Exhaust Systems Durability with Dynamic Loading

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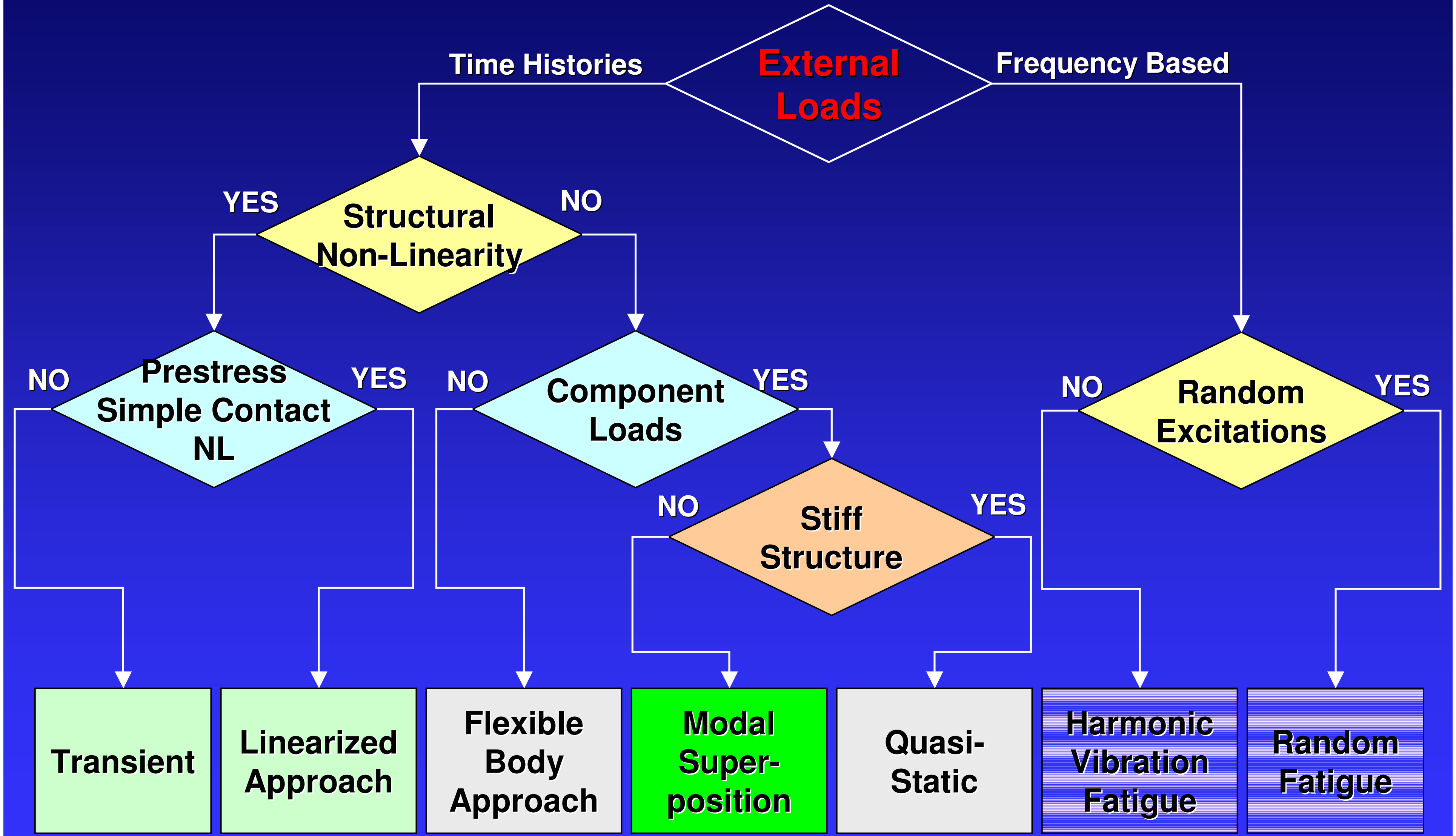
Typical Loading on Exhaust Systems

- Residual Stresses from manufocturing
- Assembly of different components
- Components misalignments
- Thermal stresses from exhaust gases
- Gas pressure under operating conditions
- Engine vibrations
- Road loads

Component Fatigue – Method Overview



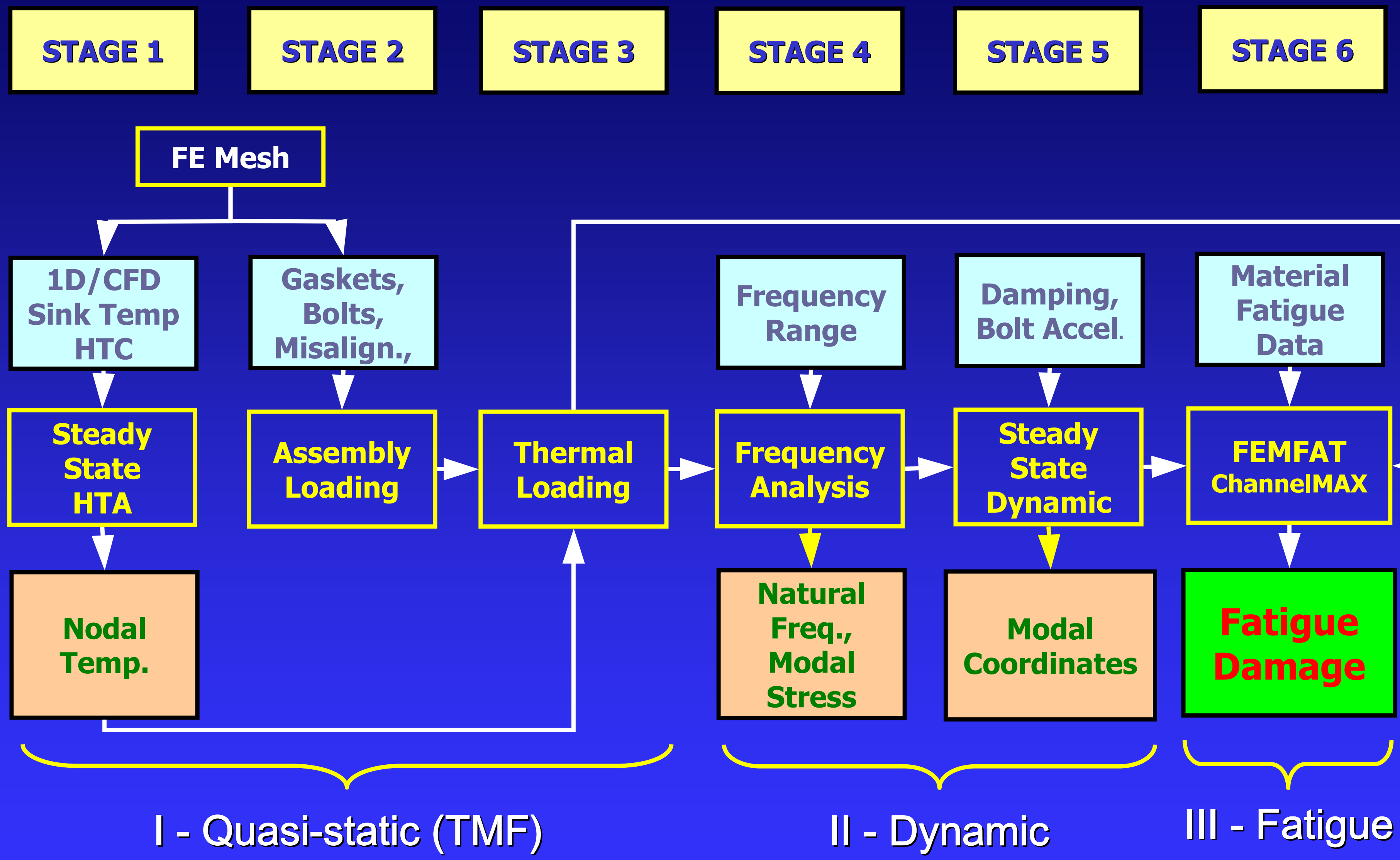
Rationale for use of Dynamic Loading

- Generally, FEA is based on quasi-static computation
- No dynamic effects are considered

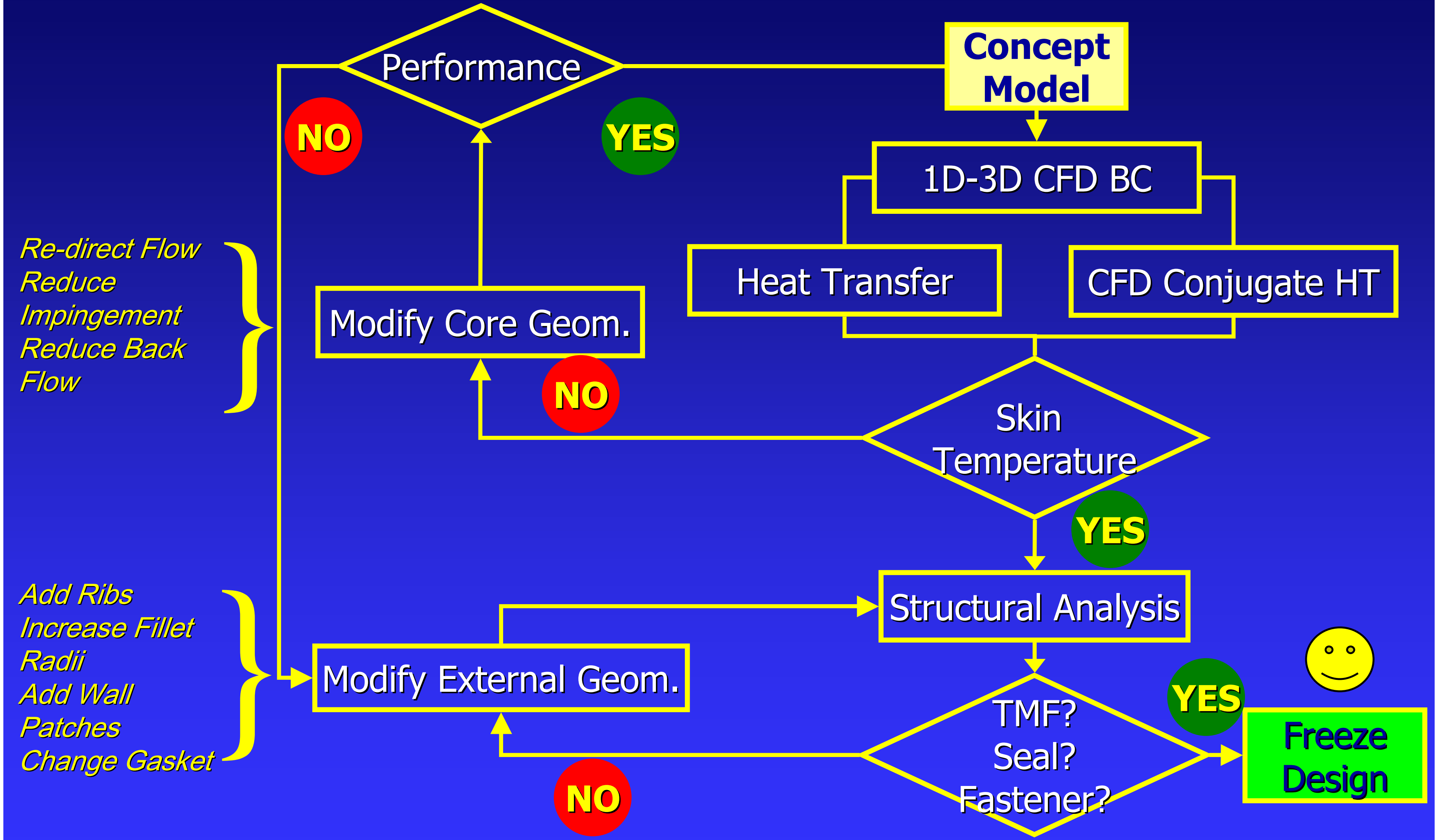
  Acceptable if natural vibrations have small or no influence on the structure

  ß May lead to considerable errors for complex systems such as components attached to engines
- Impossible to simulate vibration dominated problems

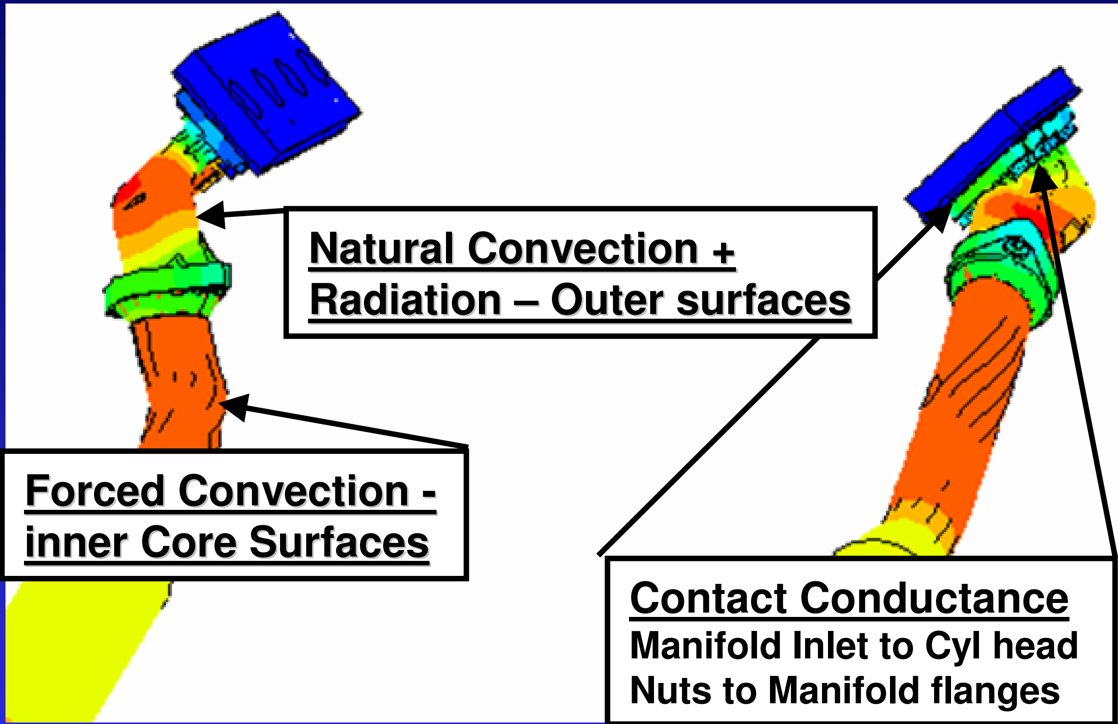
CAE Process Map

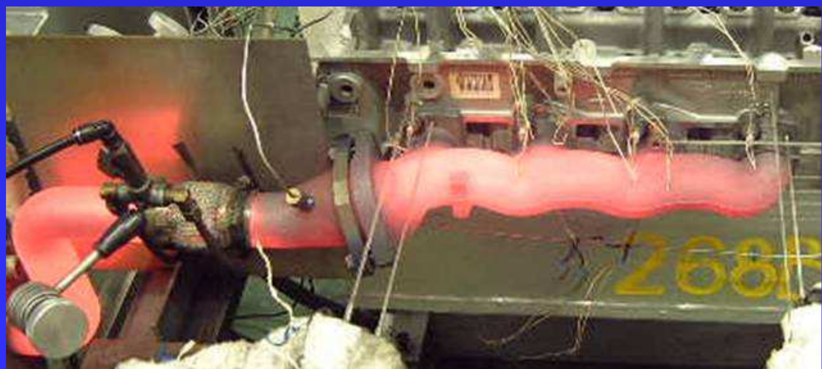


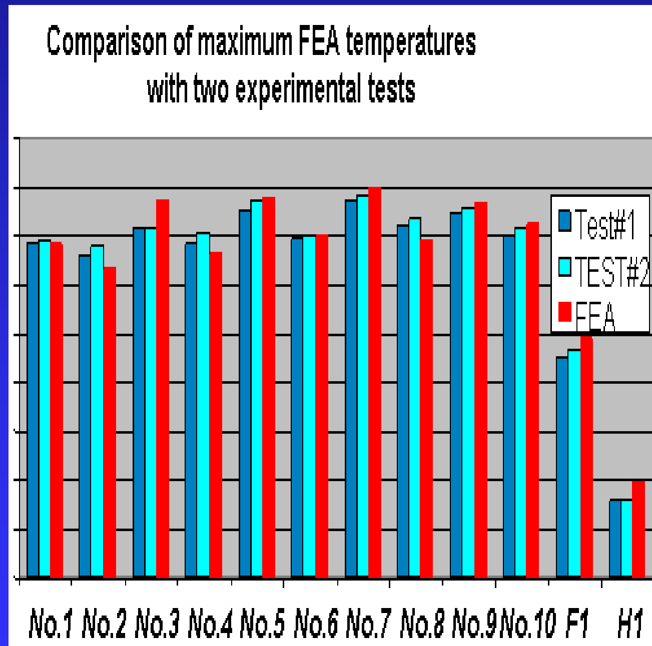
I – Quasi-Static - TMF Analysis Process Map



HTA & Test/CAE Correlation (Skin Temperature)

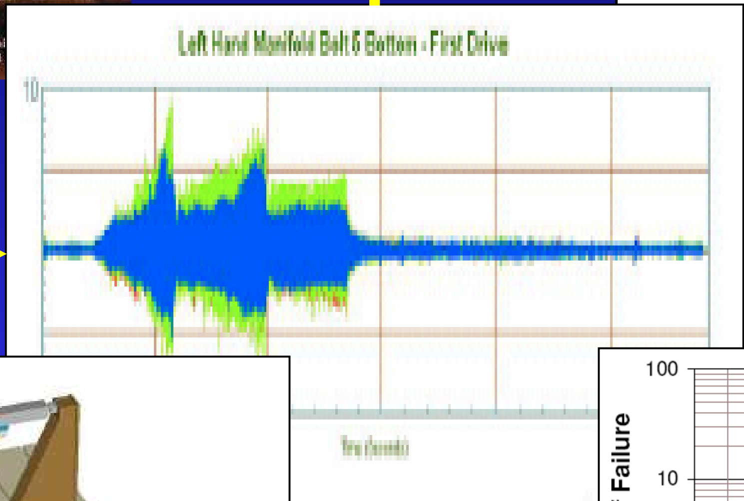


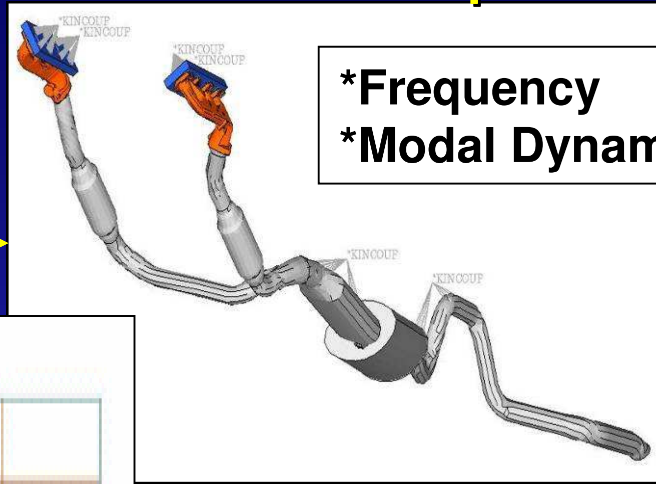




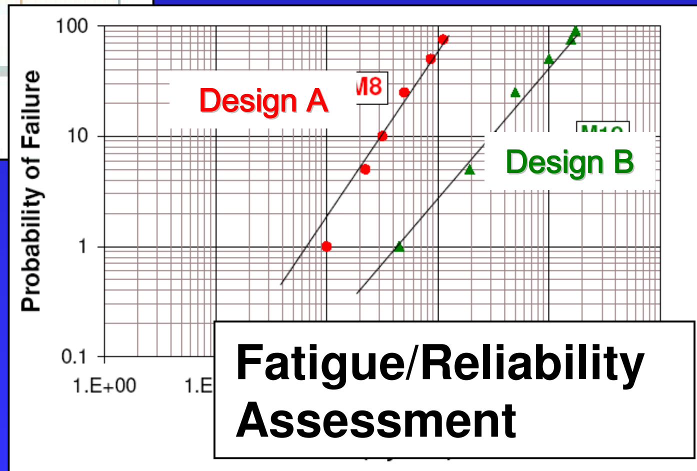
II - Dynamic Stress Analysis Process Map

RLDA

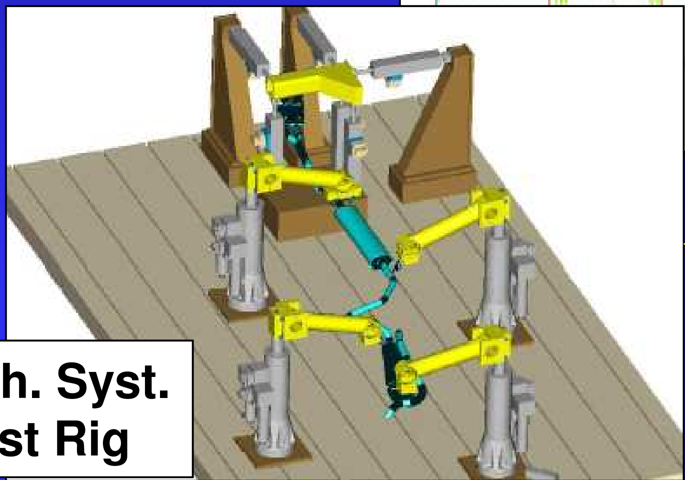




*Frequency
*Modal Dynamic



Fatigue/Reliability Assessment



Exh. Syst. Test Rig

OK?

Basis of the Mode Superposition Method

$$m\ddot{u} + c\dot{u} + ku = p(t)$$

The system displacement response is given by superposition of mode shape vectors:

$$u(t) = \sum_{r=1}^{N} \phi_r \xi_r(t)$$

Similarly, the stress response is obtained :

$$\hat{\sigma}(t) = \sum_{r=1}^{\hat{N}} S_r \xi_r(t)$$

ϕ_r:	*Normal modes*
$\xi_r(t)$:	*Modal coordinates*
S_r:	*Contribution to stress vector S due to a unit displacement of the r^{th} mode*

Modal Truncation Effect

Modal truncation in modal solutions introduces errors in stress calculation. Which may be *minor*, slightly affecting stress values or *critical*, in terms of predicting failure location.

Static Residual Attachment Modes (secondary base modes)

Residual modes may be used to compensate for truncated modes.

$$\sigma(t) = \sum_{l=1}^{m} S_l \xi_l(t) + \sum_{k=m}^{L} S_k \xi_k(t)$$

Initial Stress

The total response ξ(t) is a superposition of the response due to:

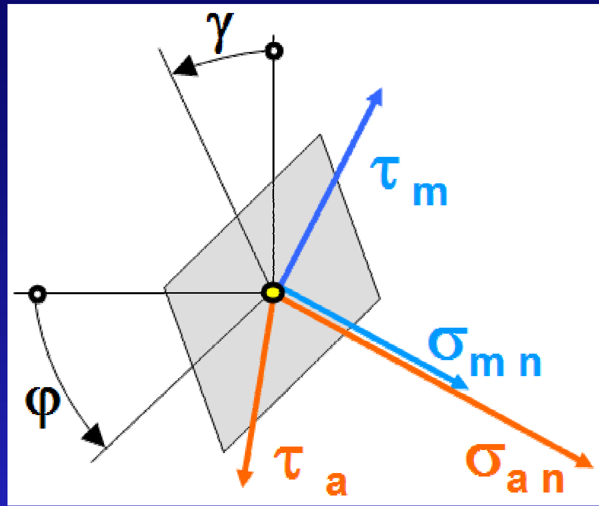
initial conditions (where ξ(t) = 1 and *S* is the initial stress tensor);

response due to excitation alone.

III - Fatigue Analysis Approach in FEMFAT

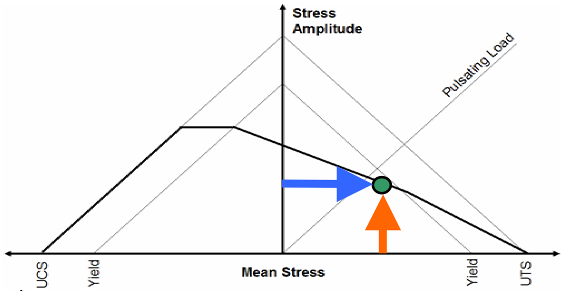
Amplitude Stress Tensor
Mean Stress Tensor

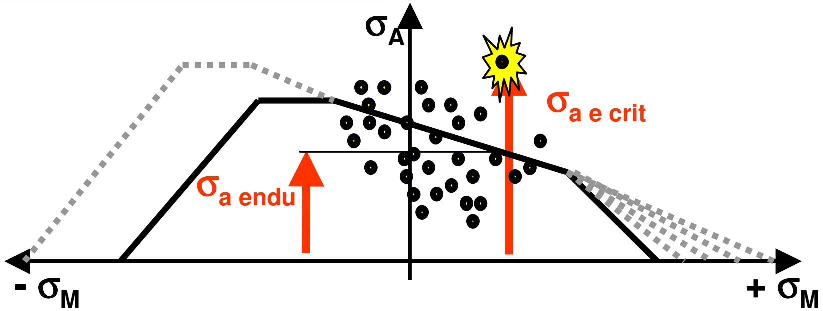
$$\overleftrightarrow{\sigma} = \begin{bmatrix} \sigma_{xx} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz} \end{bmatrix}$$



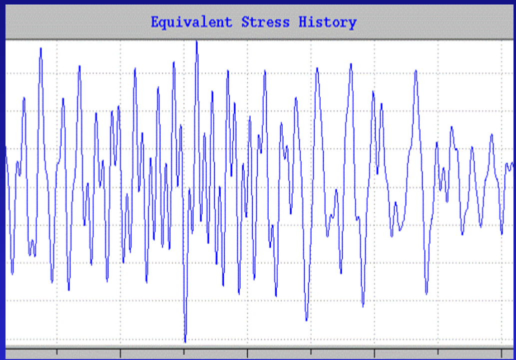
$$\sigma_{ae} = \sqrt{\sigma_{an}^2 + \left(\frac{\sigma_{alt,TC}}{\tau_{alt}}\right)^2 \cdot \tau_a^2}$$

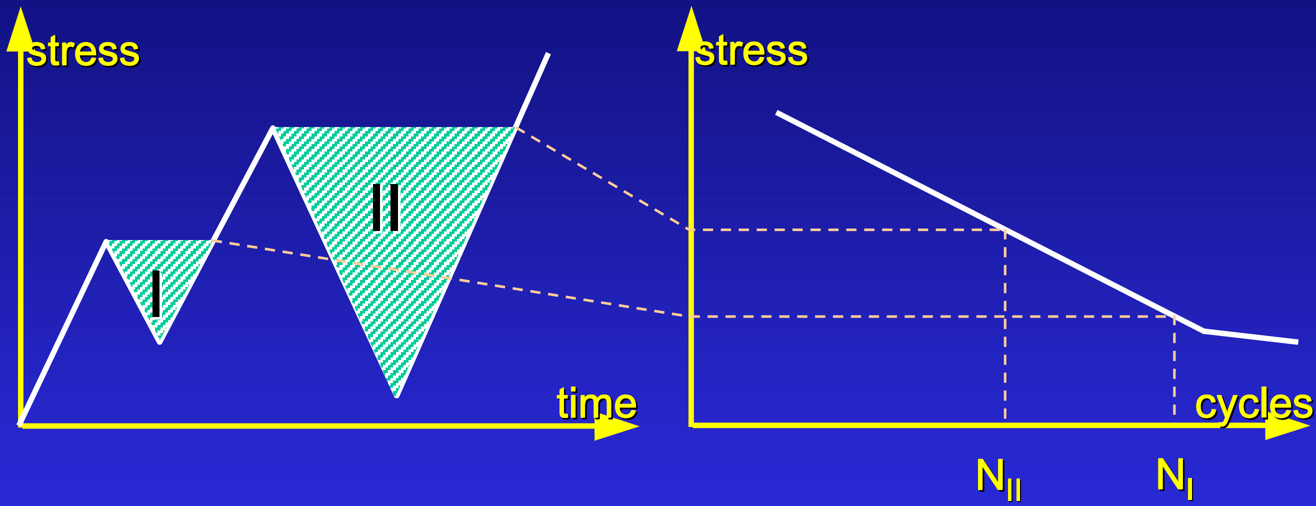
$$\sigma_{me} = sign(\sigma_{mn})\sqrt{\sigma_{mn}^2 + \left(\frac{\sigma_{yield}}{\tau_{yield}}\right)^2 \cdot \tau_m^2}$$





Rainflow Cycle Counting and Palmgren-Miner Cumulative Damage





$$\left\{ \begin{array}{l} A_1, M_1, n_1 \\ A_2, M_2, n_2 \\ . \\ A_k, M_k, n_k \end{array} \right.$$

$$d_i = \frac{n_i}{N_i}$$

Total Damage:

$$D = \Sigma\, d_i = d_1 + d_2 + \ldots + d_n$$

```
*step, nlgeom, inc=200
***--- step 1 – assembly step
*static
 1.0e-2, 1.0, 1.e-6,0.20
*boundary, op=new
 101,1, ,-0.6             (Misalignment)
 201,2, , 1.2
 nbot,1,3
*cload
 tnodes,1,12500.0
.
.
.
*end step
*step, inc=200
***--- step 3 - apply prescribed thermal load (from HTA results)
*static
0.1, 1.0, 0.00001
*temperature, input=nodaltemp.inp
.
.
*DLOAD
Pressurized_elset,P,-0.1
.
.
*end step
```

```
*step
***--- step 4 - extract natural frequencies
*frequency
        20,10,1000.0
*boundary, op=new, base name=b1
 1, 1, 3
*output, field
*element output
s,
*end step
*step
***--- step 5 - steady state dynamics
*modal dynamic
0.0002, 1.0
*select eigenmodes, generate
1,20
*modal damping,modal=direct
1,20,0.05
**---------------- base acc @ node 1
*base motion,type=acceleration,scale=1,dof=1,loadcase=1,amplitude=x,base name=b1
*base motion,type=acceleration,scale=1,dof=2,loadcase=1,amplitude=y,base name=b1
*base motion,type=acceleration,scale=1,dof=3,loadcase=1,amplitude=z,base name=b1
**----------------
*output, history, frequency=1
*modal output
gu,
*end step
```

Define Bases

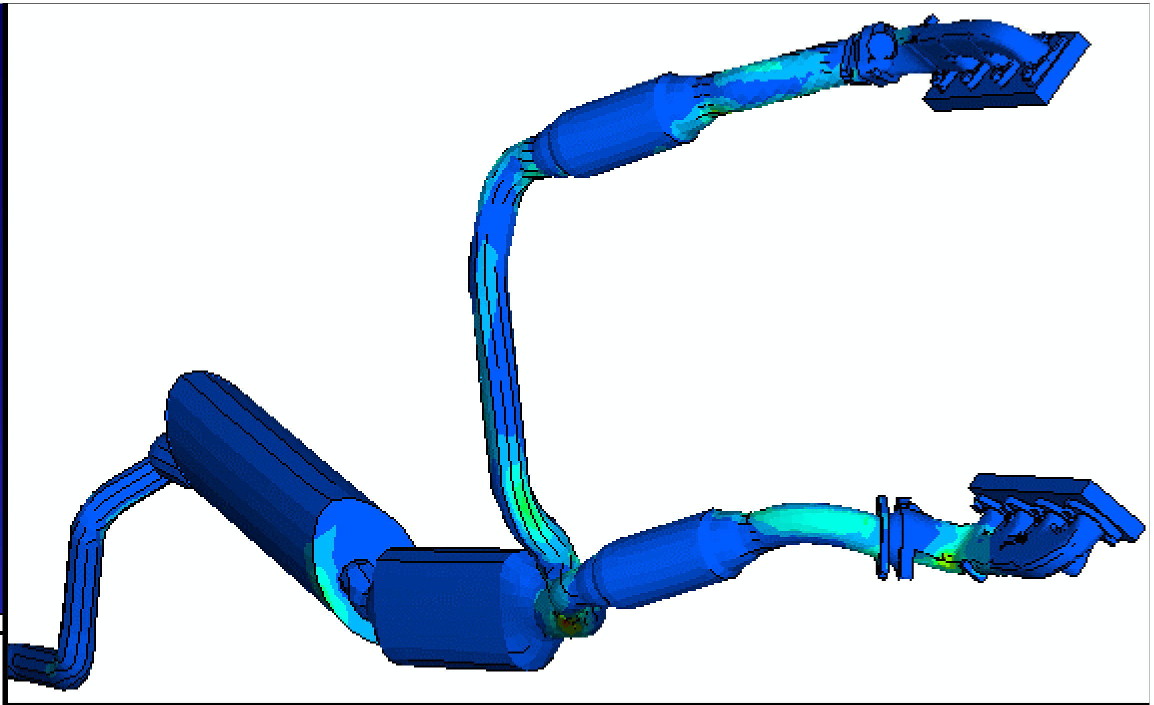
Output Modal Stresses

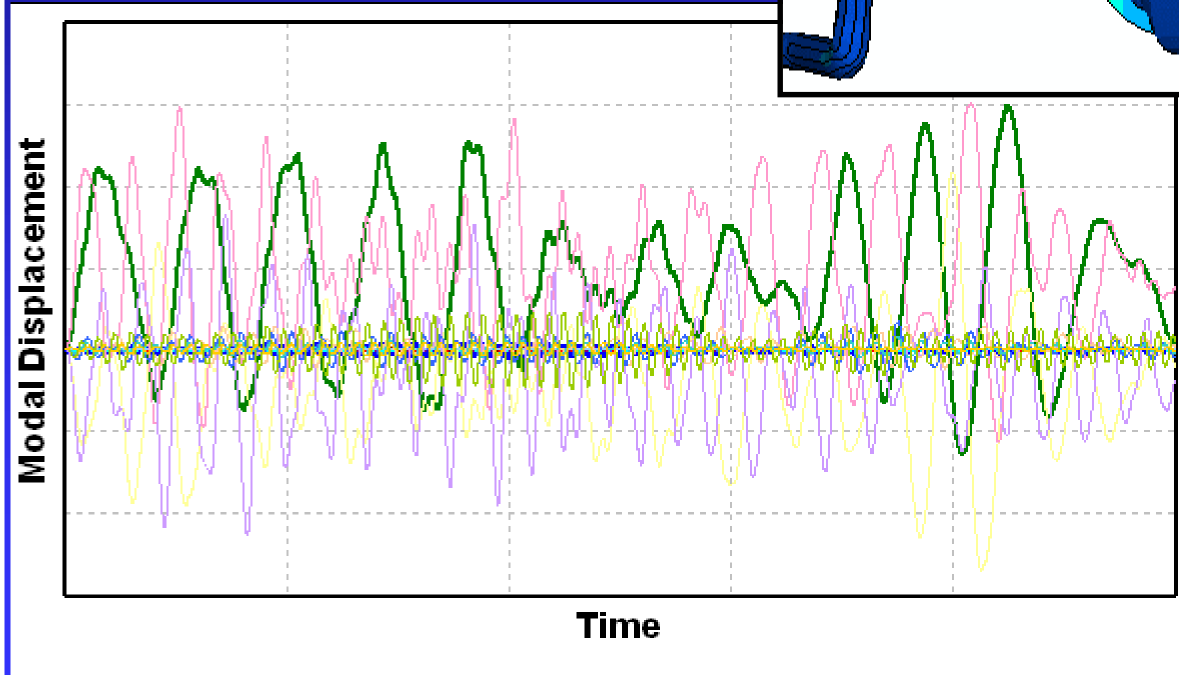
Define increment and total time

Attach Acceleration to Bases

Output Generalized Displacements

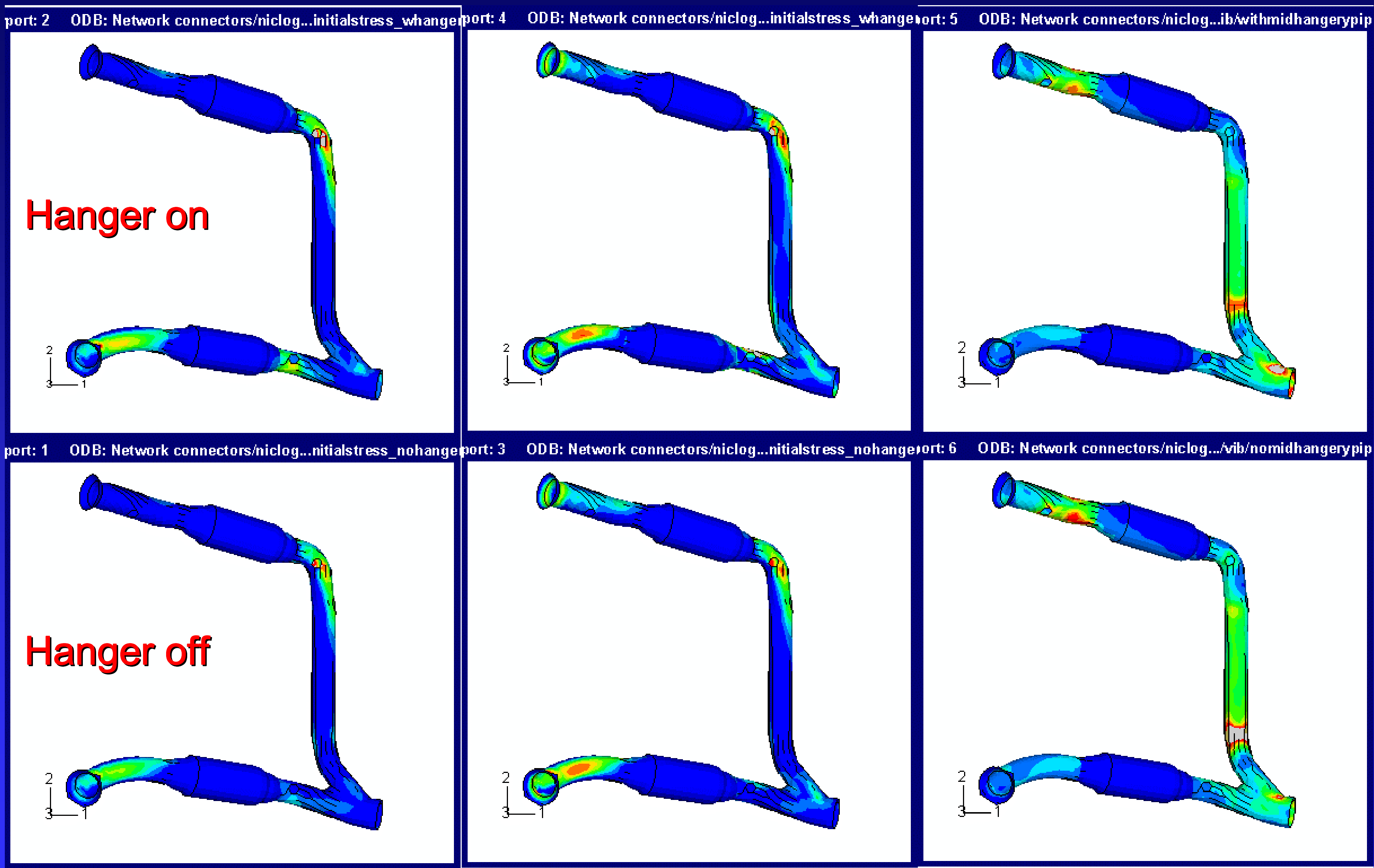
Modal Stresses from Frequency Step



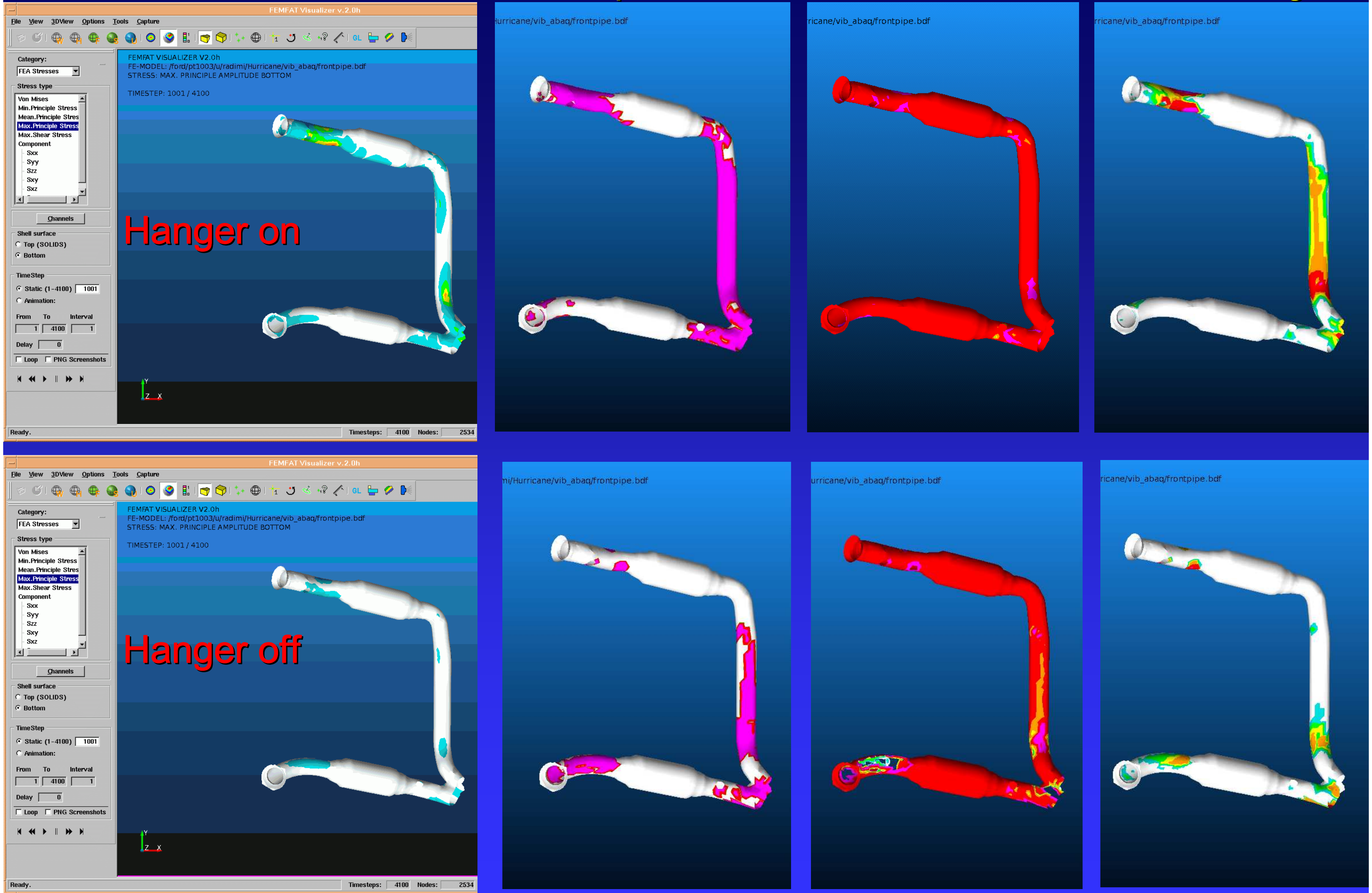


Modal Displ. from Modal Dynamic Step

Assembly Step | Thermal Step | Modal Stress (~250 Hz)



Stress Animation | Amplitude Strs | Mean Strs | Total Damage



Limitations

Modal damping: 3%-5% damping ratio to be used with all modes.

Time history of acceleration at attachment points.

Accuracy of materials fatigue properties.

Steady state dynamic analysis is a linear perturbation about a stressed state. It ignores all changes in contact/plasticity during the vibration.

Only a limited set of natural frequencies are used.

Conclusion

- The steady state dynamic response in ABAQUS provides *Modal Coordinates.*
- *Modal Stresses* are obtained in the frequency extraction step.
- Modal stresses are superposed, using the time dependent modal coordinates, in FEMFAT, which leads to:

  Vibration effects included in fatigue analysis

  Initial stresses can be considered

  Possibility to evaluate long transient time series, using a small amount of data comparatively to quasi-static/transient solutions

  Recovery of element stresses during the steady state dynamics step in ABAQUS is not necessary.

  Stress animation possible in FEMFAT