Reducing Soft Costs of Rooftop Solar Installations Attributed to Structural Considerations

SAND2015-8024PE

Principal Investigator: Stephen F Dwyer, PhD, PE; Sandia National Laboratories
Presented by: Brian Dwyer, Sandia National Laboratories

SunShot
U.S. Department of Energy

Sandia National Laboratories

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Research Team

- Sandia National Laboratories
  - Principal Investigator: Stephen F Dwyer, PhD, PE
- University. of New Mexico
  - Walter Gerstle, PhD, PE
    - Alfred Sanchez, MS, structural engineering
    - Ivan Campos, MS, structural engineering
    - Dan McFadden, graduate student

Structural Market Barrier (background)

- Original construction must meet local building codes, while modifications must meet current building and engineering codes
- In 2012, as a participant in the DOE's Solar America Cities program, the city of Madison, WI, identified the solar PV permitting process as the top barrier to new rooftop installations.
- A workshop in Madison revealed a perception that more than 80% of existing residential rooftops do not meet the current structural engineering code (ASCE 7-10 and IRC 2009), even before PV panels are installed.
- Reasons:
  - Conservative codes
  - Conservatism in engineering methodology

Structural Market Barrier (background)

- According to DOE, solar "soft costs," which include permitting and installation, make up as much as 64% of the total installed cost of solar.
- The process of inspecting rooftop strength for PV installations can affect soft costs such as permitting, inspection, and installer costs.
- In many locations across the United States, misperceptions about the strength of existing residential rooftops motivate decisions to conduct structural analyses prior to solar permitting. Time and budget constraints in executing those analyses can lead to an overly conservative methodology that underestimates load-carrying capacity, thus delaying or even blocking the PV installation.

Structural Market Barrier (background)

- Structural engineering methodologies may vary across states or jurisdictions, leading to complications for installers.
- Safety is an important factor in building codes and must be considered when there is any change to a residential or commercial structure.
- Understanding how weight loads affect the structural integrity of the roof is important to a range of stakeholders, including homeowners, code officials, solar installers, and builders.

Project Addresses Structural Market Barrier

Issues related to structural barrier and how this project addresses them

- Lack of load-carrying capacity in roof. Load-carrying capacity is '*perceived*' issue, not a '*real*' issue.
- Cost of engaging a structural engineer. Eliminate structural review (≈10% of installed cost).
- Lack of understanding of structural code. Opportunity to use empirical data rather than calculate.
- Inadequate permit application. Improved guidance.
- Multiple iterations required to get permit accepted. Eliminate.
- Existing load-carrying capacity guidance without engineering validation. Eliminate.

Codes

- American Society of Civil Engineers' 7-10 dictates *Applied Loads* (local codes generally adopt this, with occasional specifics);
- International Residential Code and the National Design Specification provide *Allowable Loads* (testing to indicate conservatism);
- American Institute of Timber Construction describes *Allowable Load Adjustment Factors*.

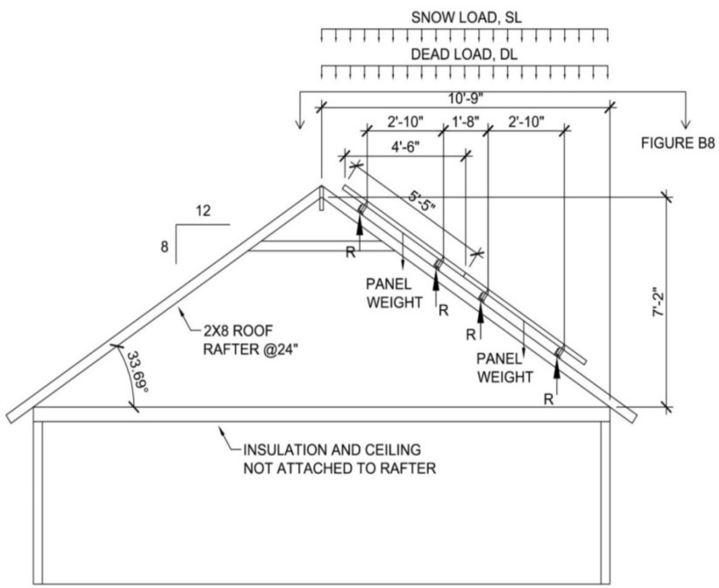
Adjustment Factors (AITC)

- *Allowable Load* tables do not include all *Adjustment Factors* per AITC: Fb'=Fb CD CM CF Cfu CL Cr Ct Ci

Cr = 1.15 (System affects) per ASTM D6555

How are Roof Strengths Calculated?

Load Application per Code



Load combinations utilized by the allowable stress design methodology to calculate load on roof based on geographic setting:

1. $D + F$
2. $D + H + F + L + T$
3. $D + H + F + (L_r \text{ or } S \text{ or } R)$
4. $D + H + F + 0.75(L + T) + 0.75(Lr \text{ or } S \text{ or } R)$
5. $D + H + F + (W \text{ or } 0.7E)$
6. $D + H + F + 0.75(W \text{ or } 0.7E) + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$
7. $0.6D + W + H$
8. $0.6D + 0.7E + H$

where:

D = dead load
E = earthquake load
F = load due to fluids with well-defined pressures and maximum heights
H = load due to lateral earth pressure, ground water pressure, or pressure of bulk materials (generally zero for roof applications)
L = live load
L_r = roof live load
R = rain load
S = snow load
T = self-straining force (generally zero for roof applications)
W = wind load

- ❑ Calculate Max Shear and Bending Stress for **SINGLE BEAM.**
- ❑ Compare to *Allowable* per Code

How are Roof Strengths Calculated?

- When engineers conduct the structural analysis on a rooftop, they often calculate stresses on the basis of an individual beam, rafter, or truss.

- This analysis assumes each component of the structure acts alone, a simplistic view that fails to consider the rooftop system as a whole or consider the load-sharing or load redistribution effects of a roof system.

- The result is a conservative analysis that does not accurately represent the roof's ability to support a PV installation.

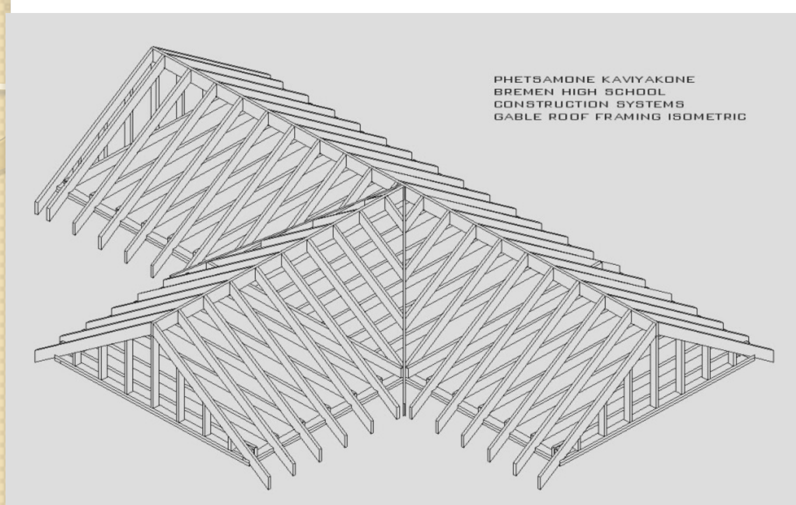
What are **Actual** Roof Strengths?

What are **Actual** Roof Strengths?

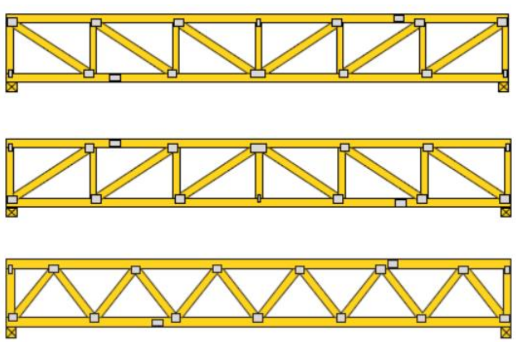
- Sandia researchers conducted a range of tests on to-scale wood roof structures to gather data on actual load-carrying capacities.

- Results were compared to loads prescribed by the International Residential Code and the National Design Standard.

Test Program Included:
Common Structural Elements – Rafters, Trusses, TJI



Rafters are sized based on load and length



Open Web Truss

Closed Web Truss
Trus Joist® TJI® Joists

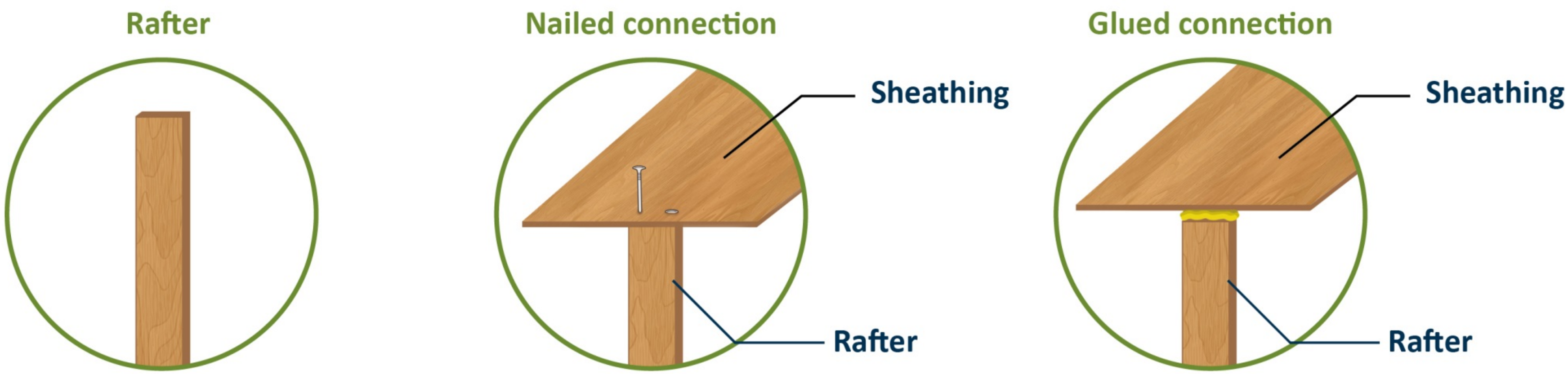
Testing of Roof Structures

Structural frame used to apply point loads

Air bladder used to apply uniform loads – one of many of various sizes

Roof section tested to failure with air bladder

Early Results – SINGLE Beam



Partial Composite Action

Composite Action

Single Rafter:
This is what an engineer considers when performing analysis

Increased strength by **35%**

Increased strength by **74%**

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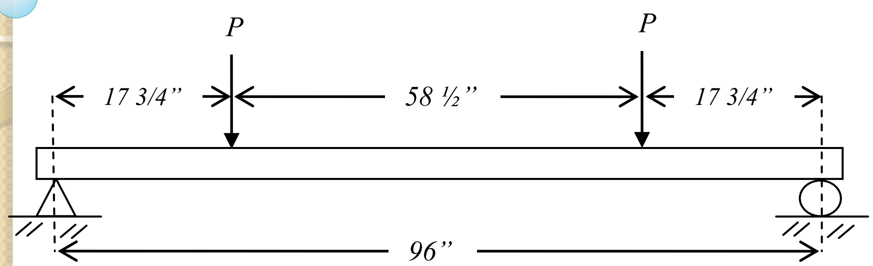
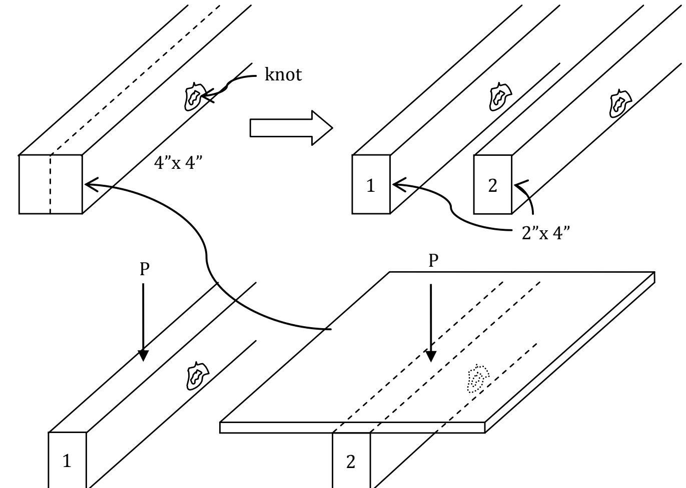
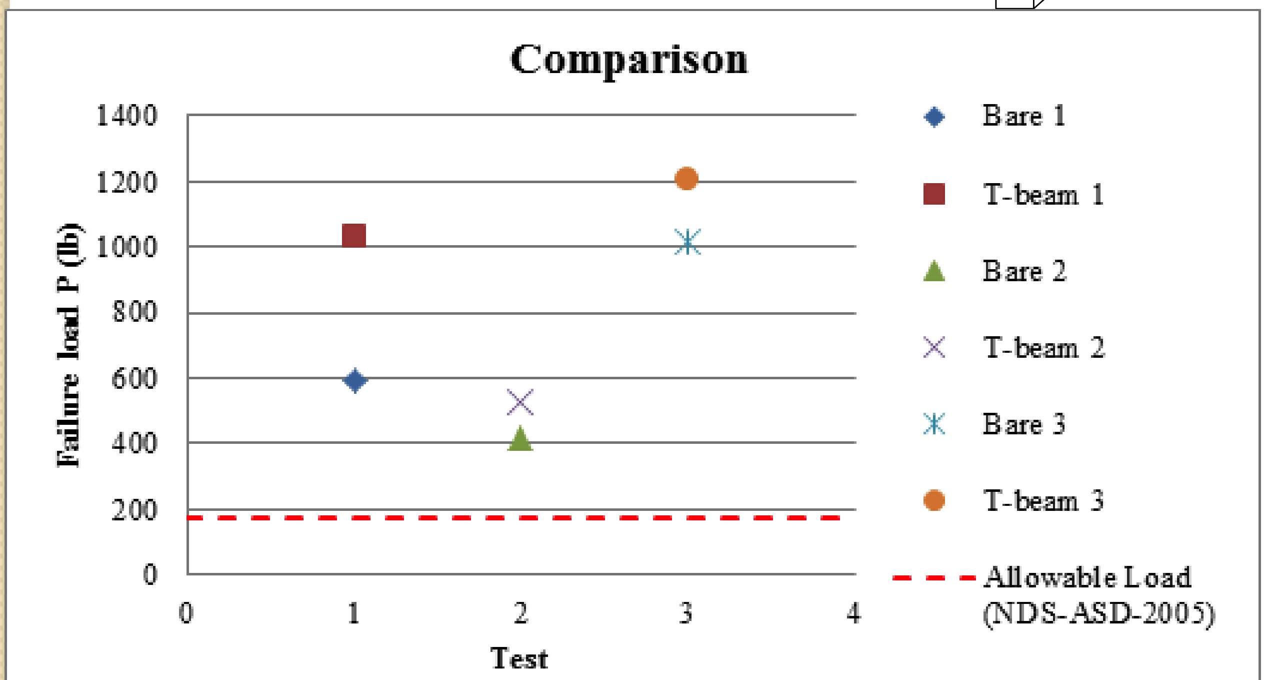
Next Step – Validate Point Load Tests:

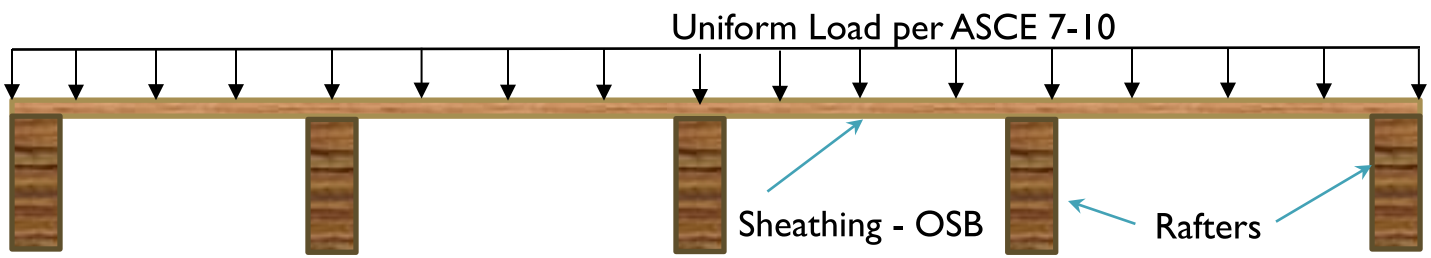
Individual vs. Composite (nailed)

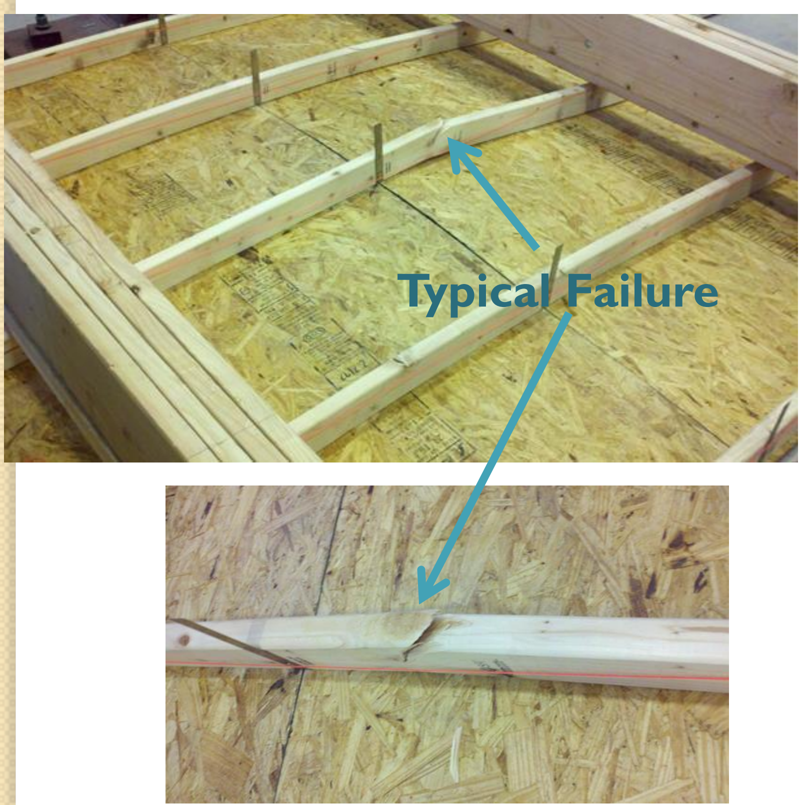






Scaled Roof Section Testing
Uniform Load Application

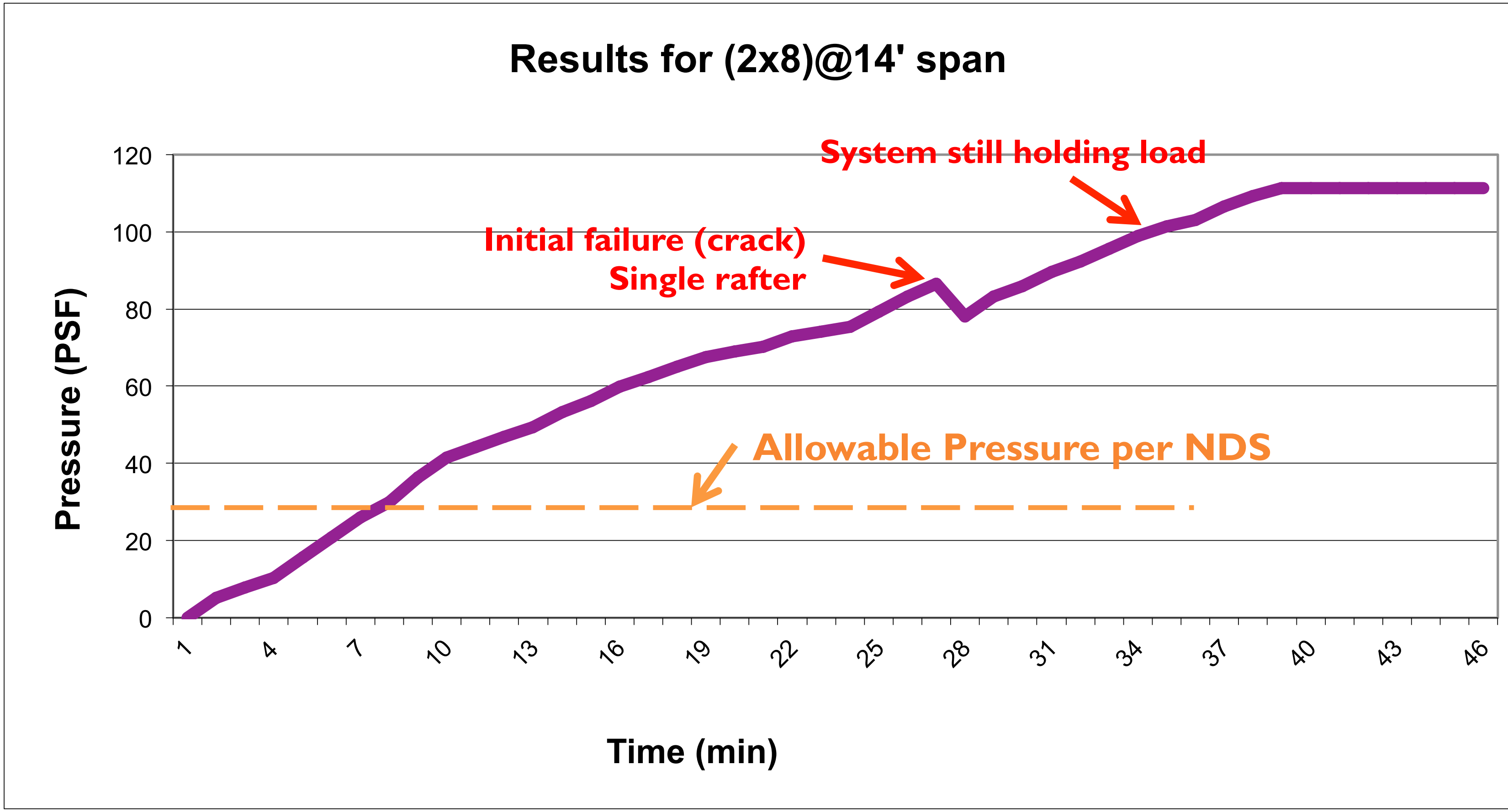




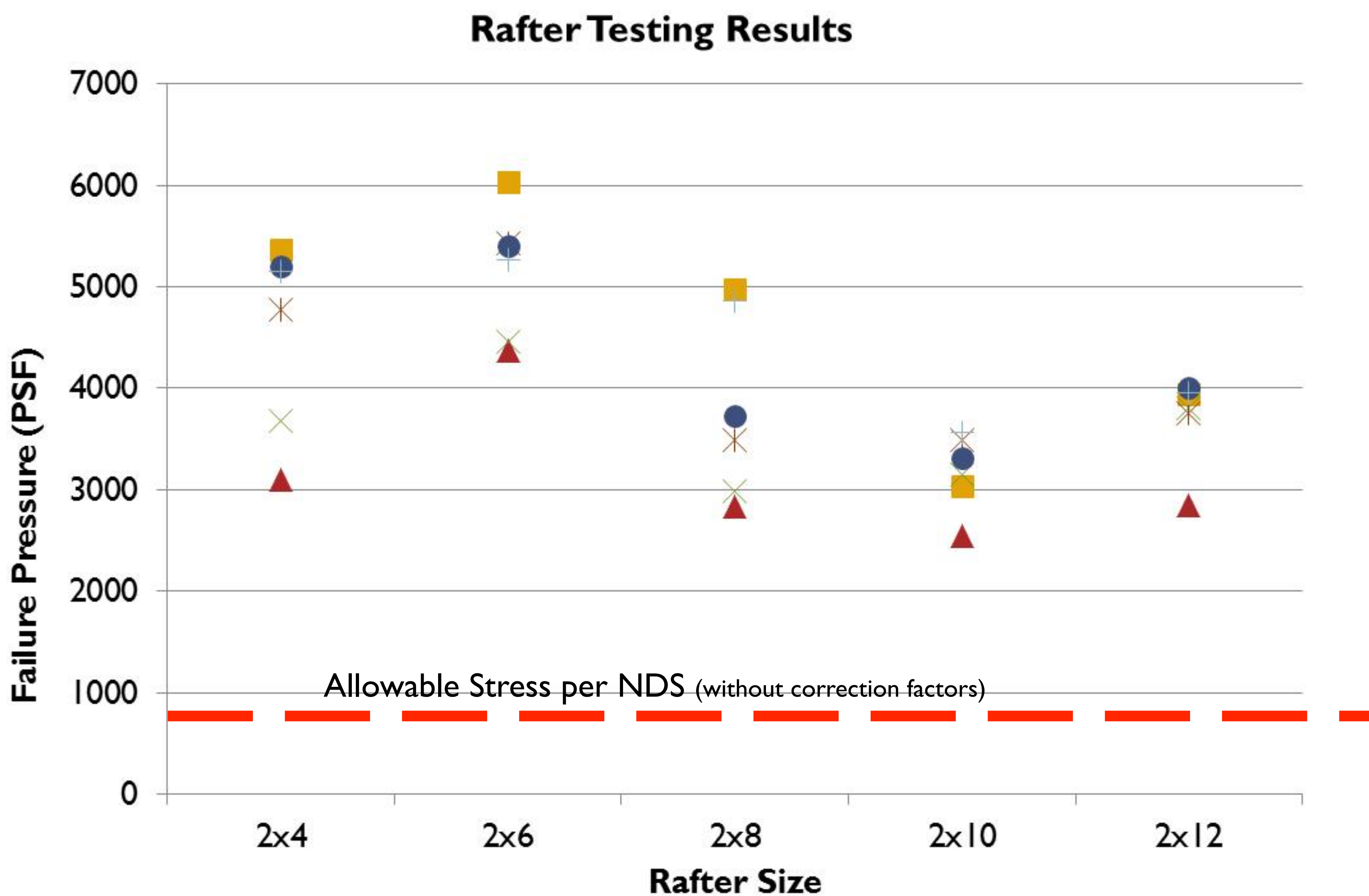
Air bladder applies uniform load

Numerous Roof-Scaled Tests (30 rafters, 6 open web truss, 6 TJI)

Load Results (Example)



Uniform Load Results: Rafters

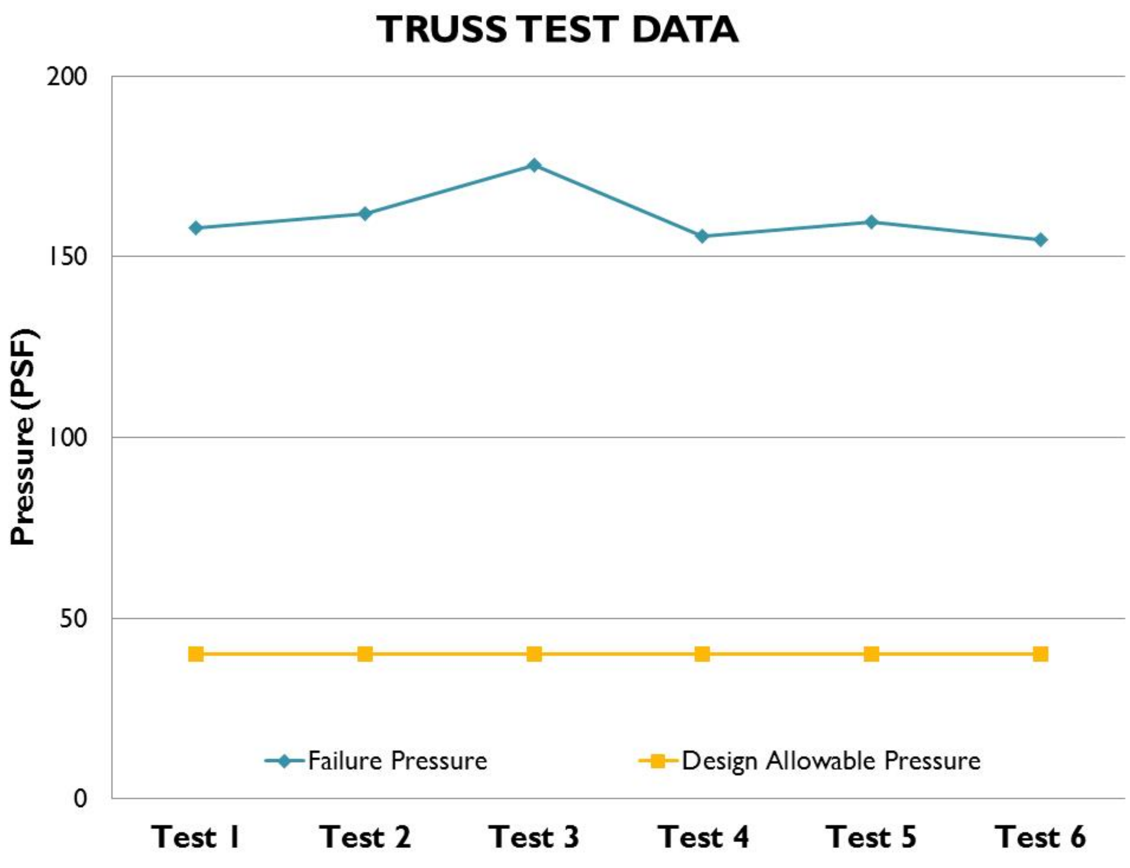


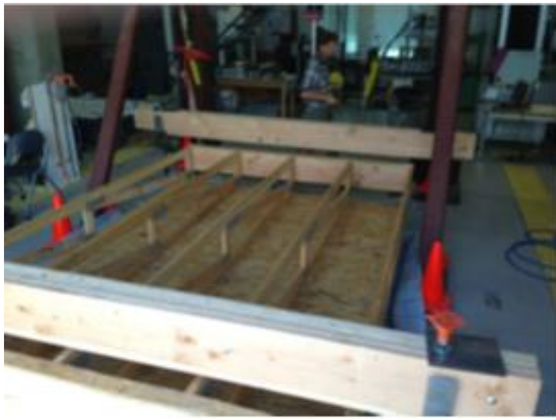
*36 total tests run to date

Rafter Testing Summary

	Factor of Safety				
	2x4	2x6	2x8	2x10	2x12
Test 1	4.5	5.3	4.5	2.8	3.8
Test 2	2.6	3.9	2.6	2.4	2.7
Test 3	3.1	3.9	2.7	3.0	3.6
Test 4	4.0	4.8	3.2	3.3	3.6
Test 5	4.3	4.7	4.4	3.3	3.8
Test 6	4.4	4.8	3.4	3.1	3.8
FS, min	2.6	3.9	2.6	2.4	2.7
FS, max	4.5	5.3	4.5	3.3	3.8
Standard deviation	0.72	0.51	0.77	0.32	0.38
Average	3.83	4.57	3.48	2.99	3.57
Median	4.02	4.66	3.40	2.99	3.65

Uniform Load Results: Truss



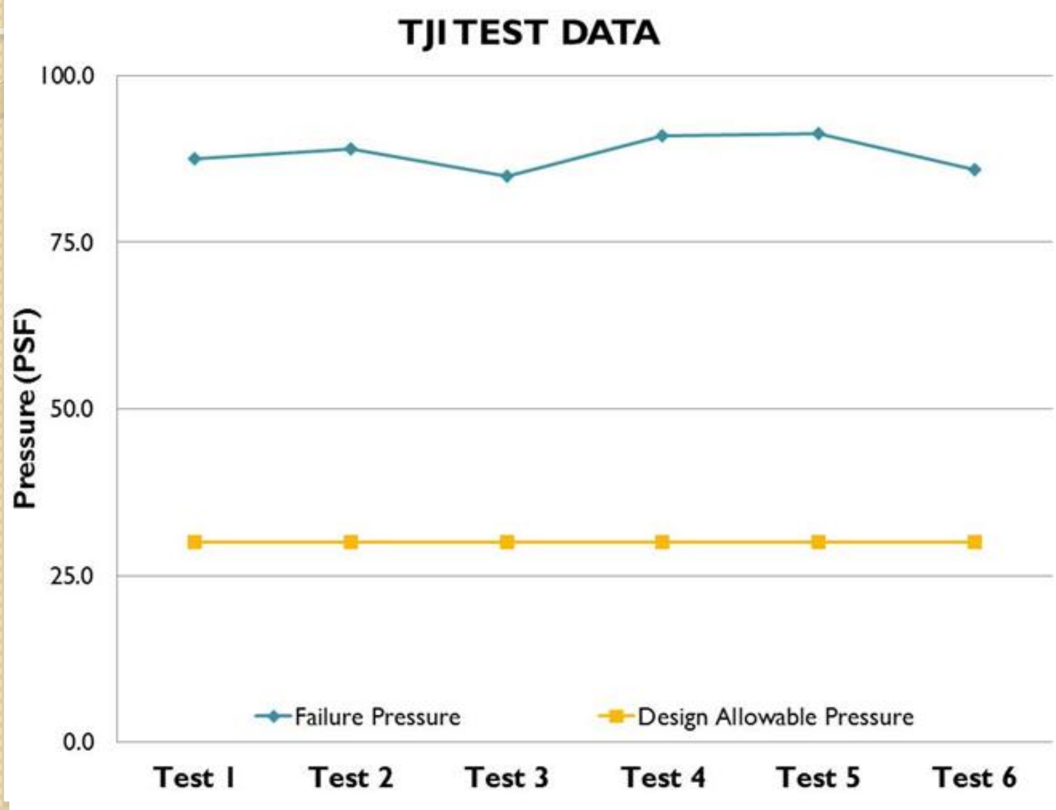


Uniform Load Results: Truss

Truss	Failure Pressure	Design Allowable Pressure	Factor of Safety
Test 1	157.8	40	3.9
Test 2	161.9	40	4.0
Test 3	175.2	40	4.4
Test 4	155.8	40	3.9
Test 5	159.7	40	4.0
Test 6	154.7	40	3.9
		Average	4.0
		Max	4.4
		Min	3.9
		Median	4.0
		SD	0.2

Allowable Pressure = Live + Dead Load ---- varies across country

Uniform Load Results: TJI

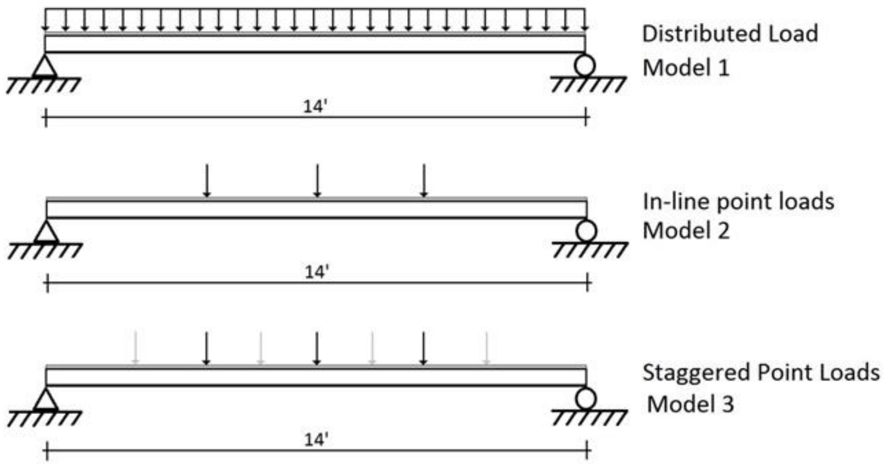


Uniform Load Results: TJI

Truss	Failure Pressure	Design Allowable Pressure	Factor of Safety
Test 1	87.5	30	2.9
Test 2	88.9	30	3.0
Test 3	84.9	30	2.8
Test 4	90.9	30	3.0
Test 5	91.2	30	3.0
Test 6	85.9	30	2.9
		Average	2.9
		Max	3.0
		Min	2.8
		Median	2.9
		SD	0.1

Design Optimization

Staggering support legs will reduce stress on roof.

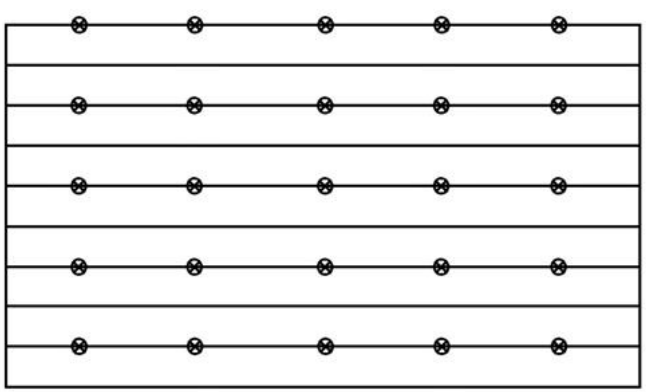


Standard Arrangement – In-line Pt Loads

Staggered Pt Loads – 10% reduction in max. bending moment

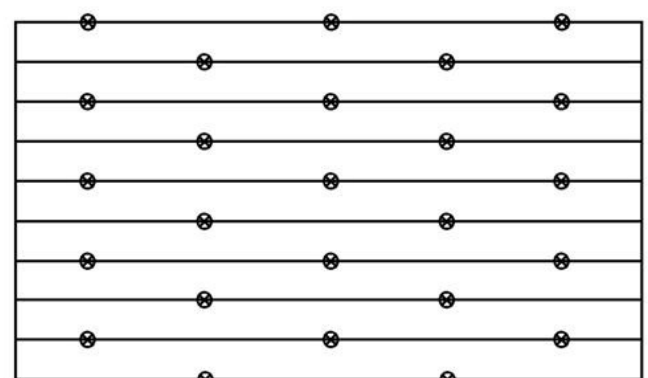
Distributed Load – 6% reduction in max. bending moment

In-line Point Loads



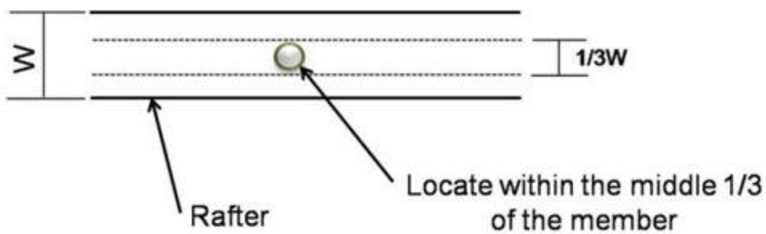
⊗ = Point load (equaly spaced)

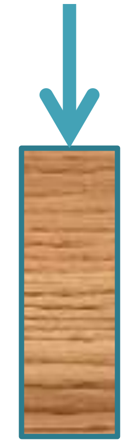
Staggered Point Loads



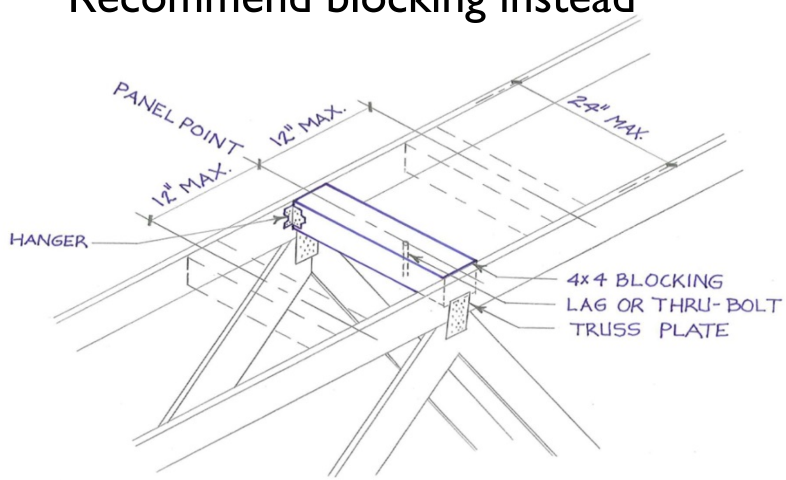
Standardized Reinforcements

Current practice warrants lag bolting to rafter/truss



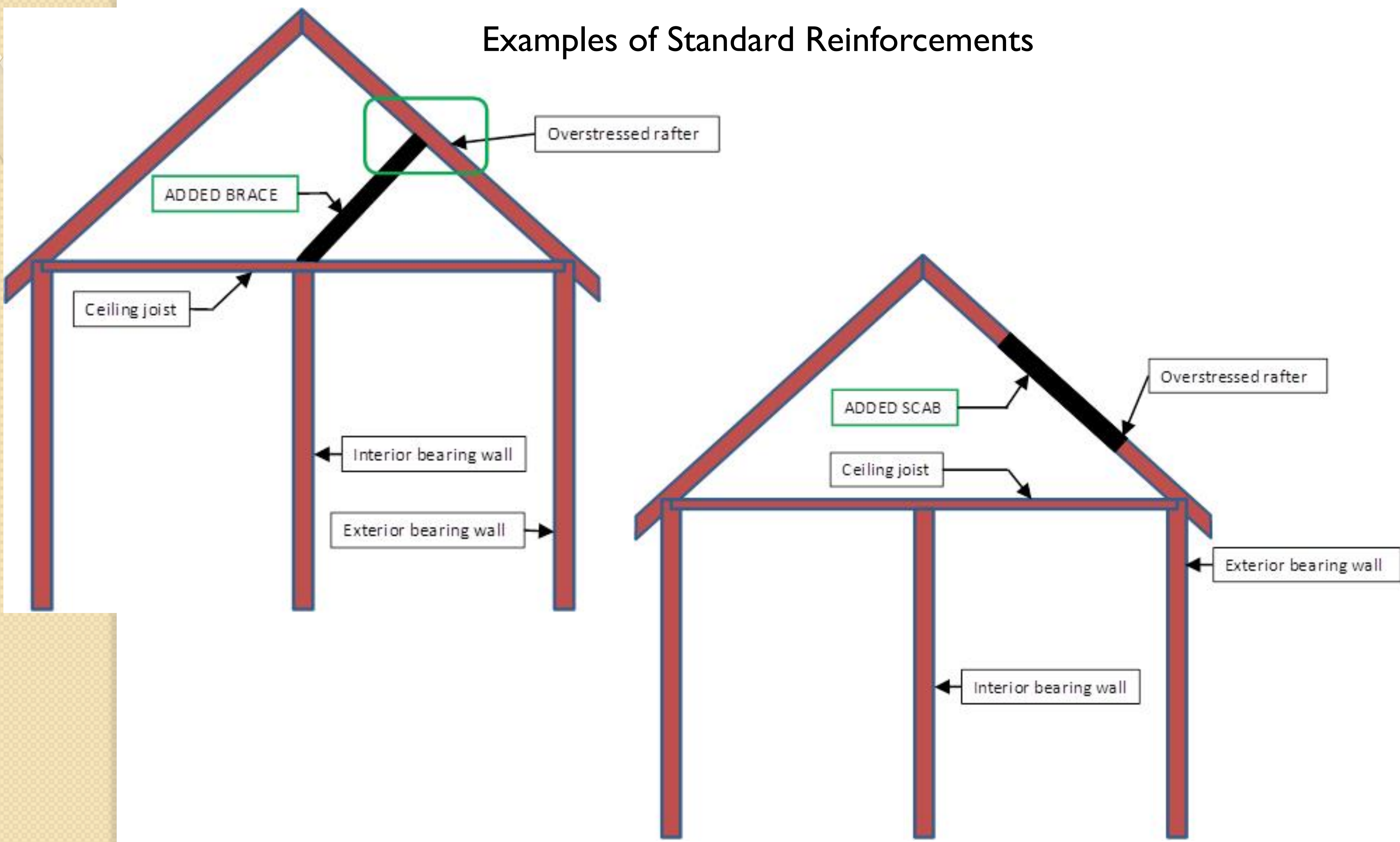


Recommend blocking instead



Standardized Reinforcements

Examples of Standard Reinforcements



Conclusions

- For all configurations tested in the project, results indicate a significantly greater load capacity than that identified in applicable codes.
- On average, rafter-based tests demonstrated a 330% excess load-bearing capacity, as compared to values computed in the National Design Standard.
- Results suggest that current residential rooftop structural evaluations are overly conservative in evaluating the ability of roofs to support additional loading from solar PV installations.

Conclusions

- The data suggest that a well-built home that meets local building standards and has not been adversely modified or damaged has adequate load-bearing capacity to support a roof-mounted PV system.

- Code officials, permitting officials, and engineers can use this Sandia report as another tool in decisions about rooftop structural analyses and solar PV permitting applications, ultimately helping to support safe, cost-effective solar rooftop installations.

- Reports and more information are available at http://pv.sandia.gov/rooftop.

Stephen F. Dwyer, PhD, MBA, PE

Principal Member of Technical Staff, Sandia National Laboratories

sfdwyer@sandia.gov

505-844-0595

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