Nastran Embedded Fatigue

Heavy Duty Truck Cab Applications & Evaluations

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Introduction

project overview
Navistar

- Heavy duty vehicle manufacturer
  - Trucks
  - Buses
  - Recreational Vehicles
  - Defense Vehicles
  - Engines

- Simulation Critical Applications
  - optimal designs
  - reduced testing
  - faster time to market
  - innovation
• Consulting Services

• 1999 Study in Best Practices
  – Model Based Product Development (MBPD) Initiative
  – evaluate all possible approaches to fatigue analysis
    • weigh expense vs. accuracy
  – recommend best practice
  – establish methodological foundation for future fatigue simulations
Historical Conclusions

- **Modal Superposition**
  - new method established
    - tested & validated
  - accounts for most physics
    - transient inertial effects
    - time history cycles
  - most analogous with shaker test

- **Other Methods**
  - less efficient
  - less accurate
  - more cumbersome
Introduction

quick fatigue overview
Fatigue Overview

component subjected to complex loading

$P_1(t)$

$P_2(t)$

Fatigue
Fatigue Overview

cyclic testing to obtain fatigue material curve (S-N, e-N)
Fatigue Overview

- **Similitude**
  - The life estimated in the test sample will coincide with those seen in a true component
  - Palmgren-Miner Damage Summation
    - \( n/N = \text{damage} \)
Introduction

What is Nastran Embedded Fatigue
What is NEF

• **NEF = Nastran Embedded Fatigue**

• **Fatigue solver embedded directly into the fea tool**
  – stress extraction transparent to user

• **Two approaches evaluated here**
  – Quai-Static
    • SOL 101
  – Modal Transient
    • SOL 112
What is NEF

• Three Components of Fatigue
  – Stress State
  – Load History
  – Materials (Life Curves)

• Historically each is handled completely separately
  – differently sourced
  – associated manually in the fatigue tool

• Stress State Recovery is the Most Challenging Component
  – NEF integrates full fatigue life prediction capability inside the most well established and trusted stress recovery tool
Embedded vs. Unembedded

**Embedded**
- single source for all components
  - stress, load, & material
  - absolute minimal manual management
- accurate & efficient stress recovery
- unified domain expertise
- cross communication efficiency

**Unembedded**
- multiple sources for each component
  - extensive manual file management
  - potential for error
- less efficient
- potentially less accurate
- separate domain experts
Model Summary

physical test
Physical Test

Shaker Stand

Standard Industry Setup
• accelerated road data

Multiple Events
• forming a complex duty cycle

Four Input Locations
• cab mounts at frame interface
General Loading

Loading Summary

Input
- 4 mount locations
- 3 axes per mount (x,y,z)
- 12 total inputs

Time Histories
- 11 events
- 12 inputs per event
- 132 total time histories

Data Points
- 620 s total duration
- 512 points per second
- 12 histories per event
- 3,802,280 total data points
# Duty Cycle

## Load Combination

### Duty Cycle
- 11 events
- 58 minutes total
- 1197 equivalent miles

### Goal
- 300,000 miles
- 250.6 repetitions of the duty cycle
- 242 hours (10.1 days)
- visual inspection following each duty cycle

<table>
<thead>
<tr>
<th>Event #</th>
<th>Name</th>
<th>Description</th>
<th>Duration (s)</th>
<th>Repeats</th>
<th>Total Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ea10</td>
<td>Empty Abbreviated Belgian Blocks at 10 mph</td>
<td>38.0</td>
<td>4</td>
<td>152.0</td>
</tr>
<tr>
<td>2</td>
<td>egvl</td>
<td>Empty Gravel Road</td>
<td>14.0</td>
<td>3</td>
<td>42.0</td>
</tr>
<tr>
<td>3</td>
<td>er20</td>
<td>Empty Railroad Crossing at 20 mph</td>
<td>6.0</td>
<td>3</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>er30</td>
<td>Empty Railroad crossing at 30 mph</td>
<td>6.0</td>
<td>3</td>
<td>18.0</td>
</tr>
<tr>
<td>5</td>
<td>lp10</td>
<td>Loaded Primary Belgian Blocks at 10 mph</td>
<td>96.0</td>
<td>5</td>
<td>480.0</td>
</tr>
<tr>
<td>6</td>
<td>lp12</td>
<td>Loaded Primary Belgian Blocks at 12 mph</td>
<td>58.0</td>
<td>29</td>
<td>1682.0</td>
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<td>7</td>
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<td>378.0</td>
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<td>3</td>
<td>18.0</td>
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<td>Loaded Railroad Crossing at 30 mph</td>
<td>6.0</td>
<td>3</td>
<td>18.0</td>
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<tr>
<td>10</td>
<td>ls20</td>
<td>Loaded Supplemental Course at 20 mph</td>
<td>34.0</td>
<td>2</td>
<td>68.0</td>
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<tr>
<td>11</td>
<td>nois</td>
<td>Shaped Noise</td>
<td>302.0</td>
<td>2</td>
<td>604.0</td>
</tr>
</tbody>
</table>
Model Summary

analysis
Capturing the Physical Test

- Extensive Volume of Data
- Balance Accuracy & Efficiency
  - solution time
  - disk space
  - manual management
    - traceability
FEA Entity Summary

Entity List

FEA
- 91,783 elements
  - 85,491 quads
  - 6,033 tri’s
  - 17 bars
  - 234 springs
  - 8 lumped masses
- 96,793 nodes
- 580,758 dof
Model Summary

common components
Common Inputs Across Analyses

• Fatigue Consists of three fundamental inputs
  – stress state
  – load history
  – fatigue materials (life curves)

• Common Across Analyses
  – load history
  – materials
  – examined here

• Stress State Completely Different
  – examined in separate sections of their own
Fatigue Materials

Common Regions

Fatigue Subsets
• Two fatigue material regions
• 64,934 element subset of full fea model

Primary Region
• A6 Galvanized Steel
• 50, 116 elements

Reinforcement Region
• 50k Galvanized Steel
• 14,818 elements
Material Definitions

Life Curves

S-N
- total life
- evaluated in original project
- available in NEF

e-N
- crack initiation
- deemed most accurate
- results presented here

Data Source
- acquired via in house testing
Loading

Common Loading

Input
- 4 mount locations
- 3 axes per mount (x,y,z)
- 12 total inputs

Time Histories
- 11 events
- 12 inputs per event
- 132 total time histories

Data Points
- 620 s total duration
- 512 points per second
- 12 histories per event
- 3,802,280 total data points
Common Fatigue Solution Parameters

- **Shell Surface**
  - top & bottom fatigue evaluation

- **Surface Finish**
  - None

- **strength reduction factors**
  - none utilized ($k_f = 1.0$)
    - notch effects
    - size effects
    - loading type

- **Strain Life (e-N) Analysis**
  - crack initiation

- **Stress Combination**
  - absolute Maximum Principal
  - no stress scaling factor

- **Certainty of survival**
  - 95.0%
  - accounts for scatter in material curves

- **Full Rainflow Cycle Counting**

- **Number of Parallel Threads = 8**
Quasi-Static Solution

Stress Recovery
Stress Recovery

- Nastran Portion of Fatigue Solution
  - SOL 101 Static Stresses

- Stress State per Load Input
  - 12 inputs
    - 4 mount locations
    - 3 axes per mount
  - 12 stress states

- Inertia Relief
  - free-free structure
  - equilibrated load balance
Stress State

Load Cases 1-6

Left Front

Left Rear

X

Y

Z

X

Y

Z
Stress State

Load Cases 7-12

Right Front

Right Rear
Quasi-Static Solution

Fatigue
Quasi-Static Fatigue Process

MSC Software Confidential

Nastran SOL 101

- Static Stress (sc1)
- Static Stress (sc2)
- Static Stress (sc…)

Directly input on TABLED1

Time History (force)

Fatigue Materials

Cycle Counter

Damage (single event)
Summary of Quasi-Static Solution

• All data completely maintained in memory

• Nastran Output Requests
  – none required
    • fatigue results only will be produced
  – can request any standard Nastran output if desired
    • will reduce solution efficiency

• Subcases
  – quasi-static subcases are combined into events
    • through association with time histories
    • vs. transient where the events are defined inherently
  – events can be combined into any combination to form duty cycles
    • and nested duty cycles
Transient Solution

Stress Recovery
Stress Recovery

• Modal Stress States
  – SOL 103 equivalent

• Free-Free Structure
  – inertia relief
    • only for calculation of residual vectors

• Residual Vectors
  – achieve equivalent static stress state
  – no dynamic response
    • NODYNRSP on RESVEC case control card
Stress Recovery

• Modes recovered up to 80Hz
  – 6 rigid body
  – 61 flexible
  – 12 residual vectors

• Fatigue
  – 73 modes utilized
    • 61 flexible + 12 residual
    • 6 rigid body modes ignored
      – via MODESELECT Case Control

• Modal Range Chosen Based on Examination of Input Signal Content
Load Input Spectrum

- ea10 – left front
- ea10 – left rear
- ea10 – right front
- ea10 – right rear

Understanding the environment
## Mode Check Summary

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Frequency (Hz)</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1-6</td>
<td>~ 0.0</td>
<td>Rigid Body Modes</td>
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<tr>
<td>7</td>
<td>10.7</td>
<td>Doors rocking on hinges and latch</td>
</tr>
<tr>
<td>8</td>
<td>11.0</td>
<td>Doors rocking on hinges and latch</td>
</tr>
<tr>
<td>9</td>
<td>16.7</td>
<td>Back panel</td>
</tr>
<tr>
<td>10</td>
<td>21.3</td>
<td>Cab parallelogram</td>
</tr>
<tr>
<td>11</td>
<td>21.9</td>
<td>Back panel</td>
</tr>
<tr>
<td>12</td>
<td>26.5</td>
<td>Doors pumping</td>
</tr>
<tr>
<td>13</td>
<td>26.8</td>
<td>Doors twisting</td>
</tr>
<tr>
<td>14</td>
<td>27.6</td>
<td>Steering column pitching</td>
</tr>
<tr>
<td>15</td>
<td>30.9</td>
<td>Back panel</td>
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</table>
### Mode List

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Frequency (Hz)</th>
<th>Mode #</th>
<th>Frequency (Hz)</th>
<th>Mode #</th>
<th>Frequency (Hz)</th>
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<th>Frequency (Hz)</th>
<th>Mode #</th>
<th>Frequency (Hz)</th>
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<tr>
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<td>40.19</td>
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<td>71.44</td>
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<td>10.96</td>
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<td>43.41</td>
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<td>56.63</td>
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<td>71.98</td>
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<td>250.14</td>
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<td>39</td>
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<td>70</td>
<td>296.64</td>
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<tr>
<td>11</td>
<td>21.82</td>
<td>26</td>
<td>46.70</td>
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<td>59.98</td>
<td>56</td>
<td>75.04</td>
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<td>12</td>
<td>26.38</td>
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<td>47.06</td>
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<td>60.13</td>
<td>57</td>
<td>75.68</td>
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<td>498.97</td>
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<td>61.96</td>
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<td>73</td>
<td>1064.77</td>
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<td>48.91</td>
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<td>62.17</td>
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<td>15</td>
<td>30.79</td>
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<td>49.13</td>
<td>45</td>
<td>62.91</td>
<td>60</td>
<td>77.69</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Notes
- **Rigid body modes** are denoted by red background.
- **Residual vectors** are denoted by green background.
- **Flexible modes** are denoted by blue background.
Modal Stress

mode 9 ~ 16.68 Hz

mode 11 ~ 21.82 Hz

mode 12 ~ 26.38 Hz

mode 14 ~ 27.14 Hz

mode 21 ~ 39.38 Hz

mode 60 ~ 77.69 Hz

flexible mode samples
Modal Stress

- Mode 62 ~ 134.34 Hz
- Mode 65 ~ 179.70 Hz
- Mode 67 ~ 215.05 Hz
- Mode 69 ~ 256.99 Hz
- Mode 70 ~ 296.64 Hz
- Mode 73 ~ 1064.77 Hz

Residual vector samples
Transient Solution

Modal Transient Response
Modal Transient Overview

- **Two Stages**
  - modal extraction
    - identical to SOL 103
    - option to restart from SOL 103 to avoid repetitive eigenvalue extraction
  - Load History Application
    - time step = .01 s (100 Hz)
      - sufficient to capture all dynamic stress cycling
    - 12 input combined history loading

- **Residual Vectors**
  - achieve equivalent static stress state
  - no dynamic response
    - NODYNRSP on RESVEC case control card
Modal Transient Overview

- **Response in Modal Space**
  - modal coordinates $\leftrightarrow$ physical coordinates
  - this transformation allows for massively reduced dof sets
  - allows for the application of the fatigue modal superposition method

- **Output**
  - scale factor on each mode
    - also known as SDISPLACEMENT
  - represents the contribution of each mode to the stress response
Modal Scalar

ea10 event

- Mode 9 ~ 16.68 Hz
- Mode 11 ~ 21.82 Hz
- Mode 12 ~ 26.38 Hz
- Mode 14 ~ 27.14 Hz
- Mode 21 ~ 39.38 Hz
- Mode 60 ~ 77.69 Hz

Time History
Transient Solution

Fatigue
Transient Fatigue Process

Nastran SOL 112

Fatigue Materials

Cycle Counter

Damage (single event)

modal stress

modal scalar
Summary of Transient Solution

- All data maintained in memory

- Nastran Output Requests
  - none required
    - fatigue results only will be produced
  - can request any standard Nastran output if desired
    - will reduce solution efficiency

- Subcases
  - the modal transient subcases are the fatigue events
    - vs. static where events are defined separately
  - events can be combined into any combination to form duty cycles
    - and nested duty cycles
Results

Quasi-Static
Life

quasi-static

log of Life (miles)

predicted life of 1,258,000,000,000
1.26 trillion miles
Life

predicted life of 316,228 miles
Results

Comparison
Critical Location Prediction

test

quasi-static

transient
Critical Location Prediction

test

quasi-static

transient
Critical Location Prediction

test

quasi-static

transient
Results

Understanding Damage
Designing & Optimizing Around Damage

• **Initial Evaluations**
  – allowed for understanding of critical regions of the structure
  – understanding of the events most contributing to damage

• **Subsequent Iterations**
  – thicken panels
  – adjust weld locations
  – adjust material selection

• **Automatic Optimization**
  – fatigue life target
  – now inherent in SOL 200
Evaluating Damage

per event

ea10

nois
Solution Expense

accuracy & efficiency
## Solution Time

### embedded vs. unembedded

**wall clock minutes**

<table>
<thead>
<tr>
<th>solution stage</th>
<th>quasi-static</th>
<th>modal transient</th>
<th>quasi-static</th>
<th>modal transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEA solve</td>
<td>1.92</td>
<td>17.84</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>fatigue input generation</td>
<td>8.44</td>
<td>21.87</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>fatigue solve</td>
<td>38.20</td>
<td>79.08</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>48.56</strong></td>
<td><strong>118.79</strong></td>
<td><strong>11.67</strong></td>
<td><strong>24.55</strong></td>
</tr>
</tbody>
</table>

4 core Intel 2.5 GHz laptop
16 Gb memory
## Disk Space Usage

### embedded vs. unembedded

Megabytes of disk occupied

<table>
<thead>
<tr>
<th>file type</th>
<th>extension</th>
<th>quasi-static</th>
<th>modal transient</th>
<th>quasi-static</th>
<th>modal transient</th>
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</thead>
<tbody>
<tr>
<td>stress storage</td>
<td>.xdb</td>
<td>79.75</td>
<td>271,546.57</td>
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<td>--</td>
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<tr>
<td>fatigue input file</td>
<td>.fin</td>
<td>0.10</td>
<td>1.28</td>
<td>--</td>
<td>--</td>
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<td>157.27</td>
<td>11,040.96</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>fatigue results</td>
<td>.fef*</td>
<td>71.40</td>
<td>71.40</td>
<td>(71.40)</td>
<td>(71.40)</td>
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<td>fatigue results</td>
<td>.op2*</td>
<td>--</td>
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<td>31.02</td>
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<td><strong>Combined</strong></td>
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<td><strong>308.52</strong></td>
<td><strong>282,660.21</strong></td>
<td><strong>31.02</strong></td>
<td><strong>31.02</strong></td>
</tr>
</tbody>
</table>

* .fef contains final duty cycle results only

*.op2 with all events & duty cycle results = 108.13 Mb
Ease of Use

### embedded vs. unembedded

files requiring manual management

<table>
<thead>
<tr>
<th>solution stage</th>
<th>type</th>
<th>extension</th>
<th>quasi-static</th>
<th>modal transient</th>
<th>quasi-static</th>
<th>modal transient</th>
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<tbody>
<tr>
<td>FEA (Nastran)</td>
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<td>.dat</td>
<td>1</td>
<td>11</td>
<td>1</td>
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<td>result</td>
<td>.xdb</td>
<td>1</td>
<td>11</td>
<td>--</td>
<td>--</td>
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<tr>
<td>fatigue</td>
<td>load history</td>
<td>.dac</td>
<td>132 (12x11)</td>
<td>132</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
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<td>input</td>
<td>.fin</td>
<td>11</td>
<td>11</td>
<td>--</td>
<td>--</td>
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<tr>
<td></td>
<td>input</td>
<td>.fes</td>
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<td>11</td>
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<td>result</td>
<td>.fef</td>
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<td>material db</td>
<td>.adb/.mdb</td>
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<td>2</td>
<td>--</td>
<td>--</td>
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<td>.adb/.tdb</td>
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<td>2</td>
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<td><strong>Combined</strong></td>
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<td></td>
<td><strong>171</strong></td>
<td><strong>191</strong></td>
<td><strong>2</strong></td>
<td><strong>2</strong></td>
</tr>
</tbody>
</table>
Conclusion
Conclusions

- Real World Truck Cab Design Simulated
  - high fidelity stress recovery
    - large FEA model
    - model consistency
      - no need for reduced dynamic model
  - extensive load data captured
    - identical replication of shaker stand testing
    - rapid processing
Conclusions

• **Superposition**
  – significantly superior
  – accuracy
    • most physically relevant
    • includes all dynamic effects
      – mass, inertia, modal contributions
    • most accurate fatigue life estimation
  – resource requirements
    • disk space
    • solution efficiency
    • still significant file management
      – somewhat ameliorated with automation
      – completely eliminated with NEF
  – now inherent in core NEF processing
    • modal transient SOL 112

• **Quasi-Static**
  – far too conservative life estimate in this case

• **Vibration**
  – too manually intensive
  – less physically accurate

• **Transient**
  – physical recovery
  – yields same results as superposition
  – far too cumbersome to be practically useful

**from 1999 study**
Conclusions

- **Design Evaluation using NEF**
  - massive amounts of data reduced to a single actionable value
    - life
  - designing with stress as a guide can be overly simplistic
  - dynamic effect inclusion is critical
    - quasi-static evaluation alone vastly underestimates life
      - when energy content of the loading signal is within the frequency spectrum of the structural modes
Conclusions

• Relation to test
  – reduce number of tests
  – improve test
    • more efficient cab examination
    • areas of interest pre-identified
  – test improves analysis
    • iterative process refines analysis methodologies
      – spot welds
      – concentration factors
      – surface roughness
      – mean stress corrections
      – certainty of survival
      – etc.
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