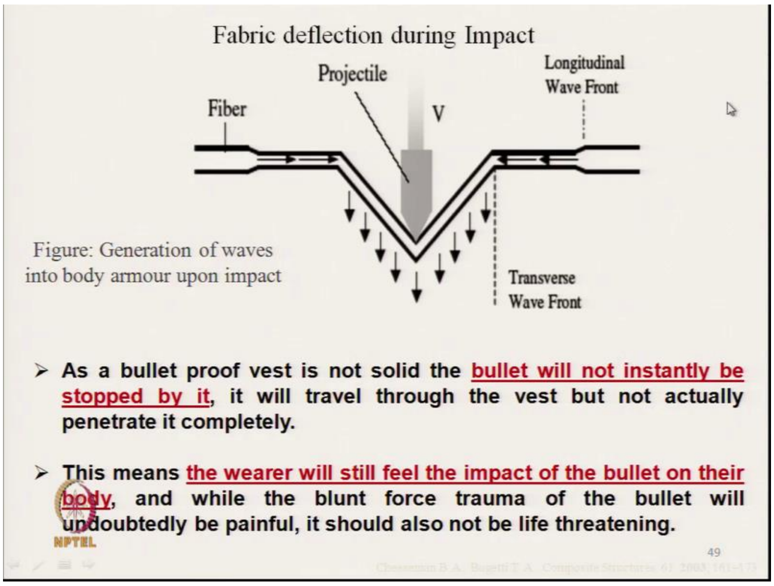

So, as we have seen that this will create and wave and that speed of this wave depends on the properties of fibre. So, as a bullet proof vest is not solid the bullet will not instantaneously be stopped. So, it will not be stopped instantly rather it will travel through the vest, but not actually penetrate it completely ok.

It will initially penetrate through few layers, but it will not be penetrating completely. This means the wearer will still feel impact of the bullet. So, that due to this deformation the wearer will feel the impact of bullet. And which will be actually blunt trauma and which may not be life threatening.

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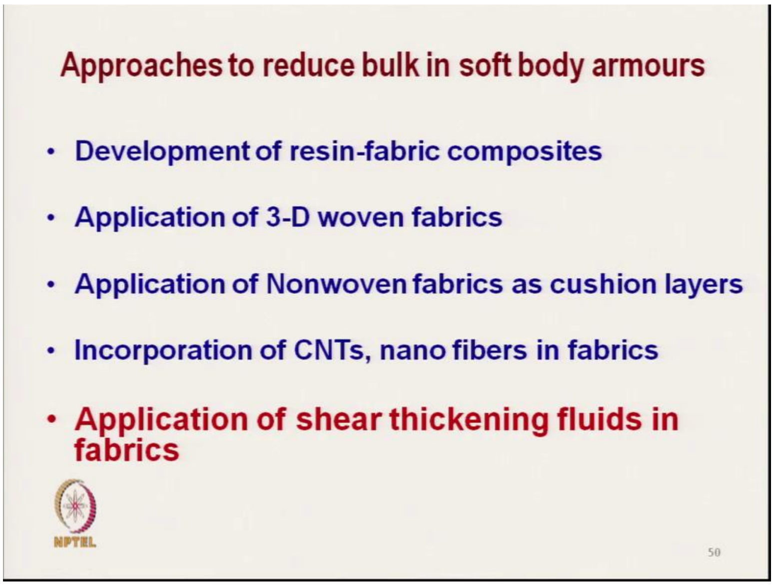

So, approaches to reduce the bulk in soft body armours. So, we have seen that in soft body armour we can use a number of layers say 30 40 layers that will effectively increase the bulk of the body armour. So, there are different approaches which reduces the bulk. These are development of resin fabric composites, application of 3-D woven fabrics, application of non woven fabrics as cushion layers.

Incorporation of carbon nano tubes or nano fibres in fabrics and application of shear thickening fluid in fabrics. This application of shear thickening fluids in fabrics are having very positive results, they have very perfect bullet proof characteristics. So, we will discuss this shear thickening fluid aspects little bit.

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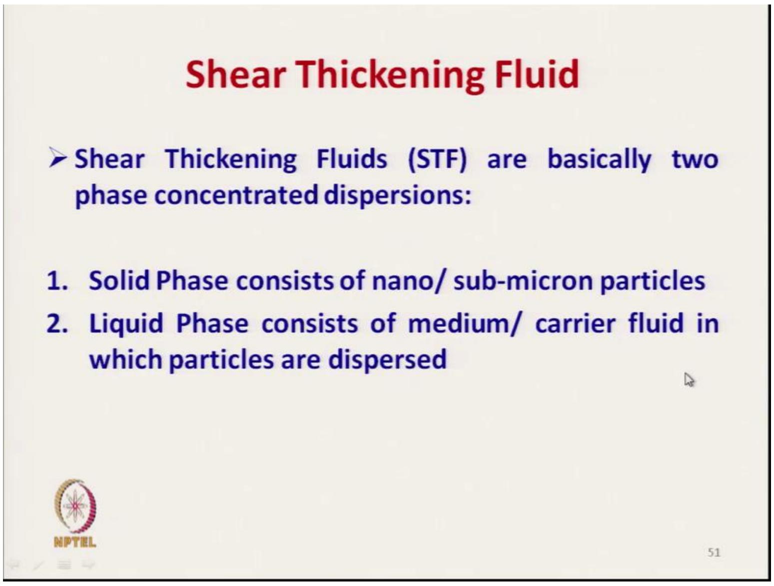

So, first you must understand what is shear thickening fluid. These are basically two phase concentrated dispersions. Phase 1; which is solid phase which consists of nano or submicron particle. And phase 2; is that liquid phase which consists of a medium or carrier fluid which carries the particles in dispersed condition.

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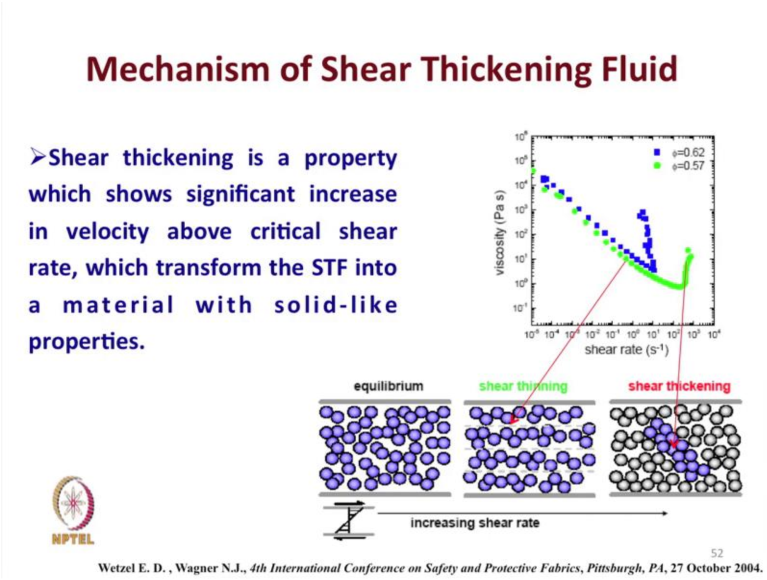

Now, if you see the mechanism of shear thickening fluid is that the shear thickening is a property which shows significant increase in velocity above critical sorry viscosity so this is the viscosity. So, shear thickening is that as we increase the shear rate shear thickening fluid will result significant increase in viscosity above a critical shear rate. So, this is the critical shear rate which transforms the shear thickening fluid into a material which is definitely solid like.

So, this here it will be like solid. So, this is the shear thickening fluid. As we increase the shear rate initially there will be shear thinning. So, viscosity is reducing at lower shear rate. But as we increase the shear rate after critical shear rate this particles will be get agglomerated and form solid like material. And this although it is a fluid at certain rate above certain rate it will behave like a solid material this is shear thickening point.

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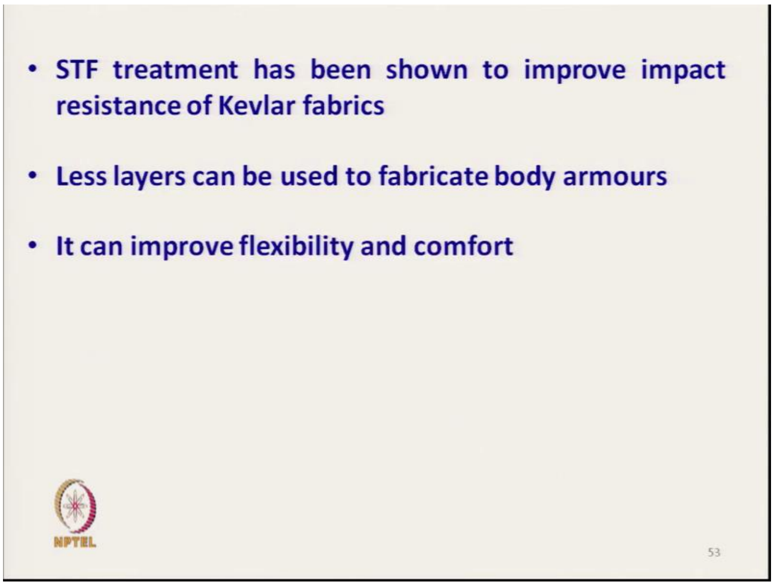

So, shear thickening fluid treatment has been shown to improve impact resistance of Kevlar fabric. So, if we use shear thickening fluid we can get effective characteristics with less number of layers. It can improve flexibility and comfort characteristics as we use less number of fabric layers.

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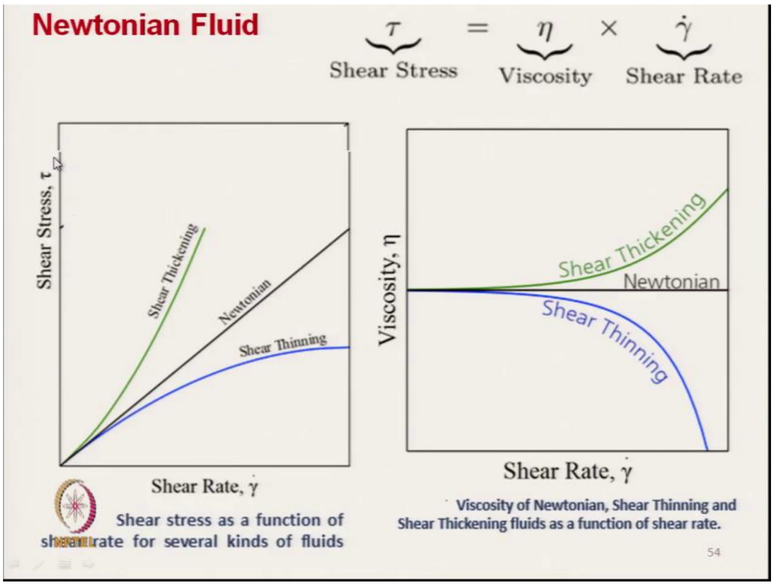

So, this curve shows that shear rate in the x axis shear stress in the y axis. For a Newtonian fluid the shear stress and shear strain they are proportional ok. So, that we will have constants so straight line. So, this is the value viscosity remains constant so for Newtonian fluid. But for non Newtonian fluid the viscosity may increase with the increase in shear rate or may decrease with the increase in shear rate.

If it decreases then the fluid is known as shear thinning. And if it increases the viscosity increases this will be shear thickening. So, this principle is being used to develop ballistic protective clothing with lower mass higher flexibility and higher comfort characteristics. So, we have come to the end of this session.

Thank you for patient hearing.