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Stress-Based Fatigue Monitoring: Methodology for Fatigue Monitoring of Class 1 Nuclear Components in a Reactor Water Environment

(EPRI technical report 1022876)

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NRC Fatigue Meeting
January 5, 2012

Presentation Objective

- Present EPRI-sponsored methodology for stress-based environmental fatigue monitoring which addresses RIS 2008-30.
- Obtain concurrence from NRC that general approach outlined here resolves the concerns expressed in the RIS.

General Objectives of EPRI Report

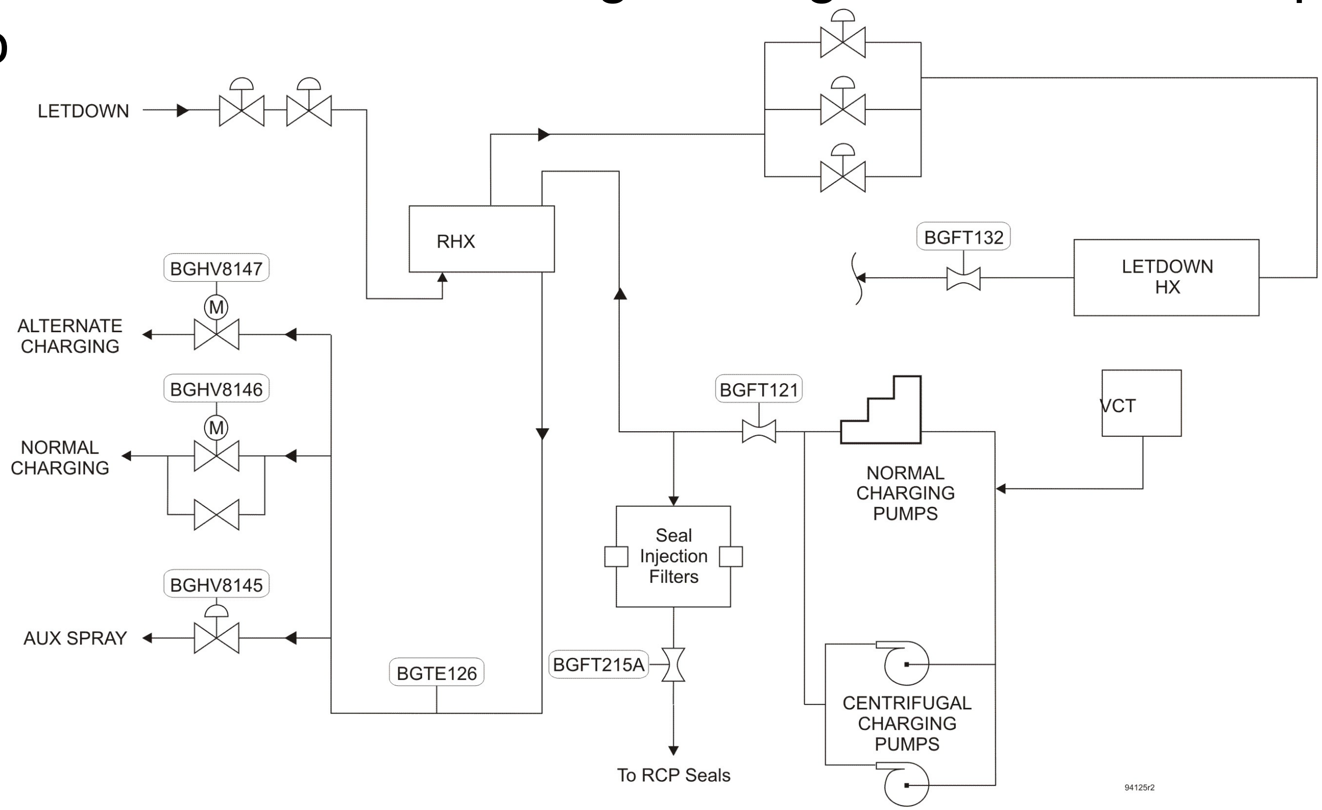
- Resolve regulatory concerns about use of single stress term in fatigue monitoring (RIS 2008-30).
- Provide for automatic calculation of environmentally-assisted fatigue (EAF) – not just ASME Code fatigue.

NRC Position on Fatigue

- Draft NRC RIS-2008-XX ("Fatigue Analysis of Nuclear Power Plant Components" May 2008) was issued to inform licensees of NRC staff concern about use of simplified single stress term in fatigue evaluations.
- NRC responded to public comments on the draft RIS in Dec 2008.
- Final RIS-2008-30 issued Dec 2008.
- Fatigue calculations must consider all six stress components in accordance with ASME Subarticle NB-3200 guidance.

What is Stress-Based Fatigue (SBF)?

- Actual plan measured data (temperatures, pressures, flow rates, valve positions, etc.) are used to compute detailed stress histories.
- From the stress histories, fatigue usage factors are computed for mo



FatiguePro and RIS-2008-30

- Historically, single stress term sometimes used for fatigue evaluations
  - Originally necessary because of computer limitations
  - Conventional stress cycle counting algorithms use single stress
  - Simplified methodology can be shown to be conservative, but great deal of judgment may be required for development
- Subsequent RAIs related to fatigue analysis question analyst judgments involved in general.

Guiding Principles for Development

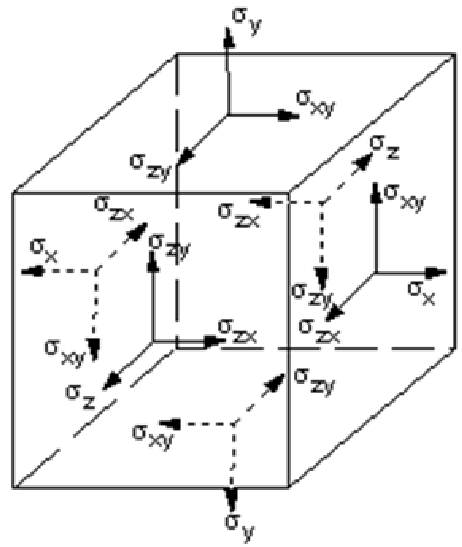
- Accuracy
  - Benchmarks reproduce known problems
  - Meet design basis (ASME Subarticle NB-3200) and regulatory requirements (NUREG-1801, GALL Report)
  - Industry guidance (EPRI's EAF Expert Panel lessons)
- Validation
  - Results make physical sense.
  - Consistent with sound science and engineering principles.
- Repeatability
  - Comply with ASME NQA-1
  - Minimize analyst and user judgments
- Transparency
  - Technical basis documented in EPRI report
  - Available for everyone to review

SBF Technical Basis
Significant Areas of New Technology

- Stress calculations (linearized membrane, bending, and peak components)
- Stress peak and valley detection
- Stress cycle pairing and fatigue calculations
- Environmental fatigue (F_{en}) calculations

Stress Calculation Objectives

- Compute time history of the 6 unique stress components for:
  - Primary plus secondary (usually linearized membrane plus bending)
  - Total stresses (including peak)
- Plus metal surface temperature



	Primary (P) + Secondary (Q)						Primary (P) + Secondary (Q) + Peak (F)						
Time	SX	SY	SZ	SXY	SYZ	SXZ	SX	SY	SZ	SXY	SYZ	SXZ	Temp
0	2.281	47.413	37.257	1.772	0.000	0.000	0.128	72.722	63.606	0.097	0.000	0.000	154.3
1	2.291	47.830	37.637	1.762	0.000	0.000	0.130	73.226	64.094	0.096	0.000	0.000	149.4
2	2.301	48.245	38.014	1.752	0.000	0.000	0.131	73.726	64.579	0.095	0.000	0.000	144.6
3	2.313	48.607	38.301	1.755	0.000	0.000	0.132	74.181	64.973	0.095	0.000	0.000	142.8
4	2.323	48.972	38.598	1.756	0.000	0.000	0.134	74.638	65.376	0.094	0.000	0.000	140.5
5	2.333	49.357	38.939	1.749	0.000	0.000	0.135	75.053	65.767	0.093	0.000	0.000	136.6

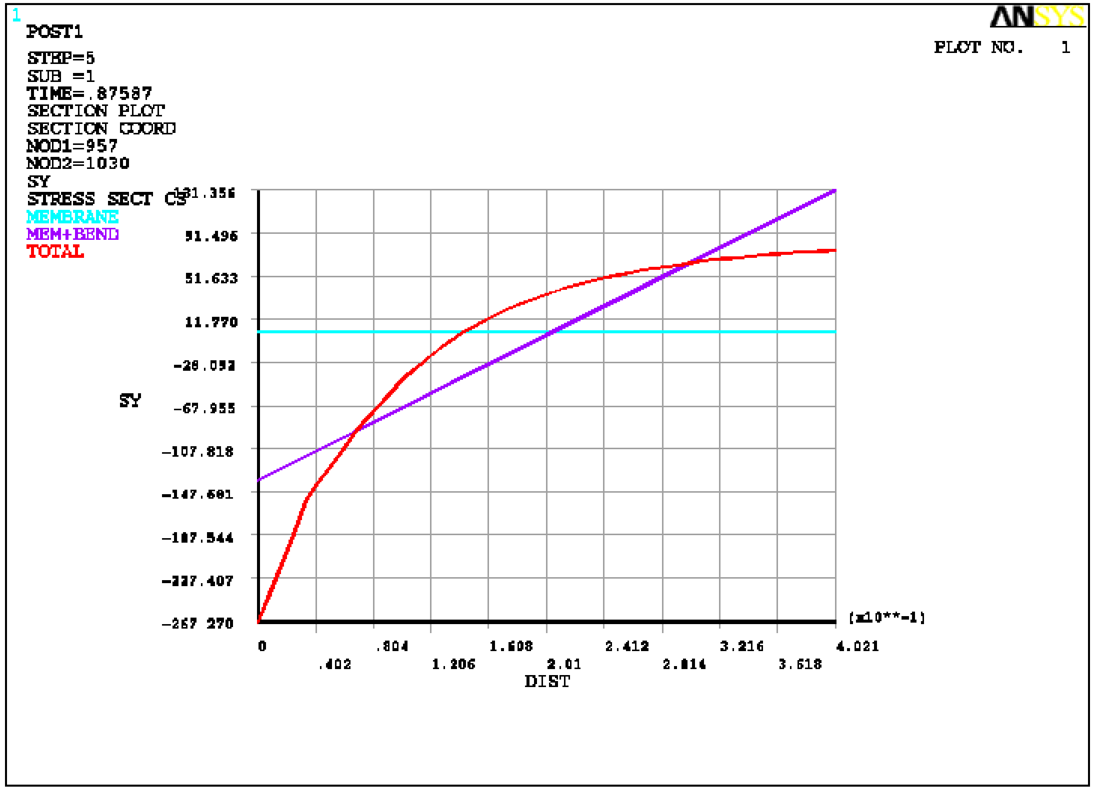
Stress Calculations (cont'd)

- Linearized stresses for static loads are scalable
  - Pressure
  - Piping interface loads (forces, moments)
- Thermal (time-dependent) stresses are calculated with Green's Functions
  - Green's Functions are simply influence functions
  - The RIS clearly states, "The Green's function methodology is not in question."

Linearized Thermal Stresses

- Requires use of appropriately conservative ratio of (P+Q) to (P+Q+F) (*analyst judgment or previously performed fatigue analysis*), OR

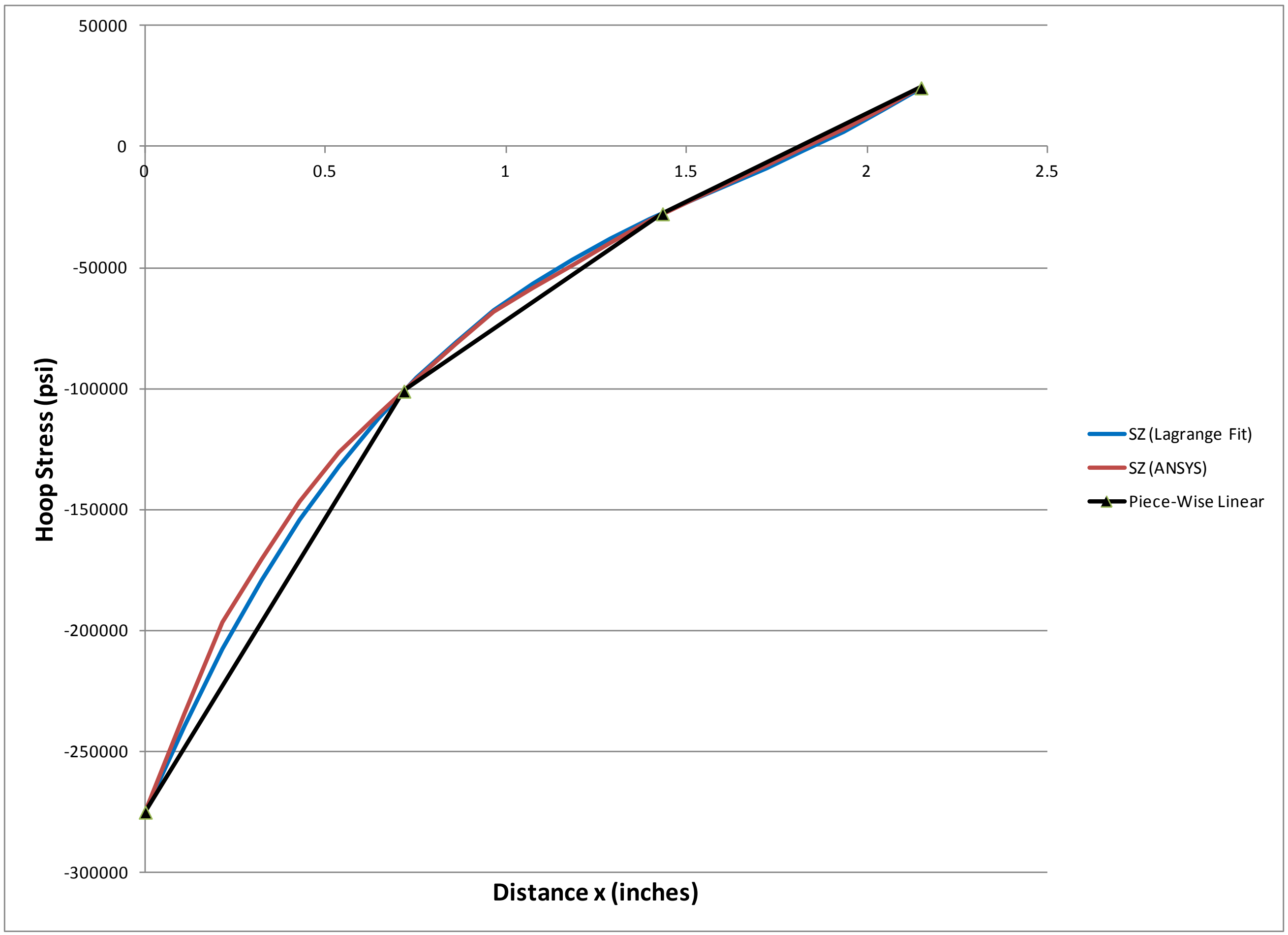
- Accurate knowledge of time-dependent, through-wall stress distribution



Implemented the latter to improve accuracy and minimize analyst judgments.

Linearized Thermal Stresses (cont'd)

- Use of either Lagrange Polynomial: $y = H_0 + H_1 x + H_2 x^2 + \ldots + H_p x^p$
- or piece-wise linear distribution



Linearized Thermal Stresses (cont'd)

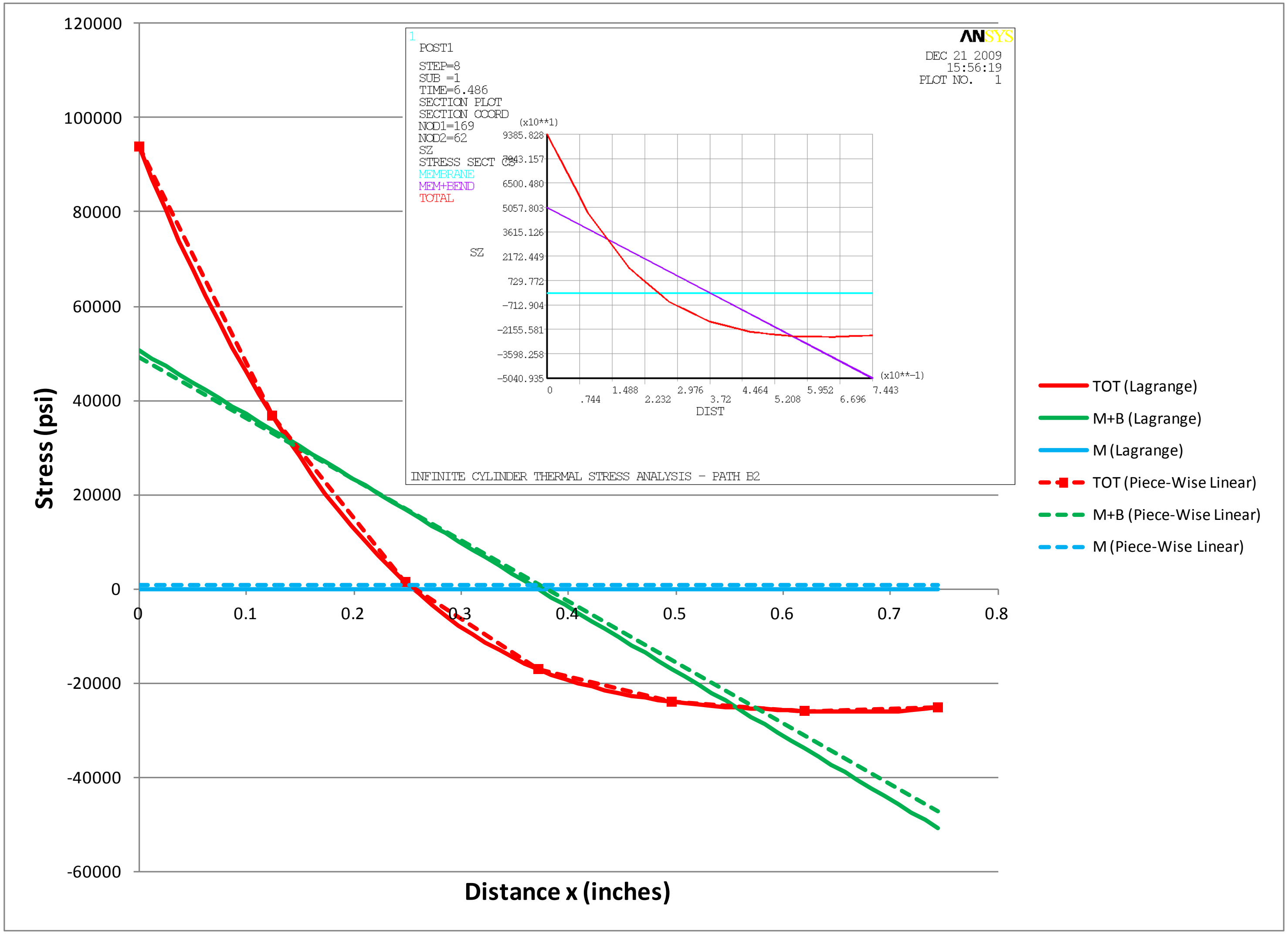
- Conventional membrane and bending stress computations.
  - "Cartesian" or generalized linearization in ANSYS
  - "Linearization for three-dimensional structures" in ABAQUS
  - Stress Linearization Procedure described in Section 5.A.4.1.2 of ANNEX 5.A of ASME Section VIII, Division 2

$$\sigma_m = \frac{1}{t}\int_0^t \sigma(x)dx$$

$$\sigma_b = \frac{6}{t^2}\int_0^t \sigma(x)\left(\frac{t}{2} - x\right)dx$$

Closed form solutions using previously determined Lagrange Polynomial

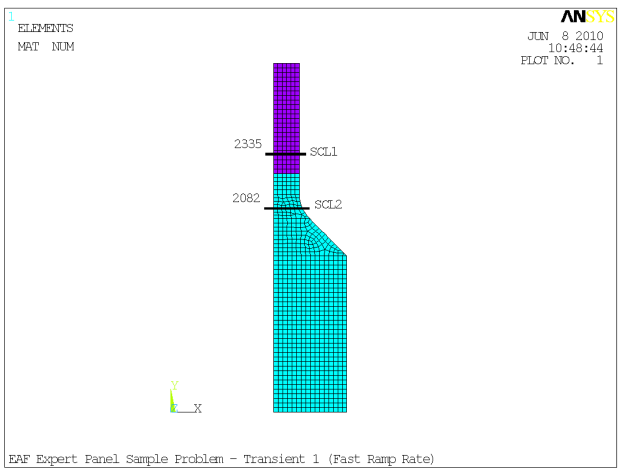
Linearized Thermal Stresses (cont'd)



Multiaxial Green's Function

Macro developed to create multiaxial Green's Function.

Includes all information necessary to compute linearized thermal stresses at a stress classification line for a given film coefficient.




```
! Created by tgilman from GRNSFN-S.rst  14:33:54
2335 ! Node 1
2327 ! Node 2
8 ! P = polynomial degree = # of thru-wall divisions
24 ! NumSet = number of time blocks in Green's Function
0 ! RSYS (results coordinate system)
1.406 ! Path Length
5.594 14 0 ! XG YG ZG (Global Coordinates Inside Node)
7 14 0 ! XG YG ZG (Global Coordinates Outside Node)
70.  653.   ! temperature range
100.   ! flow
1.E-05 ! Time
-1.817551361E-13 6.412294996E-11 1.330949231E-10 -2.133951005E-13 0 0 70
-1.182986039E-12 5.69802081E-11 1.181114205E-10 -6.42931852E-12 0 0 70
-7.523217209E-12 4.102893909E-11 8.667579707E-11 -1.237429329E-11 0 0 70
-1.092514775E-11 1.866163099E-11 5.190668012E-11 -1.527801468E-11 0 0 70
-3.111476776E-12 -7.729228141E-12 2.692269684E-11 -1.237017793E-11 0 0 70
5.560239026E-12 -1.77459226E-11 2.218901776E-11 -9.715285252E-12 0 0 70
5.860479508E-12 -3.308940149E-11 5.507489079E-12 -7.069777321E-12 0 0 70
2.858558287E-12 -4.647084963E-11 -9.696455806E-12 -3.392061972E-12 0 0 70
1.623788983E-12 -5.060145187E-11 -9.997383495E-12 2.359452966E-12 0 0 70
1.00001 ! Time
-445.518934 -84935.4003 -84453.4724 1.94566036 0 0 365.101373
-1137.78108 -12282.4275 -11023.828 1.63401116 0 0 87.3745052
-1140.6189 9149.21116 10485.4693 5.2931554 0 0 73.8726438
-835.950981 6254.25106 7352.8488 1.38770485 0 0 70.5824588
-605.695909 5927.42761 6856.73975 -21.6177287 0 0 70.0687223
-438.091397 5857.7175 6618.81317 -35.4436409 0 0 70.0040231
-287.269029 5790.13841 6400.45774 -33.2671749 0 0 70.0008471
-144.514695 5709.609 6195.58535 -19.6472641 0 0 70.000149
-1.11428874 5601.04792 5998.10791 0.857158159 0 0 70.0000296
1.99945 ! Time
-544.856995 -116254.633 -115319.552 0.924715645 0 0 443.847375
-1776.87995 -24480.513 -22233.6017 -32.6231612 0 0 136.819644
-1879.19238 8247.95241 10685.0167 -44.7392203 0 0 81.5690501
```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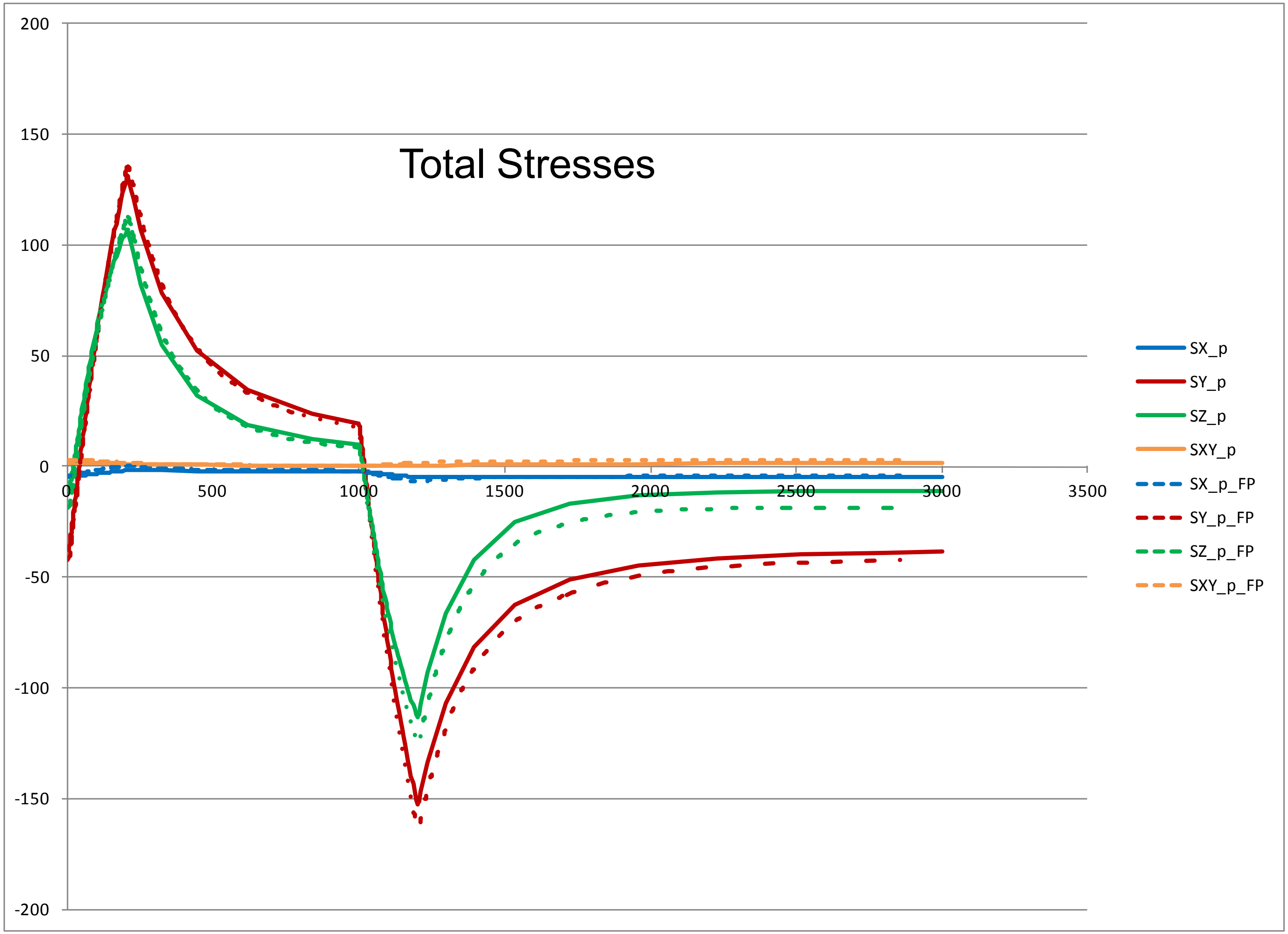
Computation of Primary Plus Secondary and Total Stresses

- Pressure, piping interface, and other “static” loads added together by scaling to pressure, temperature, etc.
  - M+B and Total
- Through-wall time-dependent thermal stresses computed using Green’s Functions
  - All six M+B components computed based on through-wall distributions
- Fatigue strength reduction factors applied on M+B stresses, as appropriate
- Thermal peak is superimposed after the FSRF/SCF is applied.
- Same methodology implemented as in the EPRI EAF Expert Panel sample problem.

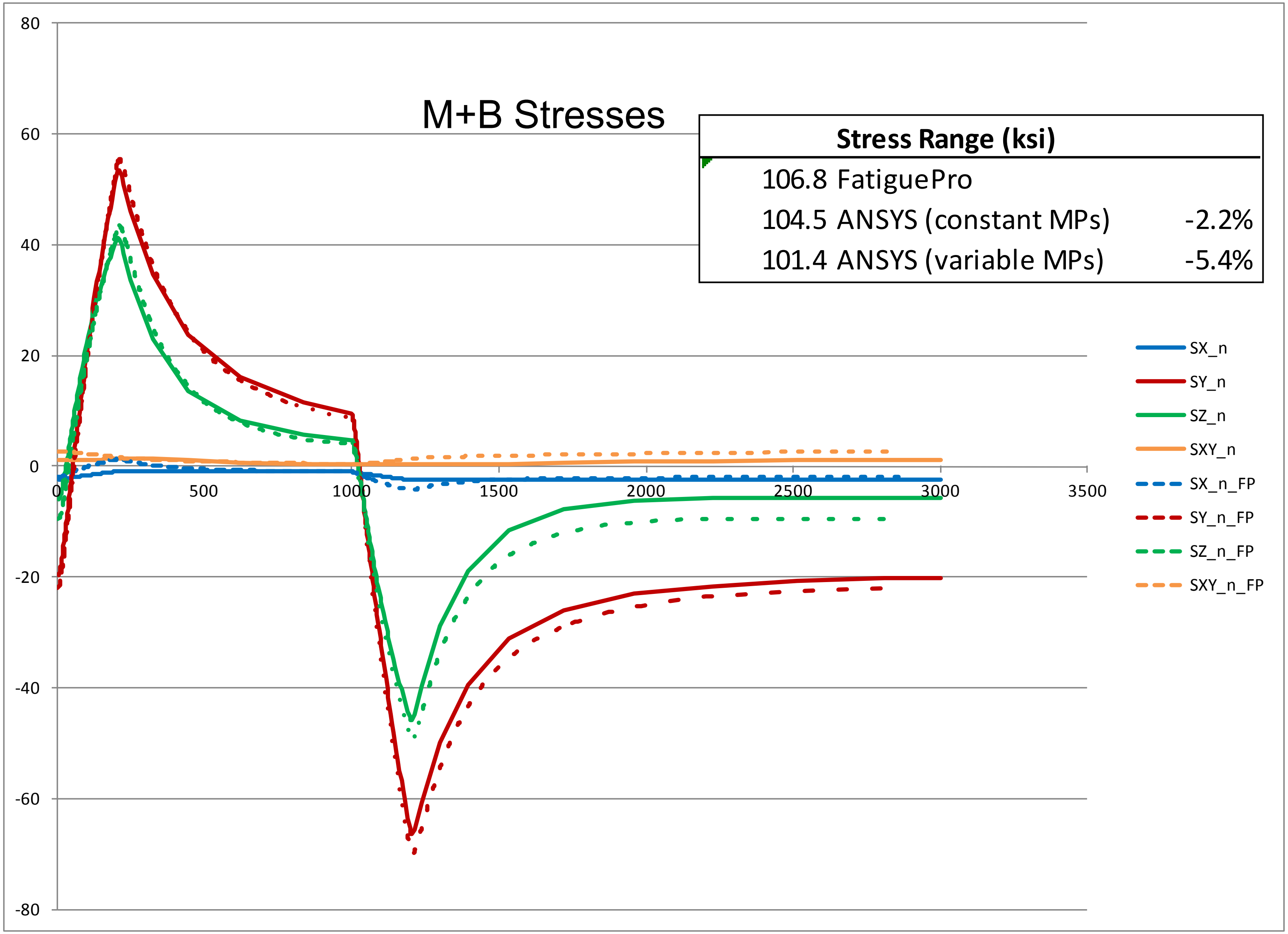
Benchmark of Stress Calculations

- Sample problem from EPRI's EAF Expert Panel performed
- Comparisons made to values computed with ANSYS using temperature-dependent material properties.
  - Total stress
  - Membrane plus bending stress
  - Temperature

Benchmark of Total Stresses

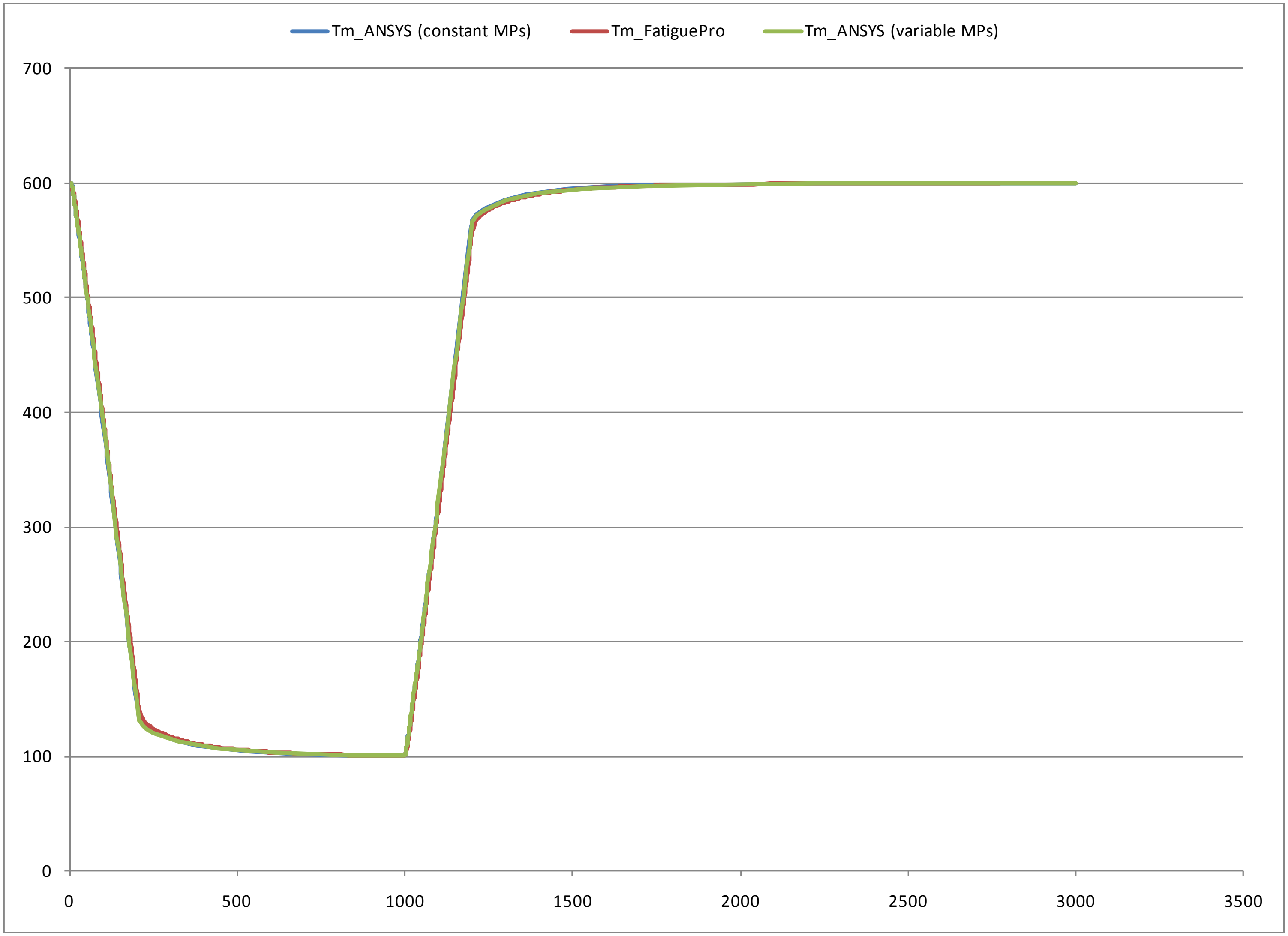


Benchmark of Linearized Thermal Stresses



Stress Range (ksi)		
106.8	FatiguePro	
104.5	ANSYS (constant MPs)	-2.2%
101.4	ANSYS (variable MPs)	-5.4%

Benchmark of Metal Temperature Calculations



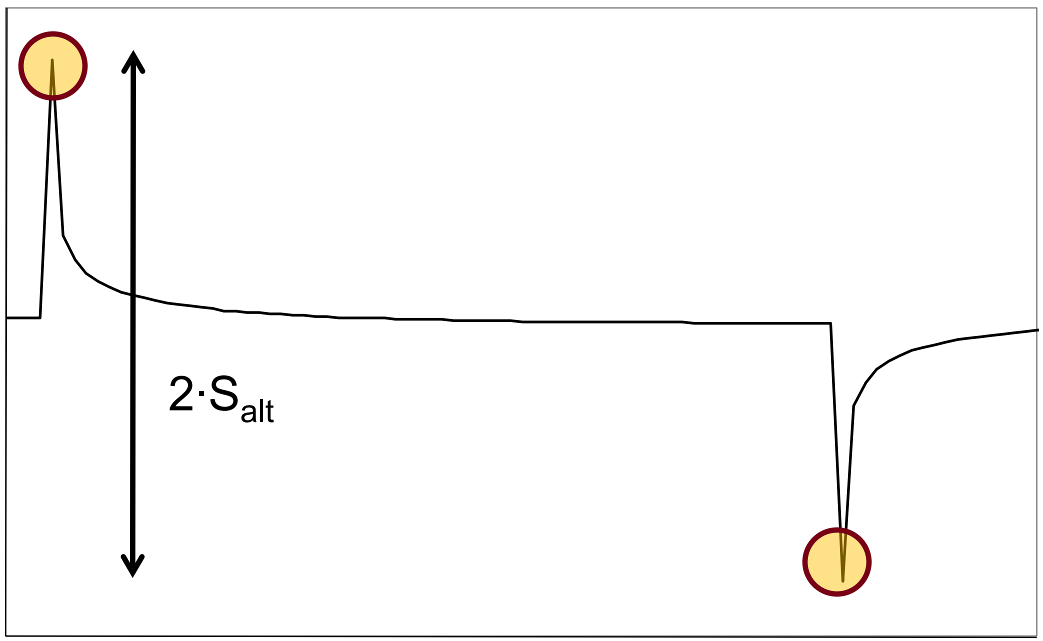
Stress Cycle Counting
Design vs. Monitoring

- Design Assumptions
  - Idealized transient definitions
  - Maximum number of cycles
  - Cycles postulated to occur in <u>worst-possible</u> order
- Monitoring
  - Real data
  - Typically less severe stress ranges, but increased complexity
  - Cycles are known to occur in <u>actual order</u>

Taking order into account using all six stress components and other ASME Code rules requires a non-trivial solution!

Idealized ASME "Stress Cycle"

"… a condition where the alternating stress difference [NB-3222.4(e)] goes from an initial value through an algebraic maximum value and an algebraic minimum value and then returns to the initial value."



An "operational cycle" can contain multiple stress cycles.

Stress Cycles
Traditional Design Analysis Example

Transient order unknown
Local extreme stress conditions (peaks or valleys) assumed to pair in worst-possible order.

Stress Cycles Monitoring Example

- Local extreme conditions evaluated in known order.
- One large stress reversal with multiple internal cycles.
- Factor of 10 (possibly more, depending on analyst judgment) difference using known order.

Sp	Ke	Salt	n	Nallow	U
200	3.333	333.3	1	54.47	0.01835873
50	1	25	18	1481072	1.21534E-05
				CUF =	0.018

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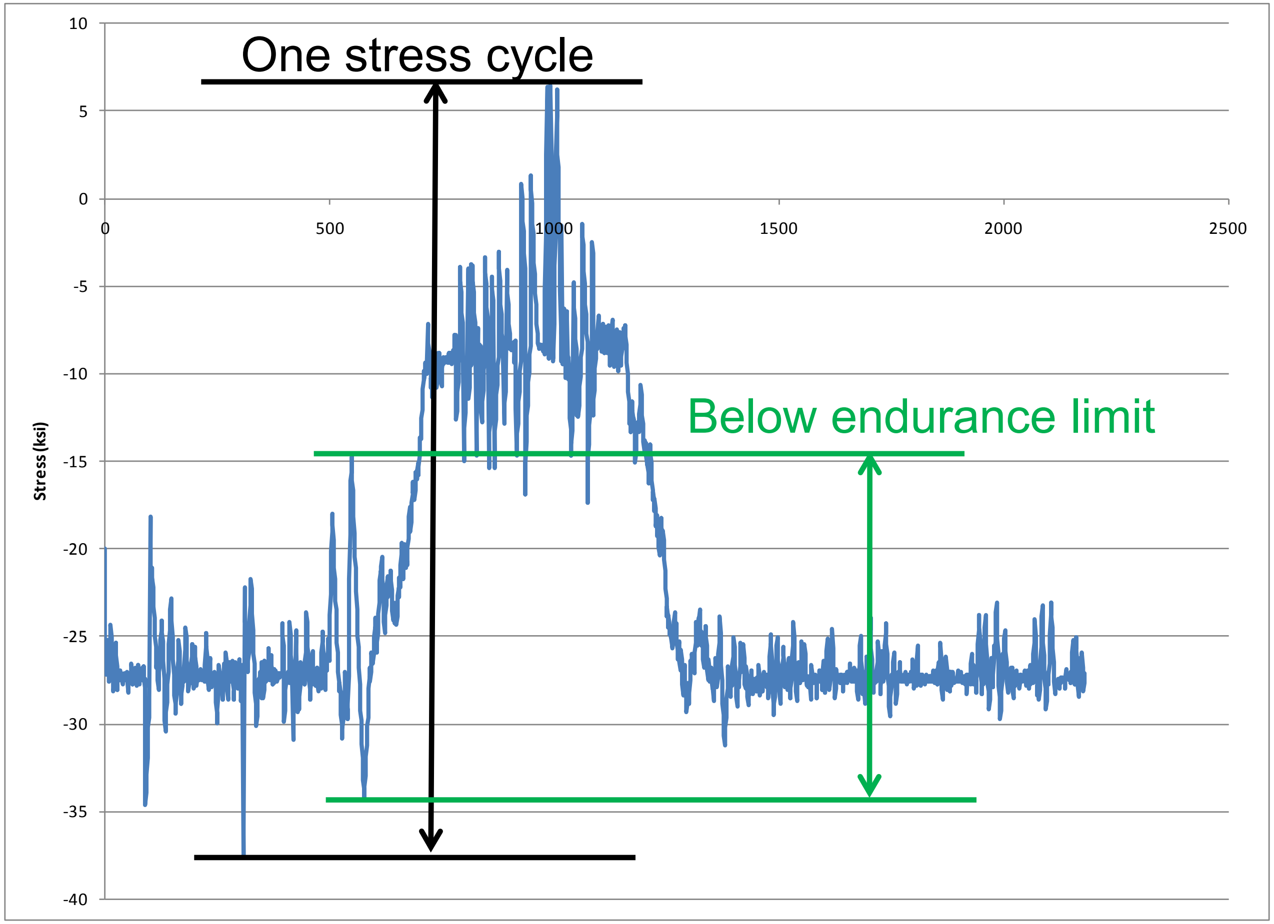
Stress Cycle Monitoring Example

Fact: Fatigue is path (order) dependent!

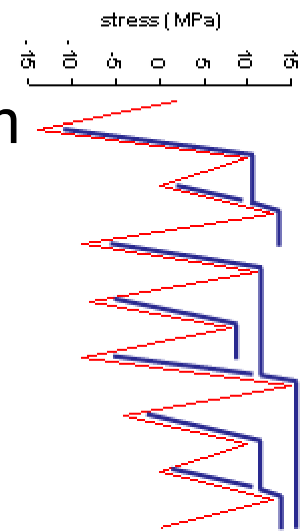


Counting Ordered Stress Cycles Using Single Stress Term

- Fatigue damage under random loading studied extensively in auto and aerospace industries.
- Several methods are available:
  - Range-pair
  - Rainflow
  - Ordered Overall Range (OOR)
- These different numerical methods produce essentially the same results.
- These methods are generally limited to single stress term using conventional algorithms.

Rainflow Algorithm

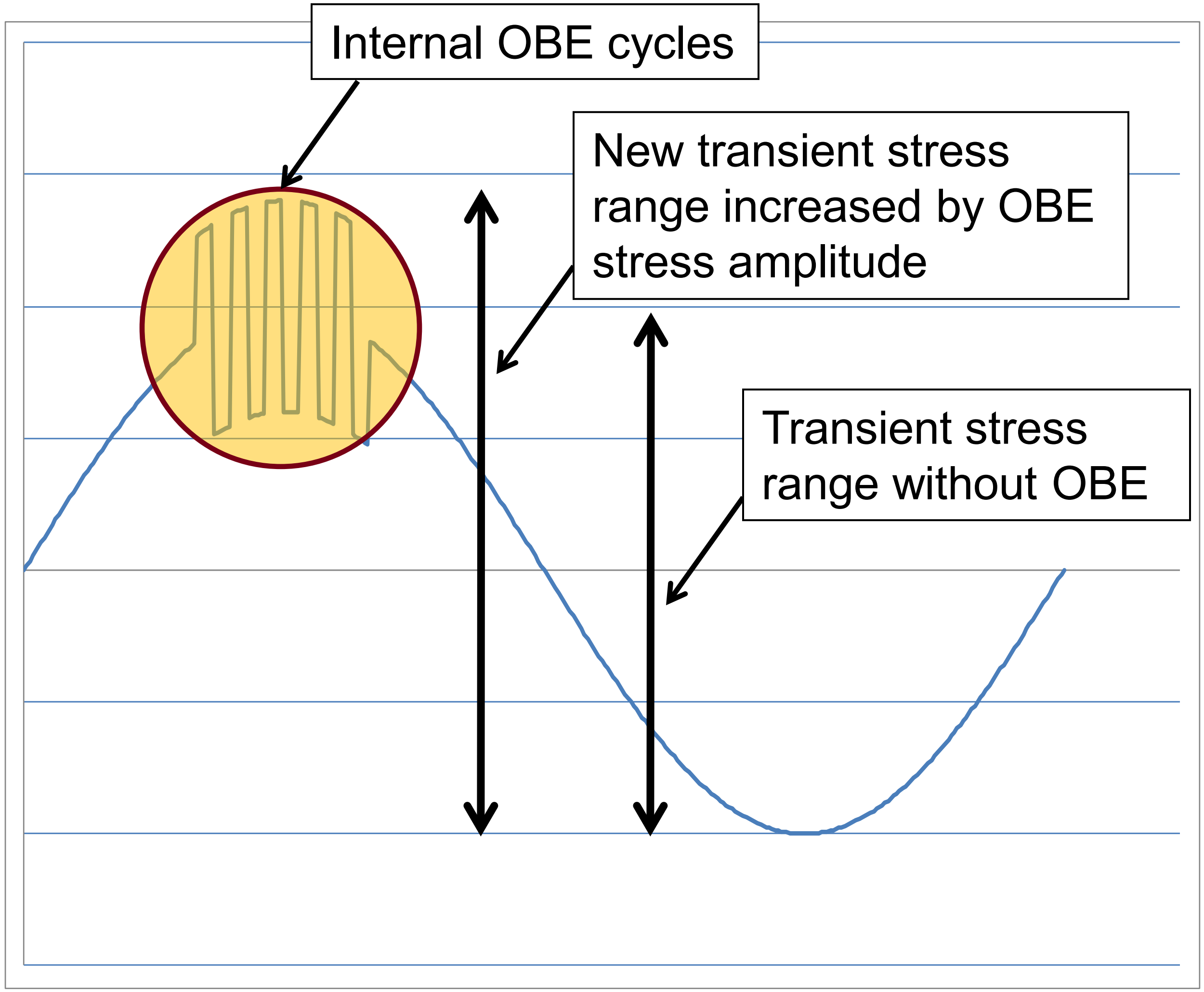
- Simplified Rainflow Cycle Counting Method documented in ASTM Standard No. E1049 (Reapproved 2005). *Standard practices for cycle counting in fatigue analysis*.
- ASME Section VIII Division 2 Annex 5.B (non-mandatory guidance).
- Peaks imagined as source of water that "drips" down a pagoda roof.
- Conventional algorithm uses single stress term
- Proportional loading



Order Dependence in ASME Code

ASME Code does not prohibit consideration of order. Methods for handling seismic events reflect order dependence.

Transient pair stress range increased by OBE stress amplitude. Remainder are internal (self) cycles.



The Multiaxial Challenge

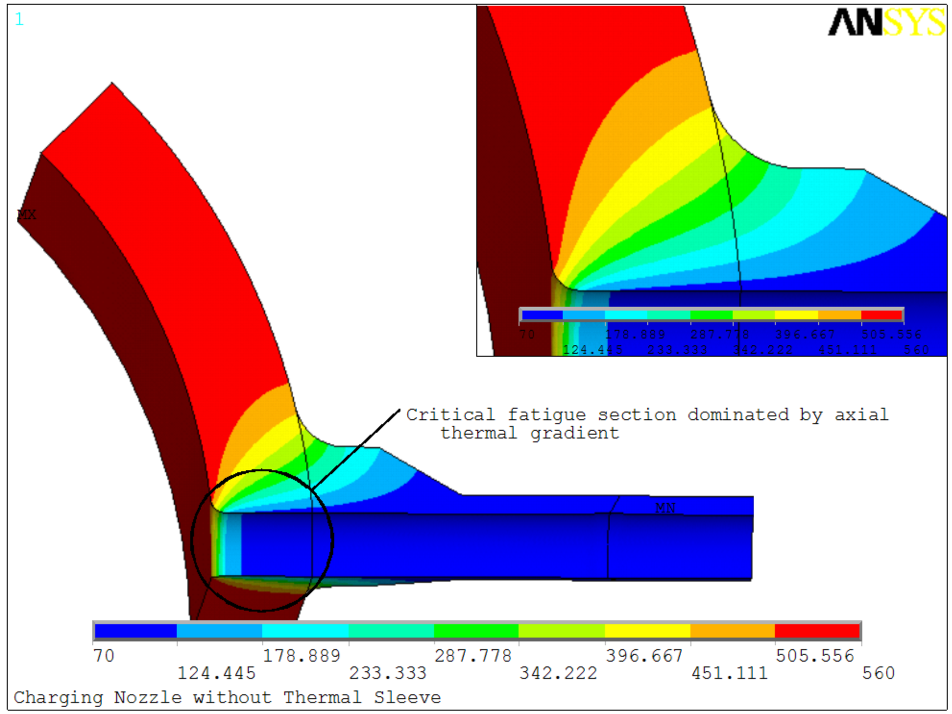
How to account for ordered stresses while meeting requirements and intent of ASME Code?

> *"In most cases it will be possible to choose at least one time during the cycle when the conditions are <u>known to be extreme</u>. In some cases it may be necessary to try different points in time to find the one which results in the largest value of alternating stress intensity."*

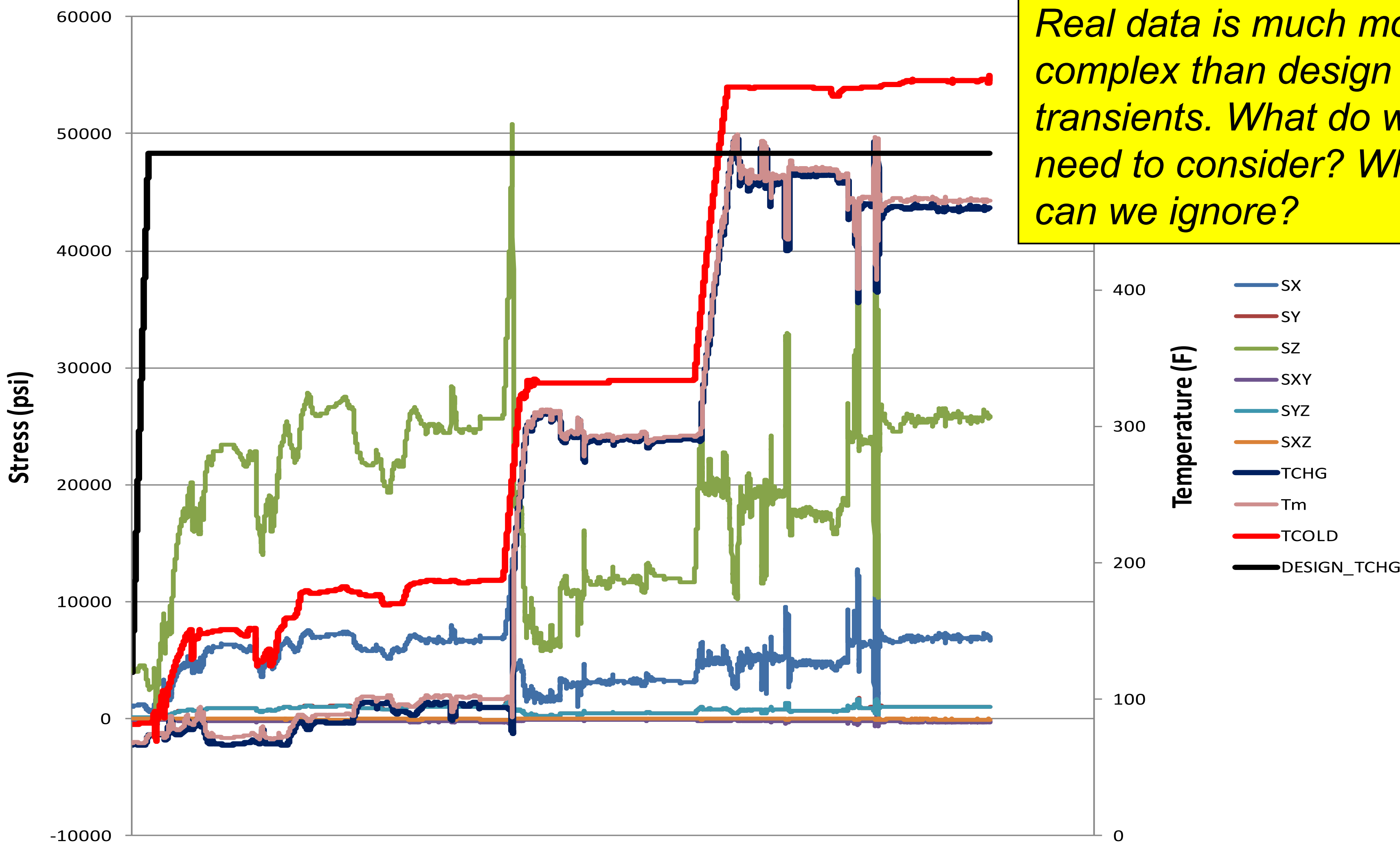
- NB-3216.2 provides guidance in computing stress intensity difference when normal and shear stresses may vary arbitrarily, and the "stress cube" that determines principal stresses may rotate.
- Challenge: SI between two points in a cycle is not equal to the stress intensity difference, which is determined based on the difference of the 6 individual stress components in going from one cycle to another.

Example - Charging Nozzle

- High steady state thermal gradient during cold injection.
- Difficulty with "design" type stress cycle pairing illustrated with complexity of real data.



Charging Nozzle – Plant Heatup



Real data is much more complex than design transients. What do we need to consider? What can we ignore?

Solution Alternatives

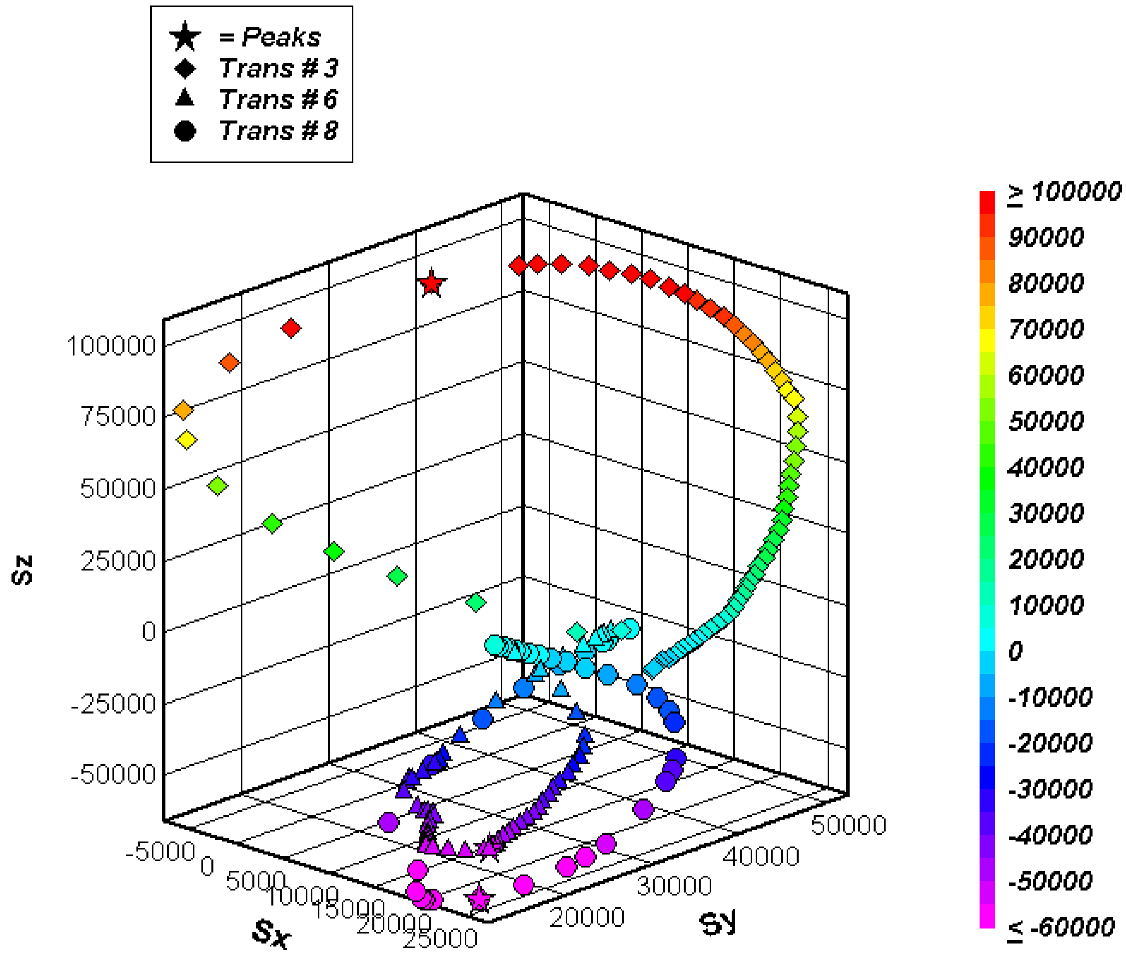
- A solution to the problem requires two important steps.
  - Multiaxial peak and valley detection logic
  - Multiaxial stress cycle pairing logic
- Several options investigated for each.
- Used together, “Rubberband” and “Rainflow-3D” produced best results across many test cases.

Criteria for Selection of Algorithm
How do we know what's right?

- When simulated in the same order, we should reproduce known problems from ASME NB-3200 design calculation examples (benchmarks for accuracy)
- Assuming a uniaxial stress with random, ordered loading, we should with our algorithms identify the same stress cycles as that from heavily vetted algorithms such as Rainflow (validation of sound engineering principles)
- Analyst judgments and manual adjustments to the stress cycle counting should not be necessary to produce consistently meaningful results (repeatability of results)

Peak/Valley Detection – "Rubberband"

- Detects points of maximum distance from the previous possible extrema.
- Looks for SI range to increase from previous extrema to a given threshold and then decrease to another threshold to identify a new extrema.
- Range varies in multiple dimensions.
- Filters out insignificant reversals well below the endurance limit
- Range of time included for each



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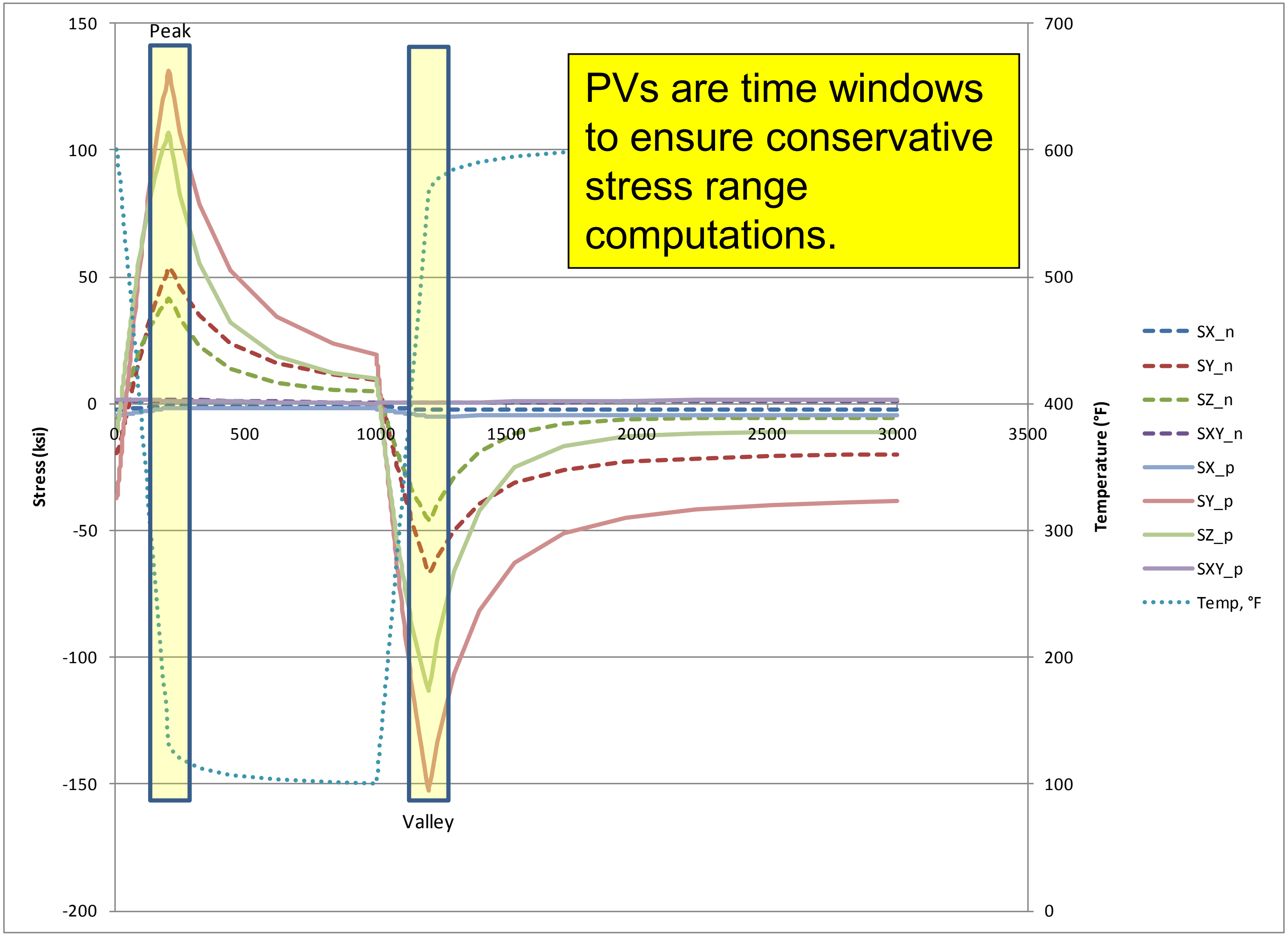
Peak/Valley Detection – "Rubberband"



"Rubberband" Addresses General Concern in NRC RIS 2011–14 (December 29, 2011)

"Although this method of analyst intervention [*manual modification of peaks and valleys*] could provide acceptable results in some cases, reliance on the user's engineering judgment and ability to modify peak and valley times/stresses, without control and documentation, could produce results that are not predictable, repeatable, or conservative."

- By taking order and multiaxial stress range into account, manual peak and valley adjustment is not required.
- Process is predictable, repeatable and conservative.

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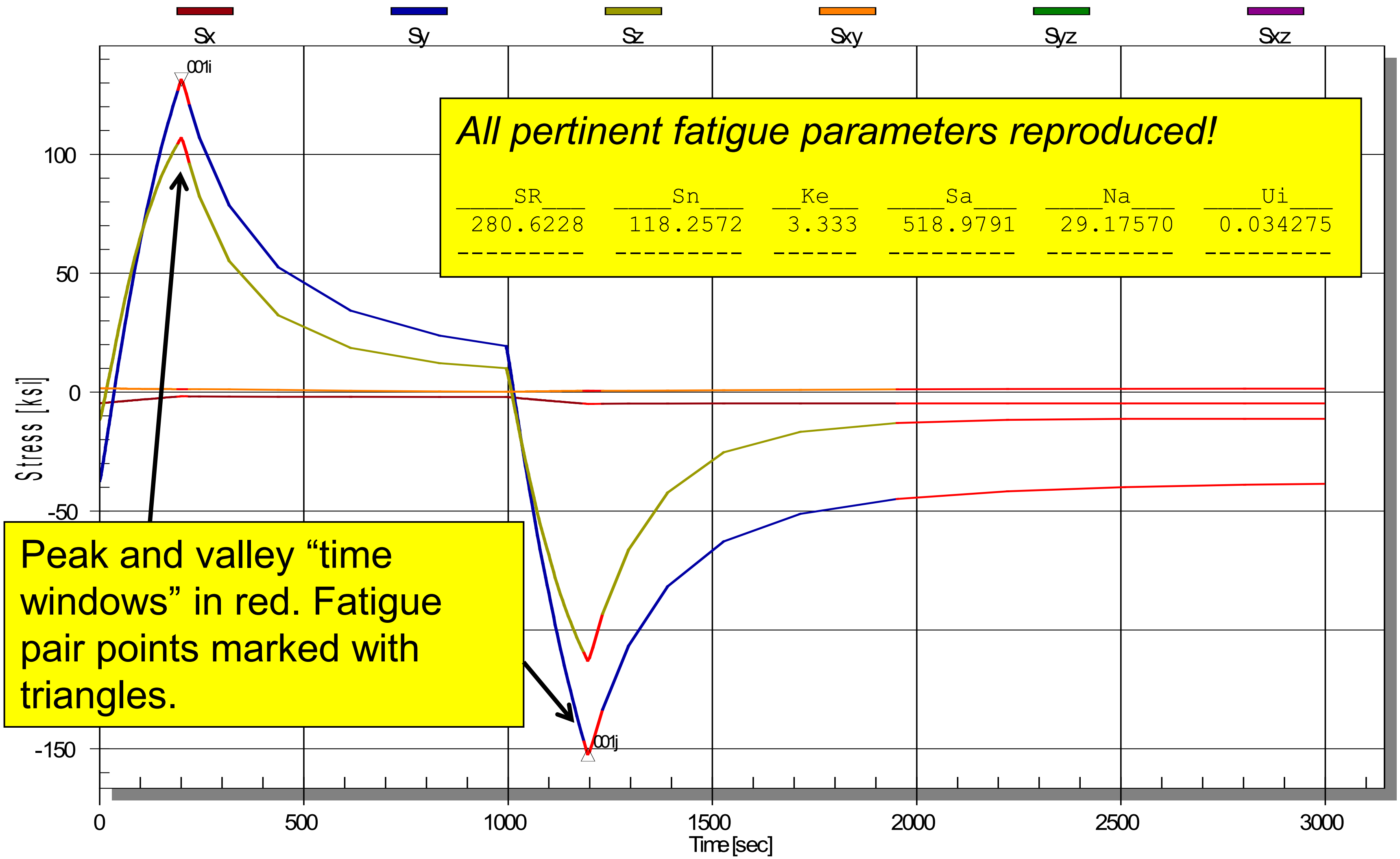
Pairing Logic – "Rainflow-3D"

- Conventional Rainflow algorithm implemented, but with following differences
  - SI range is computed between local extrema based on all six components of stress (instead of the algebraic difference in two values)
  - Each extrema contains at least one time point and likely represents a time window of more than one point.
  - Most conservative range pair selected based on combination of stress range, K_e (function of primary plus secondary stress intensity range) and the elastic modulus ratio.

Example – EAF Sample Problem Transient 1 – SCL 1

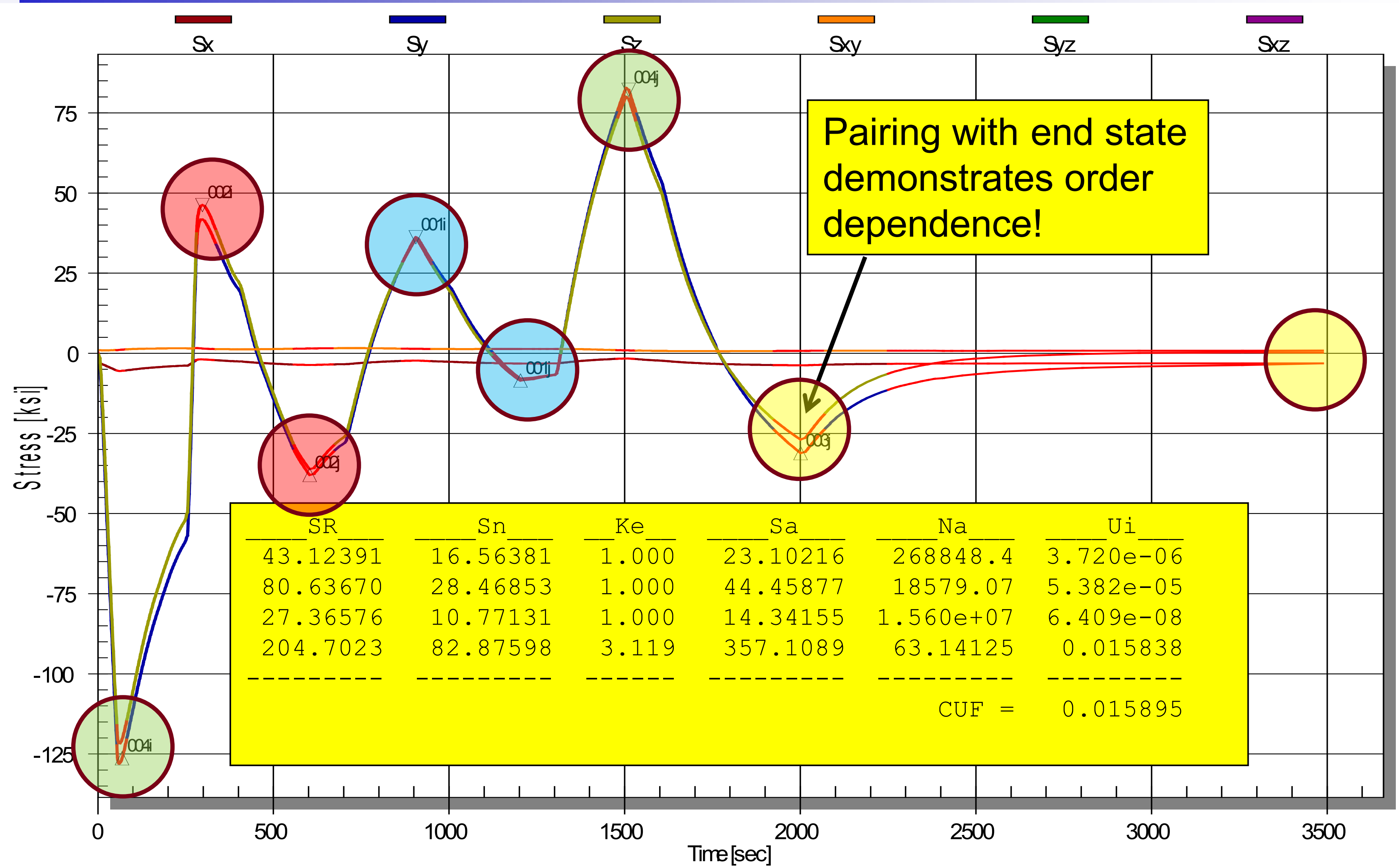


All pertinent fatigue parameters reproduced!

SR	Sn	Ke	Sa	Na	Ui
280.6228	118.2572	3.333	518.9791	29.17570	0.034275

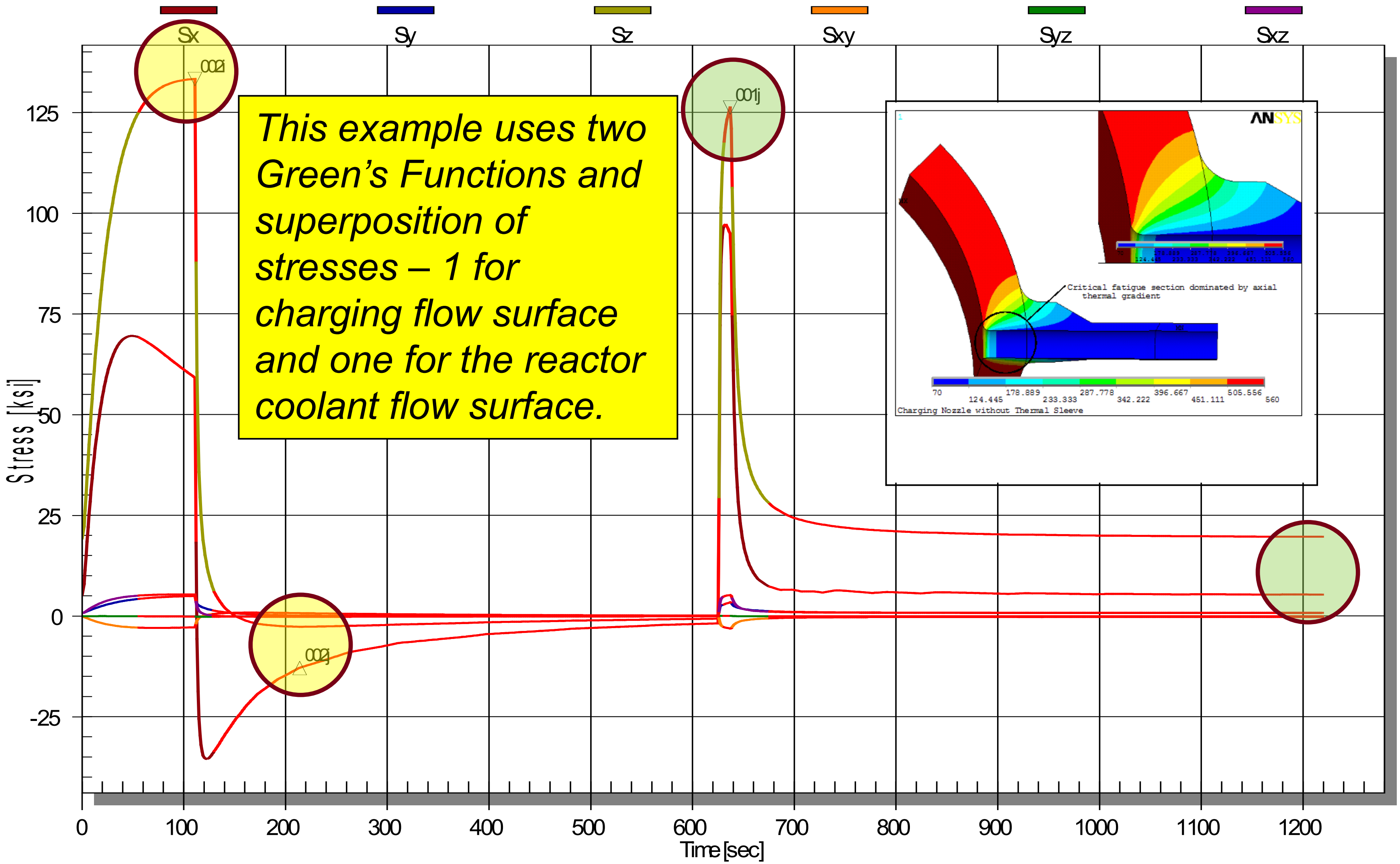
Peak and valley "time windows" in red. Fatigue pair points marked with triangles.

Operational Cycle with Multiple Stress Cycles

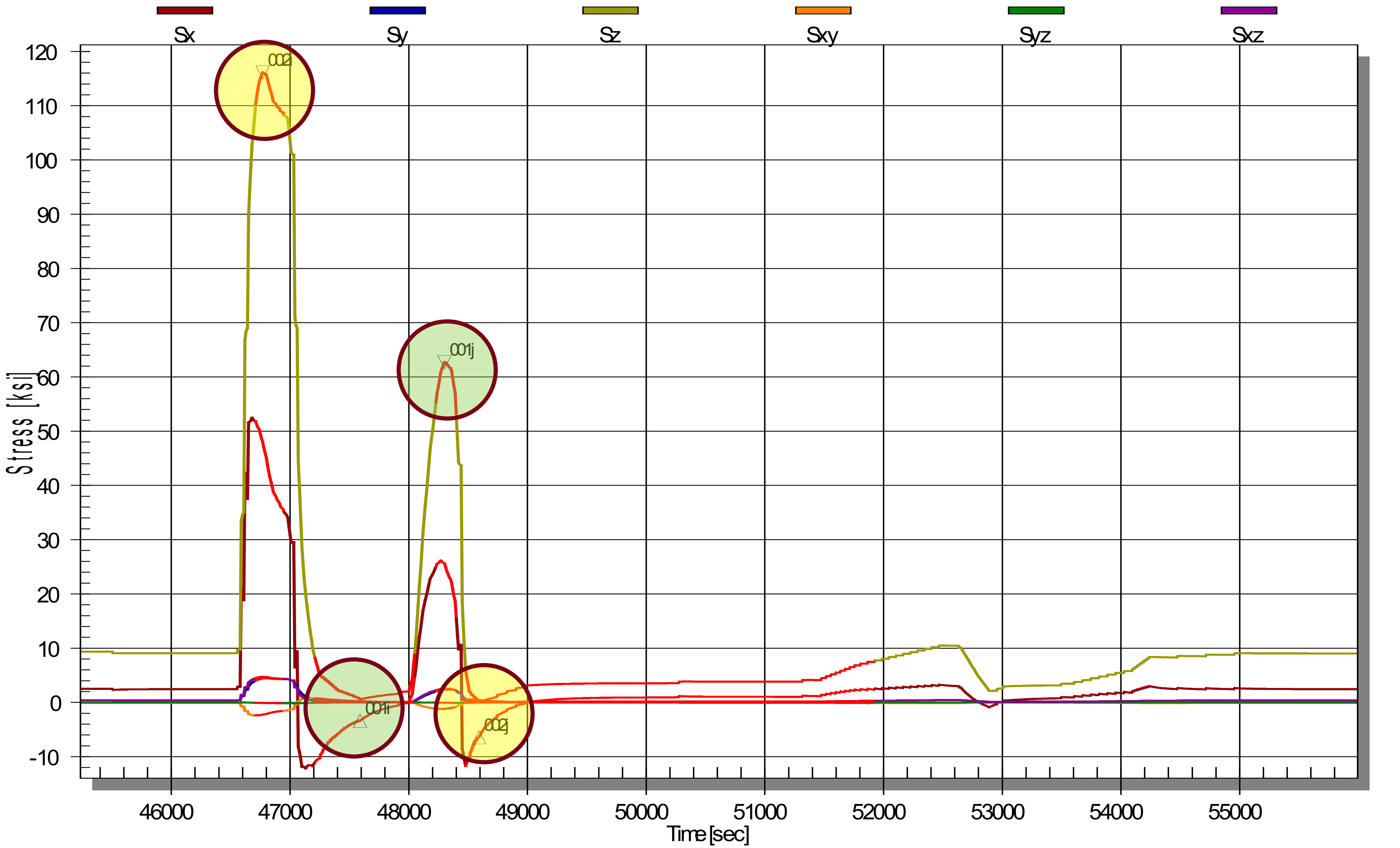


SR	Sn	Ke	Sa	Na	Ui
43.12391	16.56381	1.000	23.10216	268848.4	3.720e-06
80.63670	28.46853	1.000	44.45877	18579.07	5.382e-05
27.36576	10.77131	1.000	14.34155	1.560e+07	6.409e-08
204.7023	82.87598	3.119	357.1089	63.14125	0.015838
				CUF =	0.015895

Charging Nozzle – Simulated Loss of Letdown with Delayed Return to Service



Charging Nozzle – Multiple Letdown Trips



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Environmentally-Assisted Fatigue

- Methodology takes guidance from EPRI's EAF Expert Panel recommendations.
- Panel has reached general consensus on computation of strain rate using multiaxial stresses.
- Generally consistent with proposed Code case on strain rate (ASME Record No. 10-293) – ASME Code Case N-792-1

EAF Highlights

- Support rules of NUREG/CR-5704 / 6583 / 6909
- Computations at each time step:
  - Strain increment and strain rate
    - Auto determination of whether increasingly tensile or compressive, based on largest absolute value principal stress of the stress differences
    - Possible inclusion of K_e strain rate can reduce conservatism > 25% (not currently allowed in MRP-47 Rev. 1 or Japanese Code)
  - F_{en} as a function of:
    - Current service temperature
    - Computed strain rate
    - Dissolved oxygen level via user-input time history or direct instrumentation
    - Other user inputs (sulfur content, etc.)

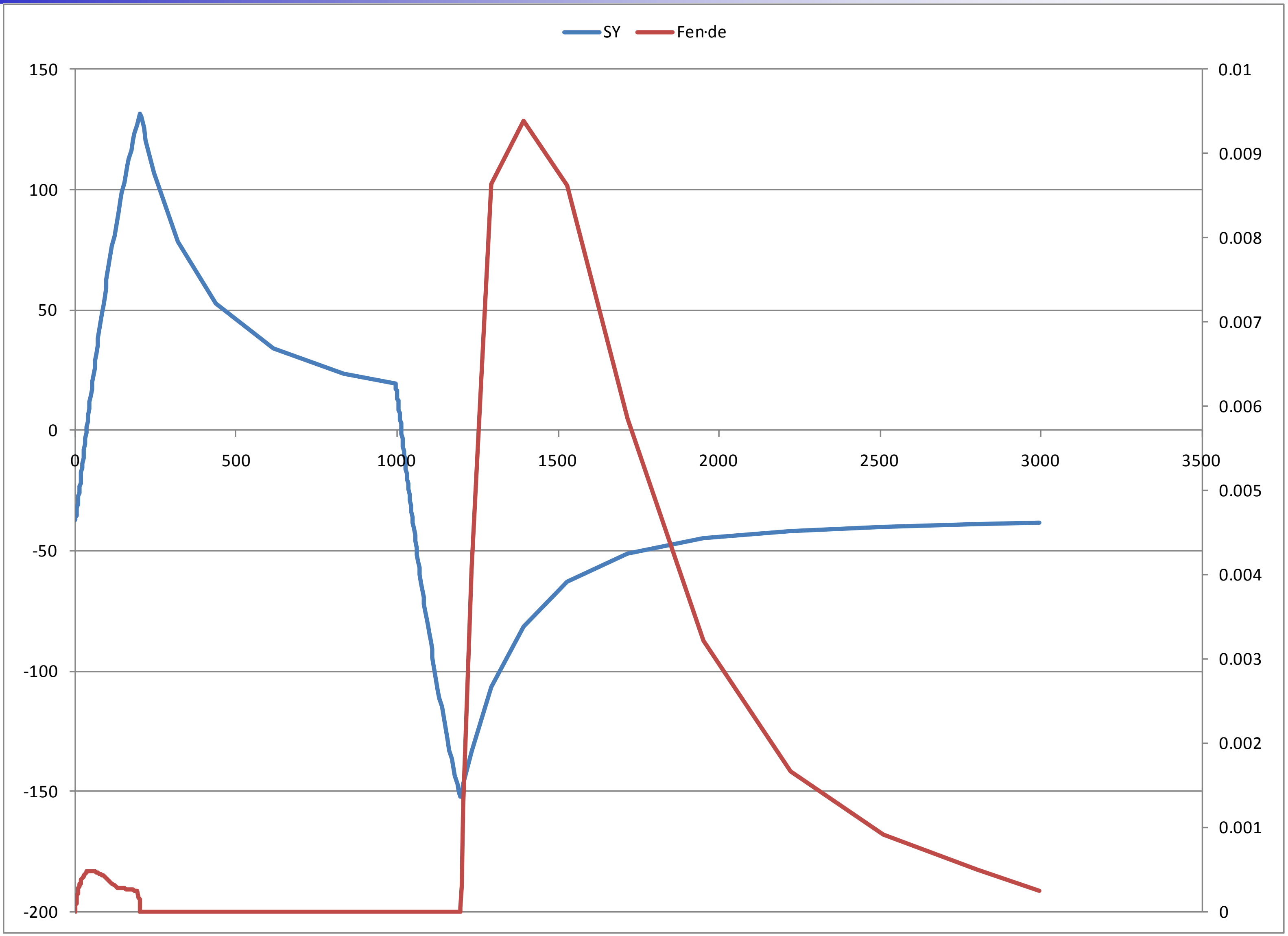
$$F_{en} = \frac{\sum F_{en,i} \Delta \varepsilon_i}{\sum \Delta \varepsilon_i}$$

- F_{en} for each stress cycle
  - Integration (modified rate) approach

EAF Sample Problem Calculation

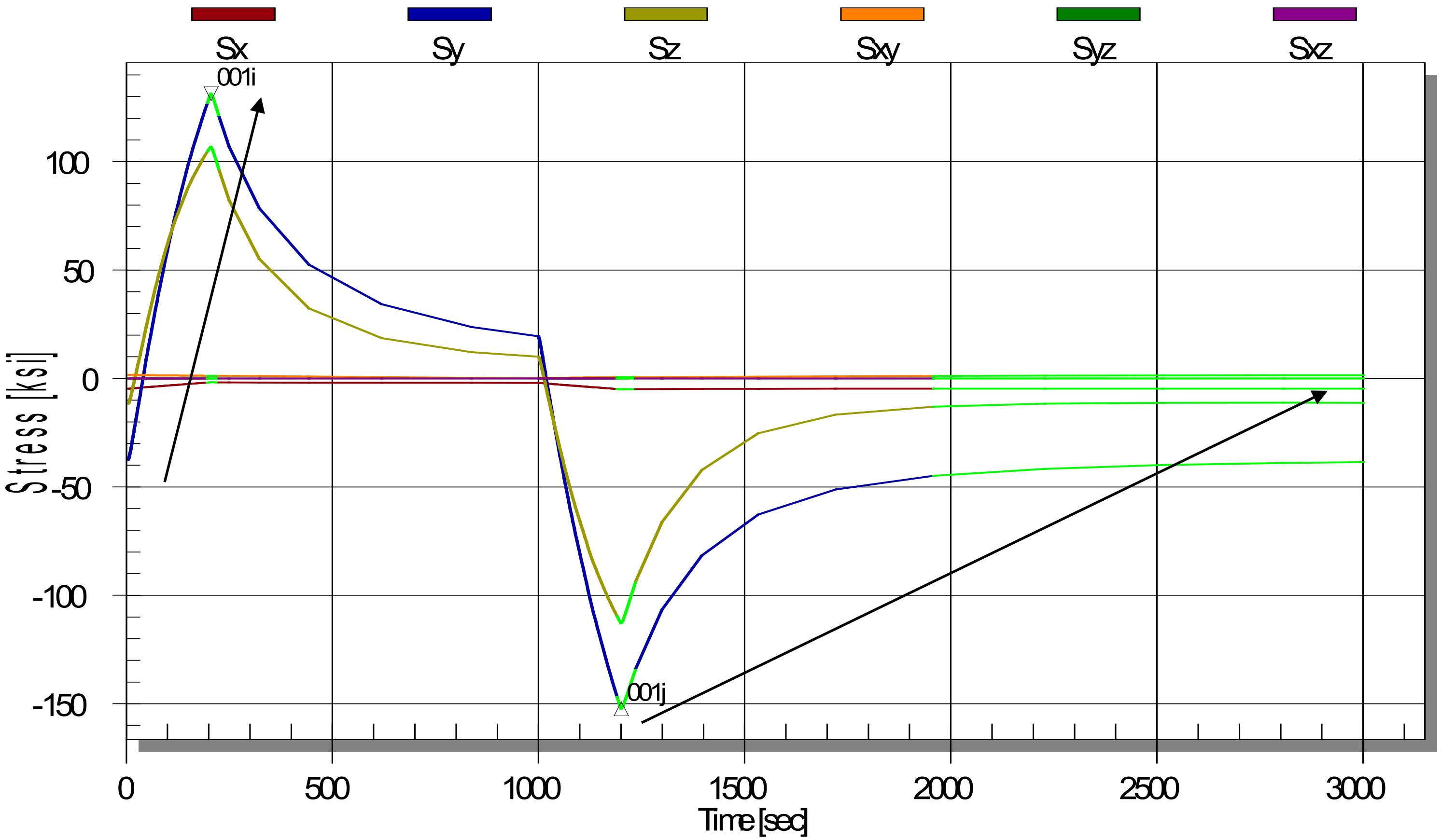
EAF Sample Problem Calculation

EAF Sample Problem Calculation

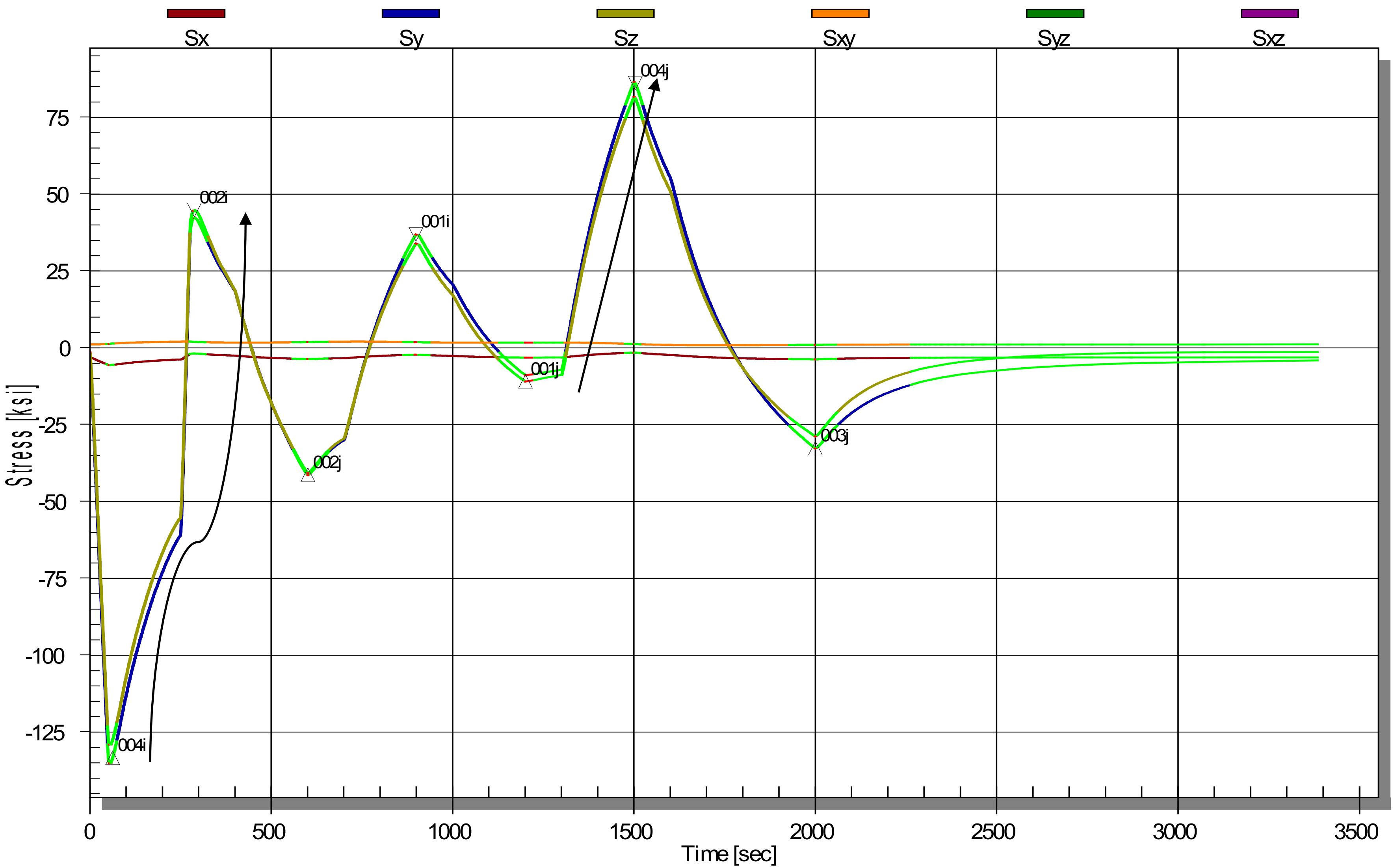


Bounds of F_{en} Integrations

- Integrates from Valley to its adjacent Peak and to Peak from its adjacent Valley



F_{en}'s for Complex Stress Cycling



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Conclusions

- Overall methodology combines many proven practices
- Basic steps in the process include:
  - Multiaxial stress calculations
    - Address NRC RIS 2008-30
    - Accurate knowledge of through-wall distributions
  - Smart Peak/Valley Detection and Stress Cycle Counting
    - Rubberband (detects reversal regions using multiaxial stress range criteria)
    - Rainflow-3D (identifies stress cycles)
  - Calculation of EAF
    - Meets GALL requirements
    - Implements Expert Panel guidance

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Questions and Comments

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