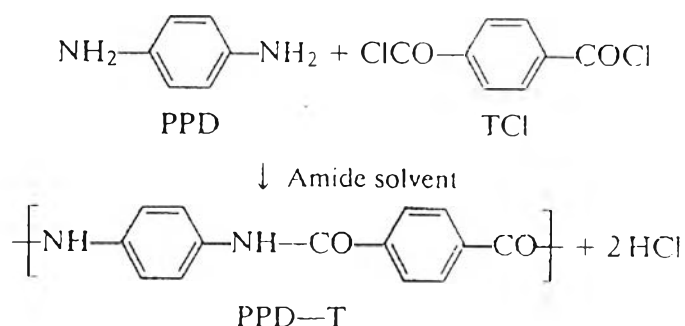# CHAPTER II

THEORY

2.1 Kevlar Aramid Fiber

Kevlar aramid fiber was invented by S.L. Kwolek of Du Pont in 1965 and was commercialized by the company in 1972. The word 'aramid' is a generic term for a manufactured fiber in which the fiber-forming substance is a long chain synthetic polyamide which at least 85% of the amide linkages are attached directly to two aromatic rings. This generic definition distinguishes aramids from the conventional polyamides, such as nylon, which mostly contain aliphatic and cycloaliphatic units in the polymer main chain. By definition, the aramid family encompasses several other commercial fibers including Nomex™, Teijinconex™, Technora™, and Twaron™ (Yang, 1993).

2.1.1 Manufacturing

In 1970, Blades and another Du Pont scientist discovered that a dry-jet, wet spinning process was unique for the anisotropic aramid polymers. It provided fibers almost twice as strong as the earlier fibers.

2.1.1.1 Preparation of polymer

Kevlar aramid fiber is based on poly(p-phenylene terephthalamide) (PPD-T), one of the para-oriented aromatic polyamides. The PPD-T synthesis involves the low temperature polycondensation of p-phenylene diamine (PPD) and terephthaloyl chloride (TCl) in a dialkyl amide solvent.

$$NH_2-\langle\bigcirc\rangle-NH_2 + ClCO-\langle\bigcirc\rangle-COCl$$

PPD   TCl

↓ Amide solvent

$$\left[NH-\langle\bigcirc\rangle-NH-CO-\langle\bigcirc\rangle-CO\right] + 2\,HCl$$

PPD—T

Scheme 1: Preparation of Kevlar™ fiber (Yang, 1993)

In this process, the amide solvent including hexamethylphosphoramide, N-methyl pyrrolidone and dimethyl acetamide can be used. Hexamethylphosphoramide was suspected to be carcinogenic. It may be used only with critical care to avoid skin contact and inhalation. The other solvents are used in single or mixed systems, often in the presence of an inorganic salt. The polymer from this reaction could be isolated by precipitation with water, neutralized, and subsequently washed and dried (Bair and Morgan, 1972, 1974).

Problems of making aramid fiber from a para-oriented symmetrical polymer molecules are all the monomers for the polymer preparation had to be synthesized and the polymer did not melt, and had to be dissolved in a particular solvent so that it could be extruded through spinneret holes to from a fiber (Bair and Morgan, 1972, 1974).

2.1.2 Commercial Kevlar aramid fiber products

The major types of Kevlar™ filament yarns commercialized at present include the following:

Grade	Major Application
Kevlar	Tire yarn
Kevlar 29	All-purpose yarn
Kevlar 49	High modulus yarn

Kevlar 68	Moderate modulus yarn
Kevlar 100	Colored yarn
Kevlar 119	High elongation yarn
Kevlar 129	High tenacity yarn
Kevlar 149	Ultra-high modulus yarn

2.1.3 Typical properties of Kevlar aramid yarns (Yang, 1993)

Table 2.1 : Properties of various grades of Kevlar™ fibers

| Yarn properties	Kevlar and Kevlar 29	Kevlar 49	Kevlar 68	Kevlar 119	Kevlar 129	Kevlar 149
Tensile strength						
gpd	23.0	23.0	23.0	24.0	26.5	18.0
Kpsi	420	420	420	440	485	340
Initial modulus						
gpd	550	950	780	430	750	1100
Mpsi	10.3	17.4	14.4	8.0	14.0	21.0
Elongation, %	3.6	2.8	3.0	4.4	3.3	1.5
Density g/cm³	1.44	1.45	1.44	1.44	1.45	1.47
Moisture regain, % 25 °C . 65% RH	6	4.3	4.3	-	-	1.5

Note:Yarn properties determined on 10 inch twisted yarns (ASTM D-885)

In general. Kevlar aramid fiber has a high breaking tenacity that is several times that of steel wire. nylon and polyester yarns. It has a much higher tensile modulus than steel wire, fiberglass, nylon. and polyester fibers. The fiber has a low elongation at break. which is comparable to that of steel. In addition, it has a relatively low density, which makes most Kevlar™- reinforced structure a lighter weight for a given strength and stiffness (Yang. 1993).
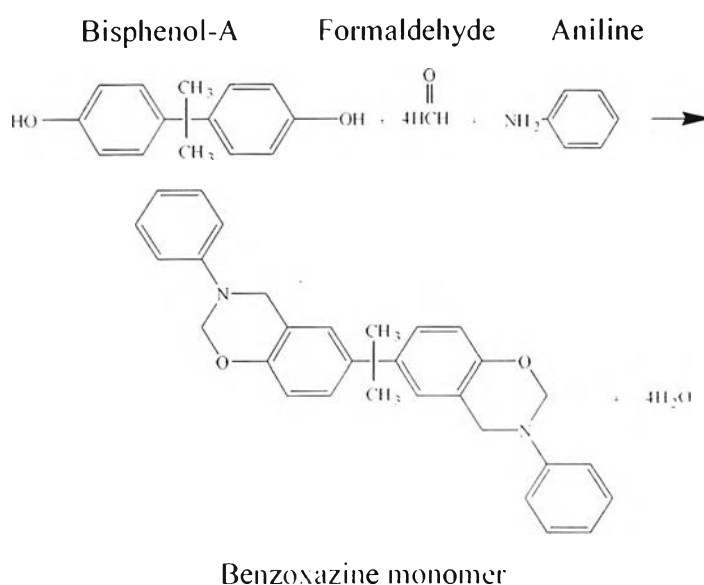
2.2 Benzoxazine Resin

Benzoxazine resin is a novel kind of phenolic resin that can be synthesized from phenol, formaldehyde, and amines. Solvent may be used in its synthesis depending on initiator and heating (Ishida, 1996; Ning and Ishida, 2000). The resin is developed to provide optimal properties in electronics or other high thermal and mechanical stability applications.

Benzoxazine resin can be classified into a monofunctional type and a bifunctional type depending on a type of phenol used as shown in scheme 2 and 3. The example for the monomer synthesis is

Phenol   Formaldehyde   Aniline   Benzoxazine monomer
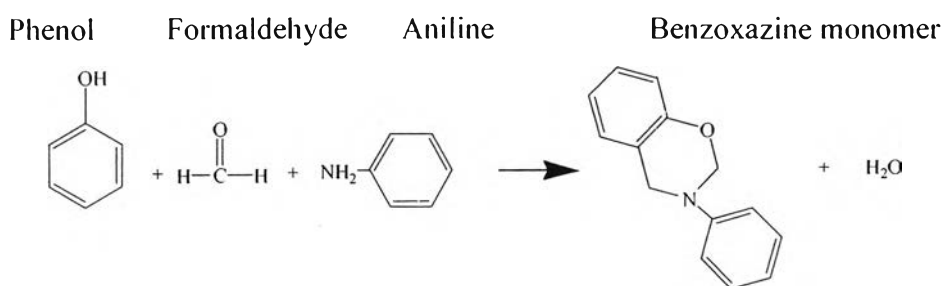
Scheme 2 : Synthesis of a monofunctional benzoxazine monomer.

Bisphenol-A   Formaldehyde   Aniline

Benzoxazine monomer

Scheme 3 : Synthesis of a bifunctional benzoxazine monomer.

The balance material properties of benzoxazine resin such as good thermal, chemical, electrical, mechanical, and physical properties make it highly attractive for several advanced applications. These new materials possess high glass transition temperatures, high char yield, high moduli, low water absorption despite the large amount of hydroxyl groups in the backbone structure, excellent resistance to chemicals and UV light, low melt viscosities compared to conventional phenolics, near-zero volumetric shrinkage or expansion upon polymerization and relatively low coefficients of thermal expansion. Furthermore, benzoxazine resin is able to be alloyed with several other polymers or resins; therefore, rendering broader useful properties including the alloys of polybenzoxazine with bisphenol A-typed epoxy (Rimdusit, 2001), with toluene diisocyanate(TDI)/polyethylene adipate polyol-typed urethane resin (Takeichi et al.,2000), flexible epoxy(EPO732) (Rimdusit et al., 2005), or with isophorone diisocyanate(IPDI)/polyether polyol-typed urethane resin (Rimdusit et al., 2005).

2.3 Urethane Elastomers

Polyurethane is class of polymer which contains urethane group. The urethane group results from the interaction of an isocyanate and a hydroxyl compound. A diisocyanate and a polyhydric compound (polyol) react together leading to a cross-linked polymer. Thus diisocyanates and diols (and polyols) are the principal raw materials used in the manufacture of polyurethanes.

$$
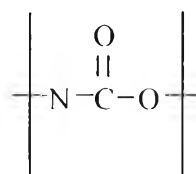-N-\overset{\overset{\textstyle O}{\textstyle \|}}{C}-O-
$$

Figure 2.1 Urethane linkage

The functionality of the hydroxyl-containing reactant or the isocyanate can be varied; therefore, a wide variety of linear, branched and crosslinked structures can be formed. The hydroxyl-containing components cover a wide range of molecular weights and types, including polyester and polyether polyols. The polyfunctional isocyanates can

be aromatic aliphatic, cycloaliphatic, or polycyclic in structure and can be used directly as produced or modified. This flexibility in the selection of urethane reactants leads to the wide range of the resulting properties.

One convenient preparation of a urethane elastomer involves reaction of the components without solvents. The glycol and triol, if desired, are added to the reactor and heated with stirring to 60-90°C. The acid component is added quickly and the mixture stirred and heated at such a rate that the water distills out rapidly. The hydroxyl and acid components are used in such a ratio that nearly all acid groups react and the hydroxyl groups are adequate to control the molecular weight in the desired range. The excellent properties of polyurethane account for the facts that their use is economically feasible and that their range of applications is steadily increasing. In some instance, they are even irreplaceable. Among these properties are unique combination of a high elastic modulus, good flexibility, exceptional tear and abrasion resistance, resistance to mineral oils and lubricants, resistance to UV radiation, and finally providing fairly easy and efficient processing (Wirpsza, 1993).

2.4 Advanced Composites Materials

Composite materials have a long history of usage. Depending on the types of matrices, composites can be categorized as polymer matrix composites, metal matrix composites, ceramic matrix composites, carbon-carbon composites, intermetallic composites or hybrid composites (Schwartz, 1997). In the other hand, based on the form of the dispersed phase, composite materials can be classified into three commonly accepted types, fibrous composites, laminated composites, and particulate composites; respectively (Jones, 1975). Fiber-reinforced composites consist of continuous or discontinuous fibers in a matrix, while laminated composites consist of layers of various materials and particulate composites are composed of particles dispersed within a matrix.

Modern structural composites frequently referred to as advanced composites. The term 'advanced' means the composites materials based on polymeric materials with oriented, high-modulus carbon, aramid, glass or ceramic fibers. Composite materials are

combination of two or more materials that are mixed on a microscopic scale to form a useful material. A resinous binder or matrix will hold the fiber in place, distribute or transfer load, protect the dispersed phase either in the structure or before fabrication and control the obtained chemical and electrical properties. The strength and stiffness of the fiber are generally much greater or multiples of those of the matrix material.

2.4.1 Fiber-reinforced composites

Fiber-reinforced materials consist of fibers in a matrix binder. They contain reinforcement having length much greater than its cross-sectional dimensions. In the other hand, a composite is considered to be a discontinuous fiber or short fiber composite if its properties vary with the fiber length. When the length of the fiber is such that any further increase in its length dose not, for example, further increase the elastic modulus of its composite, the composite is considered to be continuous fiber reinforced. Most continuous fiber composites, in fact, contain fibers that are comparable in length to the overall dimensions of a composite part.

2.5 Composite Density

The theoretical density of composite is an important factor related to the amount of filler and the void content in polymer composites, especially when a significant difference in densities between filler and matrix are involved. The theoretical density compared to actual density was calculated by a following relation ship (Piyawan, 1998):

$$\rho_c = \frac{1}{\frac{W_f}{\rho_f} + \frac{(1-W_f)}{\rho_m}}$$ (2.1)

Where W_f = filler weight fraction

$(1-W_f)$ = matrix weight fraction

ρ_f = filler density, g/cm^3

ρ_c = matrix density, g/cm^3.

2.6 Ballistic Standards (the National Institute of Justice [NIJ], 1979)

2.6.1 NIJ body armor classification

Personal body armors covered by this standard are classified into seven classes, or types, by level of ballistic performance. The ballistic threat posed by a bullet depends, among other things, on its composition, shape, caliber, mass, angle of incidence, and impact velocity. Because of the wide variety of bullets and cartridges available in a given caliber and because of the existence of handloaded ammunition, armors that will defeat a standard test round may not defeat other loadings in the same caliber. For example, an armor that prevents complete penetration by a .40 S&W test round may or may not defeat a .40 S&W round with higher velocity. In general, an armor that defeats a given lead bullet may not resist complete penetration by other bullets of the same caliber of different construction or configuration. The test ammunition specified in this NIJ standard represents general, common threats to law enforcement officers.

As of the year 2000, ballistic resistant body armor suitable for full time wear throughout an entire shift of duty is available in classification Types I, IIA, II, and IIIA, which provide increasing levels of protection from handgun threats. Type I body armor, which was first issued during the NIJ demonstration project in 1975, is the minimum level of protection that any officer should have. Officers seeking protection from lower velocity 9 mm and .40 S&W ammunition typically wear Type IIA body armor. For protection against high velocity .357 Magnum and higher velocity 9 mm ammunition, officers traditionally select Type II body armor. Type IIIA body armor provides the highest level of protection available in concealable body armor and provides protection from high velocity 9 mm and .44 Magnum ammunition.

Type IIIA armor is suitable for routine wear in many situations; however, departments located in hot, humid climates may need to carefully evaluate their use of Type IIIA body armor for their officers. Types III and IV armor, which protect against

high-powered rifle rounds, are clearly intended for use only in tactical situations when the threat warrants such protection

In December 1978, the National Bureau of Standards and National Institute of Law Enforcement and Criminal Justice (now National Institute of Justice) first classified the ballistic body armors into several categories according to projectile size and velocity in its NILE/CJ report. The current NIJ classification for police body armor is as follows:

Table 2.2 : NIJ standard of body armor showing type of caliber and bullet as well as the projectile velocity in each category.

Protection Level	Caliber	Bullet Type, Weight	Velocity(m/s)	Accept Hit Per Panel
I	.38 Special	Round Nose Lead, 158 grain (10.2 grams)	259	5
	.22 Special	Long Rifle High Velocity Lead, 40 grain,(2.6 g)	320	5
II-A	9 mm	Full Metal Jacket , 124 grain,(8.0 g)	332	5
	.40 S&W	Full Metal Jacket , 180 grain,(11.7 g)	322	5
II	9 mm	Full Metal Jacket , 124 grain,(8.0 g)	358	5
	.357 Magnum	Jacketed Soft point. 158 grain,(10.2 g)	425	5
III-A	9 mm	Full Metal Jacket . 124 grain,(8.0 g)	426	5
	.44 Magnum	Lead Semi-Wadcutter Gas Checked. 240grain, (15.5 g)	426	5
III	7.62 x 51 mm (.30 Winchester)	Full Metal Jacket . 150 grain,(9.7 g)	838	5
VI	.30 caliber	Armor Piercing. 166 grain,(10.8 g)	868	1

(source: Thailand Ministry of Defense. 2004)

2.6.2 Definition

2.6.2.1 Ballistic panel

The protective component of an armor sample or panel, primarily consisting of ballistic resistant materials, usually enclosed in a nonremovable cover. The ballistic panel is normally retained within the armor sample or panel by a separate fabric carrier, and may be removable from the carrier.

2.6.2.2 Armor carrier

A component of the armor sample or armor panel whose primary purpose is to retain the ballistic panel and provide a means of supporting and securing the armor garment to the user. These carriers are not generally ballistic resistant.

2.6.2.3 Armor sample

One complete armor garment comprised of a single wraparound style jacket, or a set (two) of front and back armor panels.

2.6.2.4 Penetration

Complete penetration (CP): The complete perforation of an armor sample or panel by a test bullet or by a fragment of the bullet or armor sample itself, as evidenced by the presence of that bullet or fragment (armor or bullet) in the backing material, or by a hole which passes through the armor and/or backing material.

Partial penetration (PP): Any impact that is not a complete penetration is considered a partial penetration.

2.6.2.5 Angle of incidence

The angle between the line of flight of the bullet and the perpendicular to the front surface of the backing material fixture.

2.6.2.6 Fair hit

A bullet that impacts the armor sample or panel at an angle of incidence no greater than $\pm 5^o$ from the intended angle of incidence, no closer to the edge of the ballistic panel than 76 mm (3.0 in) and no closer to a prior hit than 51 mm (2.0 in), at an impact velocity within ± 9.1 m/s (30 ft/s) of the required reference test velocity.

2.6.2.7 Fail hit

A bullet that impacts the armor sample or panel at an angle of incidence no greater than $\pm 5^o$ from the intended angle of incidence, no closer to the edge of the ballistic panel than 76 mm (3.0 in) and no closer to a prior hit than 51 mm (2.0 in), at an impact velocity less than 9.1 m/s (30 ft/s) below the required reference test velocity which produces a penetration or an excessive backface signature.

2.6.2.8 Accept hit

A bullet that impacts the armor sample or panel at an angle of incidence no greater than $\pm 5^o$ from the intended angle of incidence, no closer to the edge of the ballistic panel than 76 mm (3.0 in) and no closer to a prior hit than 51 mm (2.0 in), at an impact velocity more than 9.1 m/s (30 ft/s) above the required reference test velocity which does not produce a penetration or an excessive backface signature.

2.6.2.9 Backface signature (BFS)

The depth of the depression made in the backing material, created by a nonpenetrating projectile impact, measured from the plane defined by the front edge of the backing material fixture. For armor tested on built up or curved backing material, the BFS is measured from the plane defined by the top edges of the depression or crater formed by the impact.

2.6.2.10 Bullet type

2.6.2.10.1 Full metal jacketed bullet (FMJ)

A bullet consisting of a lead core completely covered, except for the base, with copper alloy (approximately 90 % copper and 10 % zinc). "Total Metal Jacket (TMJ)," "Totally Enclosed Metal Case (TEMC)," and other commercial terminology for bullets with electro deposited copper and copper alloy coatings have been tested and are considered comparable to Full Metal Jacketed (FMJ) bullets for this standard.

2.6.2.10.2 Jacketed hollow point bullet (JHP)

A bullet consisting of a lead core which has a hollow cavity or hole located in the nose of the bullet and is completely covered except for the hollow point with a copper alloy (approximately 90 % copper and 10 % zinc) jacket.

2.6.2.10.3 Jacketed soft point bullet (JSP)

A lead bullet, also known as a Semi Jacketed Soft Point (SJSP), completely covered, except for the point, with copper alloy (approximately 90 % copper and 10 % zinc) jacket.

2.6.2.10.4 Round nose bullet (RN)

A bullet with a blunt or rounded nose. A bullet with a generally blunt or rounded nose or tip, which possesses a small flat surface at the tip of the bullet, shall also be considered a round nose bullet for this standard.

2.6.2.10.5 Semi jacketed hollow point bullet (SJHP)

A bullet consisting of a lead core with a copper alloy (approximately 90 % copper and 10 % zinc) jacket covering the base and bore riding surface (major diameter), which leaves some portion of the lead core exposed, thus forming a lead nose or tip, which has a hollow cavity or hole located in the nose or tip of the bullet.

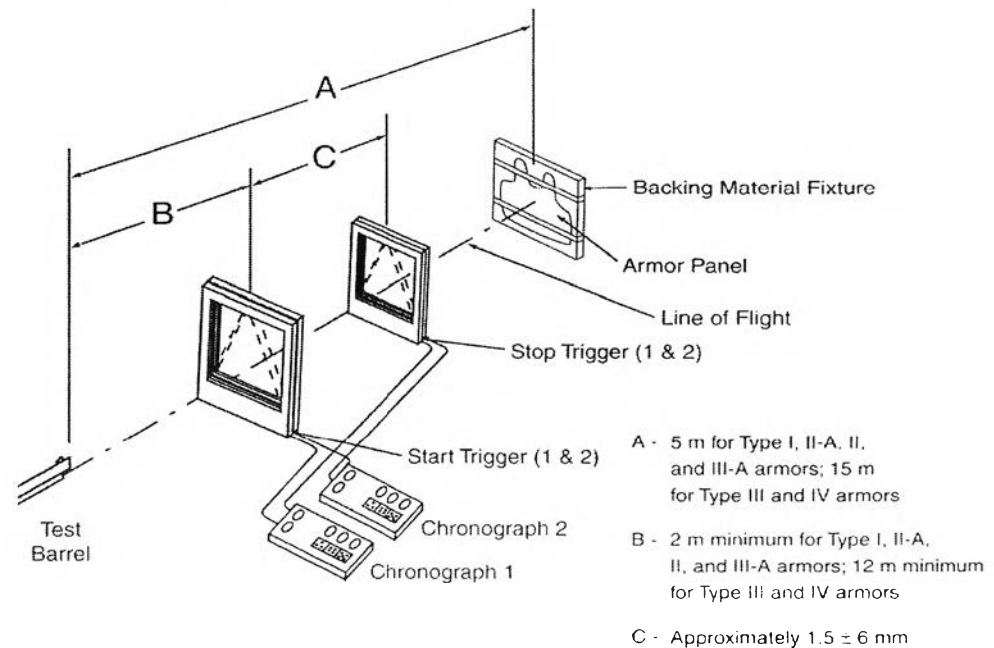### 2.6.2.10.6 Semi jacketed soft point bullet (SJSP)

A bullet, also known as a Jacketed Soft Point (JSP), consisting of a lead core with a copper alloy (approximately 90 % copper and 10 % zinc) jacket covering the base and bore riding surface (major diameter), which leaves some portion of the lead core exposed, thus forming a lead nose or tip.

2.6.3 Test method

2.6.3.1 Test preparation

Select the required test bullet for the armor type as specified in table 2. Beginning with threat round number one, fire a minimum of three pretest rounds to ensure that the first test round fired will strike the target as aimed, using a suitable targeting device (e.g., a pointing laser). These pretest rounds will also serve to "warm" or

stabilize the temperature of the barrel before further testing. Set up the test equipment as shown in figure 6. Use a test barrel appropriate for the ammunition required to test the armor (table 1), mounted in an appropriate fixture with the barrel horizontal. Dimensions A and B shall be determined from the barrel muzzle. The backing material fixture will be rigidly held by a suitable (metal) test stand, which shall permit the entire armor and backing material assembly to be shifted vertically and horizontally such that the entire assembly can be targeted by the test barrel.

- Backing Material Fixture
- Armor Panel
- Line of Flight
- Stop Trigger (1 & 2)
- Start Trigger (1 & 2)
- Chronograph 2
- Chronograph 1

Test Barrel

A - 5 m for Type I, II-A, II, and III-A armors; 15 m for Type III and IV armors

B - 2 m minimum for Type I, II-A, II, and III-A armors; 12 m minimum for Type III and IV armors

C - Approximately 1.5 ± 6 mm

Figure 2.2 Test range configuration(Science and Technology of the National Institute of Justice [NIJ], 1979)

2.6.4 Requirements

2.6.4.1 Workmanship

Each armor sample shall be free from wrinkles, blisters, cracks or fabric tears, crazing, chipped or sharp corners and edges, or other evidence of inferior

workmanship. Additionally, all samples shall be identical in appearance, size, and manner of construction.

2.6.4.2 Acceptance criteria for penetration and BFS compliance

(a) No perforation through the panel, either by the bullet or by any fragment of the bullet or armor.

(b) No measured BFS depression depth greater than 44 mm (1.73 in).

2.7 Theories on Ballistic Impact

2.7.1 The ballistic resistance of the fabric (Jacobs and Dingenen, 2001)

The ballistic resistance of a textile fabric to a projectile is generally attributed to its absorption of kinetic energy upon ballistic impact. This is analyzed by way of simple ballistic impact in the longitudinal (axial) and transverse directions of a fiber. The energy absorbed by the fabric is converted into strain energy derived from stretching of the yarns and kinetic energy due to transverse deflection of the fabric and inward movement of yarn material towards the impact point. A portion of energy is also dissipated through frictional losses. When a longitudinal impact is applied to a fiber at velocity V, a longitudinal wave will be generated along the fiber at a velocity c. The fiber material behind the wave is subjected to a strain e of

$$e = V/c \qquad (2.3)$$

$$c = \sqrt{E/\rho} \qquad (2.4)$$

Where c is the velocity of the longitudinal, E is fiber modulus and ρ is fiber density. Thus, the velocity of wave propagation increases with the square root of fiber modulus and inversely with the square root of fiber density. The higher the fiber modulus, the higher the wave velocity and the greater the volume of fiber capable of interacting with the projectile.
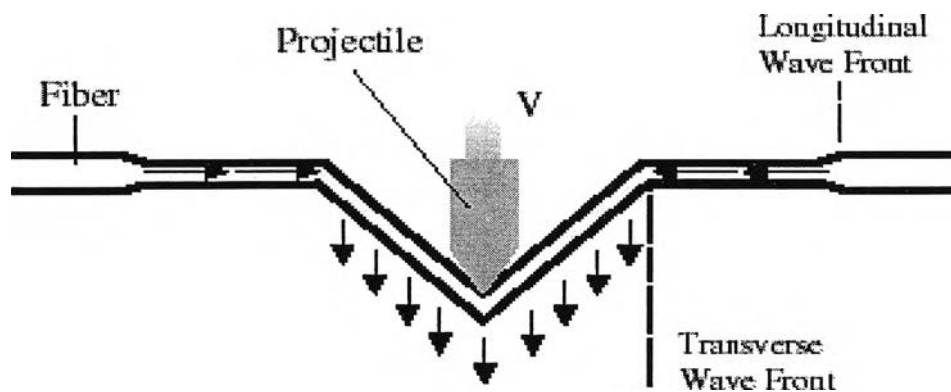
If E is expressed in grams per denier and c in m/s , the above equation can be written as

$$c = \sqrt{kE} \tag{2.5}$$

where $k = 88260$. The stress associated with the strain e is given by

$$\rho = Ee = V\sqrt{E/k} \tag{2.6}$$

The ballistic dynamics is considerably more complicated when a fiber is impacted transversely than longitudinally.

Figure 2.3 Wave propagation in a transversely impacted fiber (Jacobs and Dingenen,
2001)

The picture reveals schematically a fiber in a horizontal position which is impacted transversely by a projectile traveling downward. The ballistic impact causes the center portion of the fiber to deform before breaking. Two types of wave propagations are generated in the fiber upon impact. One is the longitudinal waves discussed above and the other is the transverse wave. The longitudinal are propagated outward along the fiber from the point of impact. The transverse waves are also propagated outward from the point of impact. At the transverse wavefront, the inward material for changes abruptly

to the projectile velocity and direction. Behind the transverse wavefront, the fiber has a straight configuration at an angle to the horizontal direction (Jacobs and Dingenen, 2001).

2.7.2 The ballistic resistance of the composite

For residual velocity testing, by measuring the velocity of the projectile entering and exiting the specimen, the amount of energy absorbed by the composite $E_{absorption}$ is calculated as (Yang, 1993):

$$E_{absorption} = 0.5 \, m_{projectiles}(\, V_{in}^2 - V_{out}^2) \qquad (2.7)$$

where is the $m_{projectiles}$ mass of the projectile and V_{in} and V_{out} are the velocities entering and exiting the specimen, respectively. This type of test method is typically used for residual strength testing where penetration resistance is not required.

The term 'ballistic limit velocity, V_{50}' is defined as the minimum velocity at which a particular projectile is expected to consistently, completely of specimen penetration. The V_{50} is the projectile velocity at which 50% of projectile will penetrate a given target, while 50% will be stopped. The military standard MIL-STD-662E was created by the army to provide a simple cost effective method for determining V_{50} the ballistic limit. It is determined by taking the average of an equal number of highest partial penetration velocities and lowest complete penetration velocities which occur within a specific velocity range for a particular specimen configuration. The velocity range requirement is necessary since an unusually high or low data point could offset the average, causing a misrepresentation of the V_{50} ballistic limit. According to standard recommendations, five partial and five complete penetrations within a 125 ft/sec range was set as the criteria for testing.

The energy absorbed by the composite was taken as the metric for impact penetration resistance. From the V_{50} ballistic limit, the amount of energy E absorbed was calculated as:

$$E = 0.5 * m_p * V_{50}^2 \qquad (2.8)$$

where m_p is the mass of the projectile.

2.7.3 Mechanisms for dissipating ballistic impact

Upon ballistic impact, polymer composites retard the projectile by reducing its kinetic energy. Different mechanisms such as the tensile failure of fibres, the elastic deformation of the composite, interlayer delamination, back-face deformation, shear between layers in the composite, and the inertia of the composite are responsible for the absorption of energy to different extents. Amongst the factors which control the energy absorption are the tensile properties of the fibre, the properties of the matrix, the arrangement of the fibres in the composite and the interfacial strength. To be able to design composite materials for ballistic protection efficiently, it is necessary to understand and quantify the energy absorbed by each of these mechanisms (Morye et al.,2000).

2.7.4 Quantification of the energy absorption by polymer composites upon ballistic impact (Morye et al.,2000).

The mathematical model has been derived to predict the energy absorbed by the composite during ballistic impacts. It gives a value of the ballistic limit, V_0, defined as the estimated highest velocity at which the projectile is stopped.

In developing the model the following assumptions had been made:

1. The projectile is rigid and remains undeformed during the impact:. this was confirmed by experiments which revealed that the projectiles used in the experiment retained their shape and mass after impact.

2. The energy lost in overcoming the frictional force between a projectile and a composite is negligible and the heat generated during the projectile/composite interaction is negligible.

3. The mechanism of failure of the composite is uniform across its thickness. This

has been confirmed subsequently by high speed photography.

4. The energy absorbed in delamination is neglected.

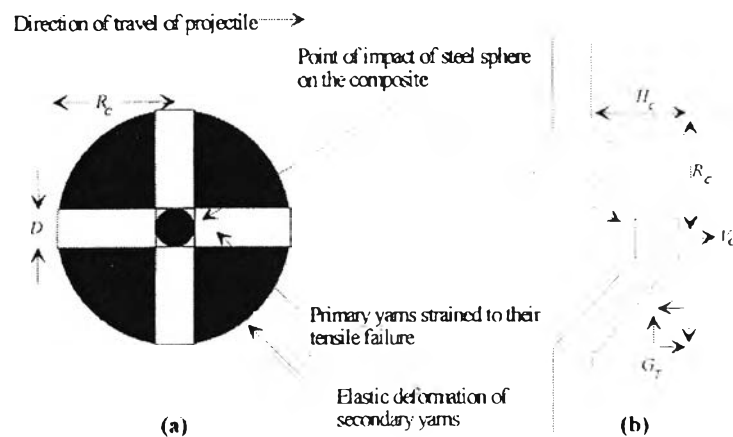The kinetic energy of a projectile of mass, m, moving with a velocity, V is given by

$$K.E. = \frac{1}{2}mV^2 \tag{2.9}$$

the ballistic limit

$$E_L = \frac{1}{2}mV_0^2 \tag{2.10}$$

where V_0 is the limiting velocity.

As discussed earlier, the impact of the projectile results in the formation of a cone on a back side of the composite through the propagation of a transverse wave shown schematically in Figure 2.4.

Figure. 2.4 Deformation of a composite during ballistic impact by a steel sphere

(a) plane of the back face and (b) side view. (Morye et al..2000)
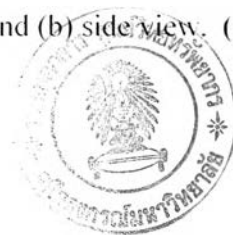
In addition to these two major energy absorbing mechanisms, due to deformation of the primary and secondary yarns, there is a third contribution, the kinetic energy of the moving portion of the composite panel. Elements of the composite panel which are at rest before the impact are put into motion by the projectile on impact and, therefore, absorb energy through the kinetic energy of the moving cone.

Thus $$E_{Total} = E_{TF} + E_{ED} + E_{KE} \qquad (2.11)$$

I. Energy absorbed in the tensile failure of primary yarns (E_{TF})

If the energy absorbed at the point of tensile failure of the composite per unit volume is E_c, then the total energy absorbed by tensile failure, E_{TF} is given by:

$$E_{TF} = E_C V \qquad (2.12)$$

where D is the projectile diameter, T is the composite thickness and R_c is the radius of the cone formed on the back face of the composite.

$$E_{TF} = 4E_c R_c DT \qquad (2.13)$$

II. Energy absorbed in the elastic deformation of secondary yarns (E_{ED})

The energy absorbed in elastic deformation of the composite at a strain ε can be obtained from the area under the stress/strain curve of the composite and because the stress/strain curve for the composite is linear, it is given by

$$E_{ED} = \frac{1}{2} M\varepsilon^2 \qquad (2.14)$$

where M is the tensile modulus of the composite.

The yarns within the deformed zone, which are not directly impacted by the projectile, experience a different strain depending on their position. Those that are closest

to the point of impact experience a strain just lower than the failure strain, while those that are farthest from the impact point do not see any strain. This imposes the following boundary conditions for the variation in strain ε, with distance from the impact point $\varepsilon=\varepsilon_0$ at $r=D/2$ and $\varepsilon=0$ at $r=R_c$, where ε_0 is the failure strain of the composite.

$$E_{ED} = \frac{\pi M \varepsilon_0^2 T}{(2R_c - D)^2}\left[\frac{R_c^4}{3} - \frac{D^2 R_c^2}{2} + \frac{D^3 R_c}{2} - \frac{D^4}{16}\right] \quad (2.15)$$

III. Kinetic energy of the cone formed on the back face of the composite upon ballistic impact (E_{KE})

The kinetic energy of the moving cone is given by

$$E_{KE} = \frac{1}{2} m_c V_c^2 \quad (2.16)$$

where m_c is the mass of the moving cone and V_c is the velocity of the moving cone.

The kinetic energy of the moving cone at the point of impact.

$$E_{KE} = \frac{1}{2}\pi R_c^2 T \rho V_c^2 \quad (2.17)$$

IV. Calculation of V_0

According to the model, the energy lost by the projectile is equal to the total energy absorbed by the composite

$$E_L = E_{Total} \quad (2.18)$$

Using Eq.(9).

$$\frac{1}{2}mV_0^2 = E_{Total} \tag{2.19}$$

$$V_o = \sqrt{\frac{2}{m}E_{Total}} \tag{2.20}$$

The determination of a theoretical prediction of V_0 from Eq.(2.20)requires the measurement of all the various parameters shown in (2.13), (2.15) and (2.17).