Some Basic Physics of 9/11

Ryan Mackey

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 The author can be contacted at: rmackey_email@earthlink.net

Additional On-Line Resources:

9/11 Myths: http://www.911myths.com

Mark Roberts' Collection: http://wtc7lies.googlepages.com/

9/11 Guide: http://911guide.googlepages.com/

Overview

- Many arguments put forth by the Truth Movement are physical in nature
  - E.g., can aircraft really penetrate steel structures?
  - Were the collapses “too fast?”
  - Is a progressive collapse likely, even possible?

- While a detailed investigation can be complicated, the basic principles are simple
  - Construct simple models to illuminate these processes
  - While these will not *prove* what happened, can demonstrate whether a given hypothesis is *reasonable*
  - This is enough to *disprove* Truth Movement claims that the “official hypothesis” is not credible

Overview: Physics of Impact

- Example Fundamental Question:

Can an aircraft penetrate a steel-framed structure?

  - Consider motivating examples from history
  - Identify what properties are important
  - Understand strength, hardness, pressure, impulse
  - Construct a simple model of the problem
  - Analyze based on simple model
  - Compare to more formal results
  - Use our model for prediction

Historical Impact Examples

Some collisions seem to do very little damage

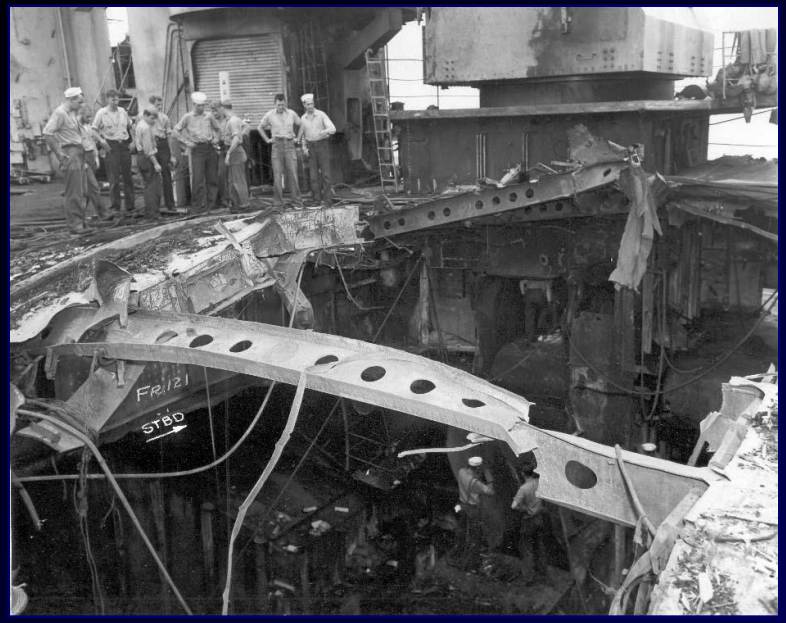
Pirelli Tower, Milan, 18 April 2002
Photo Credit: AFP

Bank of America Tower,
Tampa Florida, 5 January 2002
Photo Credit: Associated Press

Historical Impact Examples

Others do much, much more
But why? How can we tell these apart?

F-4 Impact Sled Test
Sandia National Laboratories



USS Franklin After Kamikaze Hit,
30 October 1944
Photo Credit:
Puget Sound Naval Yard

What Properties Matter?

- Some have suggested the World Trade Center steel should have survived impact because of:
  - **Hardness**: Aluminum aircraft is much softer than steel
  - **Strength**: Structural steel was far stronger
  - However, there are plenty of counter-examples…

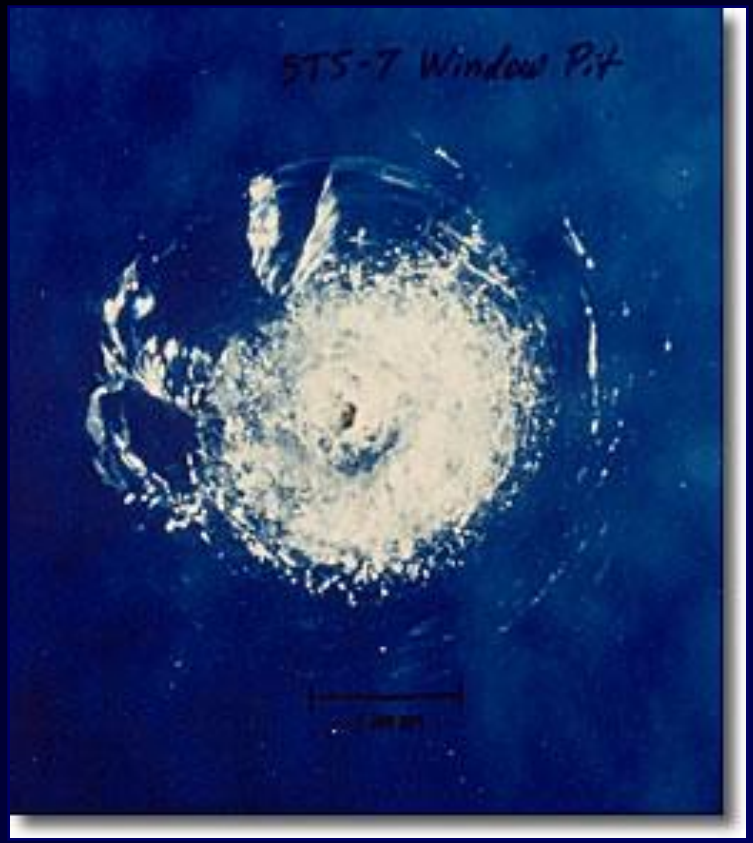
F-16 Falcon canopy bird strike testing

Photo Credit: Southwest Research Institute

What Properties Matter?

- Clearly hardness and strength only tell part of the story
- Other important quantities: Mass, speed, shape, incidence angle…

Space Shuttle Challenger (STS-7) window, damaged by a flake of paint
Photo Credit: NASA / JSC

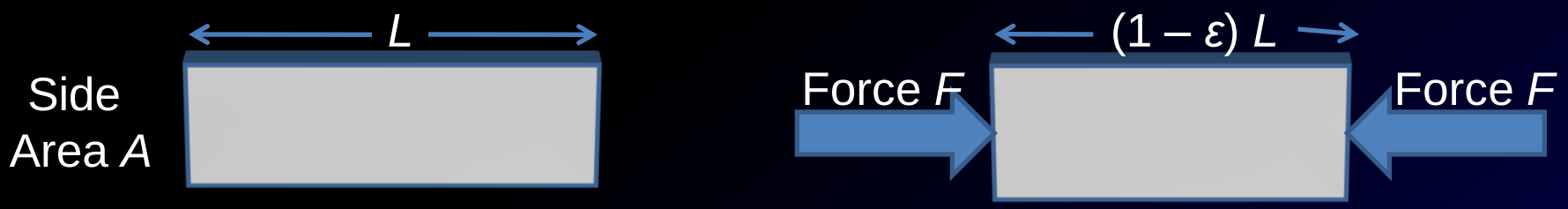


Understanding Hardness

- What is “hardness?”
  - Not well defined.
  - There are several scales, such as:
    - *Mohs Scale:* Familiar 1 to 10 mineral hardness scale
    - *Rockwell Scale:* Depth of penetration under controlled test conditions
  - Provides a basic measure of *rigidity*
    - Related to strength, but also varies with elastic/plastic behavior
    - A “hard” material can be very fragile

Understanding Strength

- So what is "strength?"
  - Defines the actual force required to break an object



Pressure on outside = F / A. We also have $\boldsymbol{\sigma = F / A}$ where σ is the *axial stress* inside the solid.

While solid remains elastic, E is constant (called the Young's Modulus)

The strain ε is the ratio of stretch the solid experiences under stress, $\boldsymbol{\sigma = E\,\varepsilon}$

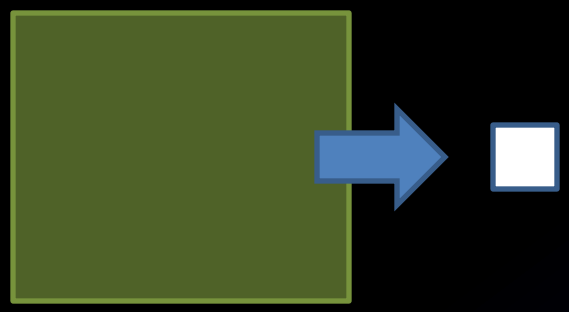
The maximum stress the solid can stand is called $\boldsymbol{\sigma_U}$ or the Ultimate Strength

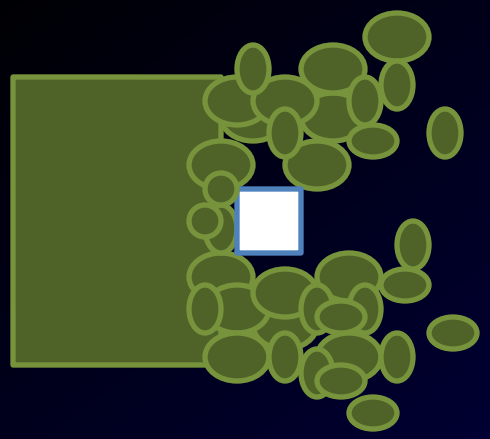
Effect of Hardness and Strength

Define four basic classes of impactor behavior:

Hardness	Strength	Meaning	Examples
Soft	Weak	Impactor deforms and breaks on impact	Water, foam, plastics
Hard	Weak	Impactor shatters on impact	Glass
Soft	Strong	Impactor deforms easily, but remains a single object until strain is extreme	Rubber
Hard	Strong	Impactor is both rigid and deformable	Spring steel

Effect of Hardness and Strength



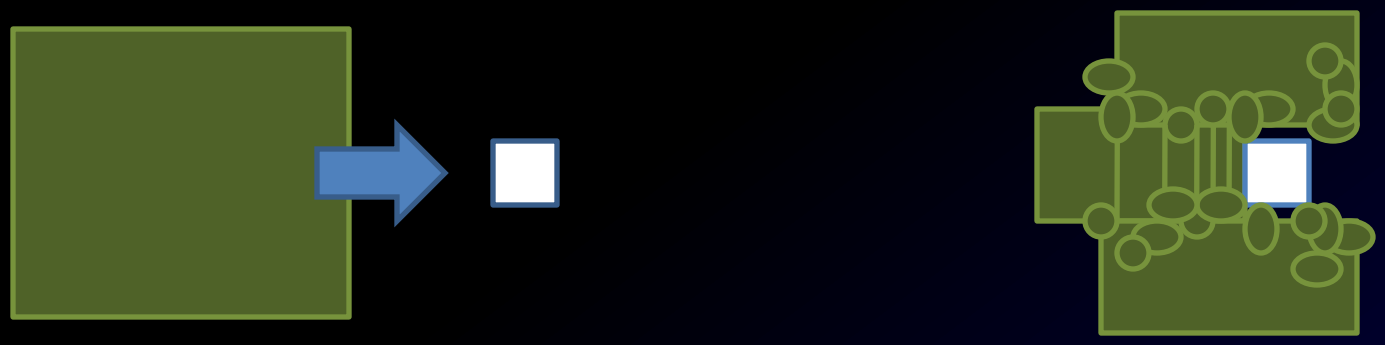


Case 1: Weak impactor flows around impacted object

Softness means only the part actually in contact transfers momentum at any given moment

Weakness means the impactor absorbs little energy as it deforms, but much of it may bypass target completely

Effect of Hardness and Strength

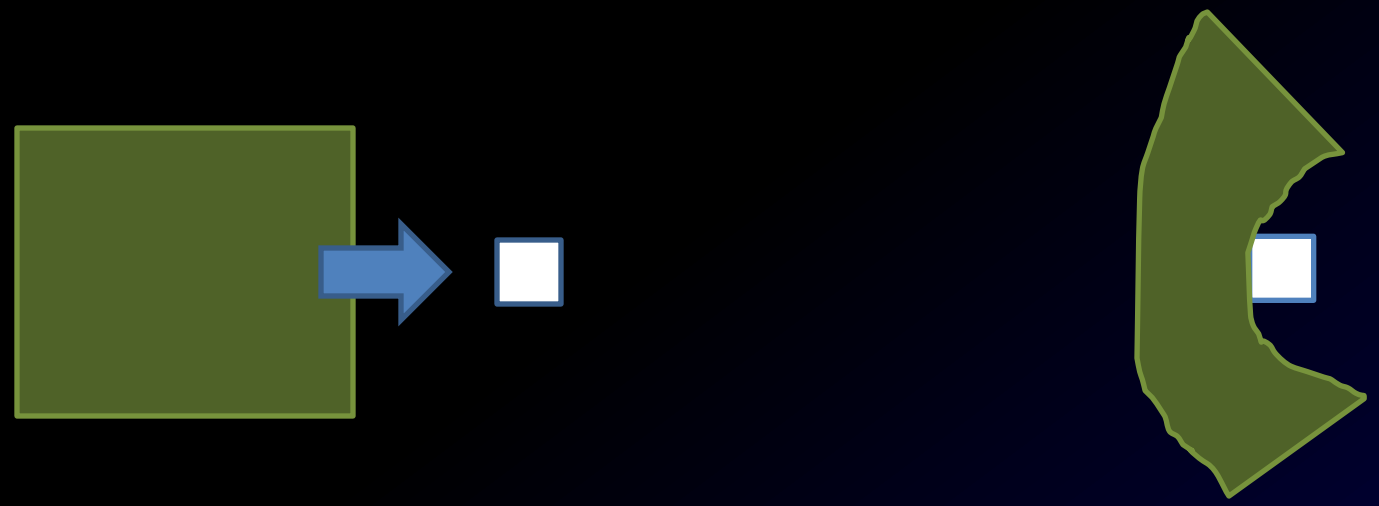


Case 2: Brittle impactor jars impacted object, then fractures

Hardness means at contact, there is a higher momentary pressure spike as mass behind contact resists compression, but then breaks

Impactor still absorbs little energy as it deforms

Effect of Hardness and Strength

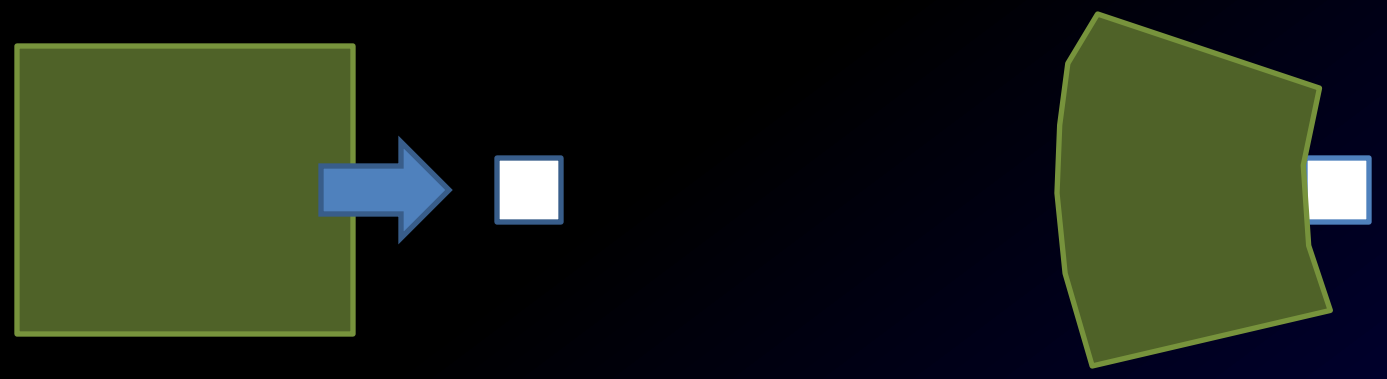


Case 3: Flexible impactor deforms until it stops or breaks

Softness means the impact is relatively gradual, with no sharp spike at contact

Strength means more of the impactor mass participates, though the impactor absorbs some energy as it stretches

Effect of Hardness and Strength



Case 4: Strong, elastic impactor undergoes slight deformation as momentum flows to the point of contact

Creates higher and sustained pressures at contact

May dissipate more energy as it deforms, but may also remain elastic if much stronger than impacted object

Impact Severity: Impulse and Pressure

- When calculating impact damage, we usually construct a *pressure-impulse* curve:
  - Pressure: Force divided by area – the "average force" of impact
  - Impulse: The total change in momentum caused by the impact ("total amount of force over time")

Newton's Second Law: $\boldsymbol{F} = \mathbf{d}\boldsymbol{p} / \mathbf{dt}$, where $\boldsymbol{p} = \mathbf{m}\,\boldsymbol{v}$

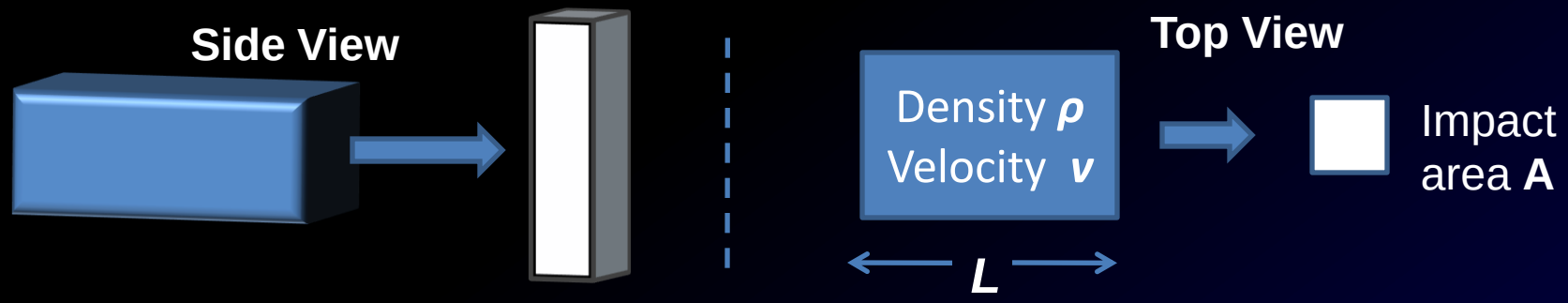
If m constant, $\mathbf{d}\boldsymbol{p} / \mathbf{dt} = \mathbf{m}\ \mathbf{d}\boldsymbol{v} / \mathbf{dt}$

$\boldsymbol{F} = \mathbf{m}\ \mathbf{d}\boldsymbol{v} / \mathbf{dt}$, so $\boldsymbol{F}\ \mathbf{dt} = \mathbf{m}\ \mathbf{d}\boldsymbol{v}$ = *Impulse*

  - Need both high pressure and a large impulse to cause damage
    - If pressure is too low, column stays elastic and springs back
    - If impulse is too low, the column will bend but won't displace enough to cause it to fail, and may spring back
    - Pressure and impulse are both related to force! They are not really independent

Simple Model: Wing Section Impact

- Now let's construct a simple model:



  - Represent aircraft wing as a slug of uniform density ***ρ*** at velocity ***v***, length ***L***, interacting with a vertical column with contact area ***A***
  - Assume we have the weakest type of impact, i.e. hardness and strength of the wing section are small
    - We ignore mass outside the contact area in this case
    - Reasonable if the fuel's momentum dominates the impact, but this will underestimate impact severity
  - What force and impulse does the column experience?

Wing Section Impact Solution

- Write Impulse Equation:
  - If column doesn't fail, assume it brings entire slug of fuel to a stop: dv = $\boldsymbol{v}$, and mass m = density times volume:

$$\boldsymbol{I} = \mathrm{m}\ \mathrm{d}v = (\rho\, A\, L)\ \boldsymbol{v}$$

  - We now have $\boldsymbol{I}$, but need to find force $\boldsymbol{F}$ to get pressure:

$$\boldsymbol{I} = \mathrm{m}\ \mathrm{d}v = \boldsymbol{F}\ \mathrm{d}t$$

  - Now dt is the length of time for the entire slug of fuel to pour into the column:

$$\mathrm{d}t = L / \boldsymbol{v}, \quad \text{so} \quad \boldsymbol{F}\, L / \boldsymbol{v} = \rho\, A\, L\, \boldsymbol{v}$$

$$\boldsymbol{F} = \rho\, A\, \boldsymbol{v}^2 \qquad \mathbf{p} = \boldsymbol{F} / A = \rho\, \boldsymbol{v}^2$$

Wing Section Impact: Numerical Estimate

- Now use our equations to estimate the impact severity
- How much fuel impacts an average column? How fast?
  - Need to find length, area, density, and velocity
  - Information can be found in NIST report, etc.

Width of perimeter column = 14” (NCSTAR1-1 pg. 10)

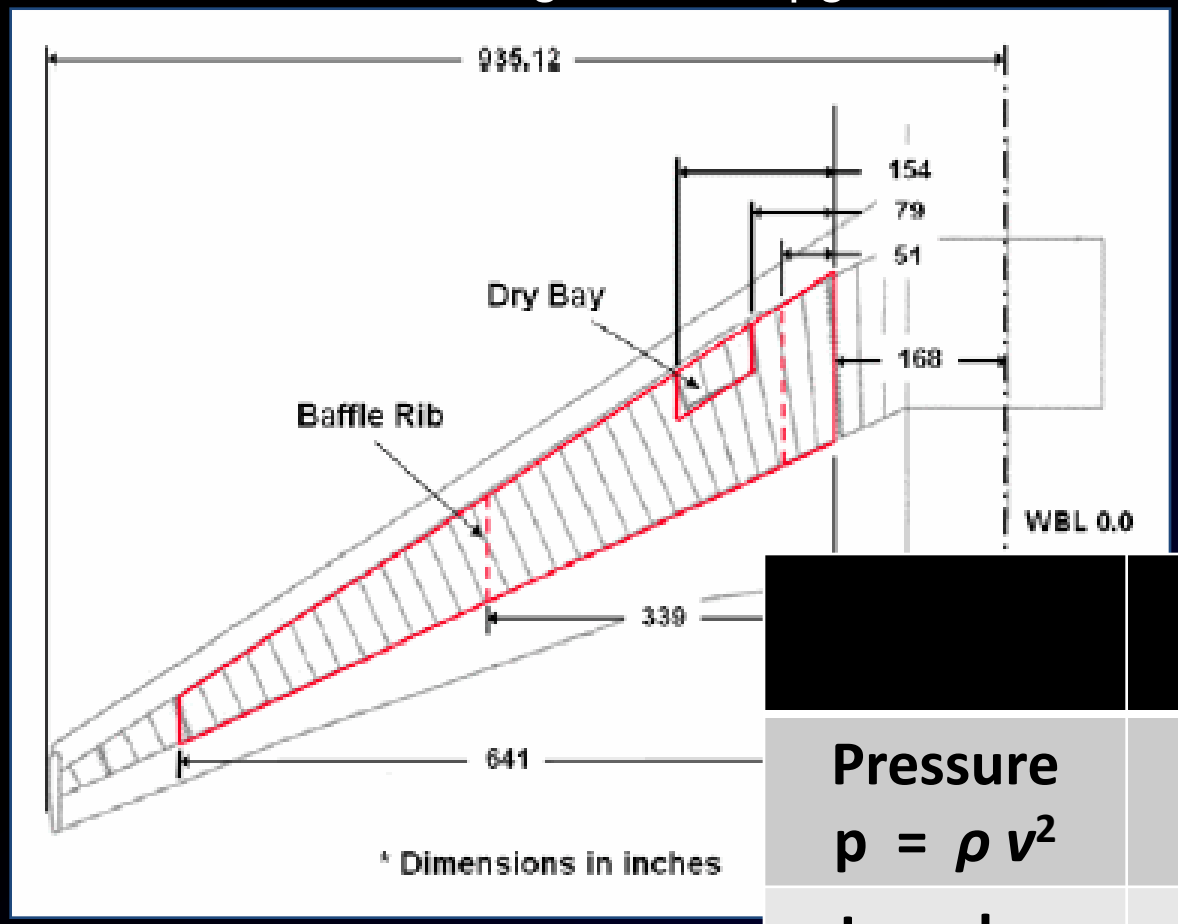
Height of wing section ~ 16”, Length of wing section ~ 120”
(NCSTAR1-2B pg. 86) (see figure on next page)

Velocity = 650 ft/s (AA 11) or 790 ft/s (UA 175)
(NCSTAR1-2B pg. 170)

Jet fuel density = 0.81 kg / ℓ = 50.5 lbm / ft^3

Wing Section Impact: Numerical Estimate

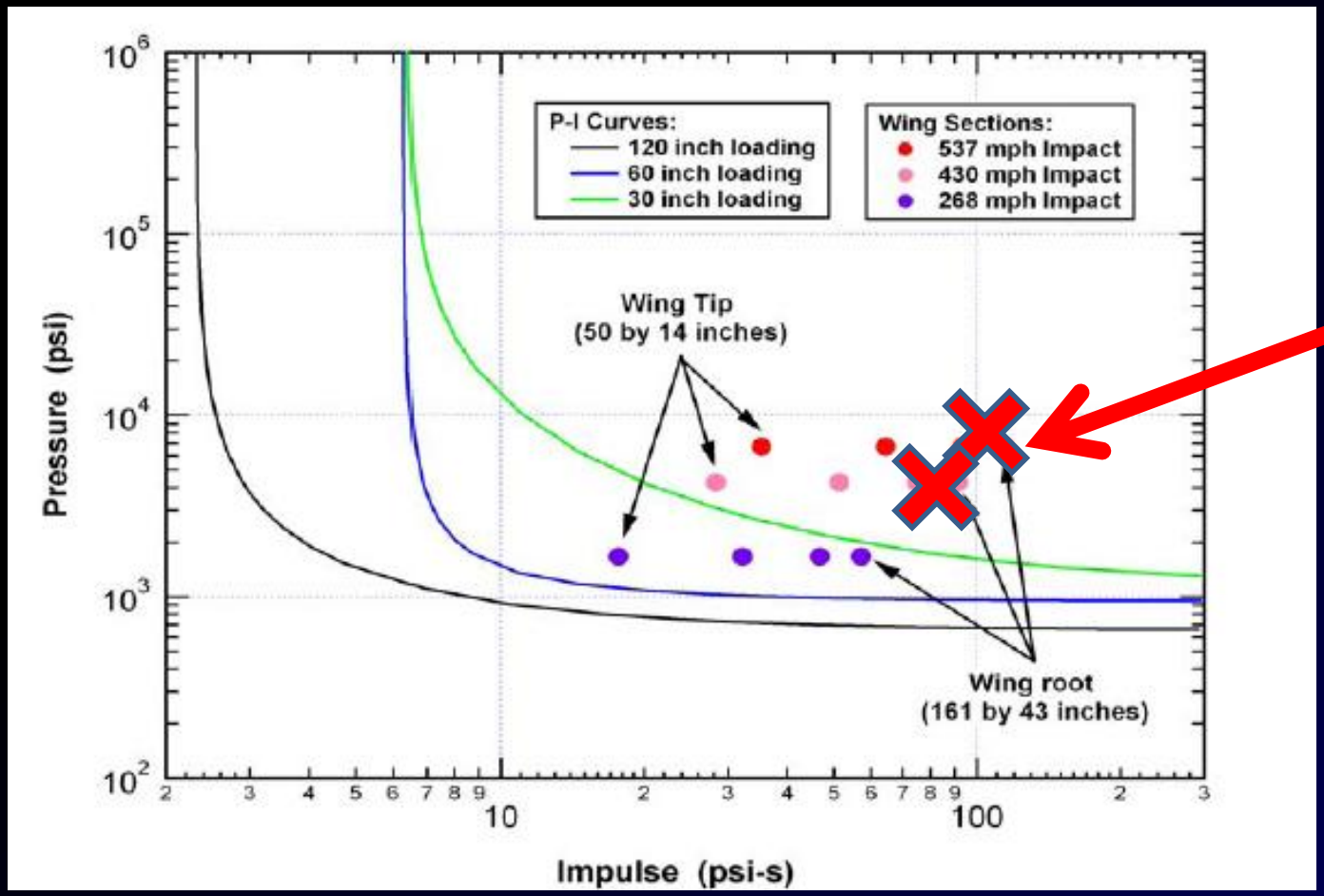
NCSTAR1-2B Figure 4-32, pg. 86



	AA 11	UA 175
Pressure $p = \rho v^2$	4600 PSI	6800 PSI
Impulse $I = \rho A L v$	15900 lbf-s	19300 lbf-s

Comparing to Column Strength

- NIST provides pressure-impulse curves required to break typical WTC core columns



NCSTAR1-2B Figure 10-5, pg. 376

Our Results

NIST graphs use impulse per square inch rather than total impulse – divide our figures by 1 ft^2 = 144 in^2 to match

Comparing to Column Strength

- Our rough calculations are pretty close to NIST rough estimates (1-2B Chap. 10)
  - Estimated pressure is right on target
  - Estimated impulse is a little high, but in family
  - NIST models (more detailed) may assume deflection of fuel parcel, or entrainment away from column by bits of aircraft structure, rather than complete collision

- Demonstrates that, at this speed, *fuel alone* can plausibly fail **core** columns

- Certainly can fail perimeter columns!

Prediction: What Speed Causes Failure?

- We can use the same equations to estimate the *minimum* speed to penetrate the perimeter
  - A significantly lower speed should bend perimeter columns, but not break them, and largely bounce off
  - Pressure is more sensitive to change in speed, since it scales as $\boldsymbol{v^2}$, while impulse only scales as $\boldsymbol{v}$
  - From NIST's P-I curve, estimate that above 800 PSI, at least some columns will not survive

$$\mathbf{p} = \boldsymbol{\rho}\, \boldsymbol{v}^2 = 800 \text{ PSI}$$

$$\boldsymbol{v} = (800 \text{ PSI} / \boldsymbol{\rho})^{1/2} = \mathbf{270} \text{ feet per second}$$

  - Therefore, we predict that an impact over 270 ft/s = 185 MPH will penetrate the structure

Self-Test: Do Our Results Make Sense?

- Does the pressure we computed make sense?
  - Fire hoses operate at about 300 PSI, and produce streams at about 100-150 MPH. Our jet fuel is traveling more than three times as fast, so we expect pressures of a few thousand PSI.
- Does the total impulse make sense?
  - 16,000 lbf-s is equivalent to the momentum of a 4,000 pound car at 80 MPH, similar to our 700 pound slug of fuel at 450 MPH
- Do our numbers agree with other investigations?
  - Yes. Our numbers are consistent with NIST first principles estimates; pressure is right on, impulse is a bit higher (about double the NIST estimate)
  - NIST may have assumed a lower effective density or total mass (partially fueled tanks, lighter wing structures, etc.), elasticity in the wing structure, or deflection of fuel

Conclusions

- Momentum from fuel alone will allow an aircraft to destroy steel columns
  - Predict speed of > 185 MPH is needed to destroy major columns
  - Explains why lower speed crashes do less damage
  - If aircraft is low on fuel, only fuselage and engines may penetrate
- Mass and momentum, not strength and hardness of the impactor, are most important quantities
  - Stronger or harder objects could mean more mass (and more momentum) affects structure rather than bypassing columns, but given enough momentum, this is simply not required
- Damage caused to WTC Towers is completely credible
  - Not *proven* – we have used many simplifications – but unless we have neglected something major, our numbers are in the right ballpark

Some Basic Physics of 9/11
Part II: Modeling

Ryan Mackey

What Is a Model?

- A *model* is a simplified representation of a real system
  - Scale models
  - Mathematical models
  - Computer models
  - Analogue systems
- Designed to replicate *behavior* of real system
  - Should contain some or all of the same physical mechanisms seen in reality
  - May let us work on one part of the problem at a time
  - May provide a cheaper, easier example that is “close enough”

How to Set Up a Model

1. Diagram the problem carefully
   - Indicate all pieces and how they interact, every step of suspected mechanism
   - Write down all assumptions about components and how they behave
2. Identify all important properties in each interaction
   - Estimate quantities where possible, round numbers are OK
3. Write down best guess equations for each interaction
   - Keep track of factors you are ignoring for now
   - Try to only ignore things that will have a minor effect
4. Use equations to determine scaling laws
   - Where possible, non-dimensionalize equations and find characteristic numbers
   - Examples: Mach number, column slenderness ratio, Reynolds number

Example: Modeling Tower Collapses

- Question: Should WTC 1 and 2 have totally collapsed?
  - Prohibitively difficult to test in full-scale
  - Complex enough that it is “non-trivial” to simulate

- A few mathematical models have been advanced
  - Bazant and Verdure, 2003
  - Bazant, Le, Benson, and Greening, 2008

Example: Modeling Tower Collapses

- The Truth Movement has attempted a few scale models:

Author anonymous
http://www.freewebs.com/democraatus

Author anonymous
http://wtcmodel.blogspot.com

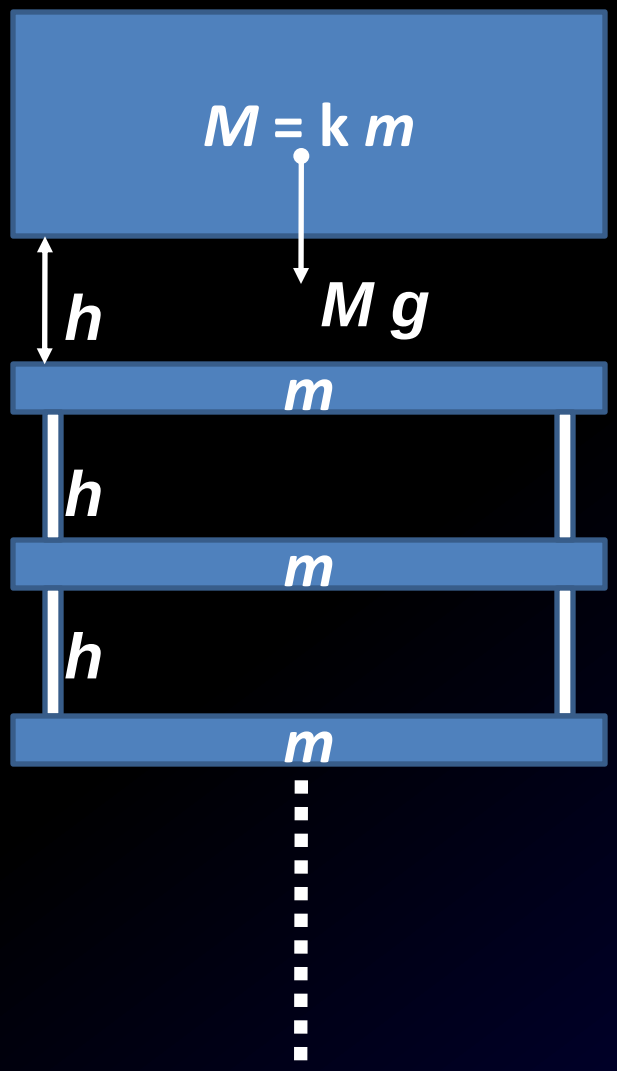
These, however, are not "good" models

Do not capture correct mechanisms
Are not properly scaled

Designing a Simple Collapse Model

- Suppose we simplify as follows:
  - Assume each floor is mass m, height h
  - Assume strength of each floor is equal to $F\,\varepsilon\,h$
    - In other words, assume F is yield strength, ε is maximum strain, so $\varepsilon\,h$ is the displacement required for failure
    - Has units of energy = force × distance
- Other parameters:
  - Number of floors above and below
  - Gravity $g = 9.8\ \mathrm{m/s^2}$
- What we're leaving out: (many things)
  - Variation in mass and strength between different floors
  - Loss of material after impacts
  - Complexity of structural failure (impact, torsion, etc.)

Model Process

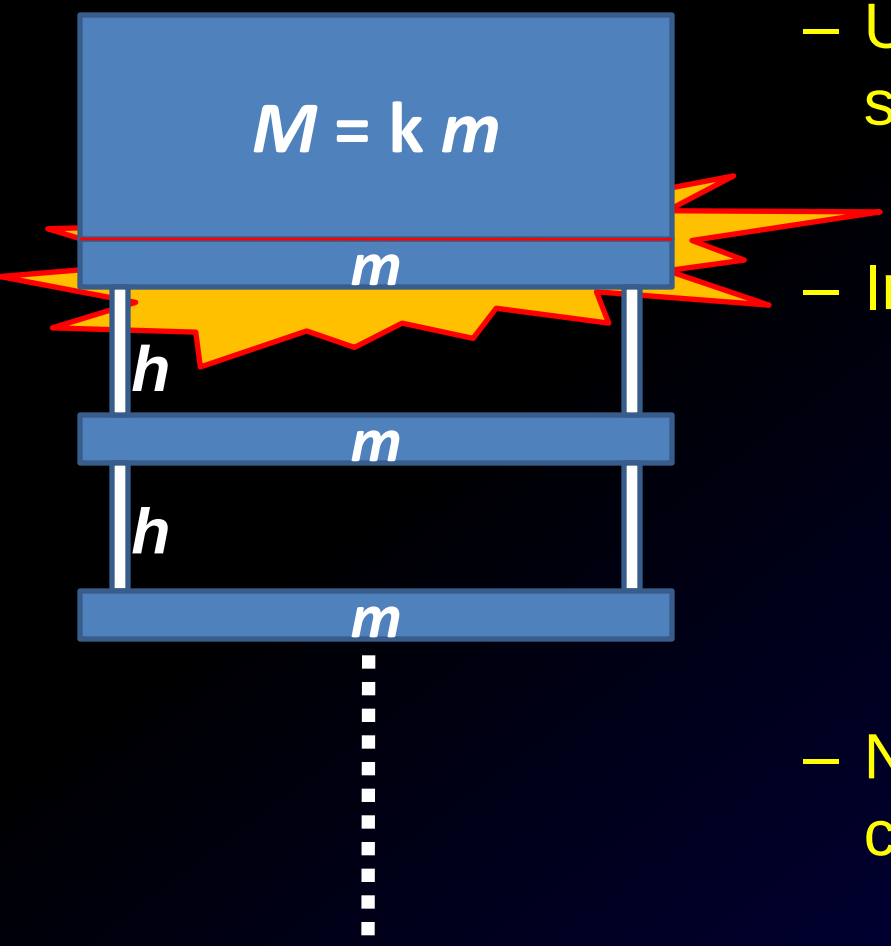


- Step 1:
  - Upper block starts with velocity v_1, falls distance h
    - For initial failure, $v_1 = 0$
  - Accelerates under force of gravity
    - But how *long* it accelerates depends on how fast it started moving, so use an energy calculation instead:

$$M v_1^2 / 2 + M g h = M v_2^2 / 2$$

    - So the faster it starts, the less time it free-falls before hitting the next floor
    - Less time means less increase in speed (but always an increase)

Model Process

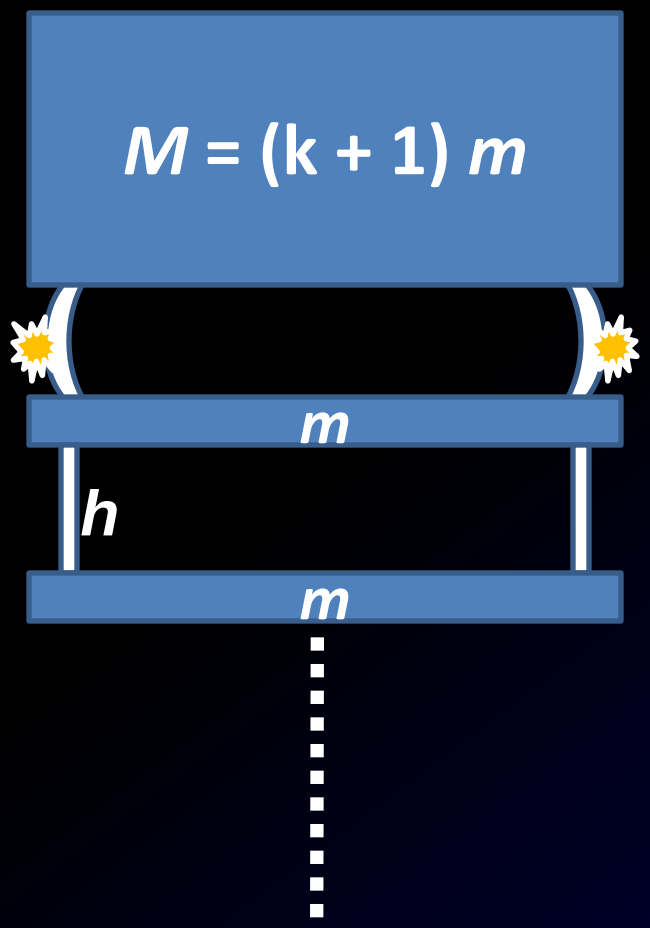


- Step 2:
  - Upper block starts with velocity v_2, strikes next floor
  - Inelastic collision occurs
    - Floors "stick" together
    - New speed found by conservation of momentum:

$$M\,v_2 + m\,\cancel{v}^{0} = (M + m)\,v_3$$

  - Note that the *kinetic energy* after collision is less than before
    - But energy is also conserved?
    - Rest becomes damage, noise, etc.

Model Process



- Step 3:
  - Columns absorb impact, until they fail and buckle
  - Again treat as conservation of energy (note *M* has gotten bigger)
    - Assume failure energy = $F \varepsilon h$

$$M v_3^2 / 2 - F \varepsilon h = M v_4^2 / 2$$

  - After this, process repeats
    - *M* and *v* have changed – increased? Decreased?
    - If *v* drops below zero, collapse stops

Basic Equations

- Now collect our equations from each step:

$$M v_1^2 / 2 + M g h = M v_2^2 / 2$$

$$M v_2 = (M + m) v_3$$

$$M v_3^2 / 2 - F \varepsilon h = M v_4^2 / 2$$

- *Any scale model we build must preserve <u>all</u> of these proportions*
  - Otherwise, behavior will not be the same
  - Rescaling means multiplying each *equation* by a scaling factor – not just multiplying the pieces
    - Need to keep those equal signs true!!

Example: Scaling By Length

- Suppose we build a model at 1/10th scale, but otherwise identical – materials, construction, etc.
- What happens to our equations?
  - Length terms *h* change by factor of ten, but it affects other things too:
  - Velocities change by factor of 10 (length divided by time)
  - Masses change by a factor of 1,000! (volume = length cubed)
  - Gravitational acceleration *g* cannot change
  - Strength *F* changes by factor of 100:
    - Same column slenderness ratio and materials, so same buckling <u>stress</u>, but force is stress times area

Scaling By Length: Equations

$$M v_1^2 / 2 + M g h = M v_2^2 / 2$$

$h \approx 1:1$

$$M v_2 = (M + m) v_3$$

$$M v_3^2 / 2 - F \varepsilon h = M v_4^2 / 2$$

$$\frac{M v_1^2 / 2}{100{,}000} + \frac{M g h}{10{,}000} = \frac{M v_2^2 / 2}{100{,}000}$$

Kinetic energy terms are 10 times too small

$h \approx 1:10$

$$\frac{M v_2}{10{,}000} = \frac{(M + m) v_3}{10{,}000}$$

This equation is OK

$$\frac{M v_3^2 / 2}{100{,}000} - \frac{F \varepsilon h}{1{,}000} = \frac{M v_4^2 / 2}{100{,}000}$$

Relative strength goes up by 100 times!

Preserving Scaling

- Can we change something else to fix this problem?
  - Yes, we can, IF we are careful
- Start by also scaling down *time* to fix first equation
  - Scale time down by a factor of $\sqrt{10}$ to fix first equation
  - This means total collapse time scales down, but also velocities scale *up* (velocity = distance / time)
  - Makes kinetic energy terms 10 times bigger (~ v^2)
  - Second equation stays OK – every term has the same time dependence (both linear in velocity)
  - But this causes another change: Structure energy ($F\ \varepsilon\ h$) also scales up (energy = force times distance ~ $1 / t^2$)
  - As a result, third equation is still not in balance

  (see next page)

Preserving Scaling: Not Quite There

Start: $$M v_3^2 / 2 \; - \; F \varepsilon h = M v_4^2 / 2$$

$h \approx 1{:}10$

$$\frac{M v_3^2 / 2}{100{,}000} - \frac{F \varepsilon h}{1{,}000} = \frac{M v_4^2 / 2}{100{,}000}$$

$t \approx \sqrt{10}{:}1$

$F \approx 10{:}1$

$$10 \times \frac{M v_3^2 / 2}{100{,}000} - 10 \times \frac{F \varepsilon h}{1{,}000} = \frac{M v_4^2 / 2}{100{,}000} \times 10$$

Column energy absorption is still 100 times too big

Preserving Scaling, Cont'd

- After scaling length down by 10 and fixing velocities, the structural energy absorption term is still 100 times too high
- How can we fix this?
  - Need to be careful, since changes can have other effects
  - For example, we could reduce *F* by 100 if we reduce material yield strength by 100
    - But if we do this, our model won't be able to stand up
    - Need to have yield strength > self-weight
  - Our expression for absorption may also be too simple
    - Depending on whether it buckles or ruptures, it may look more like a spring, or some more complicated relationship
  - One course of action: Test different model columns, by themselves, until we get the right properties

Scaling Results

- If our equations are correct, and we scale properly, we can replicate Tower behavior
  - It should verify progressive collapse feasibility
- Scaling is much more complicated than it looks
  - To scale down in size by 10, i.e. floors about 30 cm high, must reduce structural energy absorption by 100 times, and expect collapse to take about five seconds
  - To scale down by 100, i.e. floors 3 cm high (total height 3.4 meters), would need to weaken the structure by ***10,000 times***
- Other options:
  - Only model part of the collapse, viz. only a few floors
  - Computer simulation (in “full scale”)

Analyzing Model Trials

- Suppose we build a model carefully and it **doesn't** show the right behavior. Then what?
  - First, check your model for accuracy
    - Do all stages behave correctly? Do any of them look wrong?
    - Are the simplifications too simple?
    - Is it completely wrong, or just partly wrong?
  - Next determine whether problem is *qualitative* or *quantitative*
    - If you change parameters, can you reproduce the right effect? What does the solution tell you? Is it completely out of reach?
    - If you cannot cause the effect by changing parameters, what would it take? Is it possible at all?
  - If the error is *qualitative*, try to form hypotheses to explain
    - Typically caused by a bad assumption or oversimplification
    - It may also indicate previously unknown behavior

Conclusion

- Modeling is a powerful, reductionist approach to understanding physical phenomena
  - Allows *replication of results* – the very foundation of science
  - Many options – mathematical, computer model, scale model, all or just part of a given problem
- Modeling is much more difficult than it appears
  - Without carefully explaining the setup and assumptions, understanding scaling and relationships between quantities, it is easy to go astray
  - Often need to compensate for scaling with numerous changes to other parameters
- A good model *will* correctly reproduce any behavior
  - For example, it *is possible* to demonstrate the progressive collapse mechanism of the WTC Towers in subscale

Bonus Round!

The Hardfire Modeling Challenge

The Hardfire Modeling Challenge

- Clearly state the phenomenon modeled, and possible results of the test
  - Diagram carefully and identify all important quantities
  - Describe steps in the process and all equations
- Identify all assumptions and model choices
  - Show how well model matches original situation (scaling, materials used, etc.)
  - Define initial conditions of model carefully
- Carry out the test and analyze results
  - Keep testing until you have a definitive result
  - Compare result to observed phenomenon and explain
  - Identify and try to quantify sources of inaccuracy

The Hardfire Modeling Challenge, Part 2

- Seek independent evaluation of your model
  - Teachers and professors are a great resource
- Improve your model where possible, and check for consistency of results
- Try to work out what it would take to get the *opposite* result
  - Is it possible at all? With what parameters?
  - A model that accurately predicts both results, and the transition, is probably a very good one
- Share your results
  - Online discussions, engineering conferences, ?
  - Discuss with me: rmackey_email@earthlink.net