Technical Textiles
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Lecture No- 30
Ballistic Protective Textiles

Hello everyone, our today's topic is ballistic protective clothing. So first we will try to understand what is ballistic protection? Then we will see different parameters which affect the ballistic protective performance of clothing and what are the latest trends in developing the ballistic protective clothing?

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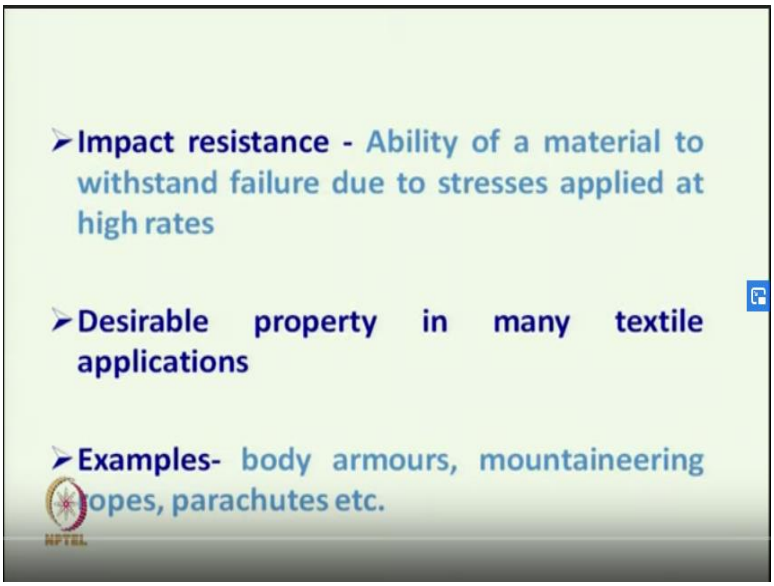

Ballistic protection means basically one aspect is that impact resistance its the ability of any material to withstand failure due to stress applied at high rate, so in ballistic material they always impact the material at very high rate of at a very high velocity and that stress is applied at very high rate. So it is a desirable property in many textile applications, these applications are basically body armors, mountaineering applications, mountaineering rope, parachute.

So in all these applications apart from many other applications, the sudden impact force is being applied and this impact force is applied at a very high rate of stress.

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Ballistic protective textiles or ballistic protection the threats are classified based on kinetic energy density KED, at different level of kinetic energy density the threats are classified like threats due to knife where velocity is typically 10 meter per second and there are two types of knife threats from a knife if it is from the blunt knife that is kinetic energy density will be around 17 Joule per square millimetre and if it is sharp it can go up to 210.

So special textiles or plates are used depending on the threat, for handgun the velocity is around 450 meter per second and the kinetic energy density initially it is 16 and after penetration finally, it is 4, so special textiles are used. Assault rifle like AK-47 where speed is around 720 meter per second kinetic energy density is 45 and composites are generally used in this type of threat, for high-velocity bullets SA 80.

Where velocity is 940 meter per second, kinetic energy density is 75 joule per square millimetre where we need that ceramic armors are used. The main problem with the ceramic armors or composite is their weight.

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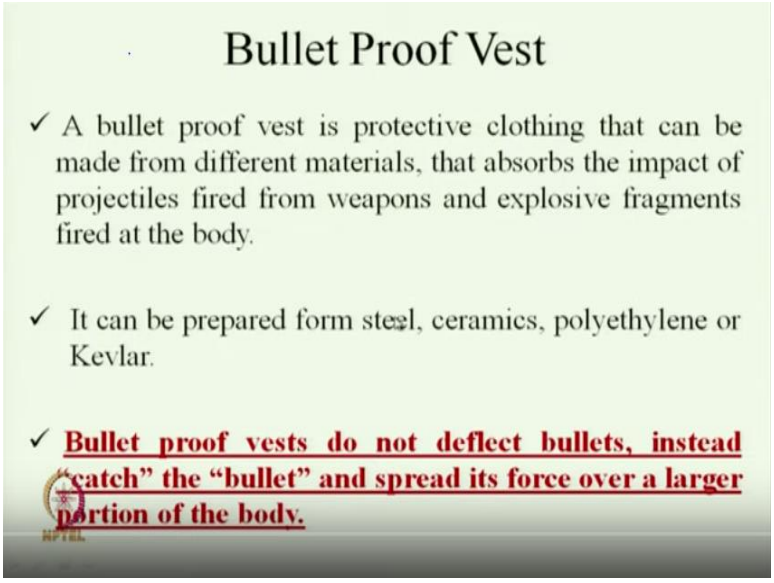

So we need bulletproof vest with lighter weight for our protection, so bulletproof vest is a protective clothing that can be made from different materials that absorb the impact of a projectile fired from weapon, basically the bulletproof vest it is function is to absorb the shock not to reflect. If we try to reflect then the impact will be on the body of the wearer instead if it absorbs the shock will be dissipated around the larger area.

So the bulletproof vest can be prepared from steel depending on the threats, ceramics, polyethylene or Kevlar, as I have already mentioned the bulletproof vest do not deflect bullets instead it catches the bullet and spread it is force over a larger portion of the body, first let us see;

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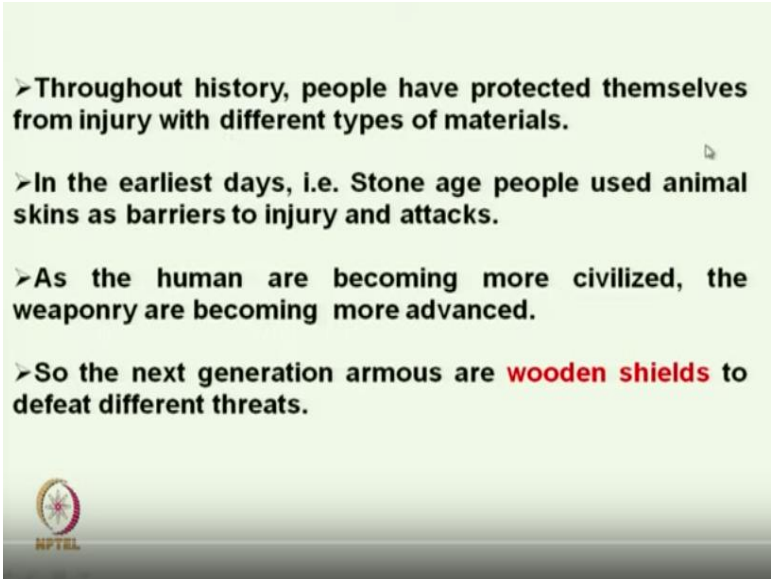

How the body armors evolved? If we see the history people have protected themselves from injury with different types of material. In the early days that is in Stone Age people used to use animal skin as a barrier to into injury and attack, so earlier this so animal skins were used, so as we keep on civilizing ourselves the weapons we use becoming more and more advanced and life threatening.

Looking at those advancements the animal skins were not enough, so the next generation armor are wooden shield to defeat different threats but main problem of wooden shields were they were not flexible and the weight wise that is heavier so it is not that convenient.

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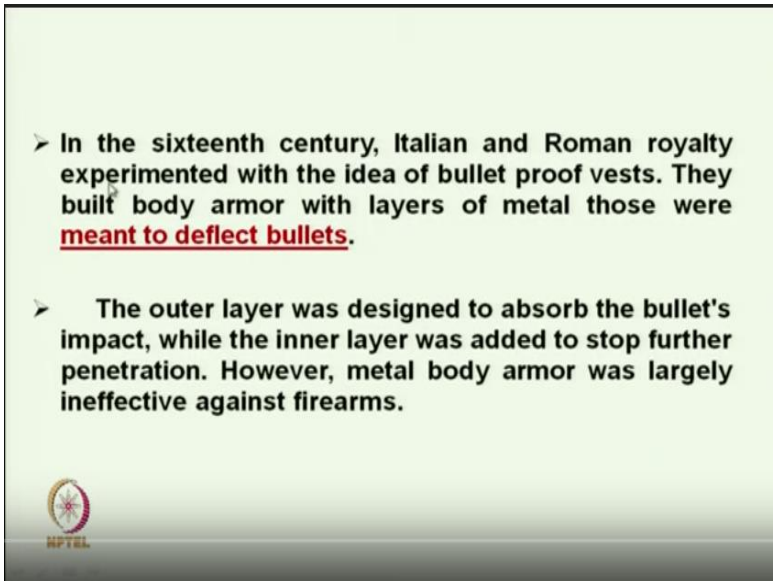

In the sixteenth century it was experimented in maybe Italy and Roman royalty with the idea of bulletproof vest they built body armor with layers of metals those were meant for deflecting the bullets. So earlier days the body amours were actually ideas to deflect the bullets with the layers of metals the outer layer was designed to absorb the bullets impact while the inner layer was added to stop further penetration, however metal body armor was largely in a largely ineffective against firearm.

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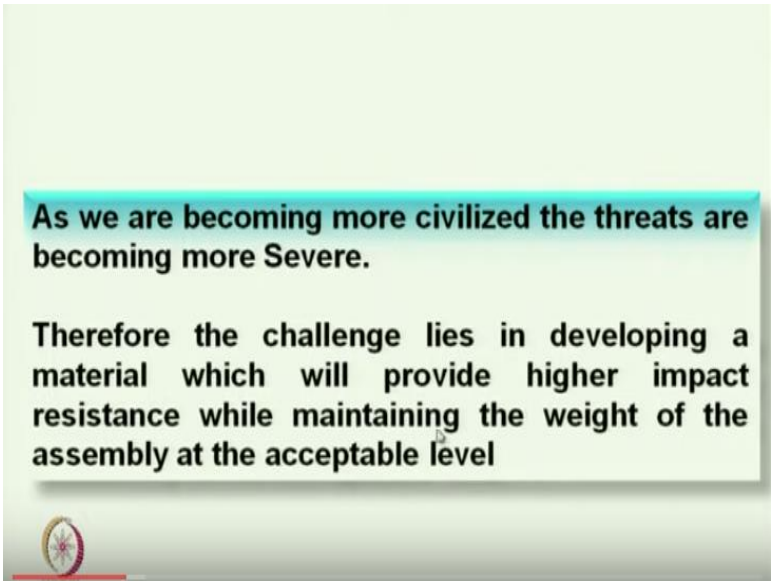

So as we are becoming more civilized the threats are becoming more severe. So therefore the challenges lie in the developing material which will provide higher impact resistance while maintaining the weight of the assembly at the acceptable limit. So as threat increases we have to protect our self but at the same time we should take care of that fact that it should not be very heavy otherwise the extra weight will affect the performance of the wearer. In modern day body armors we can divide into two categories;

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One is hard body armor, another is soft body armor.

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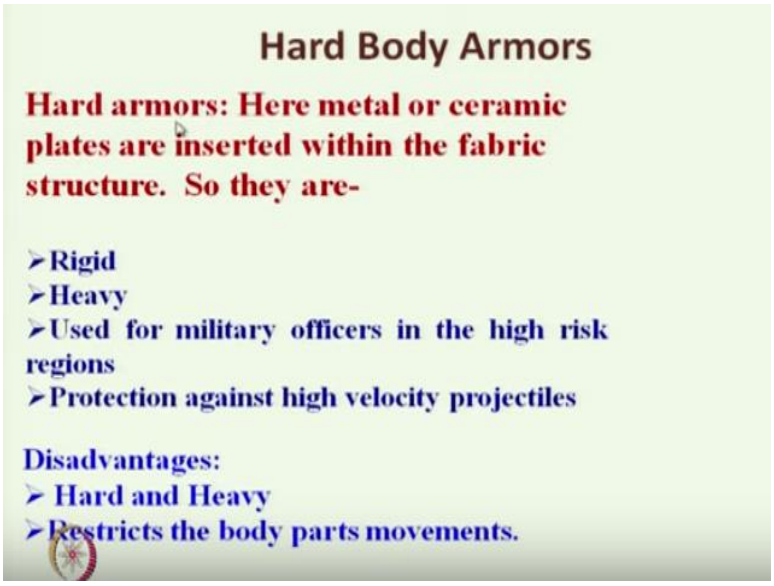

Say that it is hard here metals or ceramic plates are inserted within the fabric structure, so there will be fabric structure where metal or ceramic plates are inserted, so due to these metals or ceramic plates they are rigid, they are heavy and this metals and ceramic plates they are used for the high-risk region by military officers and their protection against high-velocity projectiles. So as they are made of metal and ceramics they are heavy.

So this is the main disadvantage of this hard body armor, they are not flexible and they are heavy in weight that is why they restrict the movement of body parts. Ideally there should have been flexibility but the hard body armor that restricts the body part movement.

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On the other hand, the soft body armor the idea was initially to enhance the flexibility with lighter weight. The soft body armors were actually are prepared using multi-layered woven fabrics or laminated fabric structure. They are more flexible than hard body armor lighter in weight and they are used for routine wear of police officers and security person, where the movement is very high frequent movement is required.

But relatively threat is less in those applications we can use soft body armors made of multi-layer woven cloth. So this soft body armors are effective for protection against low velocity projectiles but main disadvantage here, although we are trying to produce the flexible soft body armor but at least we have to use 20 to 30 layers of fabrics to provide sufficient protection, so after adding 20 to 30 layers of fabrics they become again inflexible in nature and this soft body armors can only be used for low velocity impacts where threats are less.

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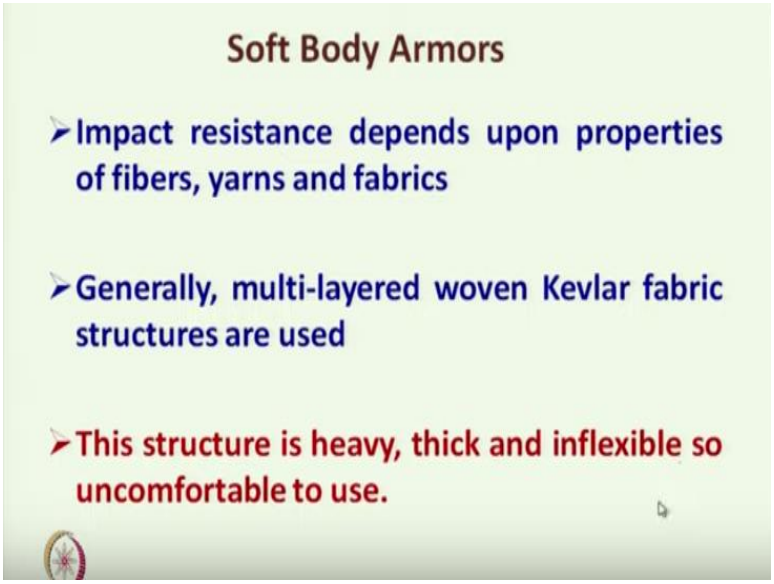

In soft body armor impact resistance depend upon the fibres, yarns and fabrics used in that fabric that in that different layers. Multi-layered Kevlar are generally used, the woven fabric made of Kevlar fibre is used in multi-layered fashion. Due to a large number of fabric layers the structure becomes again heavy and thick and they become inflexible, so again this multi-layer fabric become uncomfortable to use.

But to have sufficient protection we need a large number of layers but the present days research is in the area to reduce the number of layers and to reduce the mass of the overall body armor keeping the protection level same or to improve the protection level.

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So when we compare both hard armor and soft armor in short; it is rigid, it is more flexible, heavy, it is lighter, fabric structure combined with steel or ceramic plates, here in soft body armor we use only fabric structure and that too multi-layered woven or laminated fabric structure. Hard body armors are used for military officers in these high risk regions and soft body armor used for routine wear of police officers or security person.

Hard body armors are used for projectiles with high velocity and soft body armors are used for low velocity as of date, so soft body armor we can use for low velocity projectiles.

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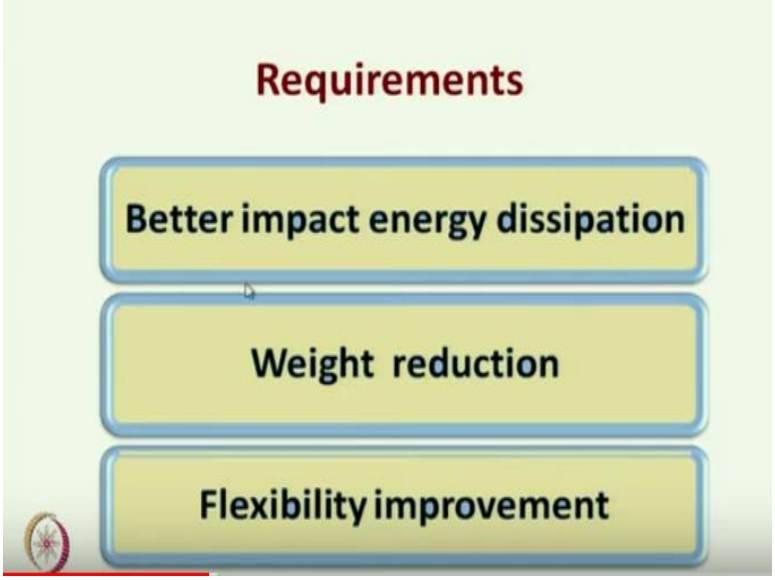

So main requirement of the body armors is that better impact energy dissipation, so it should dissipate the impact energy, so that the impact does not reach to the wearer's body, the body armor should be of lower in mass and flexibility should be there. So the target should be the weight reduction and flexibility improvement.

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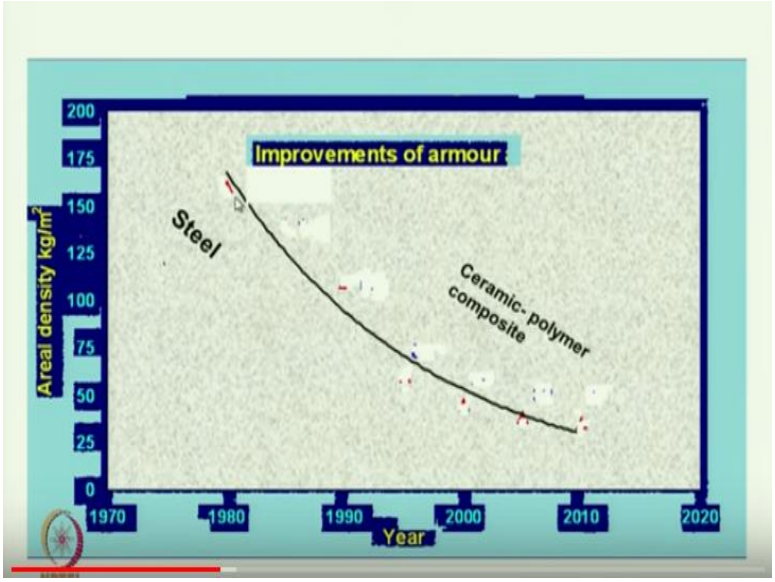

Here, if we see with the time the areal density is reducing gradually of body armors and the research direction is that to reduce this mass further so that it is very commonly used and the persons protection is high and due to the flexibility the performance, other performance will be better.

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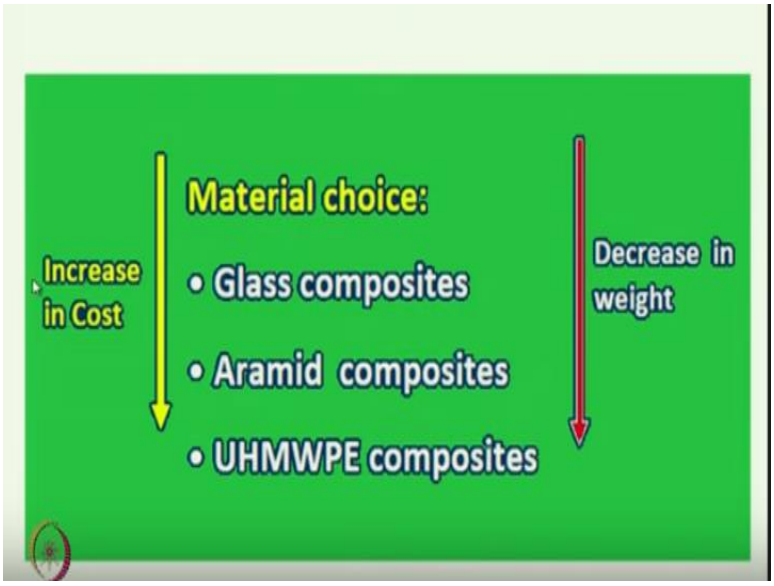

But with all these changes it goes with enhanced cost, so as we try to decrease the weight the cost is also increasing. So glass composite, Aramid composite and ultrahigh molecular weight polyethylene composites so these are actually this trend is to reduce the weight. So how this soft body armors evolved?

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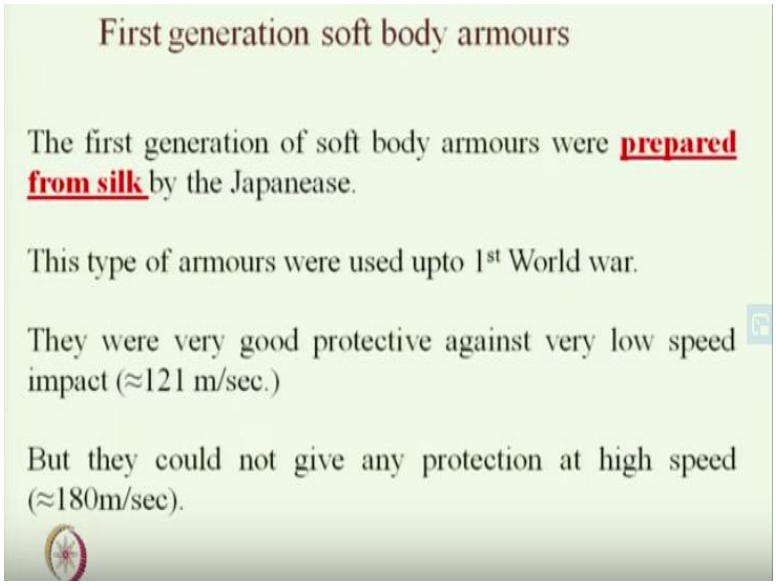

Soft body armor means with flexibility, the first generation of soft body armors were prepared from the silk by Japanese people. This type of body armors were used up to First World War with the silk, made of silk. And there the velocity protection that they are very good protection against the low speed impact around 121 meter per second. But once the projectile speed has increased due to increasing threat they could not give the sufficient protection.

So around 180 meter per second they fail. So then people started thinking of next generation that body armor. The next generation body armor was prepared from nylon flake.

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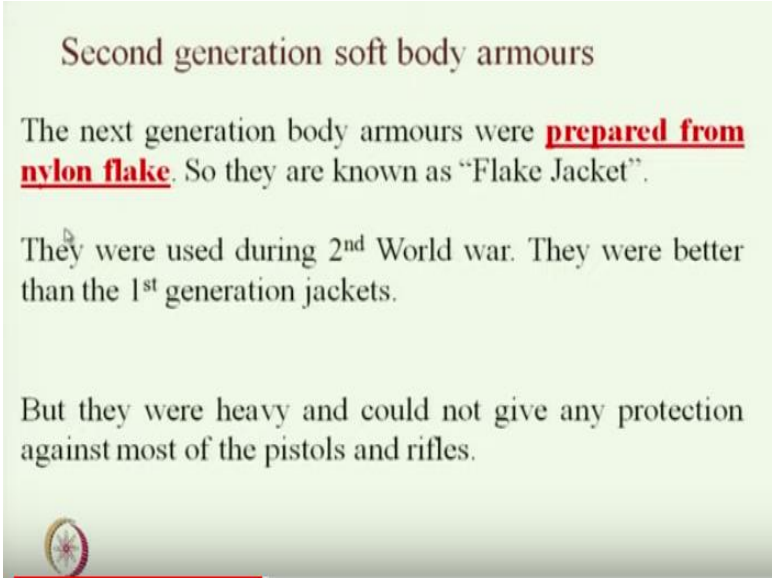

Which is inserted into the inside the jacket and that is known as the flake jacket, they were used during Second World War they are better than first generation jackets, because this flake were able to both reduce the velocity of impactor and dissipate the energy the main disadvantage of this nylon flakes or flake jackets were, they are heavy and they could not give any protection against most of the pistols and rifles.

When this pistols and rifles were developed at higher speed, they work on higher speed during due to this flake jackets failed.

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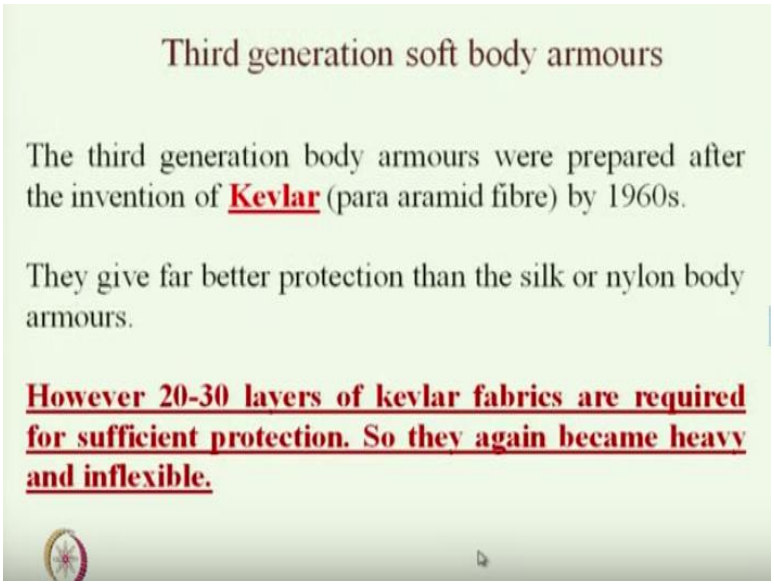

The third generation soft body armors were actually started after invention of Kevlar which is para aramid fibre, it is developed around 1960s. So after this development of Kevlar we have started developing the soft body armor. It is very strong fibre, high impact resistance, however 20 to 30 layers of Kevlar fabrics are required for sufficient protection, so they again become heavy and inflexible but still today the Kevlar is widely used for body armor application.

It may not be soft body armor due to the 20 to 30 layers of fabrics but still Kevlar's are widely used for the soft body armors.

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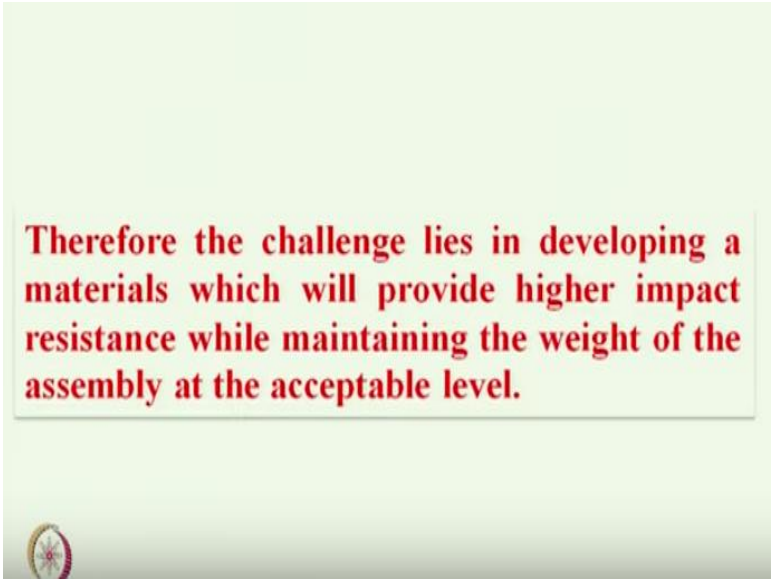

Therefore the challenge lies in developing a material which will provide a higher impact resistance while maintaining the weight of the assembly at acceptable level. That is the main challenges and the scientists they are working in this areas to reduce the weight as I have already mentioned.

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So the main requirements are better impact energy dissipation, weight reduction and flexibility improvement.

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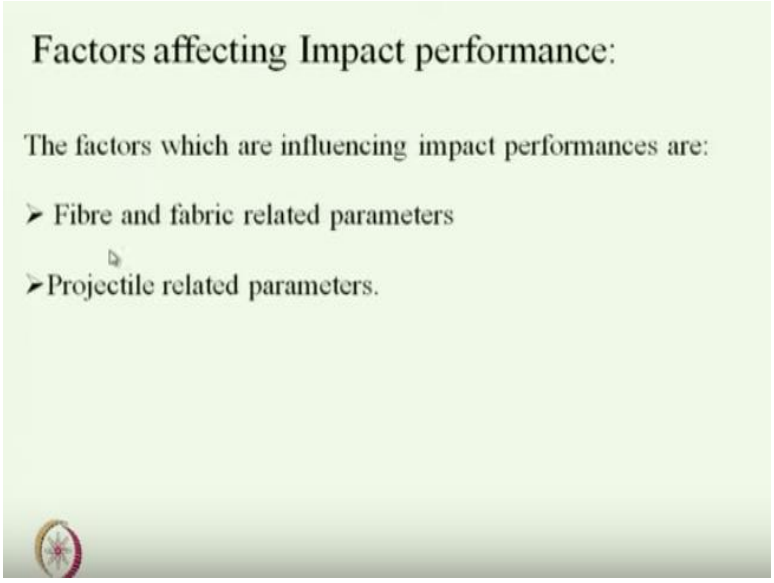

So the factors if we will try to see which affect the impact performances are fibre and fabric related parameters and second is the projectile related parameters. In fibre and fabric;

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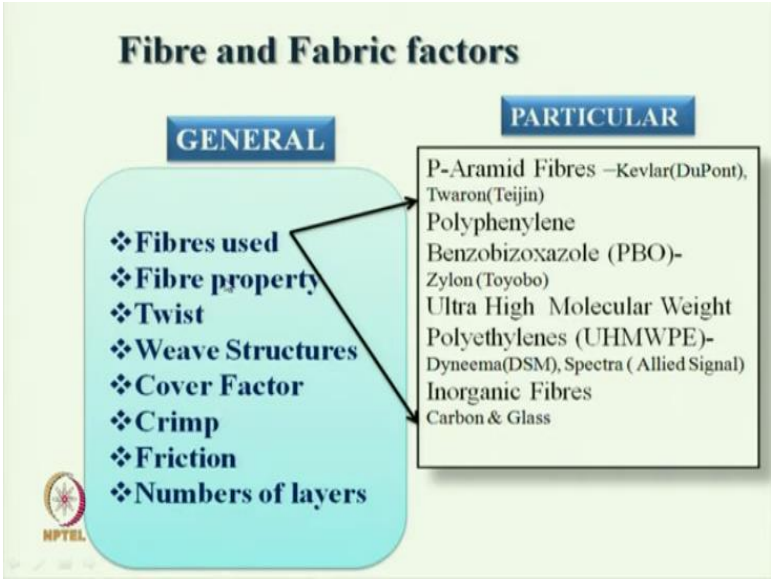

They are basically there are different parameters, if we see the fibres used mainly Para-Aramid fibres are used like Kevlar made by the DuPont, Twaron by Teijin, PBO fibres are used Zylon by Toyobo. There are different types of high-performance fibres used ultrahigh molecular weight polyethylene, Dyneema is also used in-organic fibres like carbon, glass fibres are also used, and different fibres are used for this ballistic protective clothing.

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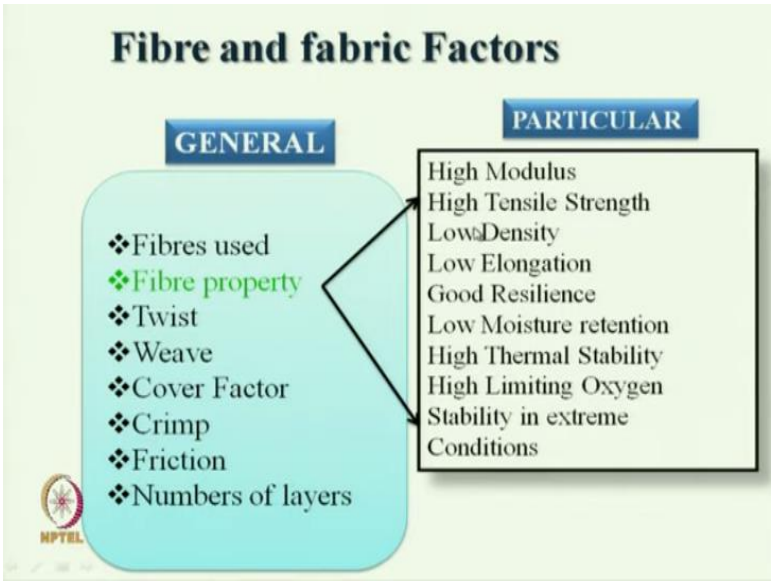

The important properties for this ballistic protective clothing, the fibre properties are it should have high modulus, so that the extension is not high, it can absorb the high-velocity impact. High tensile strength should be there it should not break due to the impact. Low density because we

need to reduce the mass of the clothing that that is the ballistic protective clothing, low elongation because if its elongation is very high then the bullet will simply penetrate it should prevent the bullet, so low elongation should be there.

Good resilience that means after impaction the structure should come back again. Low moisture retention, high thermal stability, high thermal stability is required in that fibre because during the bullet penetration at high speed the high heat generation is there, so it should not melt or shrink or deform, so high thermal stability is required, high limiting oxygen, stability in extreme condition.

Sometime it has been observed that at extreme heat or extreme cold condition the fibre gets degraded or maybe it becomes brittle it will lose their characteristics. So this fibre property is extremely important because this body armor mats are used in extreme conditions also. Now as far as a yarn characteristics is concerned twist is very important characteristics.

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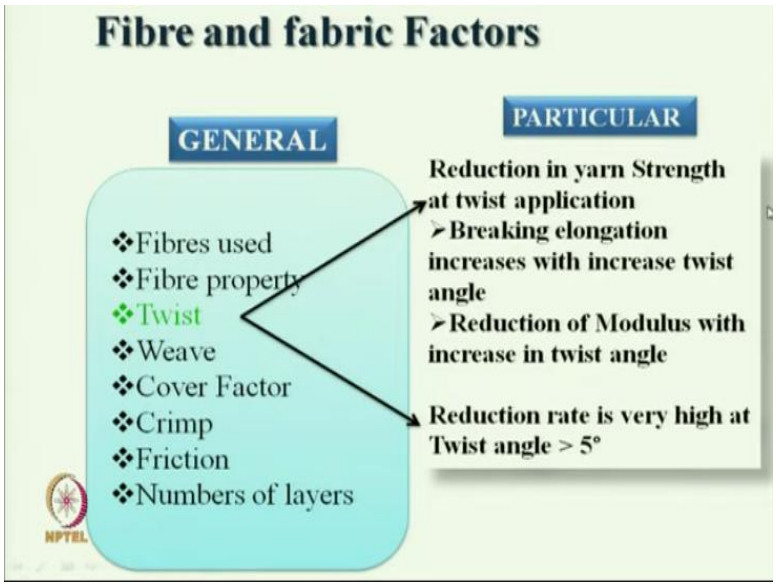

If we increase the yarn twist due to the obliquity effect the yarn strength reduces so we must try to use the twist as low as possible. Breaking extension increases with the increase in twist level so as the twist angle increases breaking extension increases and also it reduces the modulus, so we must keep the twist at lowest level and if possible we can also use the zero twisted filament.

Reduction rate is very high; reduction in modulus is very high at twist angle more than 5 degree. So twist angle always at very low level like less than 5 degree is recommended.

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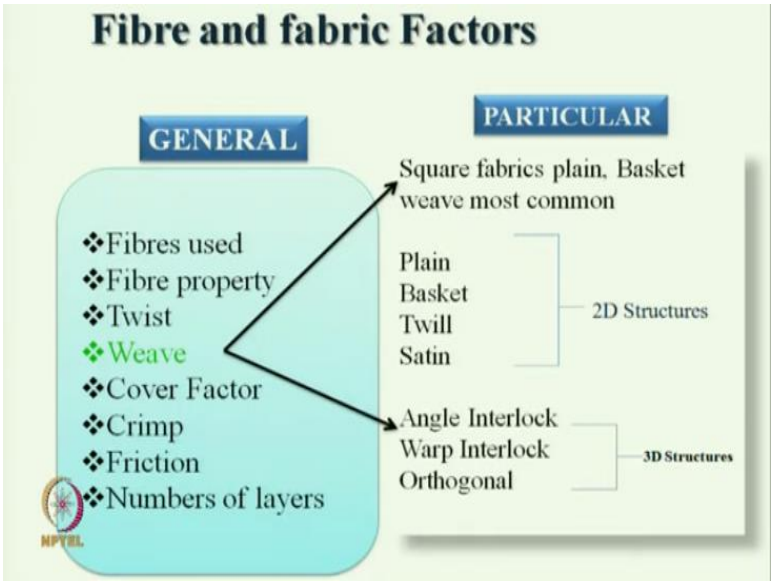

As far as if structure is concerned there are different types of weave structures are used, 2-dimensional fabrics and 3-dimensional fabrics are used. The main idea of weave structure is that we have to use basically square fabrics keeping the ends per inch and picks per inch same, so that during impact both warp and weft they come into action they perform equally. Basket-weave is most commonly used.

Apart from basket weave the plain structure, twill and satin are also used. As far as 3-dimensional structures are concerned angle interlock, warp interlock and orthogonal structures are used.

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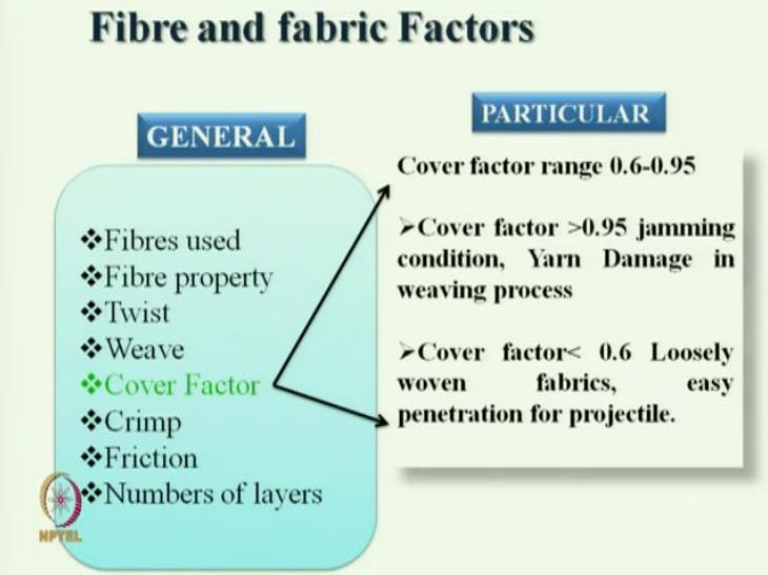

Next parameter is that cover factor, cover factor should be high because if the cover factor of fabric is layer low then the penetration or probability of penetration of the projectile is high, so cover factor range 0.6 to 0.95 within that range we must try to keep the cover factor. If the cover factor is more vary high it is more than 0.95 the jamming condition will take place, which will indirectly damage the yarn.

So once we try to enhance the cover factor increase the cover factor that means by keeping the yarns very close warp yarn and weft yarn, particularly in warp yarn if we try to keep the jamming condition during the weaving the up and down motion of the shed there will be rubbing against each other and the warp yarn, so during this rubbing there will be damages of yarn. But on the other end if we try to keep cover factor less than 0.6 the fabric structure will be loose and projectile penetration will be easy.

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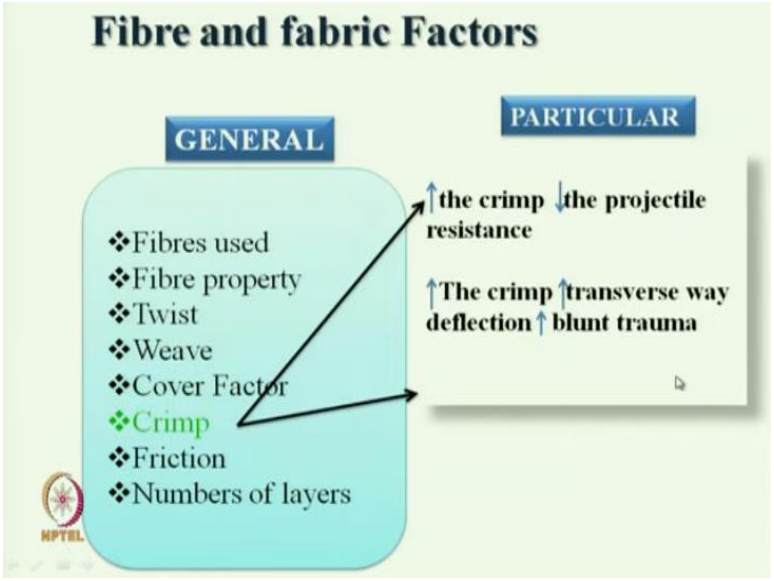

Next factor is the crimp; crimp we should try to keep as low as possible because higher crimp means the projectile resistance will reduce due to the straightening of the threads and with the increase in crimp the transverse way deflection will increase and blunt trauma will increase. So plant trauma is the damages or impact during the penetration once the bullet does not penetrate when arrested during the structure.

But the level of impact it is subjecting at the back side it is called blunt trauma. So higher crimp means while the bullet is actually striking the fabric there will be more deflection I will show

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This is a fabric with say yarn straighten there is no creep, another fabric with creep higher creep, so once the bullet is striking this is the bullet striking at high speed, so there will be deflection this deflection will be lower because the yarns are straightened and this will be absorbed by the straight yarns but in case of higher crimp once the bullet is striking initially there will be straightening of the threads straightening of the yarns will take place.

Initially the yarn is not taking the load, so once the yarns get straightened then the load will be shared by the yarn and due to this deflection at the back the other side there will be sufficient impact, this impact is known as blunt trauma.

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The bullets are not penetrating but still the wearer is getting shock higher shock, so this blunt trauma is increasing with the increase in crimp. So we must try to reduce the crimp level ideally the yarn crimp should not be there, so that the resistance is offered by that yarn.

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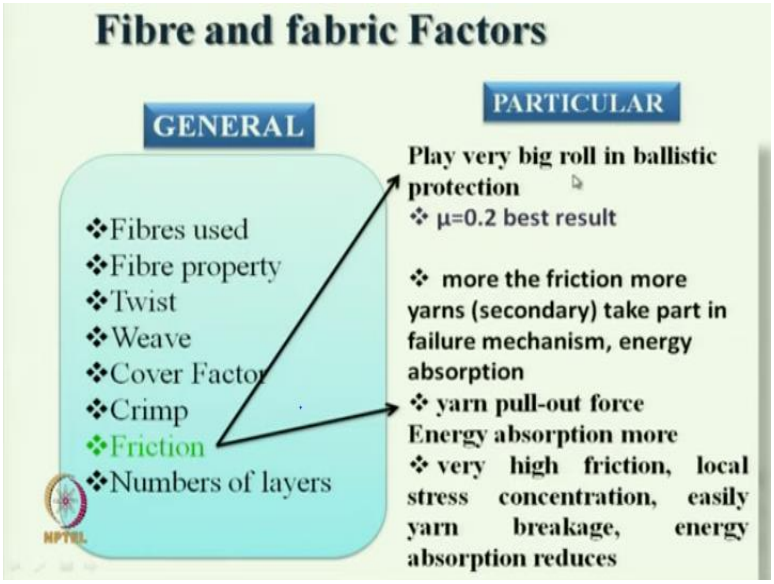

Next parameter is the friction, which is very important in ballistic protection typically the friction should be around 0.2 more friction, more yarn that take place. Because the lower fact, lower friction what will happen the individual wrap yarn will start sliding against each other and the in case of lower friction the individual yarn pull out may take place. Now let us see;

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This is one yarn the fabric made of you are with lower friction and here is another fabric made of higher friction, so meu low, meu high. Now suppose one bullet it is striking on this yarn due to low friction, yarn to yarn friction this yarn will be pulled this yarn will be pulled on the other side. So if I draw the side view, so this individual yarn will be pulled out due to low friction but here in this case once the bullet is striking on this yarn due to a high friction the other yarns will take part in absorption of the load the absorption of this energy or the bullet energy.

So this total wave will get dissipated on the other hand this yarn is will only take part in the absorption of energy. So it will simply slide it will simply pulled out from the structure.

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So yarn pulls out force that energy absorption more but at very high friction the problem is that local stress concentration will be there, easy yarn breakage and energy absorption reduces. So it should be high enough but it should not be very high. At a very high friction that energy that the localization of stress will be there and easily the yarn will break, instead the ideal situation is that with slide with small sliding the energy get that total the force, the total stress should get dissipated among the large area. Last one is that the number of layers.

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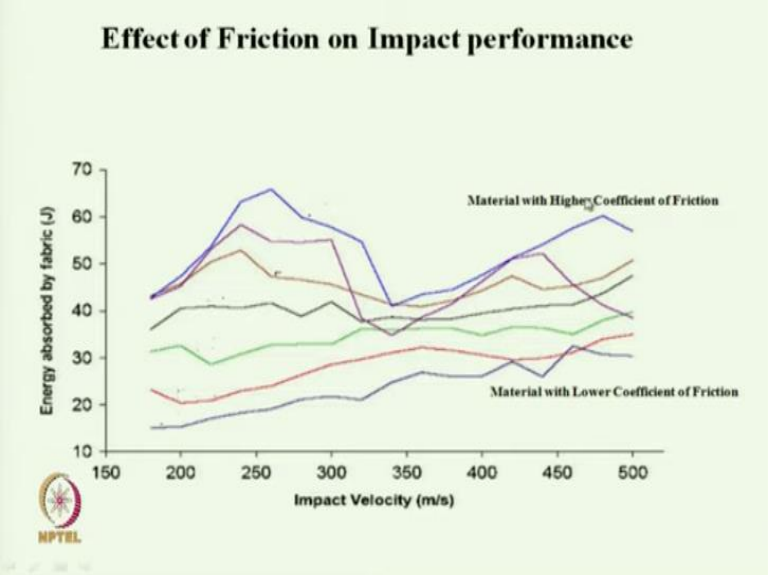

As we increase the number of layers the energy absorption becomes high here it is an impact of friction, this is the yarn with higher friction the energy absorption and this is a yarn with lower friction. So for different level of impact velocity the fabric made of higher friction yarn gives higher energy absorption.

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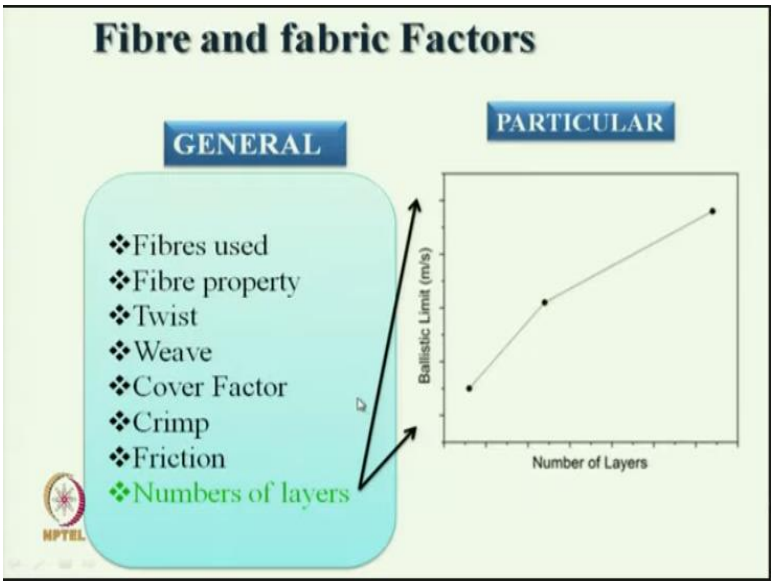

As far as numbers of layers are concerned as we increase the number of layer the ballistic limit increases. It is obvious that numbers of the more layers of fabrics are taking part.

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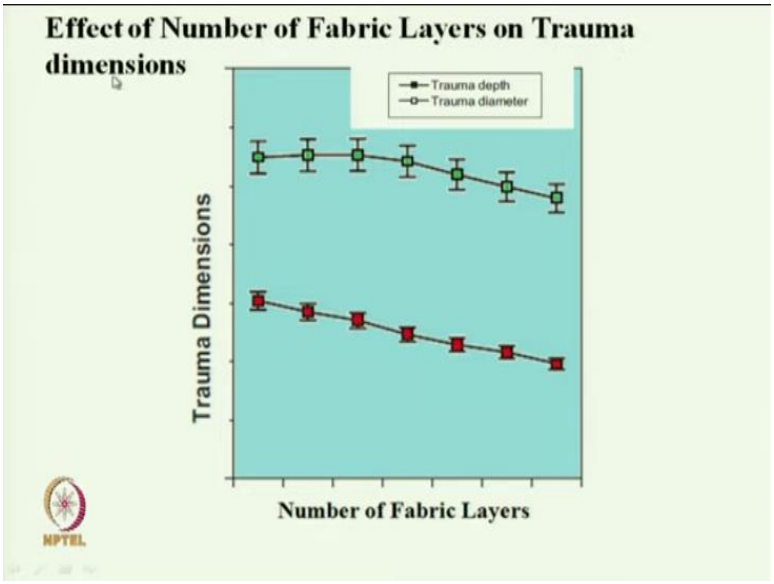

This picture also shows that the effect of number of layers on trauma dimension as I was mentioned, mentioning that the trauma these are actually expressed in terms of depth and diameter of trauma, so back face trauma.

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Now this is the fabric on this side, now the bullet is actually striking this is the bullet striking after striking the fabrics become due to the deflection. So this is and just after this fabric this soft material is placed this is some soft material some clay or some similar material is placed.

Now there will be deflection in clay and this is the depth here and this deflection this is the trauma depth initially this is the thickness and here it has been deflected, this is the trauma deflection.

This is a deflection of this surface, surface A, surface B, surface A which is facing the bullet and the diameter from this point to this point this is the trauma diameter. So if you see the front if this is the area of deflection, so this is the trauma dimension.

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So here if see we can see here, as we increase the number of layers the trauma dimension gradually reduces and here it is a trauma diameter reduces and also the depth of trauma reduce gradually.

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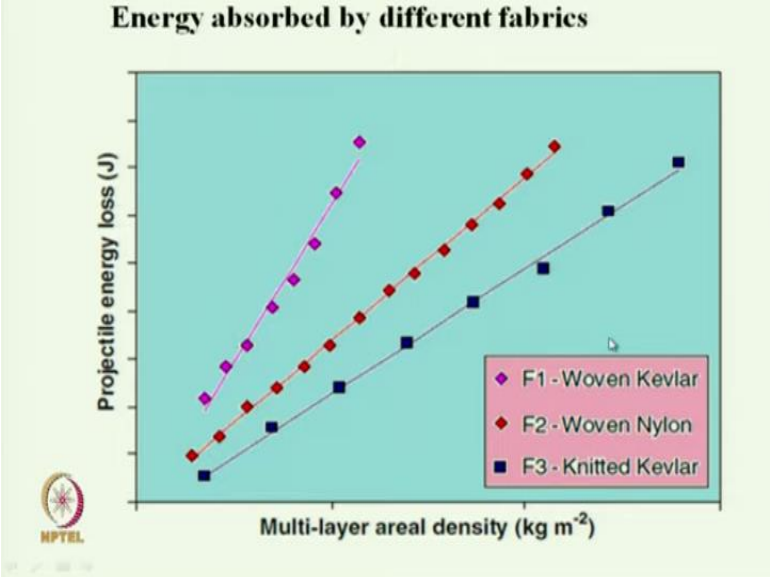

So projectile energy loss we keep on increasing the layers, as we increase the layers the projectile energy loss increases for different fabrics woven Kevlar, woven nylon and knitted Kevlar. So knitted gives less energy projectile energy loss, woven Kevlar is giving highest energy absorbed by the fabric due to its high modulus and high strength value.

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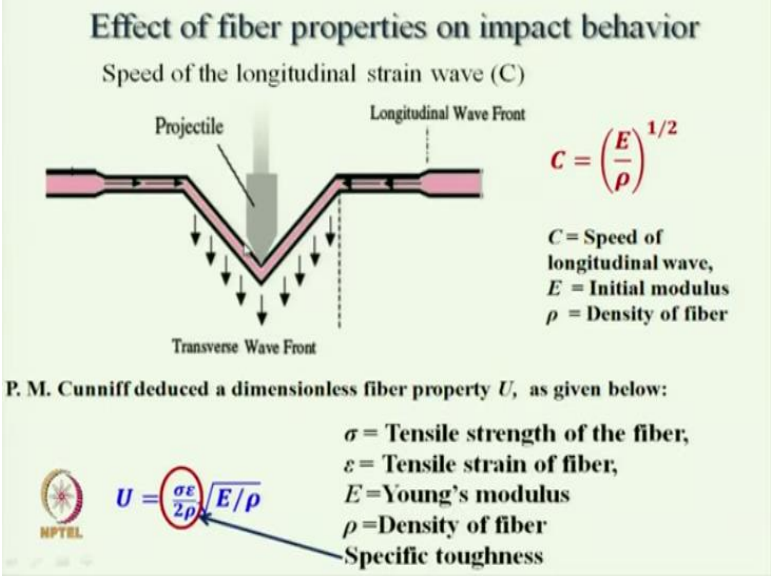

Now to select the fibers particular fibers for ballistic protective clothing we must understand few important parameters, here the projectile is striking and there are two types of waves will be there. Along the striking direction, there will be transverse wave on the fiber, this is a fiber there will be transverse wave and due to the stretch here there will be longitudinal wave front, so transverse wave front and longitudinal wave front and this wave formation.

Wave front velocity is extremely important just to know how quickly the impact energy will get dissipated, now this the term C is the speed of longitudinal wave and this is denoted by E by Rho where C is the under root E by Rho where E is the initial modulus and Rho is the density of fiber. So that means we need higher C means higher initial modulus that means quickly the wave will get dissipated the transversal that is longitudinal wave will get dissipated.

And the fiber density should be as low as possible, so to increase the value C and one parameter which dimensionless parameter fiber property which has been developed to evaluate the protective performance of the impact protective performance of a particular fiber. So the term U is given by Sigma multiplied by epsilon divided by 2 into Rho. Sigma is tensile strength of the fiber and tensile strain of the fiber and density of the fiber.

So this parameter is known as specific toughness and multiplied by the speed of longitudinal wave, so this parameter U is the dimensionless parameter and higher the U value the better will

be it is impact resistance or that for the projectile, it can hold the projectile. So higher impact behaviour will be there.

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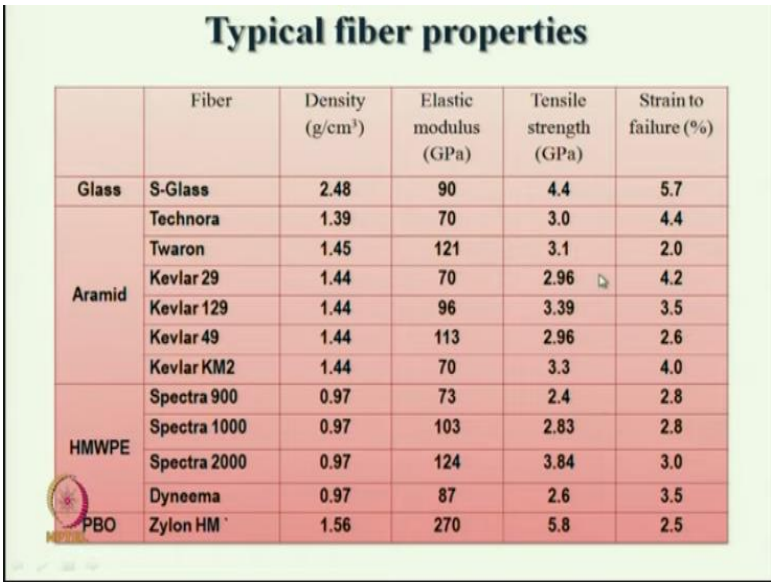

These are the general properties of some of the fibers used for ballistic protection glass, aramid, polyethylene, and then PBO. So high molecular weight polyethylenes like spectra, dyneema are used for this bullet proof fabric, PBO is also used.

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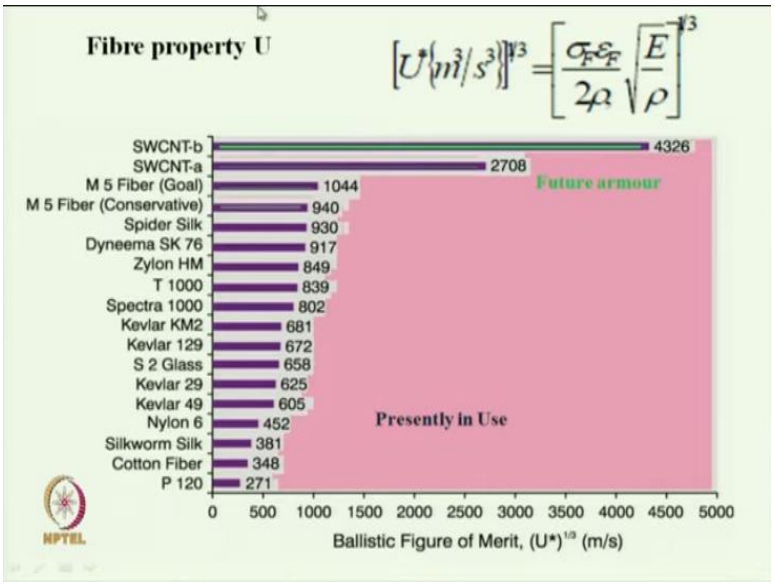

And from this if we get the knowing the property we can calculate the U-value fiber property U value, so these are the U values of different fibers used where Kevlar is around 680, spectra 802, spider silk these are the for future armor. So the development in armors body armors will be in

this direction where spider silk or different carbon nanotube composites are used apart from fiber and fabric characteristics the projectile properties are also important.

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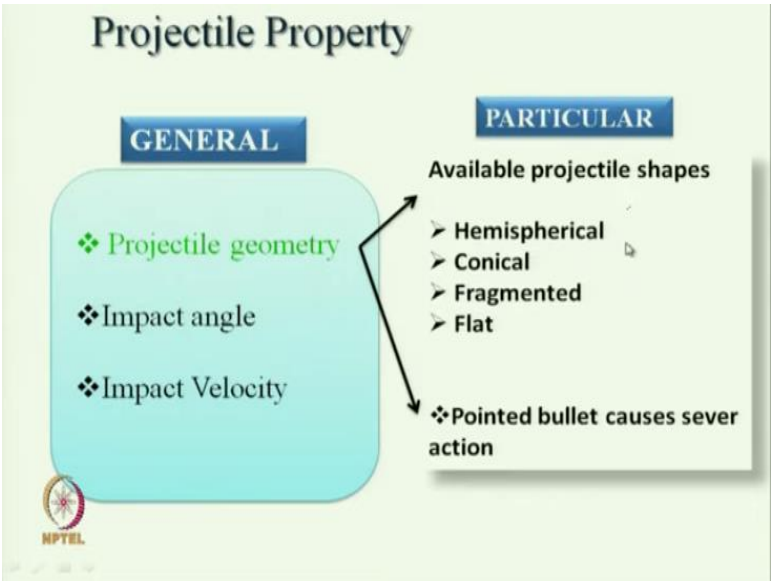

The projectile properties are; first is projectile geometry there are different types of projectiles geometric shapes are available based on the tip dimension that is the hemispherical, conical, fragmented, and flat, whereas pointed bullet causes severe action that is conical.

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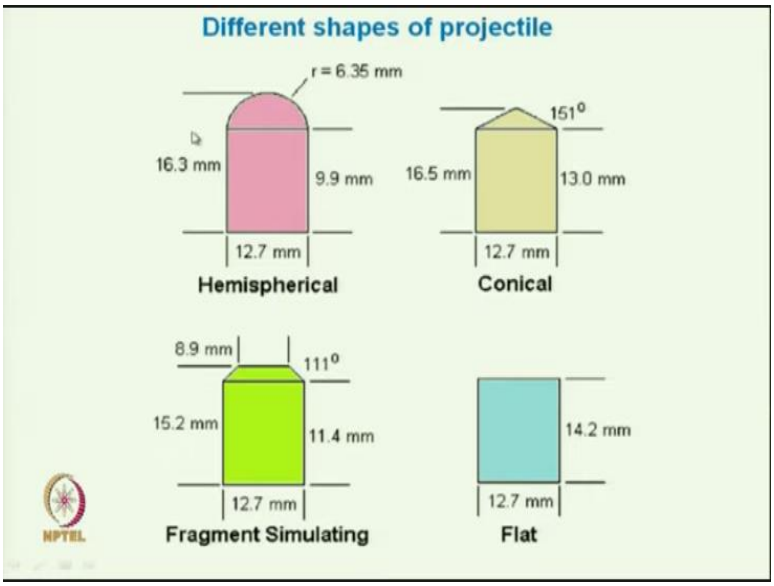

These are different shapes of projectile and also projectiles performance is dependent on the dimension of projectile, the diameter, this is fragmented, flat one.

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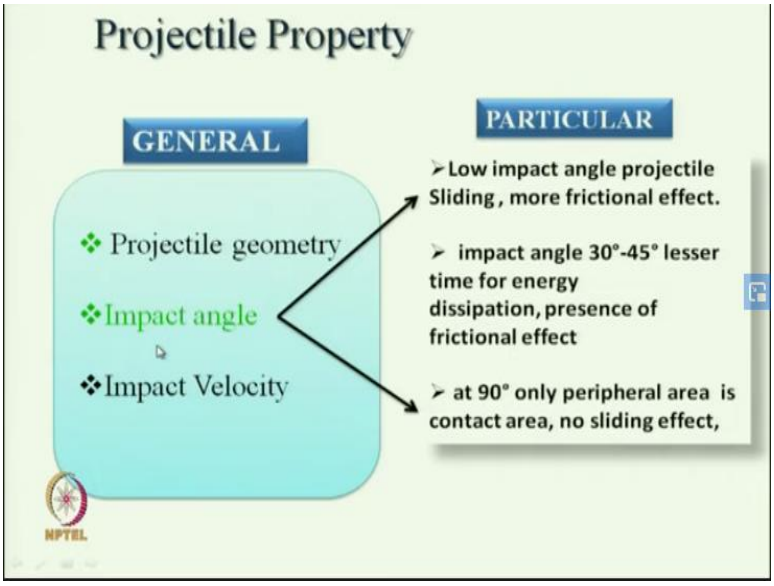

Angle of impact is also important, so low angle of impact means there will be sliding. Ideally the angle of impact if it is 90 degree there that will penetrate and there will be no sliding only peripheral area is in contact with the body armor no sliding will be there.

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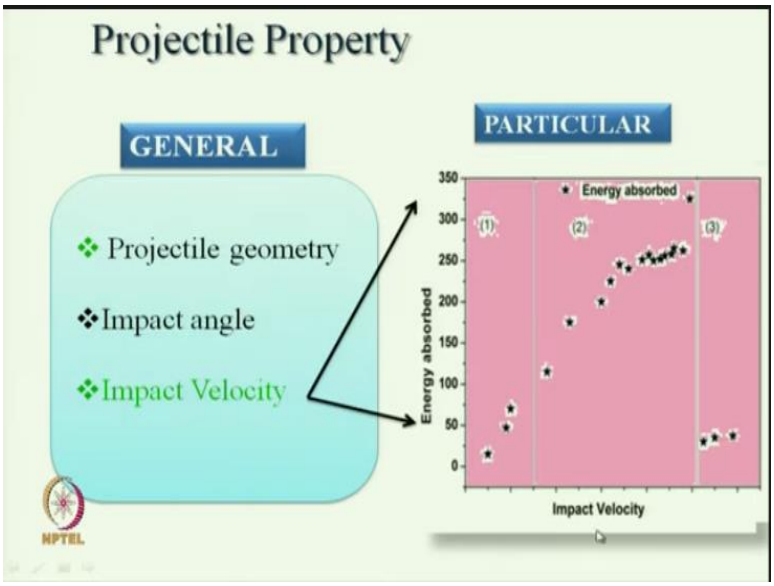

And third one is impact velocity, so higher the impact velocity higher will be the energy absorbed but if in case of very high velocity the immediately that those body armors it will penetrate inside in that case it has been observed the impact energy is absorbed energy is reduced. So to increase this absorbed energy we have to first catch those bullets if it penetrates then absorption will again reduce.

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So now coming to the evaluation of performance.

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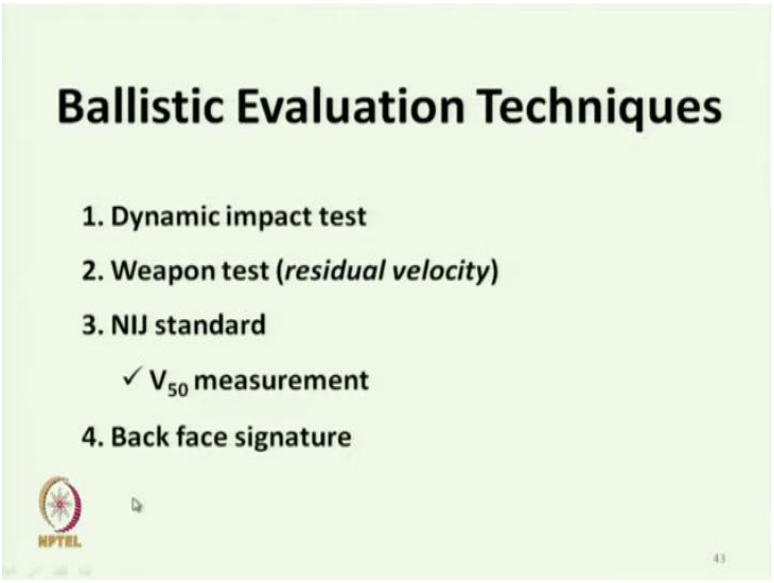

So ballistic evolution techniques are dynamic impact test by weapon test, so to measure the residual velocity and by NIJ standard, National Institute of Justice standard we follow that is V50 measurement and back face signature is also one of the ways to measure the ballistic evaluation.

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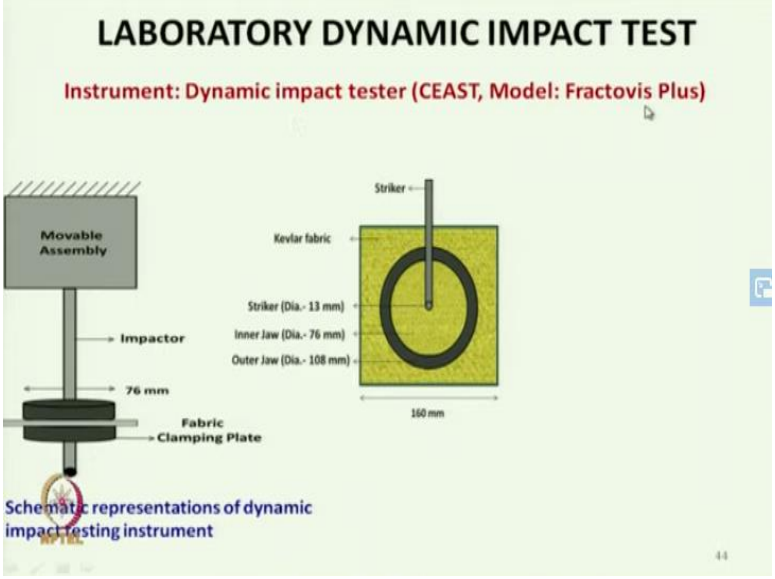

So dynamic impact test is basically laboratory method of testing and if we take the other test weapon test and NIJ test and back phase signature test they are not dynamic actually laboratory test, their actual field test. So dynamic impact test here it is a one impact dynamic impact tester is used, heavy moving assemblies are there it directly impacts on a flat surface with known dimension.

Here the striker dimension is diameter is 13 millimetre, inner jaw diameter is 76 millimetre and outer jaw is 108 millimetre and the Kevlar fabric is kept and striker is striking at certain speed. This is the photograph of one of the instruments such instrument.

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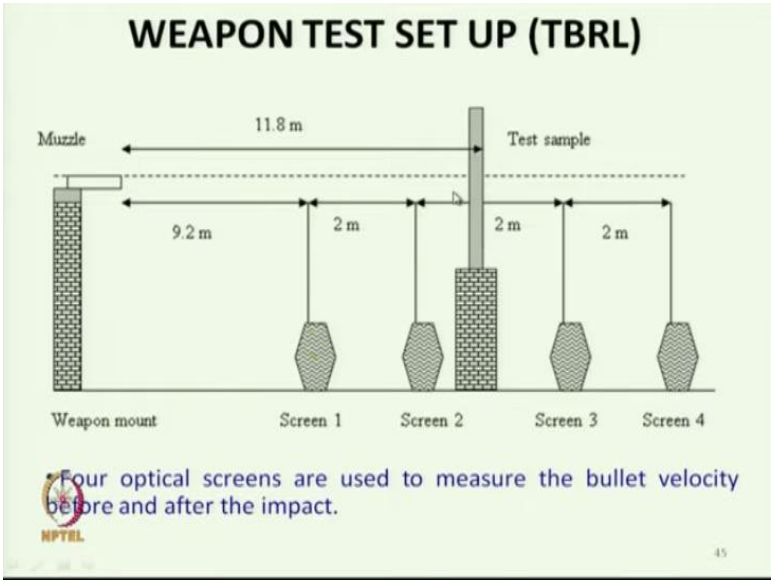

Now second is that weapon test and here this weapon test is that there are four different screens available and the bullet is short and this is a test sample. Four optical screens are used to measure the bullet velocity before and after impact, so this here at different dimension different distance we measure the bullet speed and even before impact and even after impact we measure the bullet speed at different distance.

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So this is the picture photograph of this technique, here is the specimen kept.

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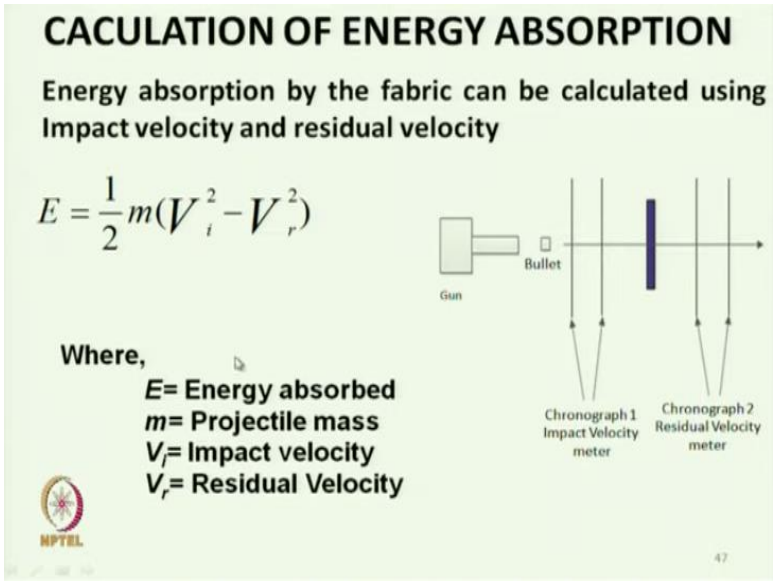

And the energy absorption calculation is simple whatever kinetic energy is absorbed it is half m Vi square minus Vr square, Vi square by a minus Vr square energy absorbed E, M is the

projectile mass and Vi is impact velocity before striking and residual velocity after it is coming out.

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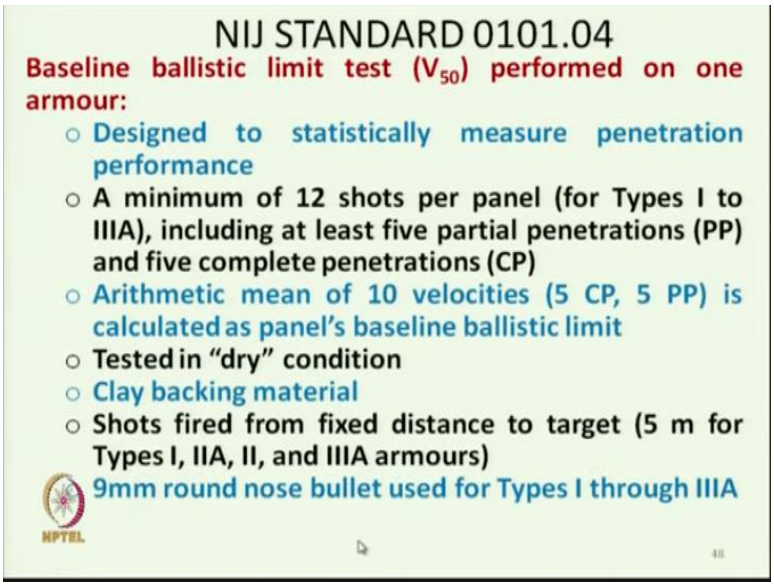

In, as per the NIJ standard baseline limit test that is V 50 is performed on the actual armor and designed to statistically measure the penetration performance the large number of bullets are shot on the armor and probability of penetration is measured and V50 is the velocity at which the probability of penetration is 50%. So typically minimum 50 for 12 shots are there per panel including at least five should be partial penetration and five should be complete penetration.

So that is the requirement if we take very high velocity where complete penetrations are there then we will not be able to get the 50% probability, so arithmetic mean of 10 velocities 5 in complete penetration and 5 in partial penetration were taken, these are tested in dry condition and clay backing materials are used to measure the back face signature, as I have already described. Shots fired from fixed distance to the target that is 5 meter for type I to II A and III A armor and 9 millimetre round nose bullets are used these are used for type I through type III A.

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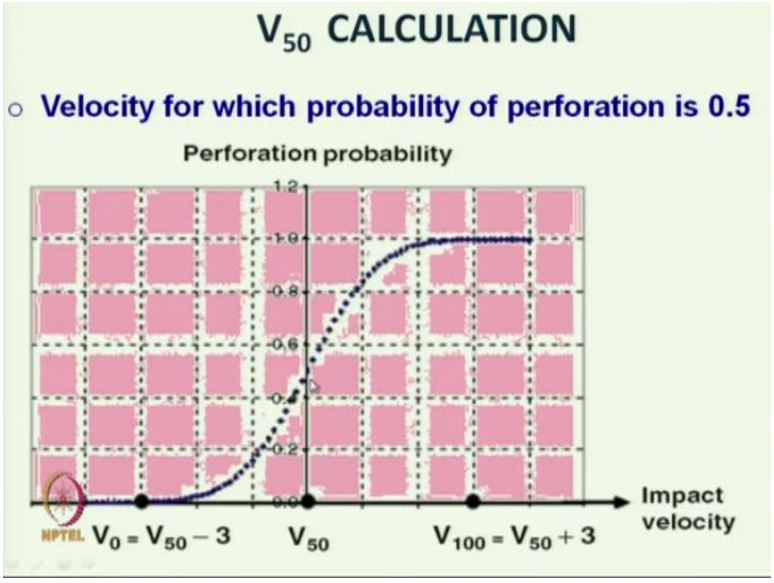

This is the velocity for which probability of penetration is 0.5 this is the 0.5 probability, so typically we increase the velocity and try to see the probability, so here this velocity it is called V50 and that is measured.

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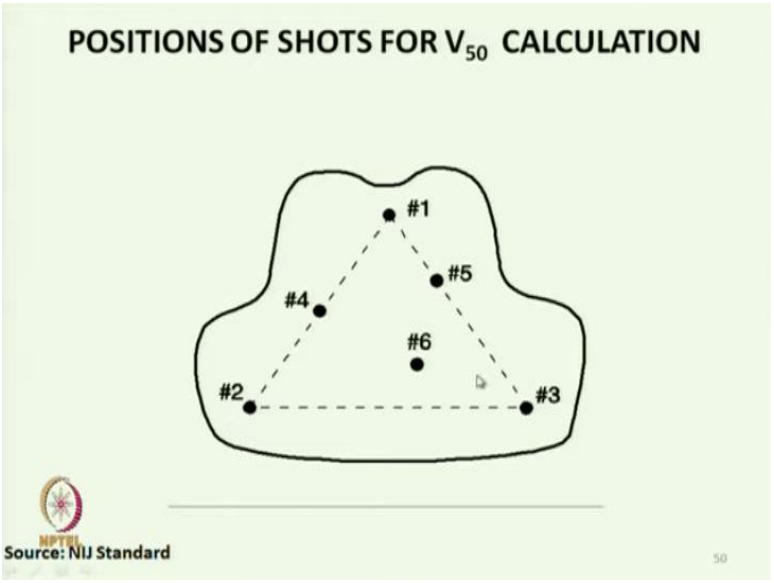

And position of shorts for NIJ standards at different places to calculate the V 50.

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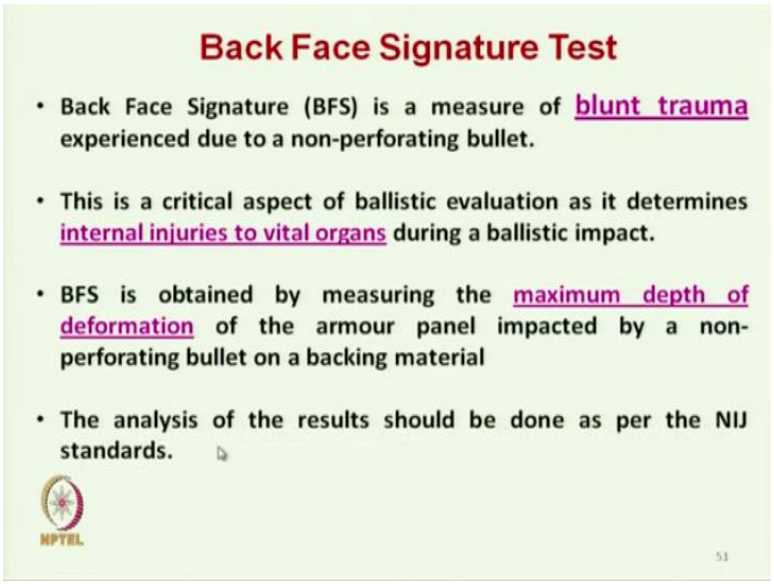

And, as far as back face signature test it is as per the again NIJ standard BFS is measured it is measure of blunt trauma experienced due to a non perforating bullet. So once it is perforating then it is entering into the body but for non perforating bullet the blunt trauma is measured, this is a critical aspect of ballistic evaluation as it determines the internal injury to vital organ during realistic impact it may damage our body without penetration.

BFS is obtained by measuring the maximum depth of deformation of the armored panel impacted by non perforating bullet on the backside of the material, so that the analysis of results should be done as per the NIJ standard.

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Now there are different approaches to reduce bulk in soft body armor as we have already mentioned the soft body armor the development should be in the area of reduction of thickness and increase in flexibility and reduction in mass. So the approaches are a development of resin fabric composite, the 3-dimensional woven fabric, we can use nonwoven fabric as cushion layer, incorporation of carbon nanotubes or nano fiber in the fabrics.

And application of shear thickening fluid in fabric. So these are the approaches one can try the research are going on in these areas. The shear thickening fluid is a viscous material where with the increase in shear rate the viscosity increase to a great extent.

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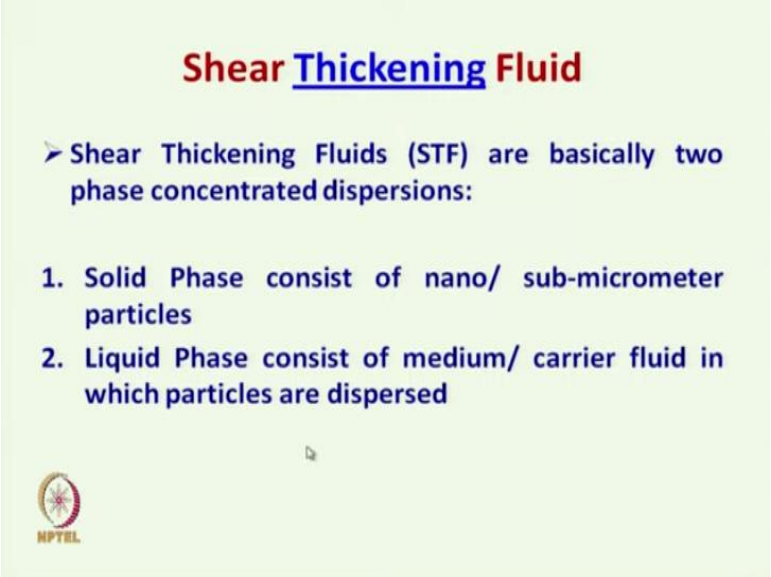

It acts as solid material, so these are they have two phase concentration dispersion, one is solid phase consists of nano or submicron particle and liquid phase which consists of a medium or carrier fluid in which particles are dispersed.

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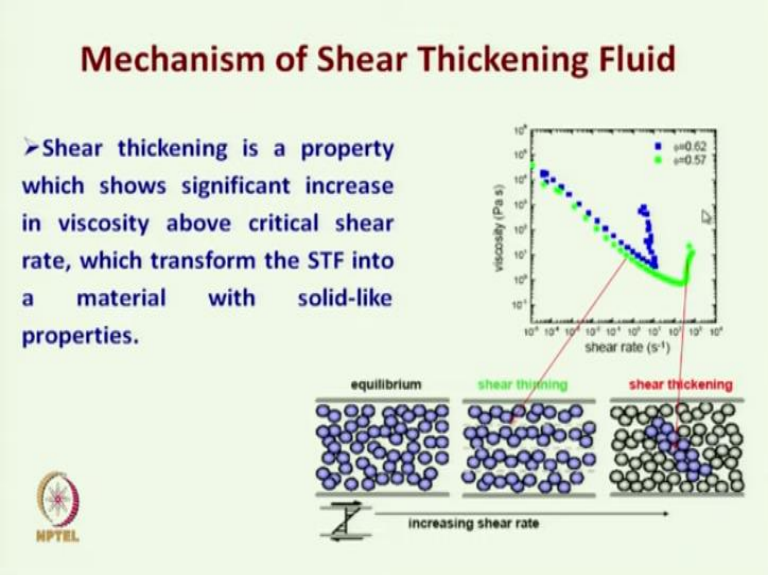

So they form a viscous liquid and the mechanism is that the shear thickening is the property which shows the significant increase in viscosity above critical shear rate that is in non-Newtonian flow takes place which transforms the shear thickening fluid into a material which will act like a solid. Here, this is at a certain speed velocity initially this shear that is viscosity reduces but after certain critical level the viscosity increases here, there this molecule the act as it is a solid, so immediately the shear viscosity increases.

So if we apply this shear thickening fluid on fabric surface when the bullet is impacted this viscous liquid viscous layers act as solid barrier. So initially at lower level of shearing this are very flexible but at higher shear rate during the bullet shot they become a solid and the protection level increases to a great extent.

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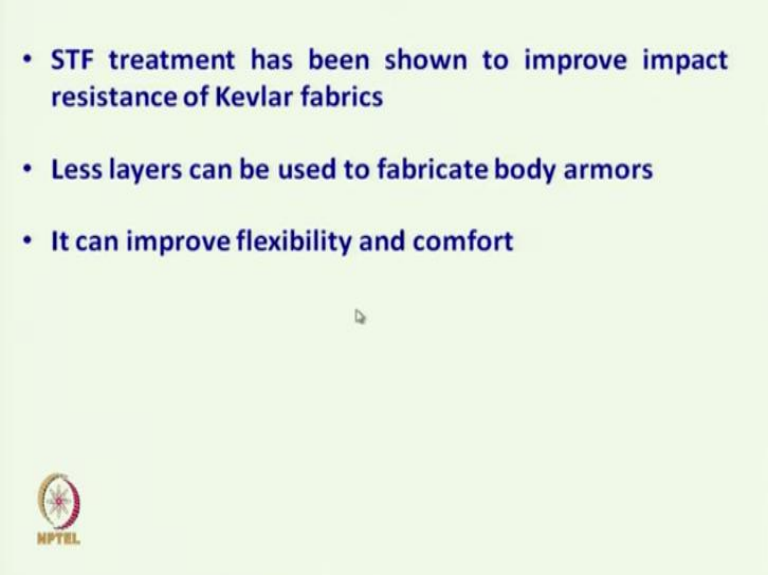

So STF treated treatment has been shown to improve impact resistance of Kevlar fabric, the less layer can be incorporated, so we can reduce the number of layers and increase the flexibility of the body armor. So along with the improvement in flexibility comfort also improve, so that is all about the ballistic protective clothing. Thank you.