



**UNIVERSITY OF DELAWARE**  
**CENTER FOR COMPOSITE MATERIALS**

*INTERNATIONALLY RECOGNIZED EXCELLENCE*



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2005 RESEARCH REVIEWS

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# **BALLISTIC DAMAGE ANALYSIS OF THICK-SECTION COMPOSITES**

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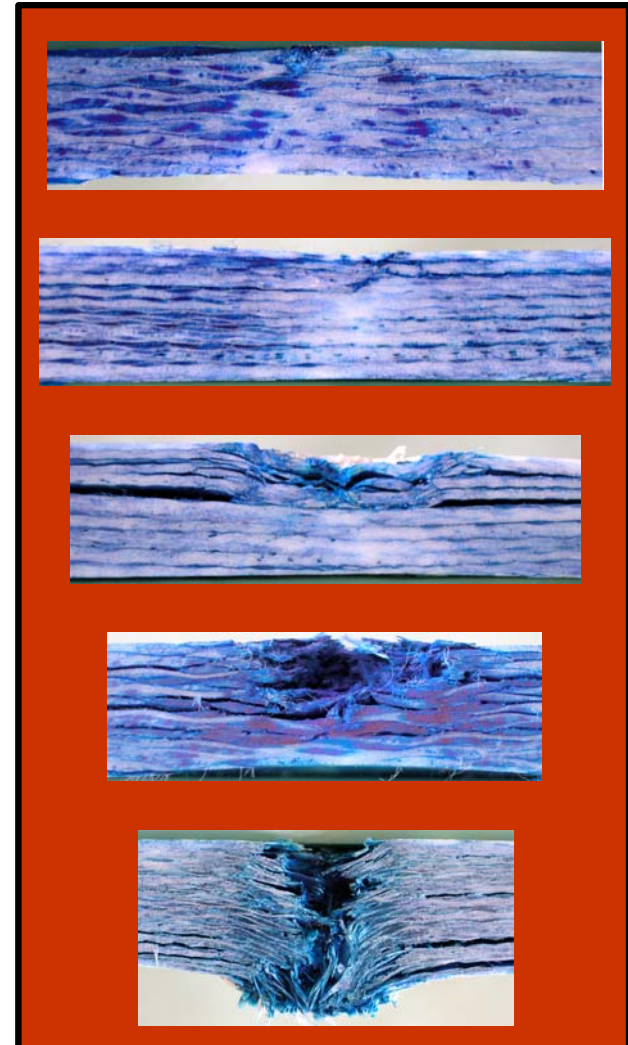
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**UD-CCM • March 2, 2005**



## BACKGROUND

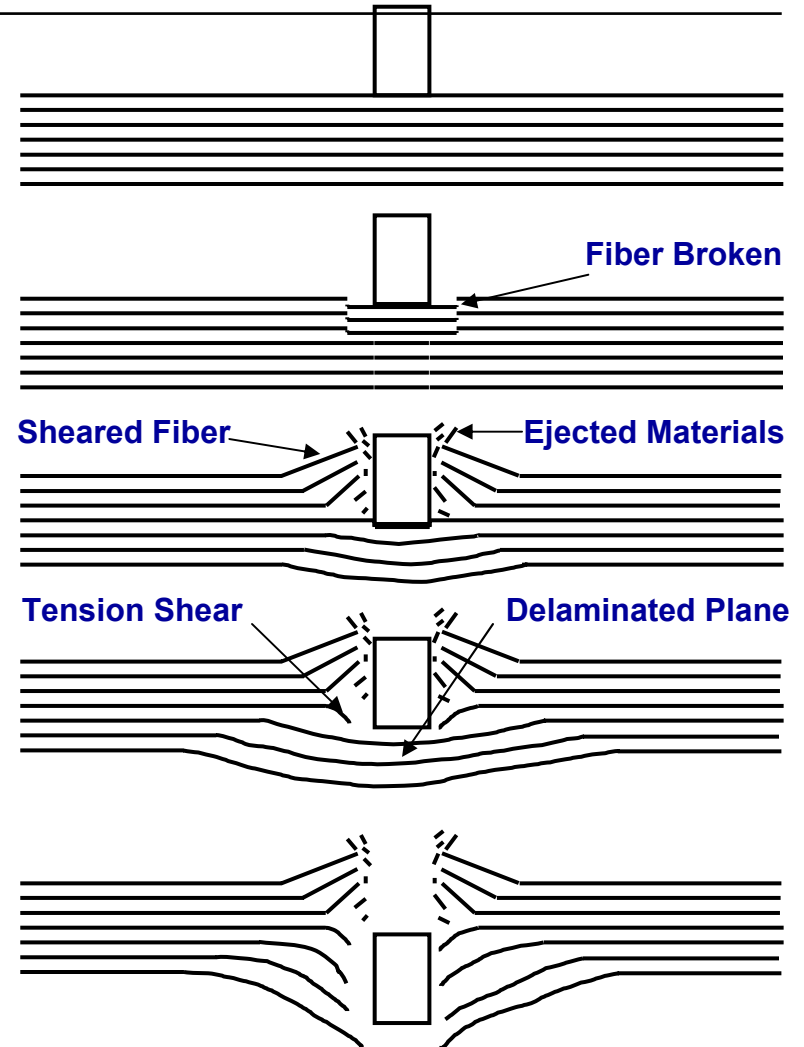
- ◆ **BALLISTIC DAMAGE MECHANISMS**
- ◆ **S. S. Morye (May, 2000)**
  - Energy Stored in Elastic Deformation
  - Kinetic Energy of the Plate
  - Tensile Failure of the Composites
- ◆ **Daniel Delfosse (Oct. 1996)**
  - Matrix Damage
  - Fiber Damage
  - Elastic Deformation
- ◆ **BALLISTIC ENERGY PARTITION**
  - Hydrostatic-Compression
  - Fiber-Shear Around Projectile
  - Interlaminar Delamination and Matrix Crack
  - Compression-Shear (Plug Formation)
  - Tension-Shear (Large Deformation)
  - Friction between Projectile and Target
  - Stored Elastic Energy
  - Stored Kinetic Energy
- ◆ **OBJECTIVES**
  - Quantify the Energy Absorbing Damage Mechanisms
  - Detail LITERATURE Review





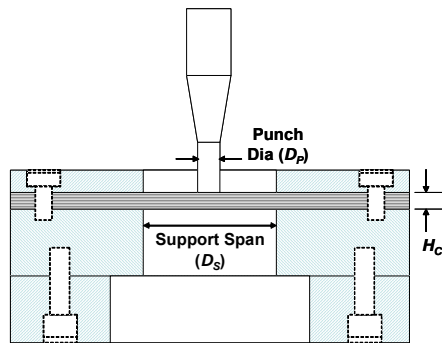
## PHASES OF BALLISTIC IMPACT AND PENETRATION

- ◆ **Phase I: Impact Contact:**
  - Projectile impacts the surface of the target at an impact velocity  $V_i$ , and the peak stress developed in the contact zone is governed by the impact-contact laws.
- ◆ **Phase II: Hydrostatic Compression:**
  - Projectile decelerates and the composite laminate under the projectile undergoes hydrostatic compression.
- ◆ **Phase III: Compression-Shear:**
  - In this stage projectile moves through the composite and the surrounding materials undergo compression-shear mode of damage.
- ◆ **Phase IV: Tension-Shear:**
  - This is the later stage of penetration, where the projectile deforms the rest half-thickness of the laminate under membrane tension.
- ◆ **Phase V: Structural Vibration:**
  - This is the end of penetration. The projectile ejects from the composite plate under dynamic friction.

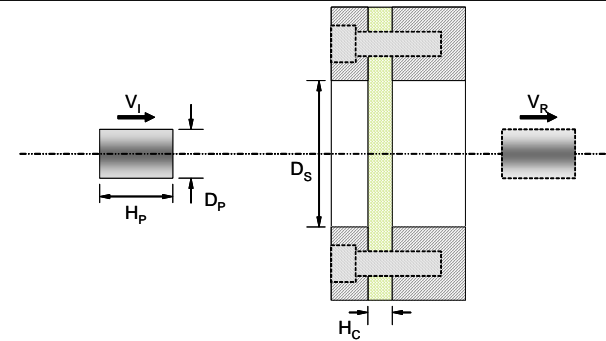




## Q-S PST AND BALLISTIC - PST



QUASI-STATIC PUNCH SHEAR TEST



BALLISTIC PUNCH SHEAR TEST

### ◆ Q-S PST ENERGY PARTITION

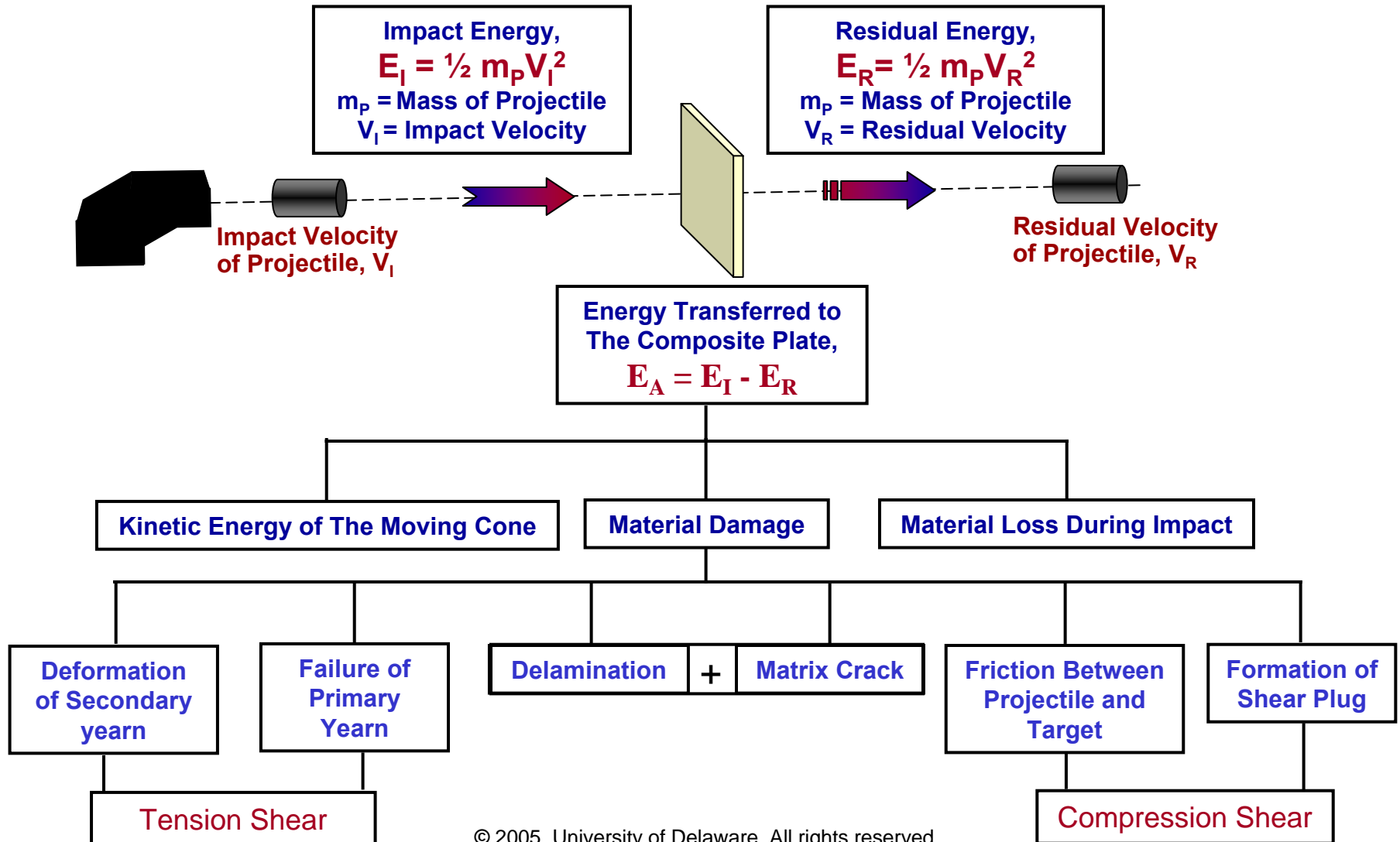
- ⇒ Hydrostatic-Compression
- ⇒ Fiber-Shear Around Projectile
- ⇒ Interlaminar Delamination & Matrix Crack
- ⇒ Compression-Shear (Plug Formation)
- ⇒ Tension-Shear (Large Deformation)
- ⇒ Friction between Projectile and Target

### ◆ BALLISTIC ENERGY PARTITION

- ⇒ All the energy absorbing mechanism in the Q-S PST
- AND
- ⇒ Stored Kinetic Energy
  - ⇒ Stored Elastic Energy



## BALLISTIC ENERGY PARTITIONING





## LAMINATE KINETIC ENERGY

### ◆ TARGET PHYSICAL PROPERTIES

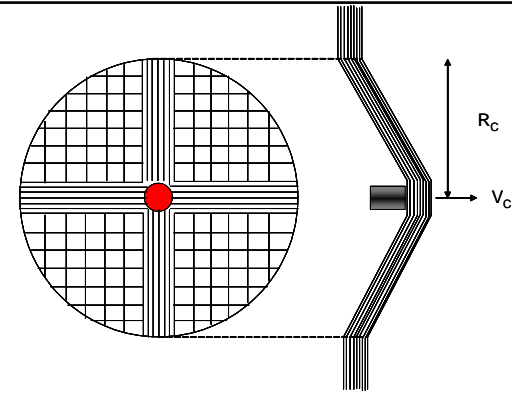
- ⇒ Density of the target =  $\rho_C$
- ⇒ Thickness =  $H_C$

### ◆ WE NEED TO FIND

- ⇒ Velocity of the moving cone =  $V_C$
- ⇒ Radius of the cone =  $R_C$

### ◆ KINETIC ENERGY OF THE MOVING CONE = $\frac{1}{2} M_C V_C^2$

- ⇒ Mass of the moving cone =  $\pi R_C^2 H_C \rho_C$



### ◆ $R_C$ CALCULATION, [S.S. Morye, 2000]

- ⇒ Cone form due to transverse wave propagation
- ⇒ Through thickness shear modulus =  $G_{1-3}$
- ⇒ Velocity of the wave,  $V_T = \sqrt{G_{1-3} / \rho_C}$
- ⇒ Radius of the cone  $R_C = t \times V_T$

### ◆ $V_C$ CALCULATION, [N.A. Naik, 2004]

- ⇒ At the point of impact, kinetic energy of the projectile =  $E_I$
- ⇒ At any instant the projectile decelerates and its kinetic energy =  $E_I'$
- ⇒ Loss of projectile kinetic energy =  $E_I - E_I'$
- ⇒ This energy is used for material damage ( $E_A$ ) and moving of the cone ( $E_A^C$ )
- ⇒  $E_I - E_I' = E_A + E_A^C$
- ⇒  $E_I - \frac{1}{2} m_P V_C^2 = E_A + \frac{1}{2} M_C V_C^2$
- ⇒  $V_C = \sqrt{[2(E_I - E_A)] / (M_P + m_C)}$



## DEFORMATION OF SECONDARY YARNS [S.S. Morye (May, 2000)]

### ◆ STRESS-STRAIN BEHAVIOR OF SECONDARY YEARN

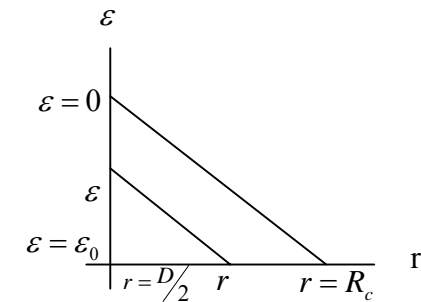
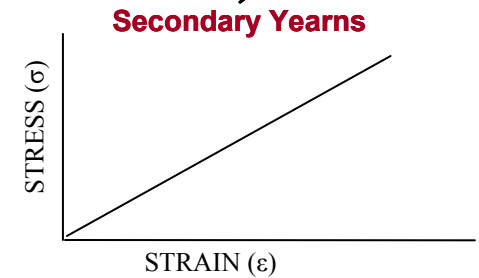
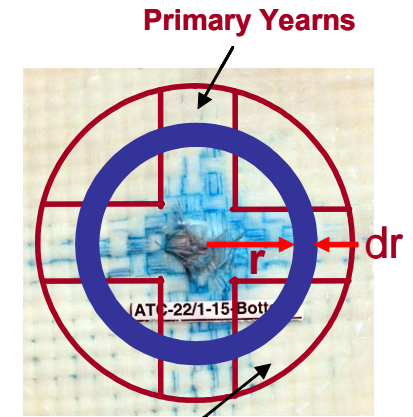
- Secondary yearn carry different strain depending on their position
- Yearn around the impact point carry equal or close to failure strain
- yarn which are away from the impact point experience less strain
- Strain variation is assumed to be linear from the closest point of impact to farthest point of impact
- Energy absorbed by the secondary yearn,  $E_{SY} = \frac{1}{2} \sigma \times \epsilon$   
 $= \frac{1}{2} M \epsilon^2$
- Tensile modulus of the target = M

### ◆ STRAIN ON SECONDARY YEARN

- Secondary yearn carry different strain depending on their position
- If  $\epsilon = \epsilon_0$  @  $r = D/2$  and  $\epsilon = 0$  @  $r = R_c$
- Strain at any point on the secondary yearn =  $\epsilon = \frac{2(R_c - r)}{2R_c - D} * \epsilon_0$
- Thickness of the target =  $H_c$

### ◆ ENERGY ABSORBED BY THE SECONDARY YEARN ( $E_{SY}$ )

$$\begin{aligned} \Rightarrow E_{SY} &= \int_{D/2}^{R_c} \frac{1}{2} M \times H_c 2\pi r dr \times 4\epsilon_0^2 \left( \frac{R_c - r}{2R_c - D} \right)^2 \\ &= \frac{MH_c \pi \epsilon_0^2}{(2R_c - D)^2} \left( \frac{R_c^4}{3} - \frac{D^2 R_c^2}{2} + \frac{D^3 R_c}{3} - \frac{D^4}{16} \right) \end{aligned}$$





## FAILURE OF PRIMARY YEARN

### ◆ TENSILE FAILURE OF PRIMARY YEARN

- Primary yearn provide the most of resistive force to penetrate the target
- When strain in the primary yearn exceeds the ultimate strain at high strain rate, penetration occurred.
- Stress-strain properties from high strain rate behavior
- At stress  $\sigma$ , failure strain  $\epsilon_0$  (high strain rate properties)
- Energy absorbed due to tensile failure of the primary yearn

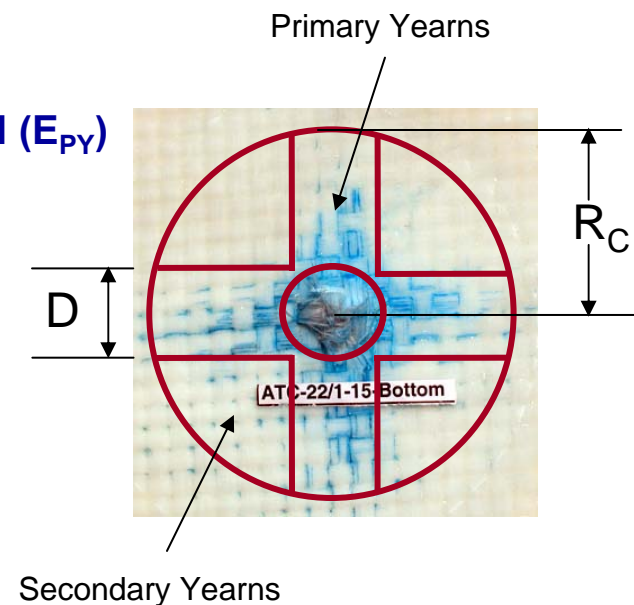
$$E_C = \int_{\epsilon=0}^{\epsilon=\epsilon_0} \sigma(\epsilon) d\epsilon$$

### ◆ TOTAL ENERGY ABSORBED BY THE PRIMARY YEARN ( $E_{PY}$ )

- $E_{PY} = E_C \times V_{PY}$
- $V_{PY}$  = Volume of the primary yearn

### ◆ VOLUME OF THE PRIMARY YEARN ( $V_{PY}$ )

- Radius of the cone =  $R_C$
- Diameter of the projectile =  $D$
- Target thickness =  $H_C$
- Volume of the primary yearn,  $V_{PY} = 4R_C D H_C$





## DELAMINATION AND MATRIX CRACK

### ◆ ENERGY ABSORBED BY THE DELAMINATION

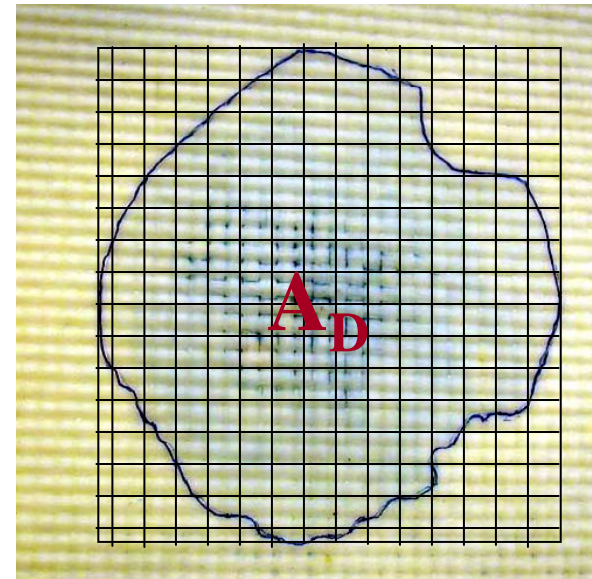
- Total delaminated area =  $A_D$ .
- Energy release rate per unit area =  $G_D$
- Energy absorbed by the delaminated area,  $E_D = A_D \times G_D$

### ◆ CALCULATION OF $A_D$

- L.M. Nunes recommended traditional manual method
- Damaged area was visually identified and manually outlined
- More reliable than the digitization methods and processing
- $A_D$  is calculated by using traditional square sampling and counting method.
- Provide precise results if the square size is small enough

### ◆ DETERMINATION OF $G_D$

- Most of the researchers recommended,  $G_D = G_{IIC}$
- Daniel Delfosse study both brittle and tough target
- For brittle target,  $G_D \approx G_{IIC}$
- For tough target,  $G_D \approx 2.5G_{IIC}$





## FRICITION BETWEEN PROJECTILE AND TARGET

### ◆ FUNCTION OF FRICTIONAL FORCE

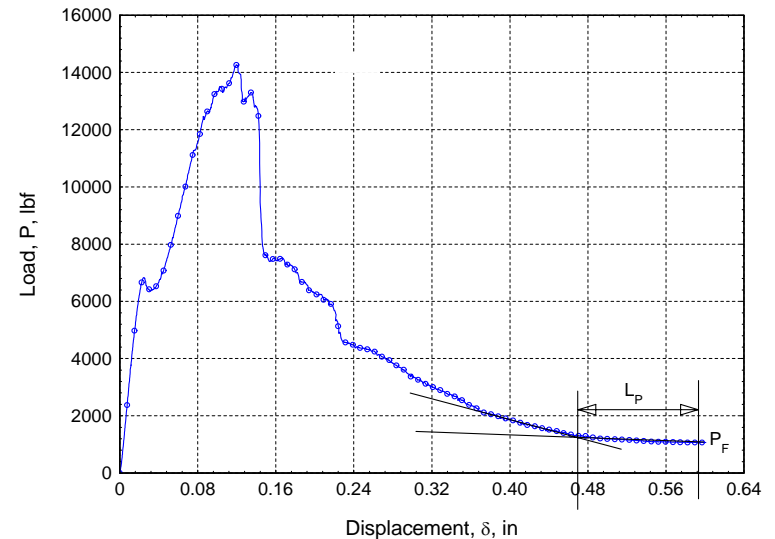
- Initially it does not play important role because the resistance force from the target is very high.
- After all the fiber broken, frictional force is the only resisting force
- It depend on the target and projectile physical properties
- Some researchers have found the energy absorbed due to friction by assuming it to be the same as that in the case of quasi-static test\*.

### ◆ QUASI-STATIC TEST

- P- $\delta$  plot from quasi-static punch shear test
- The long tail at the end of the plot represent the frictional force between target and projectile

### ◆ ENERGY LOSS DUE TO THE FRICTION

- Length of the projectile =  $L_p$
- Frictional force =  $P_F$
- Absorbed energy,  $E_F = P_F \times L_p$





## ENERGY ABSORBE BY THE FORMATION OF SHEAR PLUG

### ◆ SHEAR PLUG FORMATION

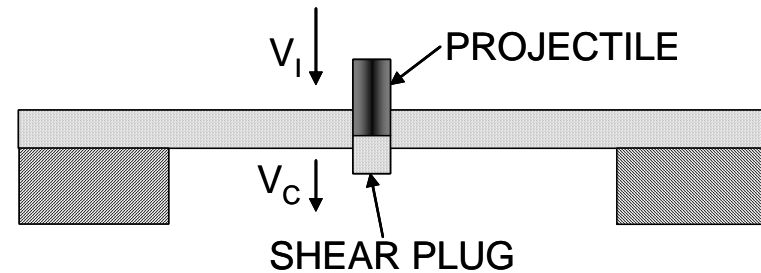
- Cantwell and Morton observed formation of shear plug during the high velocity impact test
- Shear stress act on the periphery of the projectile during impact which causes the shear plug
- Li Chen consider the projectile moving together with the plug as a whole.

### ◆ ABSORBED ENERGY BY THE SHEAR PLUG

- Projectile velocity =  $V_I$
- After impact velocity of the plug and projectile =  $V_C$
- The absorbed energy by the shear plug =  $E_{SP}$

$$E_{SP} = \frac{1}{2} m_P V_I^2 - \frac{1}{2} (m_P + m_{SP}) V_C^2$$

- Mass of the projectile =  $m_P$
- Mass of the shear plug =  $m_{SP}$





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## **SUMMARY**

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- ◆ **A literature review has been done on the ballistic damage mechanism of thick section composites.**
- ◆ **For the brittle material (carbon/epoxy) shear plugging and secondary yarn deformation are the main energy absorbing mechanism.**
- ◆ **For tougher material (glass/epoxy) tensile failure of the primary yarn and secondary yarn deformation are the main energy absorbing mechanism.**
- ◆ **We have complete understanding of QS-PST and energy partition.**
- ◆ **We will develop a detail energy balance model and validate with our experimental data.**