Construction Defects, Failures, and Repairs

(i.e. Learn From the Mistakes of Others)

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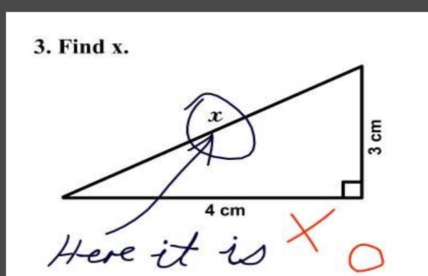
Managing Engineer



Introductions

- Paul Bennett, M.S., P.E., CBIE
  - Managing Engineer
    - Residential & Commercial Design & Construction
    - 2008 Outstanding Professional of the Year Award for Larimer County
    - Failure Investigation

Introductions

- **Who Are You?**

Learning Objectives

At the end of this program, participants will be able to:

1. Students will understand how to correctly apply the 2012 IBC and IEBC to repairs of damaged structures
2. Students will understand the most common construction defects and how to prevent them as designers, builders, plan reviewers, and inspectors
3. Students will learn how to prevent future damages from various case studies

environmental • failure analysis & prevention • health • technology development

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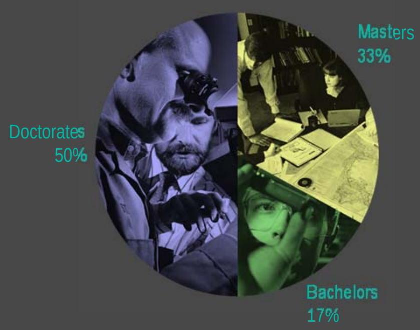

Exponent Offices

Introductions

- Hot Dogs and Attorneys

Lesson Plan

- Repair Solutions and Guidelines
  - Ch 34 IBC and IEBC
  - Case Studies in Applying IEBC
- Importance of Studying Failures
  - Famous Failures
- Most Common Types of Construction Defects Case Studies
  - Ventilation
  - Moisture Intrusion (Building Envelope Failure)
  - Structural

Code Background

- Why do Building Codes Even Exist?
  - Aren't they in place just to make the building cost more?
  - Or are they in place to protect innocent bystanders?

Code Background

- Purpose
  - Minimum Requirements for Public Safety
- History
  - Fire
  - Stability
  - Life Safety

Code Background

By Authority Ordinance No 19, 188

AN ORDINANCE

TO REGULATE THE CONSTRUCTION OF BUILDINGS IN THE CITY OF DENVER.

Be it ordained by the City Council of the City of Denver:

ARTICLE I.

REGULATIONS FOR STRENGTH AND SAFETY.

Code Background

2d. Repairs: The reconstruction or renewal of any part of a structure or things therewith connected, by which the structure shall be maintained in good order and repair, without change in its fire risk, strength or sanitation, and not made for the purpose of converting the structure, in whole or in part, into a new one.

32d. Concrete: A mortar made of cement, sharp sand and clean broken stone not larger than hens' eggs, the whole to be thoroughly mixed when dry and then add only sufficient water to make a stiff

Repair Design

- Is the Code silent?

- IRC Appendix J
- 2012 IBC (CH 34)
- 2012 IEBC

Repair Design

- Problem: No consistency among design professionals when evaluating existing buildings
- Solution: Chapter 34/IEBC
- Designers and Officials:
  - Understand what the Codes Require
  - Apply it and Enforce it
- Designers:
  - You can ask for more but make clear it is voluntary
  - Don't be the EOR if you don't like it

Repair Design

- Some major changes to the repair design chapters in the '12 code

Fundamental Questions

- What Repairs Are Necessary To Restore The Structure To Pre-loss Condition ?
- Upgrades To Elements That Have Sustained Direct Physical Damage
- Upgrades To Undamaged Building Elements
- Code-upgrades

Repair Solutions Per IBC and IEBC

- Pandora's Box
- Where do you stop??
- What does the Code say??

Building Codes

- 1997 Uniform Building Code (UBC)
- 2003 International Building Code (IBC)
- 2006 International Building Code (IBC)
- 2009 International Building Code (IBC)
- 2012 International Building Code (IBC)

UBC Repair Provisions

- 1997 UBC
  - Chapter 34
  - Cannot Create An Unsafe Condition
    - Cannot Increase Loads On Structural Components Beyond Their Capacity
    - Cannot Obstruct Egress
    - Cannot Reduce Fire Resistance

IBC Definitions

- What is an existing building?
  - *A structure erected prior to the date of adoption of the appropriate code, or one for which a legal building permit has been issued* – 2006, 9, 12 IBC and IEBC
  - Chapter 2 in 2012

IBC Chapter 34 Overview

- 3404.2 Flood hazard areas must be upgraded if the repairs or alterations are a "substantial improvement"
  - Note: Substantial improvement can be triggered by substantial damage
  - 2003,2006,2009,2012 IBC

IBC Chapter 34 Overview

- 2003, 2006 Section 3403 Additions, Alterations or Repairs
  - 3403.2 Structural
    - Additions or alterations to an existing structure shall not increase the force in any structural element by more than 5 percent, unless the increased forces on the element are still in compliance with the code for new structures, nor shall the strength of any structural element be decreased to less than that required by this code for new structures. ***Where repairs are made to structural elements of an existing building, and uncovered structural elements are found to be unsound or otherwise structurally deficient, such elements shall be made to conform to the requirements for new structures***.

IBC Chapter 34 Overview

- Historic Buildings Section 3409
- Definition:
  - Buildings that are listed in or eligible for listing on the National Register of Historic Places or designated historic under an appropriate state or local law.
- Provisions not applicable where the AHJ has determined the building does not constitute a distinct life safety hazard.
- Flood hazard rehabilitation not required for substantial improvement if Historic

IBC Chapter 34 Overview

- Section 3403 Additions, Alterations or Repairs
  - *3403.1 Portions of the structure not altered and not affected by the alteration are not required to comply with the code requirements of a new structure.*
  - *2003,2006 IBC*
  - *Much Different in 2009 IBC*

IBC Repair Provisions

- 2009, 2012 IBC Repairs
- Repaired Elements Shall Be Upgraded
- Provisions For Undamaged Components

IBC Upgrades

- 2009, 2012 IBC Chapter 34, Very different chapter
- A new repair section is now in place
  - Explicit that new and replacement materials must meet current code, 3401.4.2

IBC Upgrades

- 2009, 2012 IBC Chapter 34, Very different chapter
  - Substantial Structural Damage to:
    - Lateral System
      - Entire building must be rehabilitated to be in conformance with the new code
    - Gravity System
      - Only the damaged members and those that receive loads from them need to be upgraded

IBC Upgrades

- 2009, 2012
  - New Definitions for Dangerous
  - Dangerous conditions upgrades are up to the Building Official
  - Reads like 2006 IEBC

IBC Upgrades

- 2012 Chapter 34 IBC
- Prior to 2009 There was no Definition of Dangerous in IBC, see IEBC

Dangerous Building

- IEBC Section 202; 2003,2006 IEBC
  - Definition Of Dangerous

DANGEROUS. Any building or structure or any individual member with any of the structural conditions or defects described below shall be deemed dangerous:

1. The stress in a member or portion thereof due to all factored dead and live loads is more than one and one third the nominal strength allowed in the *International Building Code* for new buildings of similar structure, purpose, or location.
2. Any portion, member, or appurtenance thereof likely to fail, or to become detached or dislodged, or to collapse and thereby injure persons.
3. Any portion of a building, or any member, appurtenance, or ornamentation on the exterior thereof is not of sufficient strength or stability, or is not anchored, attached, or fastened in place so as to be capable of resisting a wind pressure of two thirds of that specified in the *International Building Code* for new buildings of similar structure, purpose, or location without exceeding the nominal strength permitted in the *International Building Code* for such buildings.
4. The building, or any portion thereof, is likely to collapse partially or completely because of dilapidation, deterioration or decay; construction in violation of the *International Building Code*; the removal, movement or instability of any portion of the ground necessary for the purpose of supporting such building; the deterioration, decay or inadequacy of its foundation; damage due to fire, earthquake, wind or flood; or any other similar cause.
5. The exterior walls or other vertical structural members list, lean, or buckle to such an extent that a plumb line passing through the center of gravity does not fall inside the middle one third of the base.

IBC Upgrades

- 2009, 2012 Chapter 34 IBC – Dangerous:

DANGEROUS. Any *building*, *structure* or portion thereof that meets any of the conditions described below shall be deemed dangerous:

1. The *building* or *structure* has collapsed, has partially collapsed, has moved off its foundation or lacks the necessary support of the ground.
2. There exists a significant risk of collapse, detachment or dislodgment of any portion, member, appurtenance or ornamentation of the *building* or *structure* under service loads.

3401.5 Dangerous conditions. The *building official* shall have the authority to require the elimination of conditions deemed *dangerous*.

IBC Upgrades

- Dangerous in 1991 UCADB:

Sec. 302. For the purpose of this code, any building or structure which has any or all of the conditions or defects hereinafter described shall be deemed to be a dangerous building, provided that such conditions or defects exist to the extent that the life, health, property or safety of the public or its occupants are endangered:

1. Whenever any door, aisle, passageway, stairway or other means of exit is not of sufficient width or size or is not so arranged as to provide safe and adequate means of exit in case of fire or panic.

2. Whenever the walking surface of any aisle, passageway, stairway or other means of exit is so warped, worn, loose, torn or otherwise unsafe as to not provide safe and adequate means of exit in case of fire or panic.

3. Whenever the stress in any materials, member or portion thereof, due to all dead and live loads, is more than one and one half times the working stress or stresses allowed in the Building Code for new buildings of similar structure, purpose or location.

4. Whenever any portion thereof has been damaged by fire, earthquake, wind, flood or by any other cause, to such an extent that the structural strength or stability thereof is materially less than it was before such catastrophe and is less than the minimum requirements of the Building Code for new buildings of similar structure, purpose or location.

5. Whenever any portion or member or appurtenance thereof is likely to fail, or to become detached or dislodged, or to collapse and thereby injure persons or damage property.

IBC Upgrades

- Dangerous in 1991 UCADB:

6. Whenever any portion of a building, or any member, appurtenance or ornamentation on the exterior thereof is not of sufficient strength or stability, or is not so anchored, attached or fastened in place so as to be capable of resisting a wind pressure of one half of that specified in the Building Code for new buildings of similar structure, purpose or location without exceeding the working stresses permitted in the Building Code for such buildings.

7. Whenever any portion thereof has wracked, warped, buckled or settled to such an extent that walls or other structural portions have materially less resistance to winds or earthquakes than is required in the case of similar new construction.

8. Whenever the building or structure, or any portion thereof, because of (i) dilapidation, deterioration or decay; (ii) faulty construction; (iii) the removal, movement or instability of any portion of the ground necessary for the purpose of supporting such building; (iv) the deterioration, decay or inadequacy of its foundation; or (v) any other cause, is likely to partially or completely collapse.

9. Whenever, for any reason, the building or structure, or any portion thereof, is manifestly unsafe for the purpose for which it is being used.

10. Whenever the exterior walls or other vertical structural members list, lean or buckle to such an extent that a plumb line passing through the center of gravity does not fall inside the middle one third of the base.

11. Whenever the building or structure, exclusive of the foundation, shows 33 percent or more damage or deterioration of its supporting member or members, or 50 percent damage or deterioration of its nonsupporting members, enclosing or outside walls or coverings.

IBC Upgrades

- Dangerous in 1991 UCADB:

12. Whenever the building or structure has been so damaged by fire, wind, earthquake or flood, or has become so dilapidated or deteriorated as to become (i) an attractive nuisance to children; (ii) a harbor for vagrants, criminals or immoral persons; or as to (iii) enable persons to resort thereto for the purpose of committing unlawful or immoral acts.

13. Whenever any building or structure has been constructed, exists or is maintained in violation of any specific requirement or prohibition applicable to such building or structure provided by the building regulations of this jurisdiction, as specified in the Building Code or Housing Code, or of any law or ordinance of this state or jurisdiction relating to the condition, location or structure of buildings.

14. Whenever any building or structure which, whether or not erected in accordance with all applicable laws and ordinances, has in any nonsupporting part, member or portion less than 50 percent, or in any supporting part, member or portion less than 66 percent of the (i) strength, (ii) fire-resisting qualities or characteristics, or (iii) weather-resisting qualities or characteristics required by law in the case of a newly constructed building of like area, height and occupancy in the same location.

15. Whenever a building or structure, used or intended to be used for dwelling purposes, because of inadequate maintenance, dilapidation, decay, damage, faulty construction or arrangement, inadequate light, air or sanitation facilities, or

Dangerous Buildings

Dangerous Buildings

Dangerous Buildings

IBC Upgrades

- 2012 Chapter 34 IBC

SUBSTANTIAL STRUCTURAL DAMAGE. A condition where:

1. In any *story*, the vertical elements of the lateral force-resisting system have suffered damage such that the lateral load-carrying capacity of the structure in any horizontal direction has been reduced by more than 33 percent from its predamage condition; or
2. The capacity of any vertical gravity load-carrying component, or any group of such components, that supports more than 30 percent of the total area of the structure's floors and roofs has been reduced more than 20 percent from its predamage condition and the remaining capacity of such affected elements, with respect to all dead and *live loads*, is less than 75 percent of that required by this code for new buildings of similar structure, purpose and location.

IBC Upgrades

- 2012 Chapter 34 IBC - Changes
- SSD Definition, Changed from 20% to 33%

IBC Upgrades

- 2012 Chapter 34 IBC
  - What if SSD is not Triggered?
  - No Problem, Repair in Place 3405.4

3405.4 Less than substantial structural damage. For damage less than *substantial structural damage*, *repairs* shall be allowed that restore the building to its pre-damage state, based on material properties and design strengths applicable at the time of original construction. New structural members and connections used for this repair shall comply with the detailing provisions of this code for new buildings of similar structure, purpose and location.

IBC Upgrades

- 2012 Chapter 34 IBC - Changes
- Less than SSD, Clarified its Material Strengths we are Using.

IBC Upgrades

- 2012 Chapter 34 IBC - Changes
- SSD to Lateral System

IBC Upgrades

- 2012 Chapter 34 IBC - Changes
- What if SSD to Lateral System?

3405.2 Substantial structural damage to vertical elements of the lateral force-resisting system. A building that has sustained substantial structural damage to the vertical elements of its lateral force-resisting system shall be evaluated and repaired in accordance with the applicable provisions of Sections 3405.2.1 through 3405.2.3.

IBC Upgrades

- 2012 Chapter 34 IBC - Changes
- New Exceptions

Exceptions:

1. Buildings assigned to *Seismic Design Category* A, B, or C whose *substantial structural damage* was not caused by earthquake need not be evaluated or rehabilitated for load combinations that include earthquake effects.
2. One- and two-family dwellings need not be evaluated or rehabilitated for load combinations that include earthquake effects.

IBC Upgrades

- 2012 Chapter 34 IBC -

3405.2.1 Evaluation. The building shall be evaluated by a *registered design professional*, and the evaluation findings shall be submitted to the *building official*. The evaluation shall establish whether the damaged building, if repaired to its pre-damage state, would comply with the provisions of this code for wind and earthquake loads.

Wind loads for this evaluation shall be those prescribed in Section 1609. Earthquake loads for this evaluation, if required, shall be permitted to be 75 percent of those prescribed in Section 1613.

3405.2.2 Extent of repair for compliant buildings. If the evaluation establishes compliance of the pre-damage building in accordance with Section 3405.2.1, then repairs shall be permitted that restore the building to its pre-damage state, based on material properties and design strengths applicable at the time of original construction.

IBC Upgrades

- 2012 Chapter 34 IBC -

3405.2.3 Extent of repair for noncompliant buildings. If the evaluation does not establish compliance of the pre-damage building in accordance with Section 3404.2.1, then the building shall be rehabilitated to comply with applicable provisions of this code for load combinations that include wind or seismic loads. The wind loads for the repair shall be as required by the building code in effect at the time of original construction, unless the damage was caused by wind, in which case the wind loads shall be as required by this code. Earthquake loads for this rehabilitation design shall be those required for the design of the pre-damage building, but not less than 75 percent of those prescribed in Section 1613. New structural members and connections required by this rehabilitation design shall comply with the detailing provisions of this code for new buildings of similar structure, purpose and location.

IBC Upgrades

- 2012 Chapter 34 IBC – Changes
- What if SSD to Gravity System?

3405.3 Substantial structural damage to gravity load-carrying components. Gravity load-carrying components that have sustained *substantial structural damage* shall be rehabilitated to comply with the applicable provisions of this code for dead and live loads. Snow loads shall be considered if the *substantial structural damage* was caused by or related to snow load effects. Existing gravity load-carrying structural elements shall be permitted to be designed for live loads *approved* prior to the damage. Nondamaged gravity load-carrying components that receive dead, live or snow loads from rehabilitated components shall also be rehabilitated or shown to have the capacity to carry the design loads of the rehabilitation design. New structural members and connections required by this rehabilitation design shall comply with the detailing provisions of this code for new buildings of similar structure, purpose and location.

IBC Upgrades

- 2012 Chapter 34 IBC – Changes
- What if SSD to Gravity System?

3405.3.1 Lateral force-resisting elements. Regardless of the level of damage to vertical elements of the lateral force-resisting system, if *substantial structural damage* to gravity load-carrying components was caused primarily by wind or earthquake effects, then the building shall be evaluated in accordance with Section 3405.2.1 and, if noncompliant, rehabilitated in accordance with Section 3405.2.3.

Exceptions:

1. One- and two-family dwellings need not be evaluated or rehabilitated for load combinations that include earthquake effects.
2. Buildings assigned to *Seismic Design Category* A, B, or C whose *substantial structural damage* was not caused by earthquake need not be evaluated or rehabilitated for load combinations that include earthquake effects.

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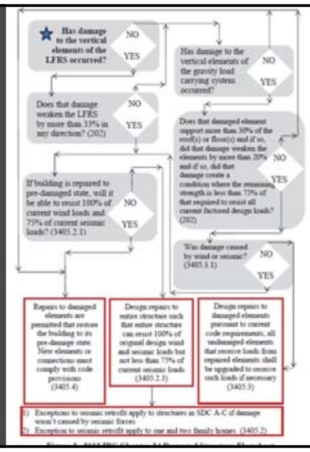
The Building Code and Repairs to Damaged Structures

Paul James Bennett, PE, CBIE, M. ASCE[1]



IBC Upgrades

- 2012 Chapter 34 IBC – Changes
- What About Fires, Decay, Vehicle Impact?
- 2015 Code Cycle

Code Upgrade Controversy

- What if only one member broke but the remaining members look likely to collapse?
- This still meets the definition of dangerous in 2009 and is up to AHJ

Code Upgrade Controversy

- A dilemma is presented:
  - If only 20% of the building is damaged by a major event, isn't that what we hoped for?

Code Upgrade Controversy

- A dilemma is presented:
- ASCE 7-05 Section 1.4 "capable of resisting those loads without collapse"
- Life Safety: Structural damage without partial or total collapse which might pose a risk to life
- Collapse Prevention: Damage (structural or non-structural) which exceeds 30% of replacement value

Code Upgrade Controversy

- Engineering analysis:
  - How can you investigate a structure without destructive testing?
  - Usually you can find ways
  - Assumptions may have to be made

Code Upgrade Controversy

- For 2009:
  - The engineer is not required to evaluate more than the damaged member unless SSD thresholds are triggered
  - Dangerous is much more liberal and is not mandated to be abated
  - This solves the Denver snow example dilemma
  - But new dilemma's are created, such as:

Code Upgrade Controversy

- What about: snow load causes damage.

3405.3 Substantial structural damage to gravity load-carrying components. Gravity load-carrying components that have sustained *substantial structural damage* shall be rehabilitated to comply with the applicable provisions of this code for dead and live loads. Snow loads shall be considered if the *substantial structural damage* was caused by or related to snow load effects. Existing gravity load-carrying structural elements shall be permitted to be designed for live loads *approved* prior to the damage. Nondamaged gravity load-carrying components that receive dead, live or snow loads from rehabilitated components shall also be rehabilitated or shown to have the capacity to carry the design loads of the rehabilitation design. New structural members and connections required by this rehabilitation design shall comply with the detailing provisions of this code for new buildings of similar structure, purpose and location.

Case Study – Unreinforced Masonry

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Case Study – Unreinforced Masonry

Investigation

- **Jurisdiction has accepted IEBC**
  - **Qualifies as dangerous**
  - **Qualifies as substantial structural damage**
  - **Rebuild entire structure**

- If chapter 2006 IBC Ch 34 were used:
  - Repair damage per IBC

Case Study – Unreinforced Masonry

- **Lessons Learned**
  - **Unreinforced masonry structures will often require great repairs under this code**

Case Study – Unreinforced Masonry

- **Masonry Building, SDC ‘D’**
- **Partial Roof Collapse Under Snow Loads**
- **Which Code?**

Case Study – Unreinforced Masonry

Case Study – Unreinforced Masonry

Case Study – Unreinforced Masonry

Dangerous?

- Historic Building
- Two Previous Fires

Dangerous?

Dangerous?

Dangerous?

Dangerous?

Dangerous?

The Study of Failures

Importance of Failures

- Importance of studying failures
- We Learn From our Past Mistakes
  - GEN X & Y don't believe it until you prove it

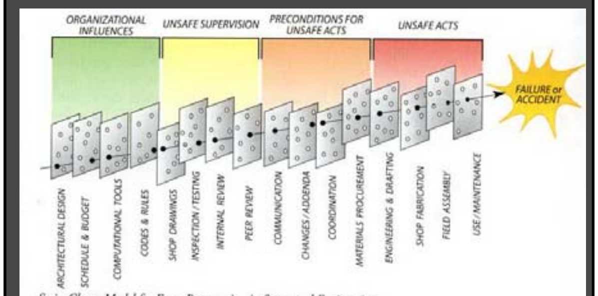
Caveats

- A view from the dark side
  - Overall performance of our building stock is excellent – catastrophic failures are rare
  - Performance, financial, and aesthetic failures are all too common
- Failures are powerful learning tools
  - Reminder of our responsibilities
  - Reminder of fallibility of our systems
  - Advance understanding and practice
- Structure-centric

The Code of Hammurabi – 1730BC

- If a builder builds a house for some one, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death.

Failure Trajectory



Swiss Cheese Model for Error Propagation in Structural Engineering.

The Devil is in the Details – Mighty Failures From Little Acorns Grow

For want of a nail,
the shoe was lost.
For want of a shoe,
the horse was lost.
For want of a horse,
the rider was lost.
For want of a rider,
the battle was lost.
For want of a battle,
the kingdom was lost.
And all for the want
of a horseshoe nail.

A Designer's Worst Nightmare

Famous Failures

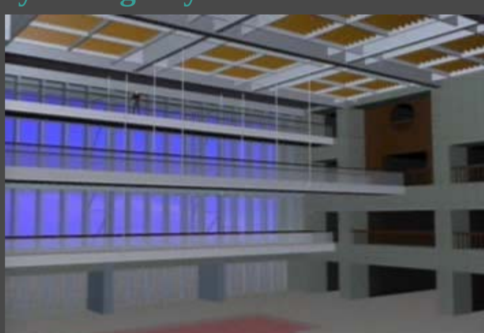
- Hyatt Regency Walkway
  - Walkways suspended by six 32mm hanger rods
  - Opened in 1980, 4 years to construct
  - July 17, 1981, 2000 ppl on atrium and walkways
  - Walkways collapsed, 114 killed, 200+ injured

Famous Failures

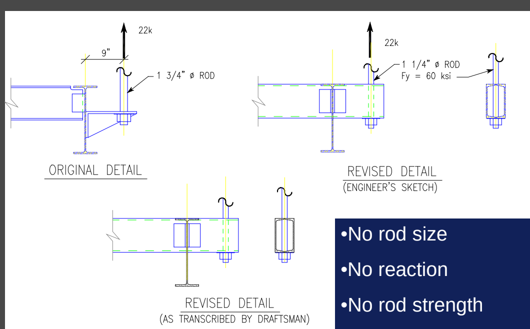
Famous Failures

Hyatt Regency Walkway, Kansas City, MO – 7.17.81

Hyatt Regency



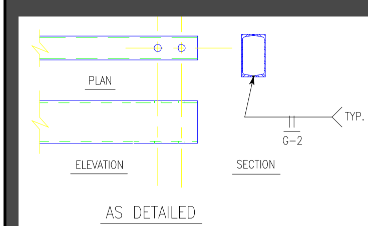
Design Phase – Bridge Connection



- No rod size
- No reaction
- No rod strength

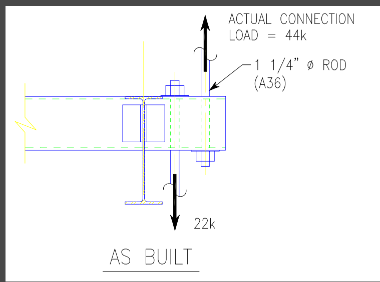
Design Drawings vs. Shop Drawings

- Changes During Shop Drawings
  - Requested two rods by phone
  - Approved by phone with caveat "submit through channels"



The shop drawings are checked by a technician who did not work on the project. Questions are raised about the strength of the rod.

Design Drawings vs. Shop Drawings



- THIS CONNECTION WAS NEVER DESIGNED, NEVER DRAWN AND NEVER SUBMITTED FOR APPROVAL

Famous Failures

- Investigation revealed:
  - An impractical original design
  - No redundancy
  - Engineer approved contractor's change without performing calculations
  - Connection was near failure with just dead load
  - Even if the detail wasn't changed it likely would have failed due to inadequate bearing area

Famous Failures

- Lessons Learned
  - Redundancy is a good thing
  - Failures often occur at small connections, not big picture items
  - Peer review needs to be thorough

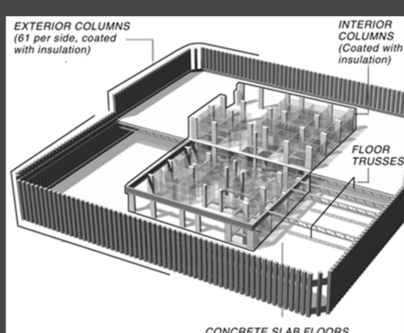
World Trade Center Towers

- Design & Construction 1962 – 1973
- 110 Stories
- 1362/1368’ Tall
- Tallest buildings constructed since Empire State Bldg in 1932
- 9,500,000 Sq. Ft.
- Designed to withstand impact of B-707
- Public Works Project

World Trade Center Towers

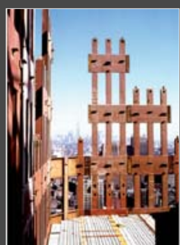
- First use of wind tunnel for design
- Research regarding human tolerance for motion
- First use of structural dampers
- First use of computer for design
- Very lightweight structures
- First use of sky lobbies
- Many more…

Lightweight, highly optimized structure



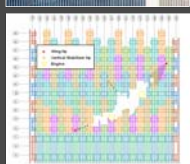
Modular Construction

- Modular fabrication and erection techniques
- Three story high columns connected by deep spandrel plates (Trees)



- Trees fabricated in shop, transported to site and erected
- Tree modules staggered to offset column splices
- Floors were 4-inch lightweight concrete over 1-1/2-in. metal deck (22 gauge)

Impact and Damage to WTC 2



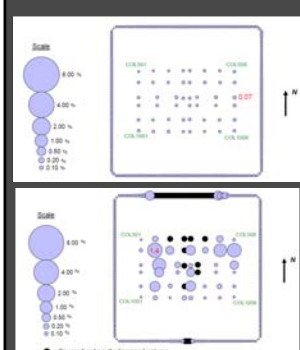
- 78th to 84th floor affected
- 33 exterior columns severed; 1 heavily damaged
- 10 core columns severed; 1 heavily damaged
- 39 of 47 core columns stripped of insulation on one or more floors.
- Insulation stripped from trusses covering 80,000 ft^2 of floor area.
- Structure retained integrity and strength for 56 minutes

Simulation of Damage to WTC 2

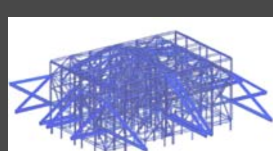
Why not immediate collapse?

Redundancy & Redistribution of Load

Redistribution of Load



- Column strains before and 10 minutes after impact on WTC-1



schematic of hat truss

Why Ultimate Collapse?

Fire Ignition

- At impact, each aircraft contained ~10,000 gallons of fuel
- Between 1,000 and 3,000 gallons of fuel consumed in fireballs
- Rest flowed down tower or remained on impact floors
- Most of remaining jet fuel consumed within first few minutes of fire
- Burning fuel ignited combustibles present on affected floors

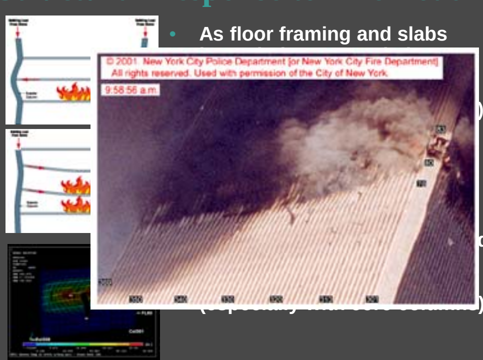
Fire Development

- Since fire protection systems compromised, fire development and growth was unchecked
- Ceiling temperatures approximately 800 – 2000 °F (depending on location, fuel load, and ventilation)
- High temperatures heated structural steel within towers

Structural Response to Fire Loading

- Impact compromised fireproofing
- Elevated stress on columns due to impact and destroyed elements
- Portions of framing directly below partially collapsed area carried substantially greater loads
- Fire spread and raised temperatures further weakened structure until unable to support weight.

Structural Response to Fire Loading



- As floor framing and slabs

Progression of Collapse

- As unsupported height of freestanding columns increased, they buckled at bolted column splice connections and collapsed
- Initiation of collapse converted potential energy into kinetic energy
- Progressive failure as floors above accelerated and impacted floor below

OK City & WTC Lessons

- Increased attention to Progressive Collapse (Disproportionate Collapse)
- Increased attention to relationship between fire ratings and structural systems
- Increased attention to fire safety in highrises

OK City & WTC Lessons

- Collapse mechanisms are readily explainable if structural systems are understood
- No need for, nor legitimate evidence of, any conspiracy related to structural damage and collapse

Closure

- Most failures are a sequence or intersection of multiple events and are preceded by warning signals
  - Heeding warning signals averts failure!
- The Devil is in the details
  - A chain is only as strong as its weakest link!
- Innovate and create, but
  - Be skeptical

Case Studies in Failures

Construction Defect Case Studies!!

Construction Defect Case Studies!!

Construction Defect Case Studies!!

Construction Defects

Moisture Intrusion

Construction Defects

"As every dam engineer knows, water also has one job, and that is to get past anything in its way" – Macauley 2000

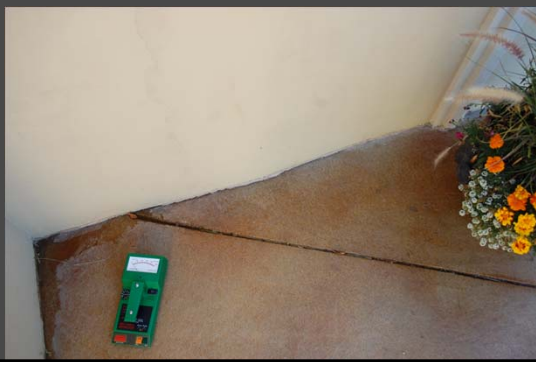
Moisture Intrusion

- Building science
  - Many materials are porous
  - Know the product, EIFS, Stucco, Flashing, Roofing, ect..
  - Ask for installation instructions

Case Study – Moisture Intrusion

- Background
  - 3 Year Old Home
  - $1.1 Million
  - Above Grade Deck with Outdoor Living Area Below
  - Water Damage to Soffit Below Deck and Walk Out Basement
  - EIFS Bulging
  - Rim Joist EIFS Detaching

Case Study – Moisture Intrusion



Case Study – Moisture Intrusion

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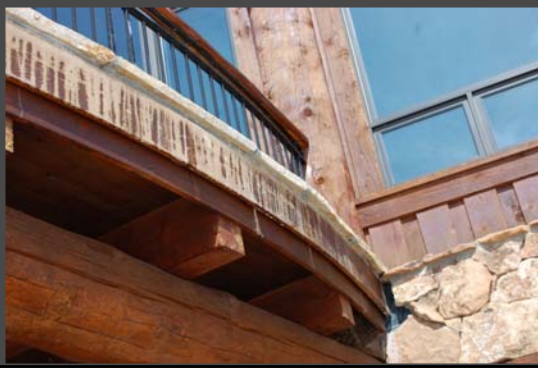
- **Background:**
  - **Finished Above Grade Deck**

Case Study – Moisture Intrusion

Case Study – Moisture Intrusion

Case Study – Moisture Intrusion



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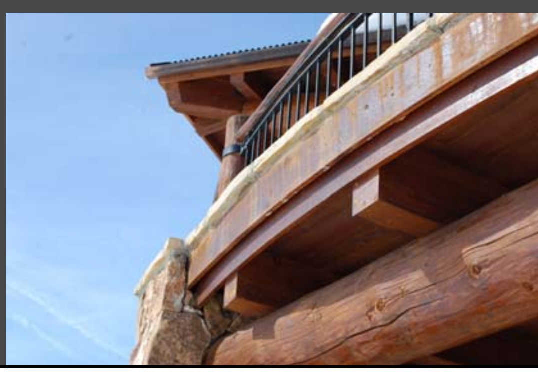

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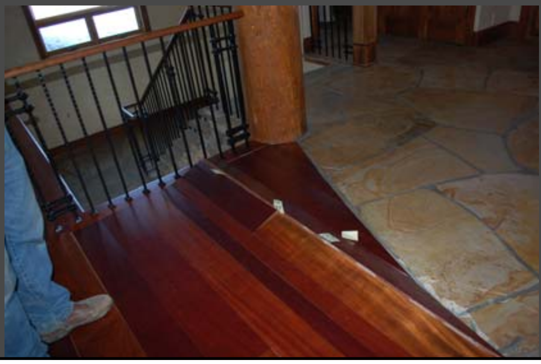


Case Study – Moisture Intrusion

Construction Defects

Ventilation

Inadequate Ventilation

- Attic Ventilation
  - First Required in 1964 UBC
    - *"Enclosed attics shall have clear ventilation area to the outside of not less than one square inch (1 sq. in.) per ten square feet (10 sq. ft.) of horizontal attic area."*

Inadequate Ventilation

- Attic Ventilation Code Changes
  - 1967 UBC
    - Cross Ventilation
  - 1991 UBC
    - Vapor Barriers

Inadequate Ventilation

- Language in the Code:

"The net free ventilating area shall not be less than 1/150 of the area of the space ventilated, except that the area may be 1/300 provided at least 50 percent of the required ventilated area is provided by ventilators located in the upper portion of the space to be ventilated at least three feet (3') above eave or cornice vents."

Inadequate Ventilation

- Why ??
  - Summer
    - Heat Build Up In Daytime
      - +70 Degrees
    - Cool Down At Night
      - Adds Moisture Into Insulation

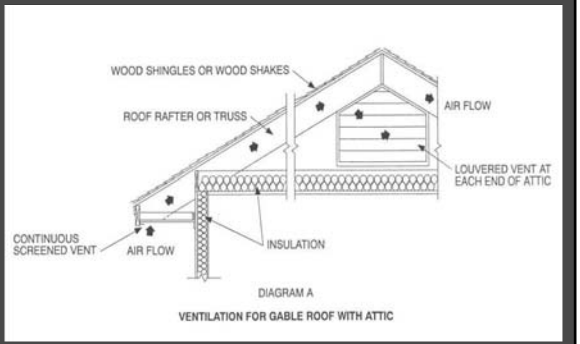
Inadequate Ventilation

- National Design Specification (Wood Code)
  - Sustained exposure to elevated temperatures up to 150 degrees results in up to a 50% decrease in the structural capacity of a wood member.

Inadequate Ventilation

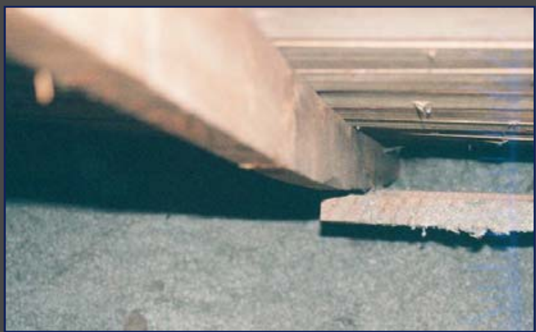
- National Design Specification (Wood Code)
  - Sustained moisture contents of greater than 19% results in up to a 33% decrease in the structural capacity of a wood member.
  - Elevated Temperatures and Moisture Content results in accelerated "creep" deflection.

Attic Ventilation



Inadequate Ventilation

Inadequate Ventilation



Inadequate Ventilation

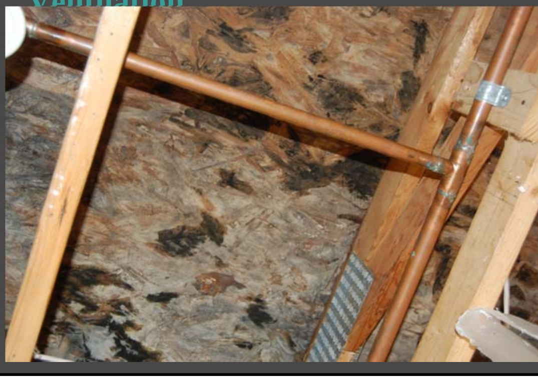
Inadequate Ventilation

- Summary
  - Heat-Cool Cycle
    - Causes Condensation
      - Reduces Strength of Wood
      - Causes Wood to Rot
      - Causes Wood to Deflect

Case Study – Inadequate Ventilation

- Background
  - 7 Year Old Commercial Buildings
  - Smells Musty

Case Study – Inadequate Ventilation



Case Study – Inadequate Ventilation

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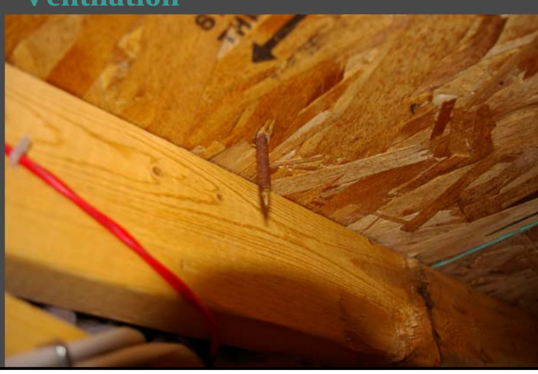


Case Study – Inadequate Ventilation

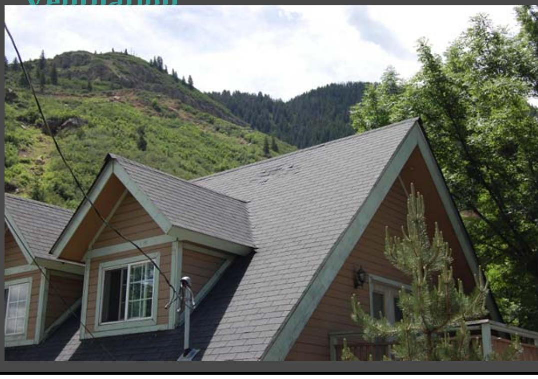
Case Study – Inadequate Ventilation

- Lessons Learned
  - All attic areas need ventilation
  - Accomplished GC's make mistakes

Case Study – Inadequate Ventilation

- Background
  - 7 Year Old Home
  - Stick Framed Roof
  - Depressions in Roof
  - I've Been Doing in That way for 30 years….

Case Study – Inadequate Ventilation



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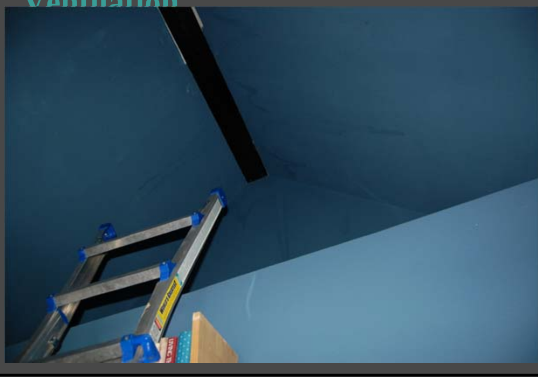

Case Study – Inadequate Ventilation

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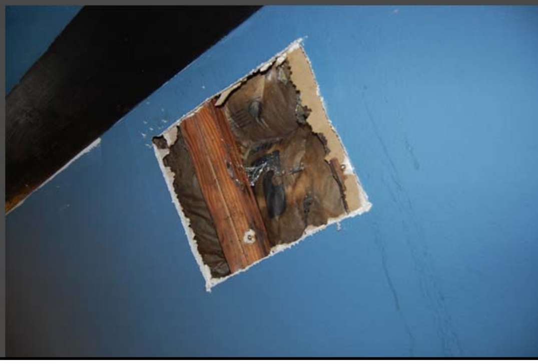


Case Study – Inadequate Ventilation

Case Study – Inadequate Ventilation

- Lessons Learned
  - Stick Framed Roofs Need Ventilation
  - Past Experience is Not Always a Good Indication of Future Performance

Construction Defects

Structural

Construction Defects

- "When utilizing past experience in the design of a new structure we proceed by analogy and no conclusion by analogy can be considered valid unless all the vital factors involved in the cases subject to comparison are practically identical. *Experience does not tell us anything about the nature of these factors and many engineers who are proud of their experience do not even suspect the conditions required for the validity of their mental operations*. Hence our practical experience can be very misleading unless it combines with it a fairly accurate conception of the mechanics of the phenomena under consideration."

  - Karl Terzaghi 1939

Case Study – Structural

- Background
  - Recently Completed Riding Arena
  - PEMB
  - SNOW!!
  - RAM Tough™

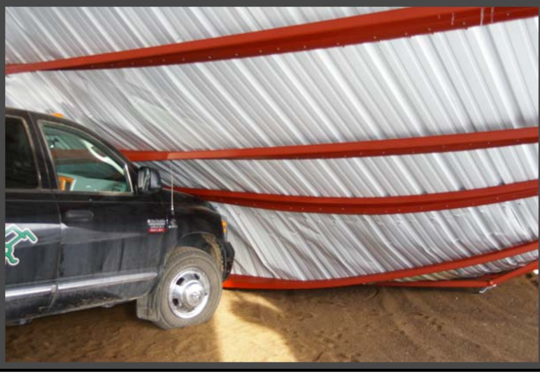
Case Study – Structural

Case Study – Structural

Case Study – Structural

Case Study – Structural

Case Study – Structural



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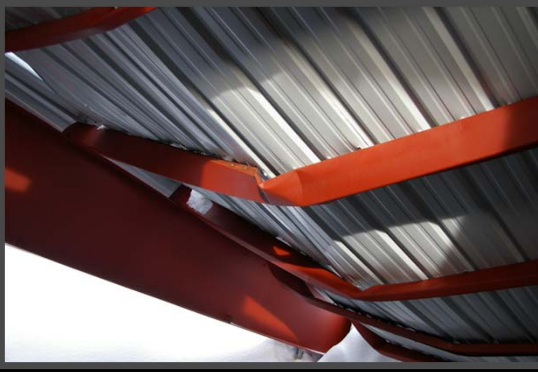

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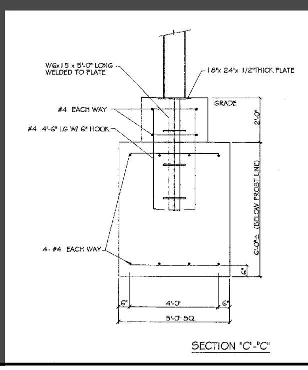

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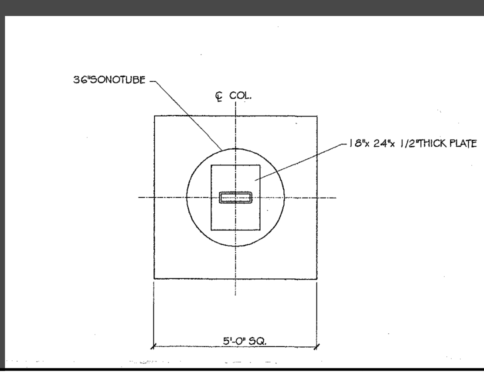

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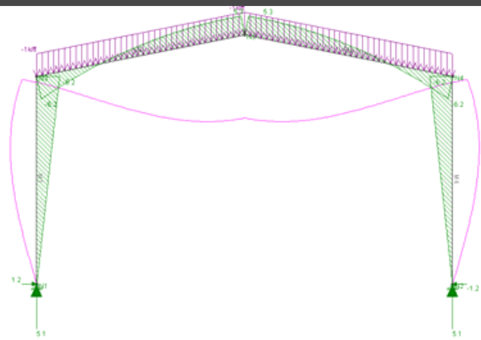

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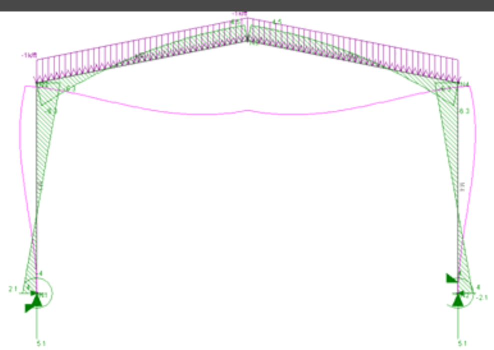

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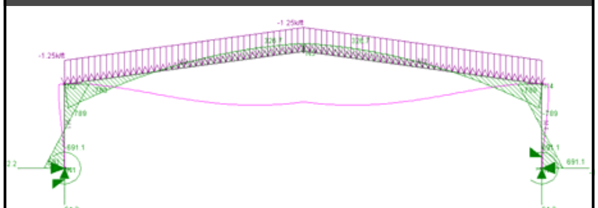


Case Study – Structural

Case Study – Structural

Case Study – Structural

PEMB Design: EOR

- Really That Important?

PEMB Design: EOR

- Answer is… YES!
- Engineer-of-Record (EOR):
  - Design Load Oversight
  - Coordination Between Trades and Engineers
  - Coordination Between Engineers

Case Study – Structural

- Lessons Learned
  - Dodge's are strong
  - Knowledge of AutoCad...
  - Understand PEMB's
  - EOR is CRITICAL!!!

Case Study – Structural

- Background
  - PEMB
  - Snow Load Problems

Case Study – Structural

- Alleged Defects
  - Inadequate Resistance to Snow Load
  - Inadequate Foundations
  - Design Errors

Case Study – Structural

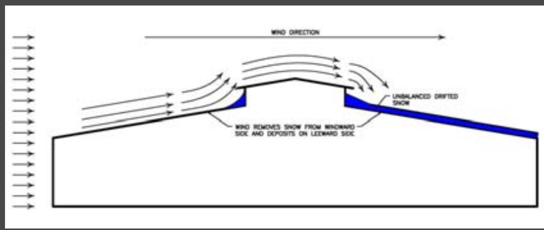
- Issues:
  - Large Expansive Roofs and Drifting
  - Ground Snow vs. Roof Snow
  - Failure in 2003, 2006
  - Reduction of Snow Loads (0.7)
  - Importance Factor
  - ASD vs. LRFD
  - Unique Design of Moment Frames
  - Load Paths

Case Study – Structural

Case Study – Structural

Case Study – Structural

Case Study – Structural



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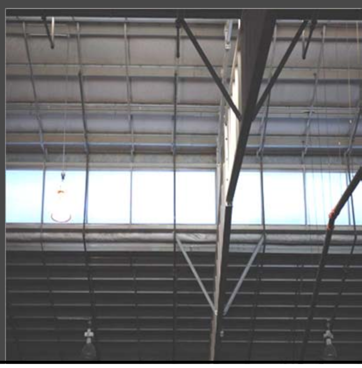

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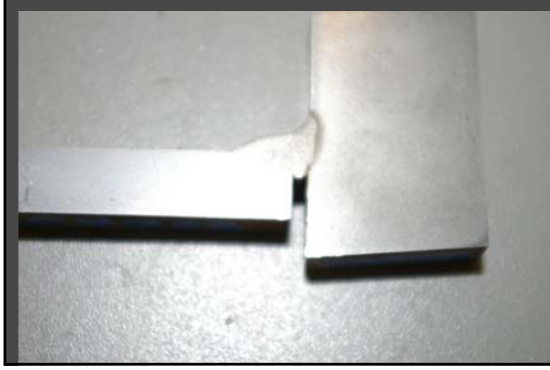

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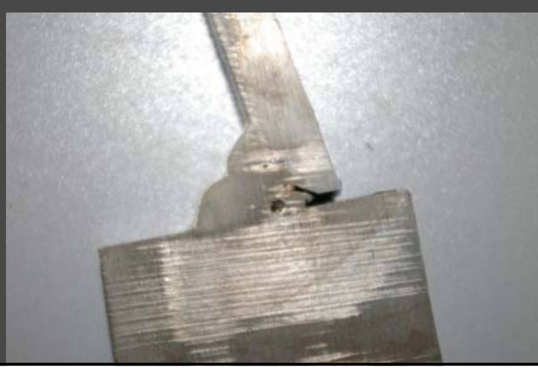

Case Study – Structural

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- Background
  - PEMB
  - Aircraft Hanger

Case Study – Structural

Case Study – Structural

Case Study – Structural

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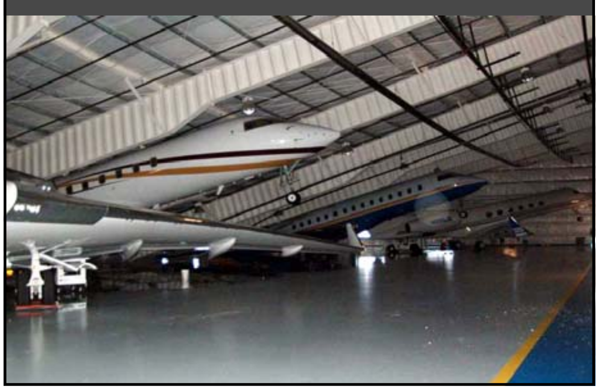

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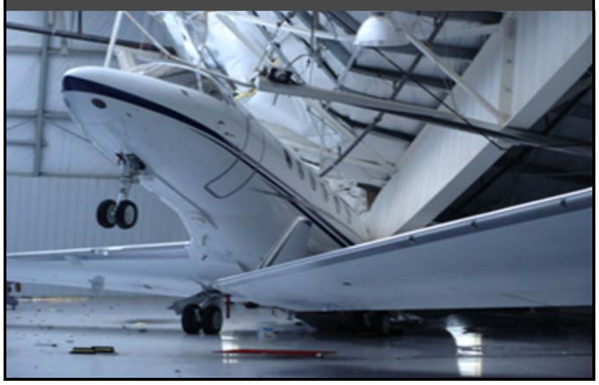

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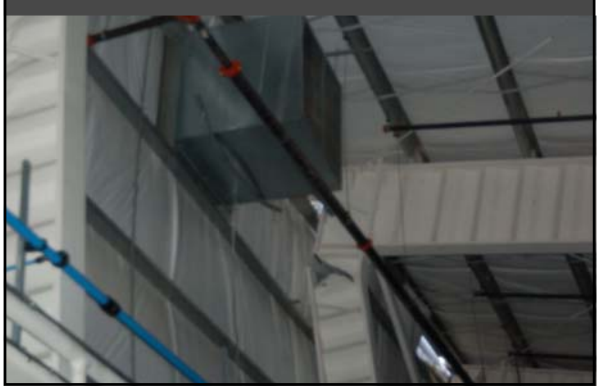

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