Fragment Penetration Modeling of Anthropometric Ballistic Mannequins

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Introduction

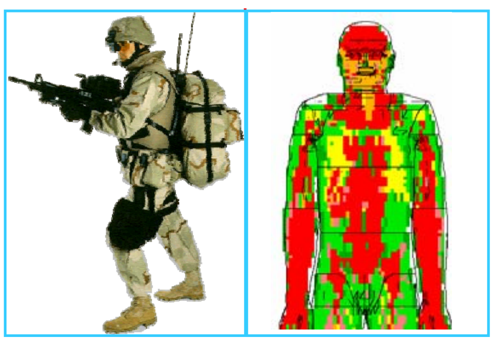
ORCA Model
An Integrated Methodology for Survivability Assessment

BURNSIM - THERMAL
(U.S. Air Force Research Laboratory)

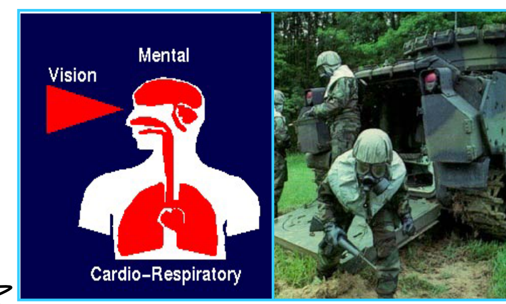
INJURY - BLAST OVERPRESSURE
(U.S. Army Medical Research and Materiel Command)

AMANDA - ACCELERATION
(U.S. Army Aeromedical Research Laboratory)

Operational Requirement-based Casualty Assessment



COMPUTERMAN
(U.S. Army Research Laboratory)



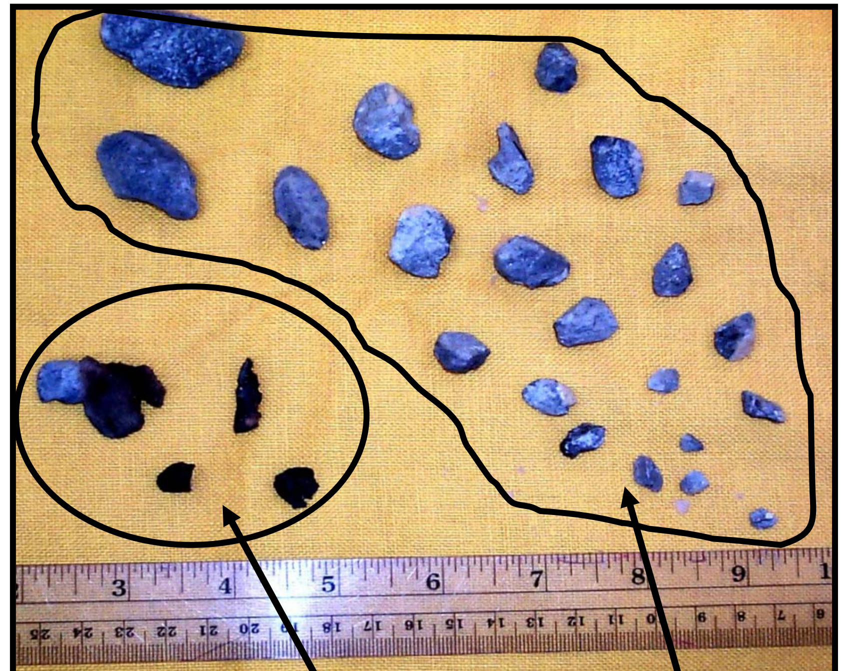
CHEMICAL MAN
(U.S. Army Research Laboratory)

- **Standard Injury Description**
- **Standard Military Task Inputs**
- **Common Integrated Crew Casualty Assessment Methodology**

Secondary Debris from Concrete Wall Front Surface

Debris cloud from warhead impact

Recovered steel warhead fragments and aggregate debris

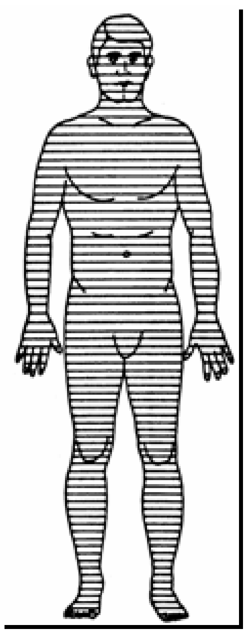


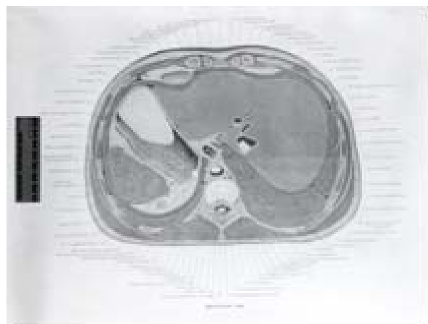
Steel fragments
Mass: 0.13g - 8g

Aggregate (stone)
Mass: 0.05g - 9g

ORCA / Computerman

3-D Anatomical Man





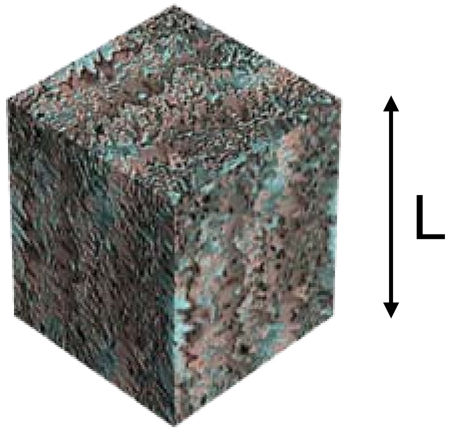
Plywood Mannequin

Wound Ballistics Modeling:

- Input : Mass, Velocity, Shape Factor , Entry & Exit Points
- Data Source: Plywood Penetration & Ballistic Gel Retardation
- Output : Expected Incapacitation (EI) of a Soldier

Projectile Characteristics

- Shape: Cube, Natural Aggregate
- Mass: 0.1g – 41g
- Size (Length): 0.22cm – 1.75cm
- Materials**
  - Steel
  - Aluminum
  - Aggregate
  - Granite
- Velocity: 150m/s – 1000m/s



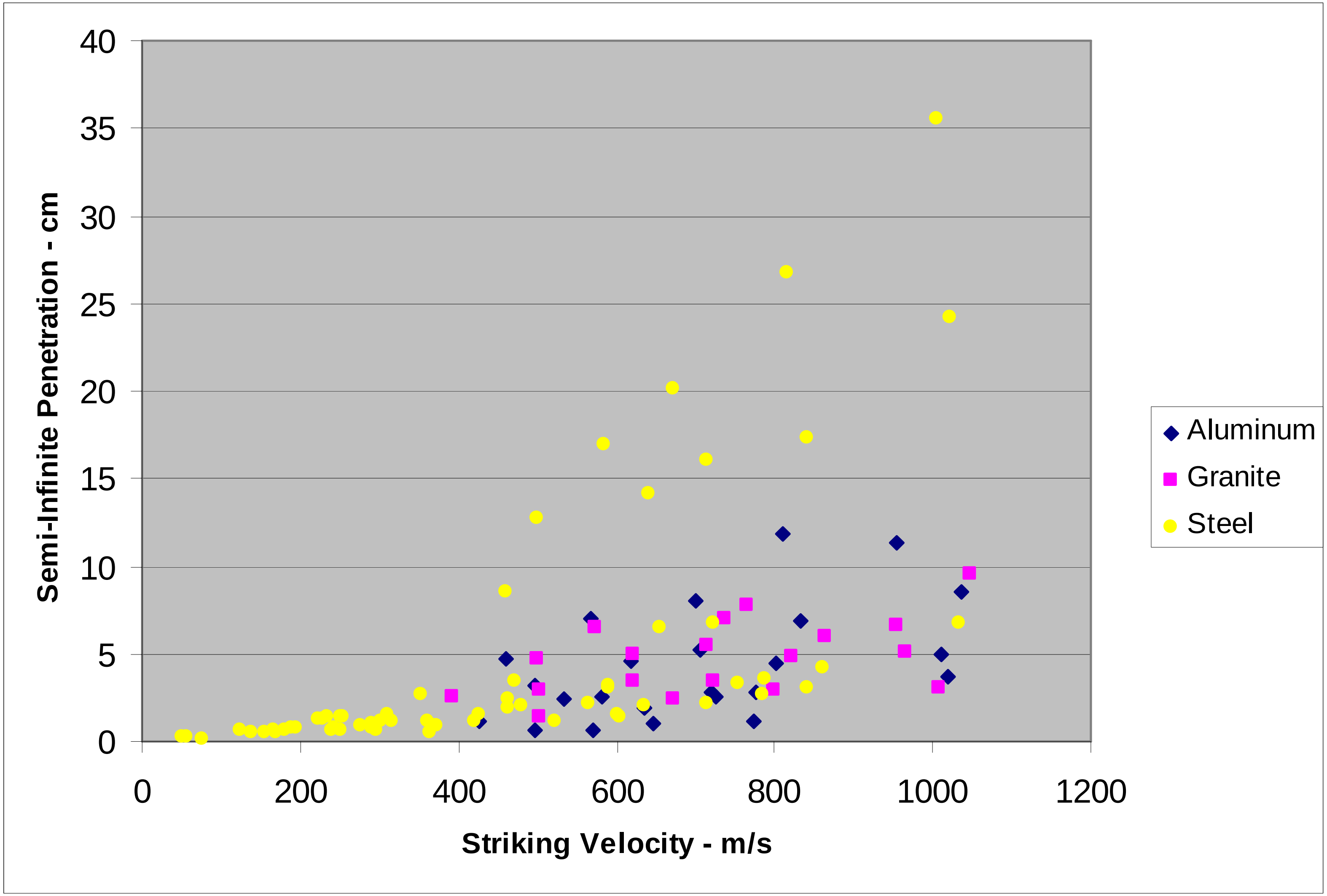
**Note: All projectiles penetrated as rigid bodies

Target Characteristics

- Material: ¾ in Marine Grade Plywood
- Density: 0.35 g/cc
- Configuration
  - Semi-infinite stack, i.e. semi-infinite target
  - Single layer, i.e. finite target
- Obliquity
  - Semi-infinite, 0^o obliquity
  - Finite, 0^o and 60^o obliquity

Semi-Infinite Penetration (All Cubes)

Raw Data – Aluminum, Granite, and Steel



Penetration Model

After Tate and Alekseevskii:

$\dot{L} = V - U$ (erosion kinematics)

$L\,\dot{U} = -Y/r_r$ (rod deceleration)

$\frac{1}{2}\, r_r (U-V)^2 + Y = \frac{1}{2}\, r_t + R$ (interface stress balance)

"Approaches to Penetration Problems", T. Wright, K. Frank, U.S. Army Ballistic Research Laboratory, TR-2957, December 1988

For Fragment Penetration of Plywood:

- $V-U = 0$
- $R > Y$

Semi-Infinite Plywood Penetration Analysis

Differential Form of Penetration Equation:

-mv(dv/dx) = ½ rbAv2 + sA

where: r = 0.35 g/cc

s = strength of plywood, dynes/cm^2

A = Average Presented Area of Fragment, (cubes), cm^2

v = striking velocity, cm/sec

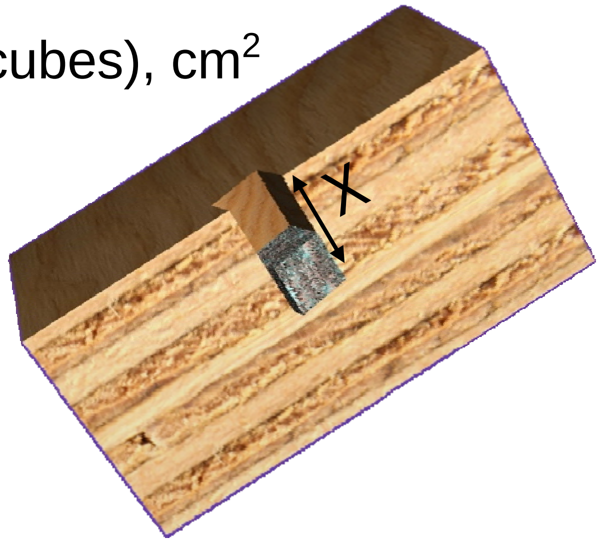
m = fragment mass, g

X = plywood penetration depth, cm

a = A/m

g = ½ r

b = Shape Factor



Integrating the above equation for v and x:

$$X = \frac{-1}{2}\cdot\frac{\ln(\sigma) - \ln\left(v_0^{\,2}\cdot\gamma\cdot\beta + \sigma\right)}{\alpha\cdot\gamma\cdot\beta}$$

Solution requires determination of two unknowns: b, s (optimized over all fragment masses, areas, and densities => NLLS solution for b,s)

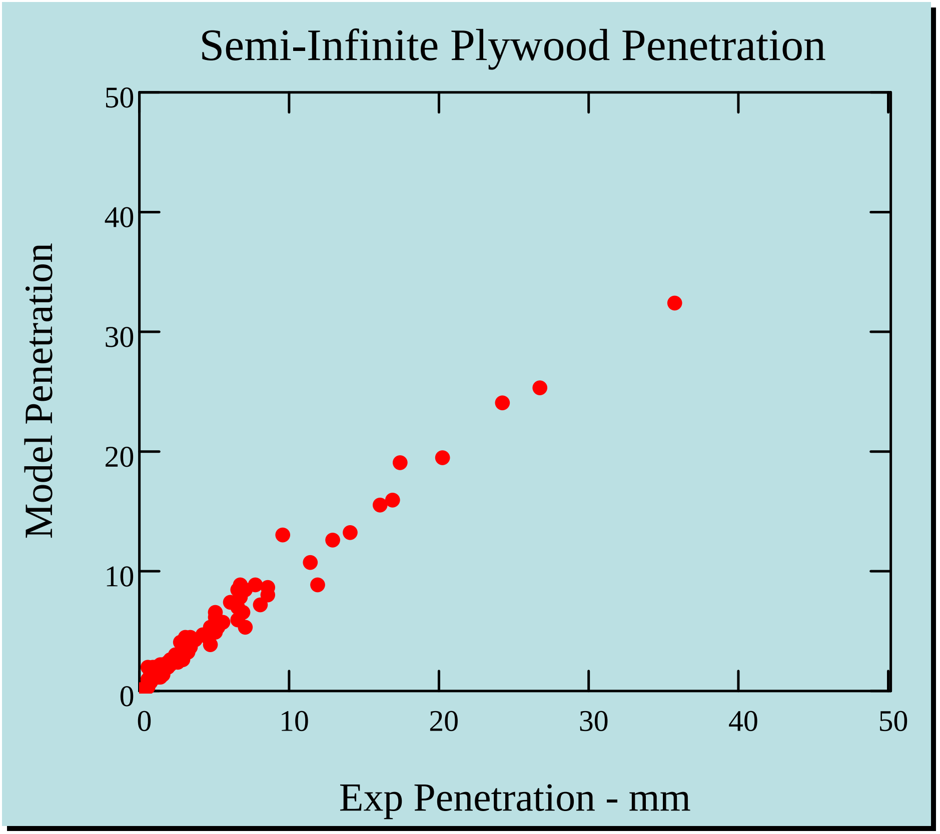
Results of Analysis (Penetration Prediction)

Number of Data Points: 105
Average Miss Distance (average of all (x_{pred} - x_{obs})): -0.253 mm

b = 1.014
s = 7.007 x 10^8 dynes/cm^2

$$X = \frac{-1}{2} \cdot \frac{\ln(\sigma) - \ln\left(v_0^{\,2} \cdot \gamma \cdot \beta + \sigma\right)}{\alpha \cdot \gamma \cdot \beta}$$

Indicates how well penetration is predicted for any fragment at a given striking velocity.

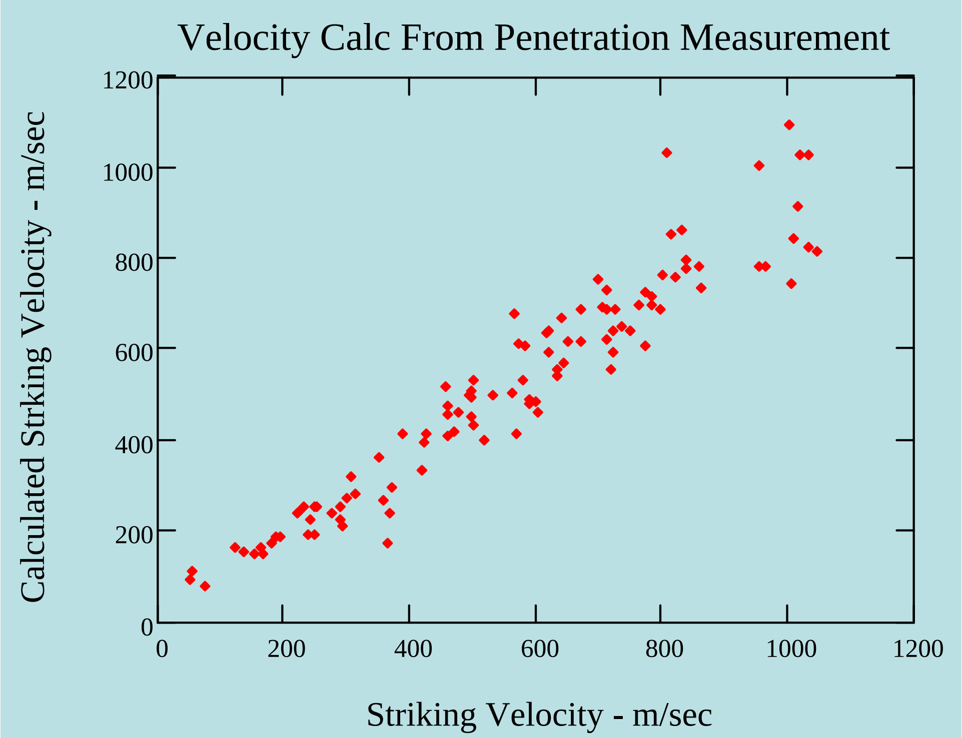


Results of Analysis (Velocity Prediction)

$$V_s = \frac{1}{e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}\cdot\gamma\cdot\beta}\cdot\left[\left[-e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}\right]\cdot\gamma\cdot\beta\cdot\sigma\cdot\left[e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}-1\right]\right]^{\frac{1}{2}}$$

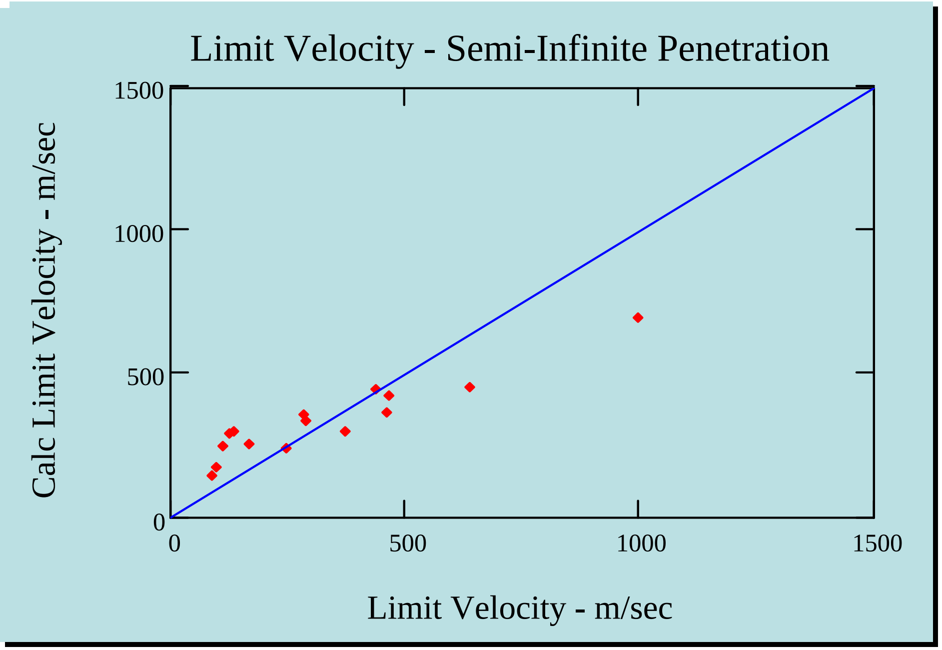
b = 1.014

s = 7.007 x 10^8 dynes/cm^2



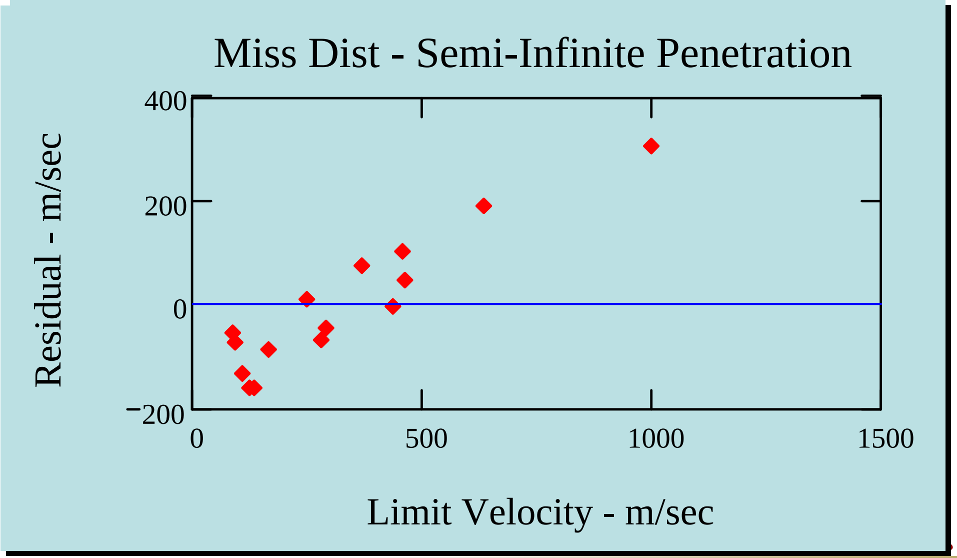
Limit Velocity Prediction ¾” Plywood

- Assume no finite target effect, i.e. limit velocity equals velocity needed to penetrate ¾-in into semi-infinite plywood

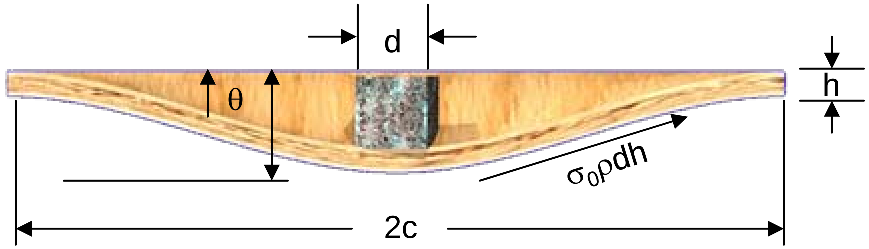


- Analysis of residuals show linear trend → finite thickness effect

*Residual = ($X_{observed}$ –$X_{predicted}$)



Finite Plywood Correction



$$mv \cdot \frac{dv}{dx} = \sigma_0 \cdot \pi \cdot d \cdot h \cdot \frac{x}{c}$$

$$\int_{v_f}^{0} v\,dv = \int_{0}^{x} -\sigma_0 \cdot \pi \cdot d \cdot h \cdot \frac{x}{c \cdot m}\,dx$$

$$v_f^{\,2} = x^2 \cdot \sigma_0 \cdot \pi \cdot d \cdot \frac{h}{c \cdot m}$$

→ $v_f \sim (A_p/m)^{1/2}$

"The Limit Velocity of Fragments Impacting Lightweight Armor Materials: An Ad Hoc Model", W. Bruchey, BRL MR-2677, Sep 1976

Finite Thickness Correction

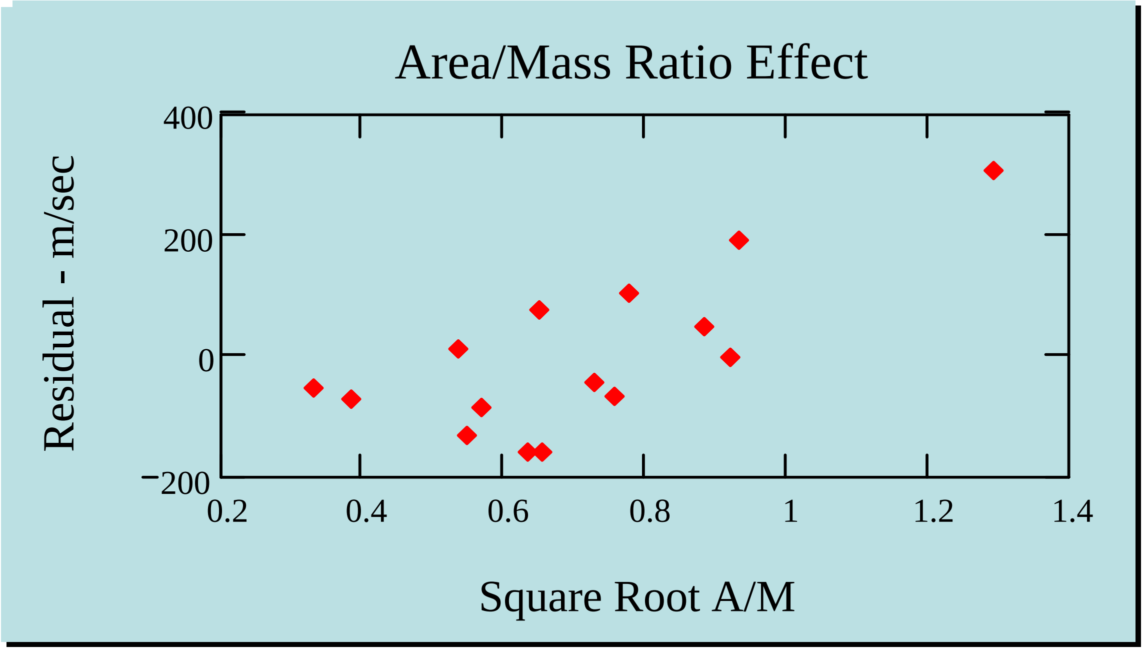
Assume:

- Initial penetration is given by semi-infinite penetration analysis
- At some thickness < ¾-in, the plywood fails and acts as if it is a membrane
- Membrane analysis shows that the failure velocity is proportional to $(A_p/m)^{1/2}$

Linear relationship

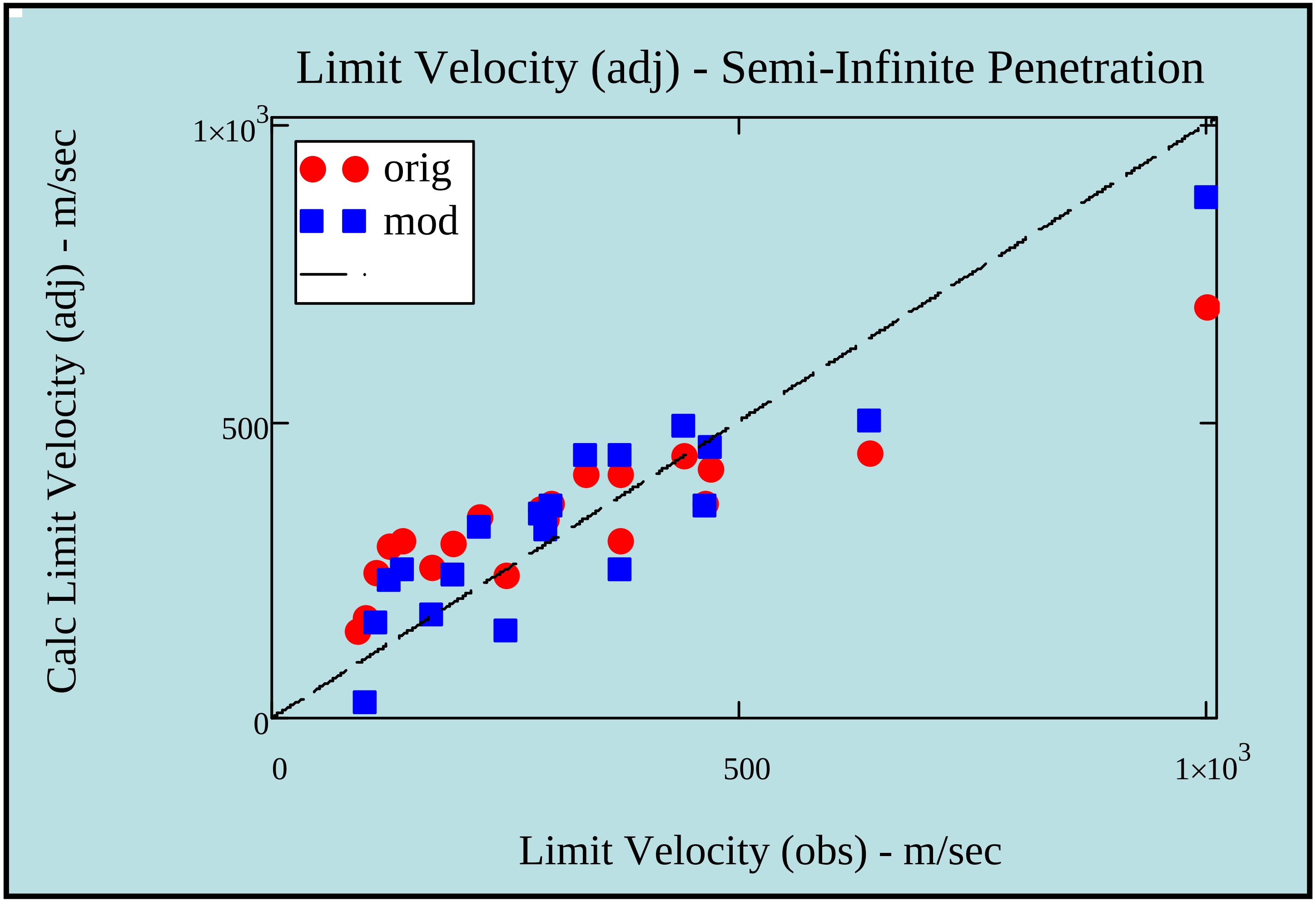
Residual = $a + b(A_p/m)^{1/2}$

$a = -2.846 * 10^4$
$b = 3.601 * 10^4$



Limit Velocity
Calculated from Semi-Infinite Penetration

Calculated Limit Velocity with Adjustment for finite thickness versus the Observed Limit Velocity



Conclusion

This model provides an estimate of fragment penetration into semi-infinite stacks of marine-grade plywood. Limit velocities can be estimated from semi-infinite penetration utilizing a correction factor for finite target breakout effects.

Resulting Equations:

- Semi- Infinite

$$V_S = \frac{1}{e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}\cdot\gamma\cdot\beta}\cdot\left[\left[-e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}\right]\cdot\gamma\cdot\beta\cdot\sigma\cdot\left[e^{(-2)\cdot x\cdot\alpha\cdot\gamma\cdot\beta}-1\right]\right]^{\frac{1}{2}}$$

- Finite (¾-in Marine Plywood)

  Semi- Infinite solution plus breakout correction

  $a + b(A_p/m)^{1/2}$