THE UNIVERSITY OF ARIZONA.

Seismic Structural Design Associates, INC.

Steel Moment Frame Damage Predictions Using Low-Cycle Fatigue

Scott Campbell, PhD, PE

Ralph Richard, PhD, PE

James Partridge, PE

Structural Analysis Consulting Group

Background

- Fatigue is understood to be a significant cause of failures in steel structures
- Research dates back to the early 1900’s
- 1960’s & 70’s: Renewed interest
  - Bertero and Popov (1965)
  - Srinivasan and Munse (1972)
  - Kasiraj (1972)
  - Suidan and Eubanks (1973)
  - Mizuhata et al. (1977)

Background

- 1980's: New methodologies
  - **Proposed seismic damage measures**
    - **Park and Ang (1985)**
    - **McCabe and Hall (1987)**
  - **Proposed testing methods**
    - **Krawinkler, 1983**
- Recent work
  - Taucer et al. (2000)
  - Barsom and Pellegrino (2002)
  - Stojadinovic (2003)

“maximum ductility factors alone are not an adequate measure of performance”

(Krawinkler et al. 1983)

Damage Calculation

ASCE 7

- Performance Criteria
  - Allowable damage not specified in code
  - It's there anyway - implicit
- Nonlinear Behavior
  - Not allowed under design loads
  - Expected under actual loads

FEMA 356/ASCE 41

- Performance Criteria
  - Explicit
  - Flexible – owner/jurisdiction decision
- Nonlinear Behavior
  - Directly modeled
  - Limits based on peak response
  - Account for cyclic indirectly

ASCE 7/41

- Advantages
  - Codified: Refer to documents
  - Accepted
- Disadvantages
  - Based on peak response only
  - Pass/Fail only

"New" Alternative Fatigue Damage Calculation

Directly account for the cumulative nature of damage during earthquakes

"new" because this has been proposed before – in different forms

Cumulative Damage Calculation

- Park and Ang (1985)
  - Combines peak response and energy dissipation damage
- McCabe and Hall (1989)
  - Positive and negative phase energy dissipation
- Chai (2005)
  - Duration dependent low-cycle fatigue response spectra

Why aren’t these methods used?

- Complex
  - Difficult to incorporate into existing models
- Iterative
  - Require information about response as input
- Undefined
  - Some parameters aren’t currently known

Proposed Method

Use fatigue life calculation to evaluate the structure

Start with Experimental Data

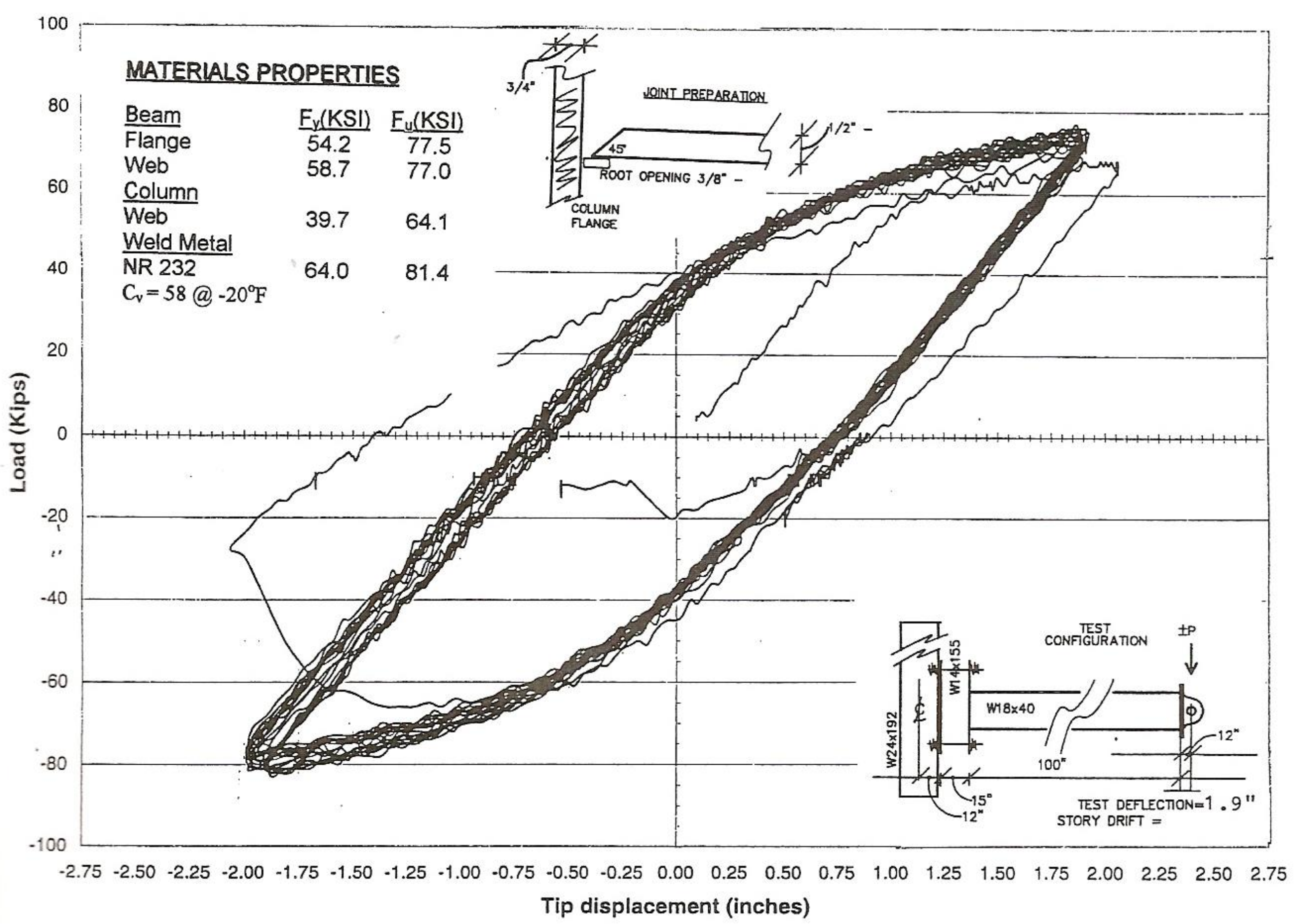
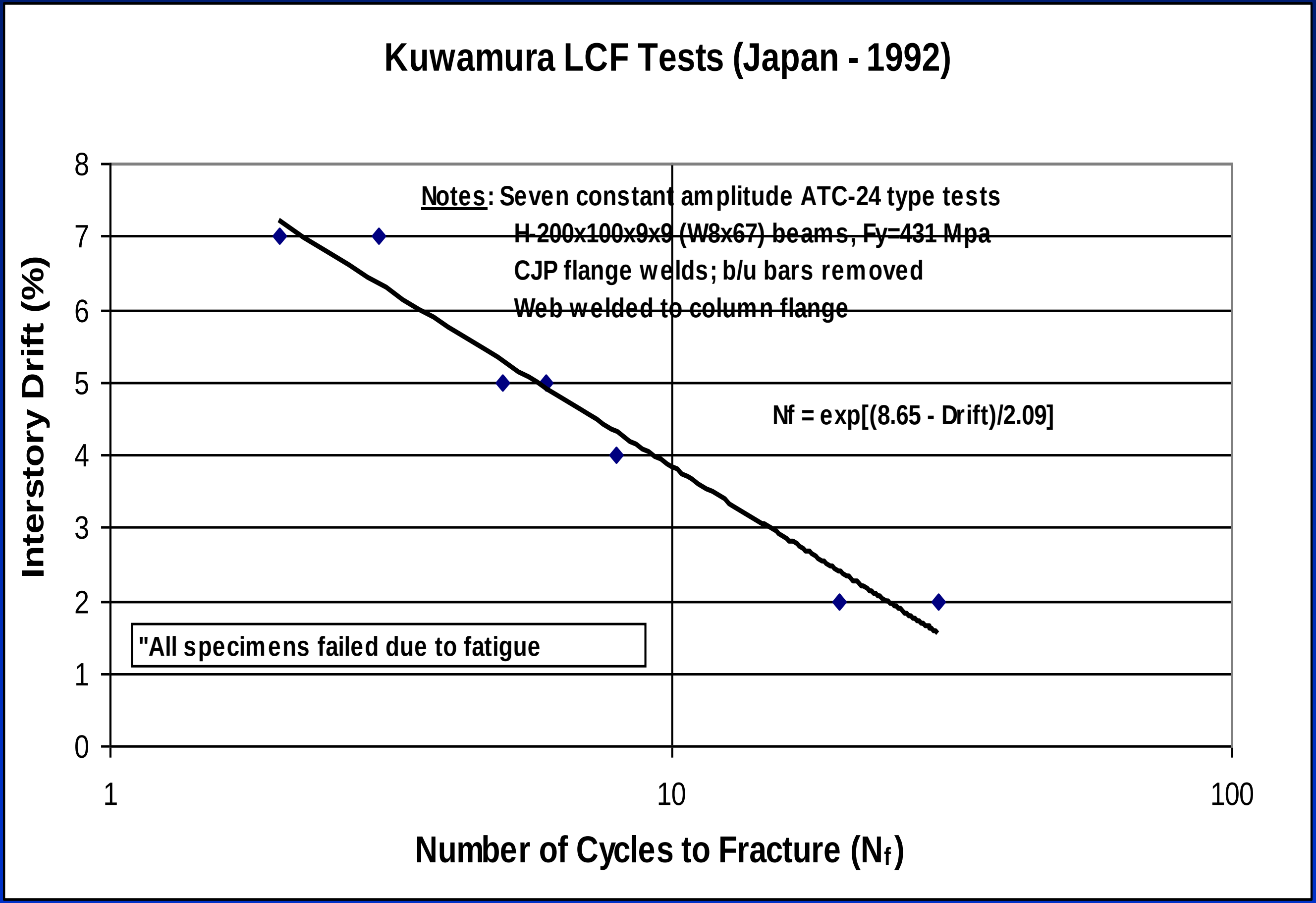
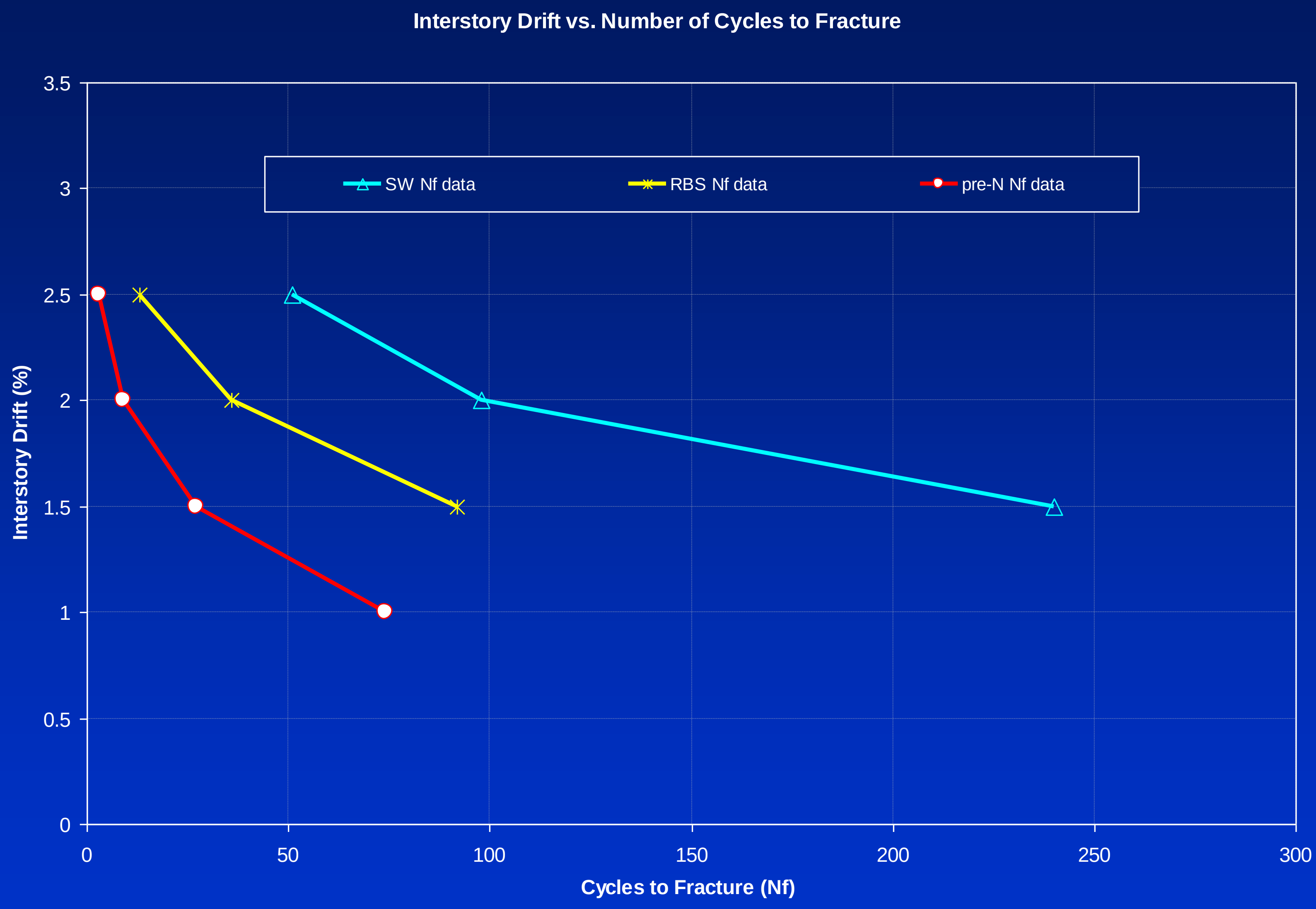


Figure JP-3D. Pre-Northridge Cyclic Test #4 @ 1.9" – February 17, 2000.

Fatigue Life Curve




Interstory Drift vs. Number of Cycles to Fracture
SW Nf data
RBS Nf data
pre-N Nf data
Interstory Drift (%)
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
200
250
300
Cycles to Fracture (Nf)

Lack of Data - Potential Solution

- Similitude equations (Kuwamura and Takagi, 2004)
- $$N_f = \frac{\eta_{pM}}{\mu_p}\left(\frac{\eta_{pM}}{\mu_p} - 1\right)^{\frac{2}{3}} \qquad \frac{\eta_{pM}}{\mu_p} \geq 2$$
- Predict fatigue life data based on monotonic test results
- Work currently underway to categorize monotonic failures

How do you calculate fatigue life?

Structures

Start with Nonlinear Analysis

- Determine the response
  - Nonlinear, dynamic model of structure
  - Use FEMA 356/ASCE 41 modeling parameters
  - Output of interest: Time history of
    - Interstory drift
    - Plastic (or total) end rotation of beams

Calculate Fatigue Damage
Miner's Rule

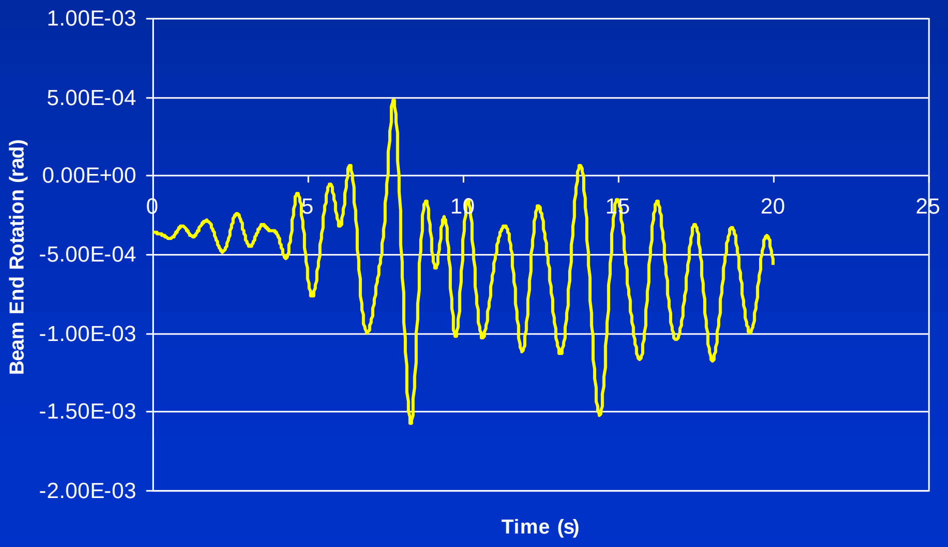
- *Assume* damage per cycle is 1/# cycles to failure
- Sum damage over all cycles
  - $$D = \sum_{i=1}^{N} \frac{1}{N_{fi}}$$
  - N = number of cycles
  - N_{fi} = cycles to failure for current cycle amplitude

Problem

Loading is not consistent cycles as in testing or mechanical parts.

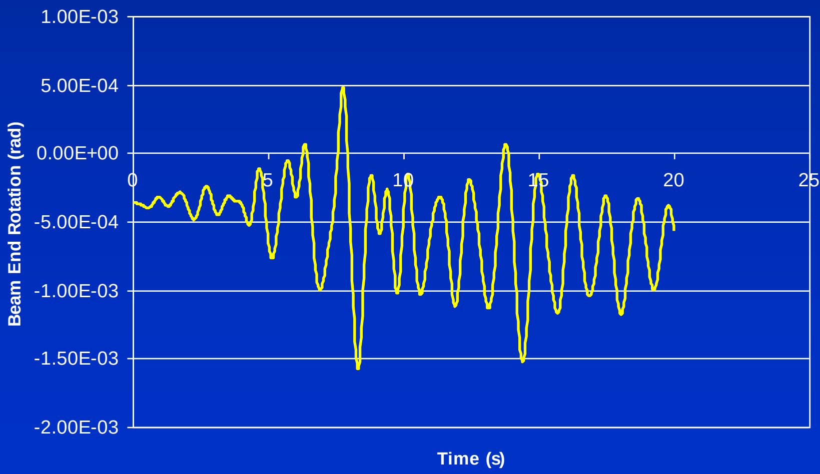
Earthquake "Cycles"

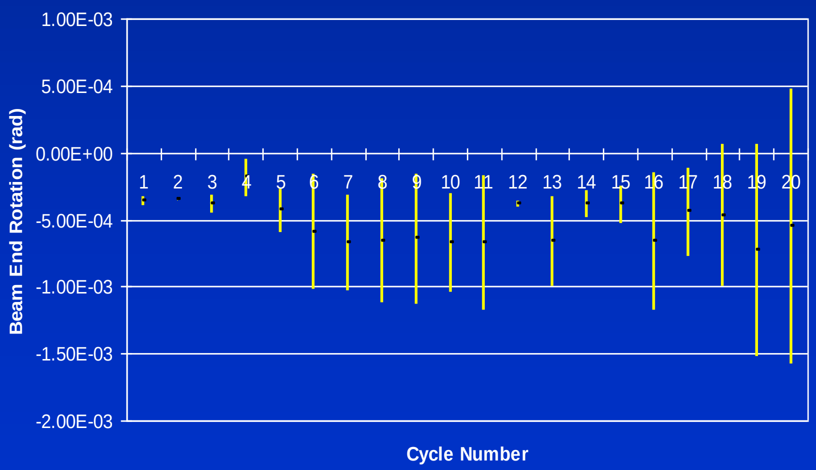
- What is a cycle in earthquake response?
- Amplitude is not constant
- Many partial cycles (do not cross axis)



Cycle Counting

- Use “rainflow” method – ASTM E-1049
- Calculate cycle range and mean value
- Does not preserve time-ordering of cycles





Fatigue Damage Calculation

Once cycles are determined go back to damage equation

$$D = \sum_{i=1}^{N} \frac{1}{N_{fi}}$$

Fatigue Damage Calculation

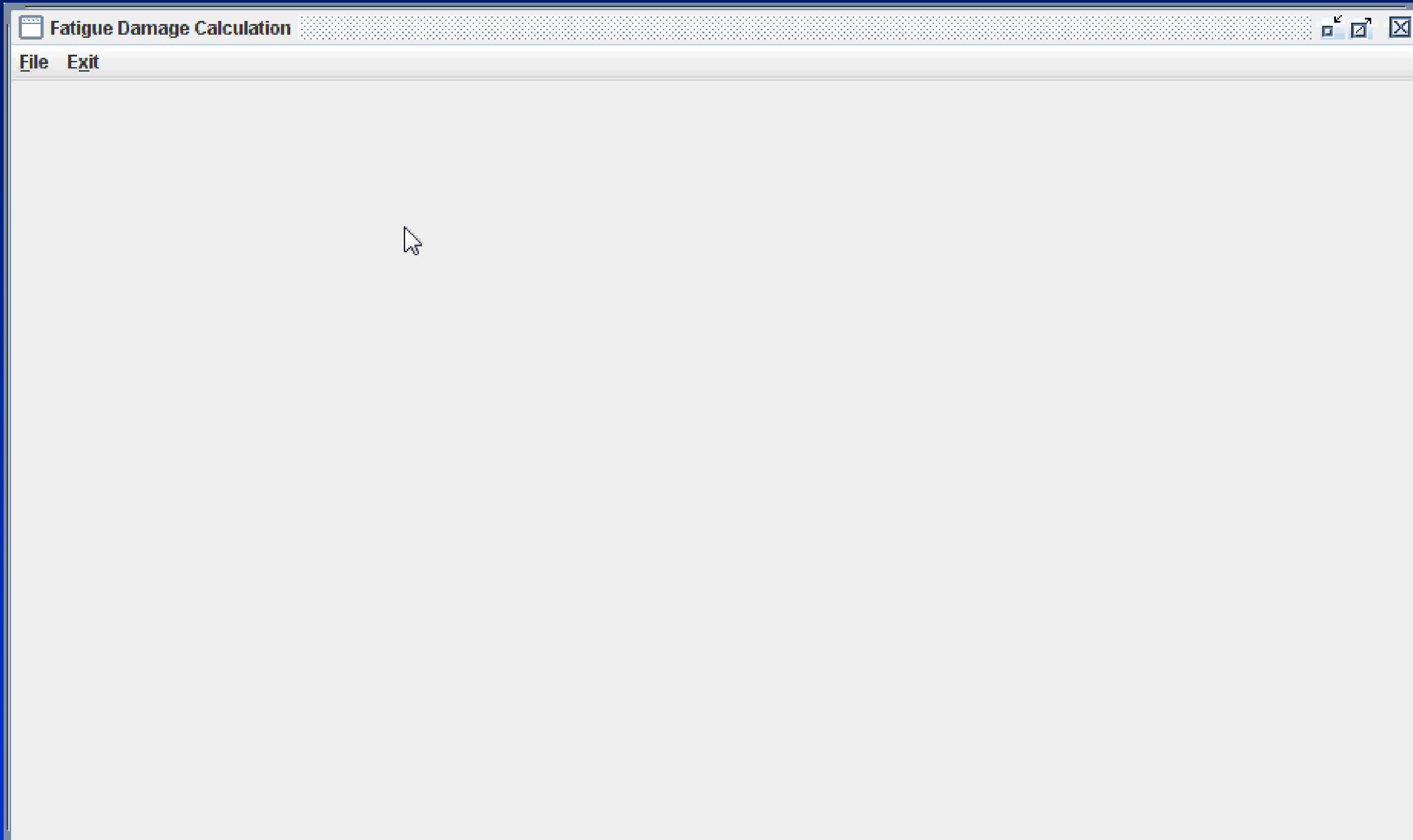
- Accepts output from PERFORM
  – Beam end rotations
  – Story drifts
- Calculates fraction of fatigue life
  – Determine cycle magnitude and number
  – Calculate damage from each cycle then sum

Output Interpretation

- Fatigue damage index >1 indicates failure
  - Cannot tell *when* failure occurs
  - Same as ASCE 7/41
- Fatigue damage index <1
  - Fraction of fatigue life “used” by earthquake
  - Estimate of remaining fatigue life

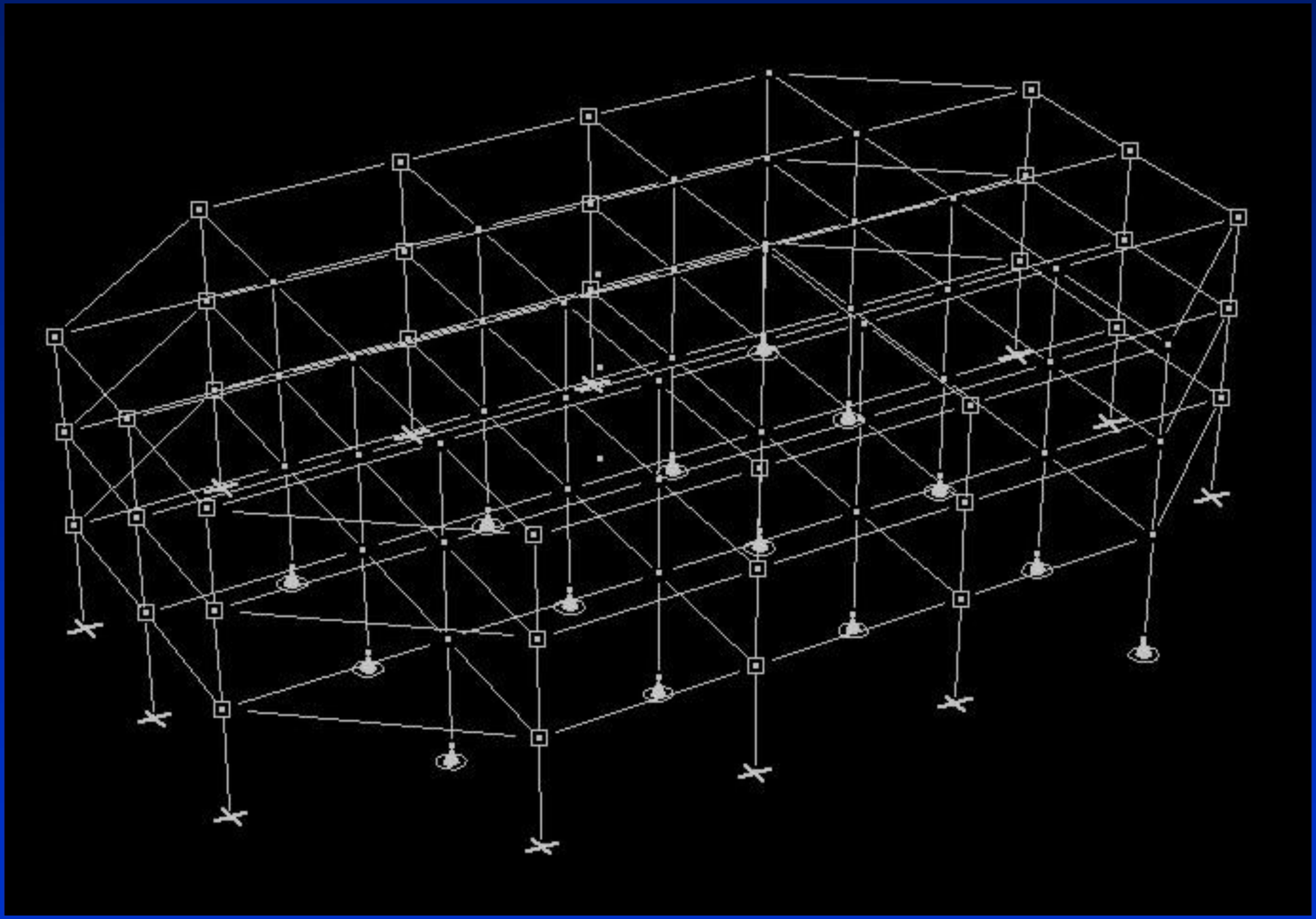
Fatigue Damage Calculation Program

Sample



Example

Example Structure



Properties

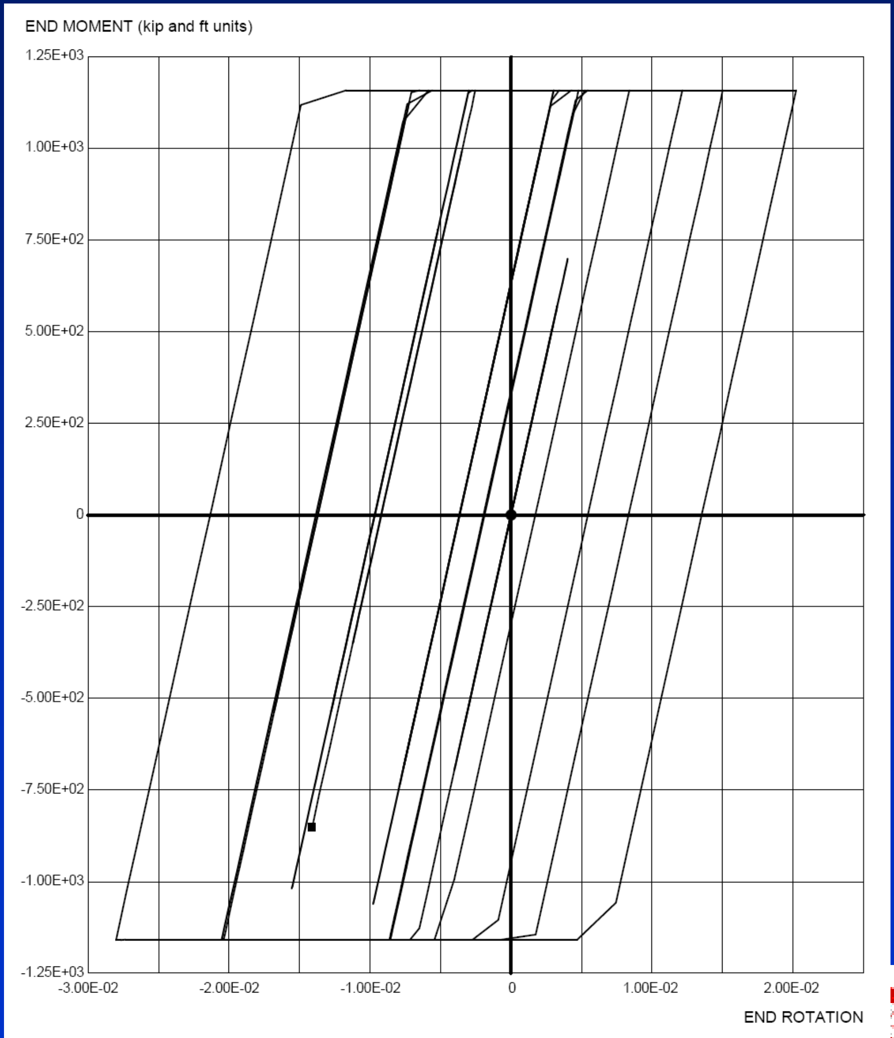
- Moment Resisting Frame
  - Girders: W27x94 (1)
  - Columns: W14x159
  - Panel Zones: Doubler plates added
- Loading
  - Gravity: DL + 0.25LL
  - Earthquake: Peak Acceleration = 0.632g

Results – One Beam (Worst Case)

ASCE-41 Usage Ratios			Fatigue Damage Index		
IO	LS	CP	Pre-N	RBS	SW
4.2	0.7	0.53	1.24	0.40	0.13

Key Point

- LS Ductility = 6
- Multiple cycles at ductilities of 3, 4, 5
- These cycles damage the connection
  - Not accounted for directly in single value from ASCE 41



Interpretation

- FEMA 356/ASCE 41
  - Structure fails IO performance criteria
  - Structure passes LS/CP performance criteria
- Fatigue Damage
  - Pre-Northridge has fractures present
  - RBS has used up 40% of it's fatigue life
  - SWC has used up 13% of it's fatigue life

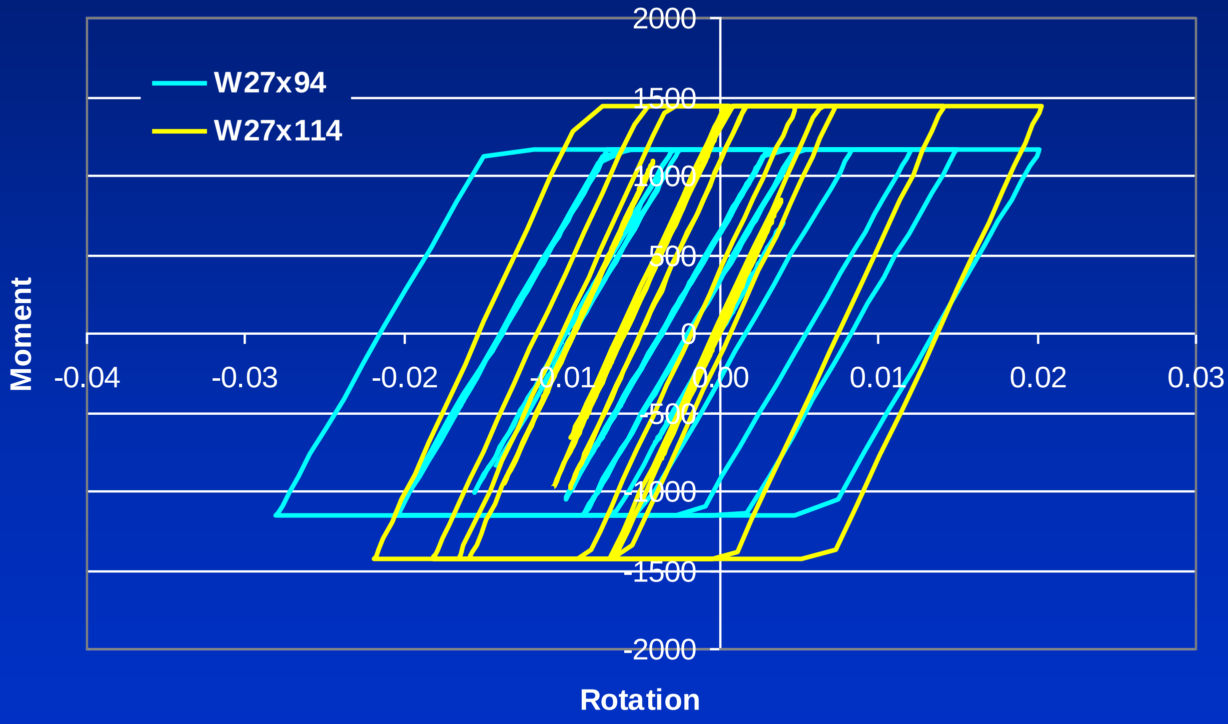
Now Change the Properties

- Girders: W27x114

	ASCE-41 Usage Ratios			Fatigue Damage Index		
	IO	LS	CP	Pre-N	RBS	SW
	3.3	0.55	0.41	0.47	0.15	0.06
Difference w/W27x94 (%)	21	21	18	62	62	54

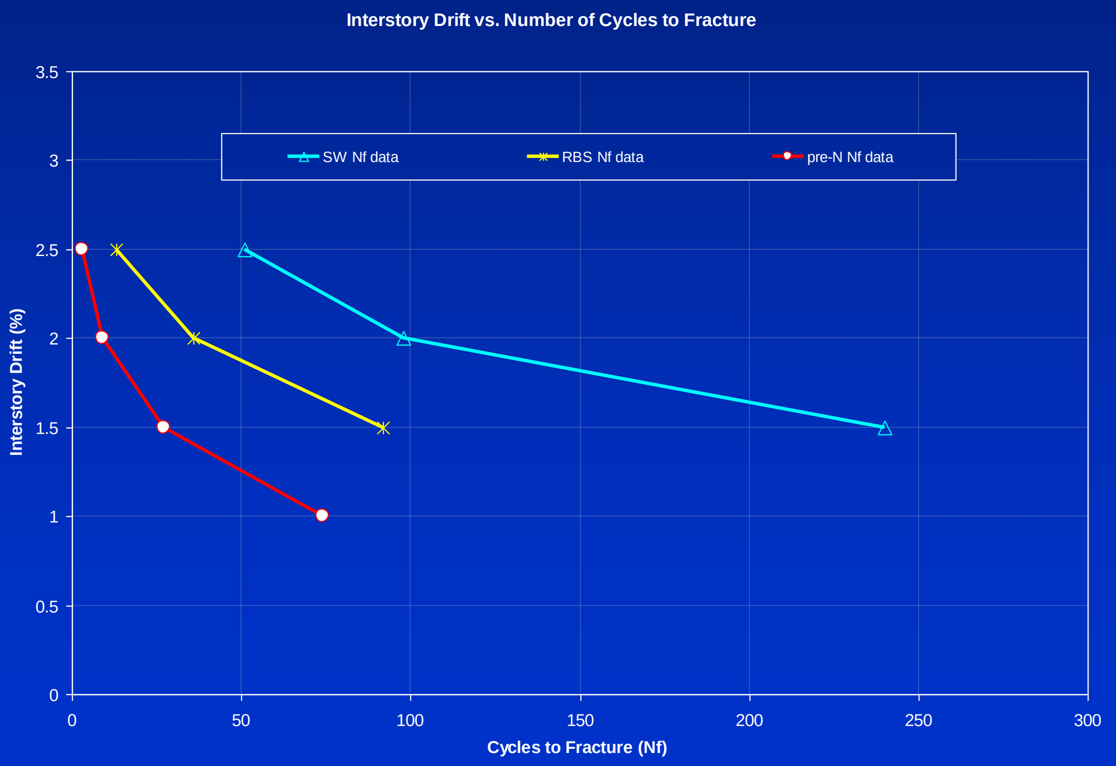
Why the difference?

Changes in Cycles



Not only does the peak rotation decrease, all other cyclic rotations also decrease

This has a large effect on the damage.



Conclusions

- It is possible to predict fatigue damage in steel structures
- Calculations are straightforward and require little additional effort
- Provide further insight into behavior