Vector Reconstruction – a new Gradient Computation Method

ECS Simulation Conference 2021

Date: June 21 / Author: Gerhard Spindelberger

Agenda

Quickstart

Date: May 2021 / Author: Gerhard Spindelberger

The Key Information in less than 2 Minutes

Completely new method for stress gradient calculation: “Vector Reconstruction“

Only consideration of positive stress gradients (no support effect for stress increase)

Affects all modules with gradient (BASIC, MAX, SPECTRAL)

new handling of middle nodes in case of parabolic elements

Advantages: max. gradient is computed (perpendicular to surface), unified method for all modules, no influence of number of channels in ChannelMAX.

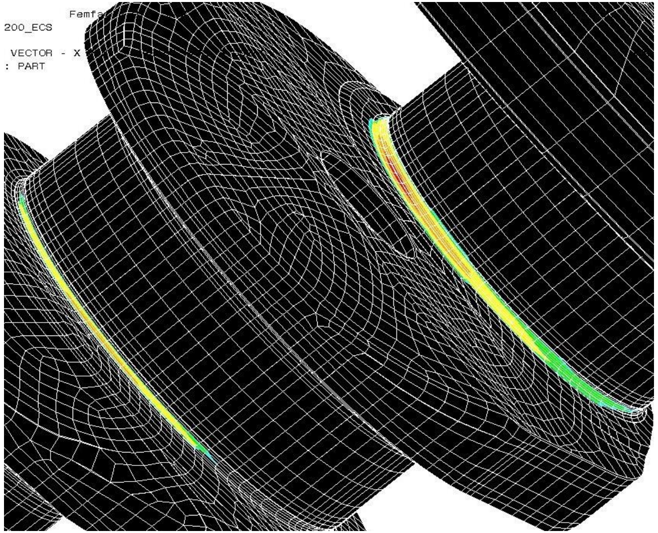
Introduction

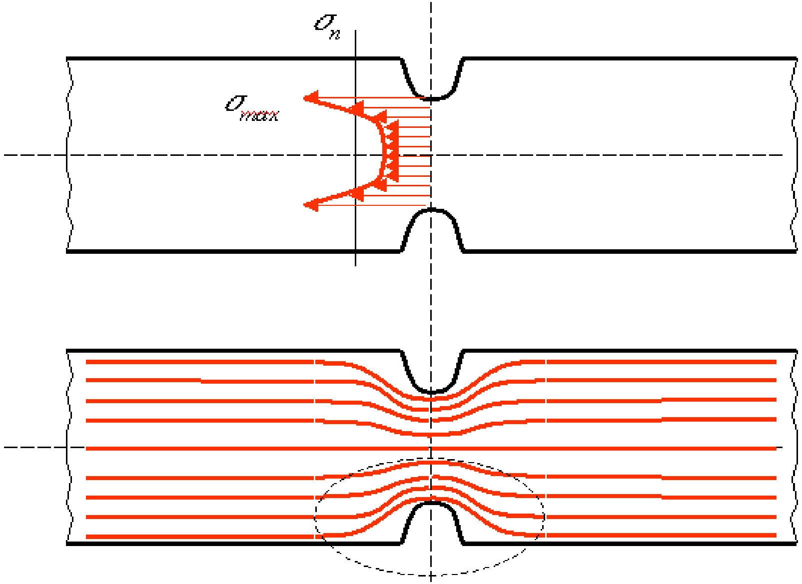
Date: May 2021 / Author: Gerhard Spindelberger

Introduction in Four Questions (1/4)

What is the stress gradient?

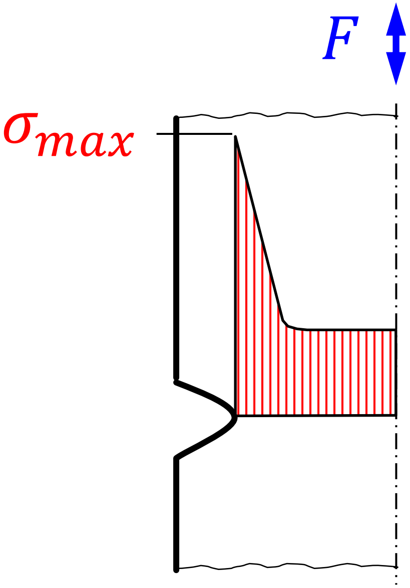
Due to geometric and design properties, locations with stress concentrations (notches) often occur in reality. Typically the stress distribution is not constant, but has a peak in the notch with decaying values for the surrounding material.





Introduction in Four Questions (2/4)

How can we consider the stress gradient, how can it be computed for arbitrarily complex geometries?



The gradient is calculated from the difference of the stress tensors of neighboring nodes as well as their distance.

For fatigue analysis the relative stress gradient is used which is independent of the loading level

Stress Gradient

$$\boxed{\chi = \frac{d\sigma}{dx}}$$

Relative Stress Gradient

$$\boxed{\chi' = \frac{1}{\sigma_{\max}}\left(\frac{d\sigma}{dx}\right)}$$

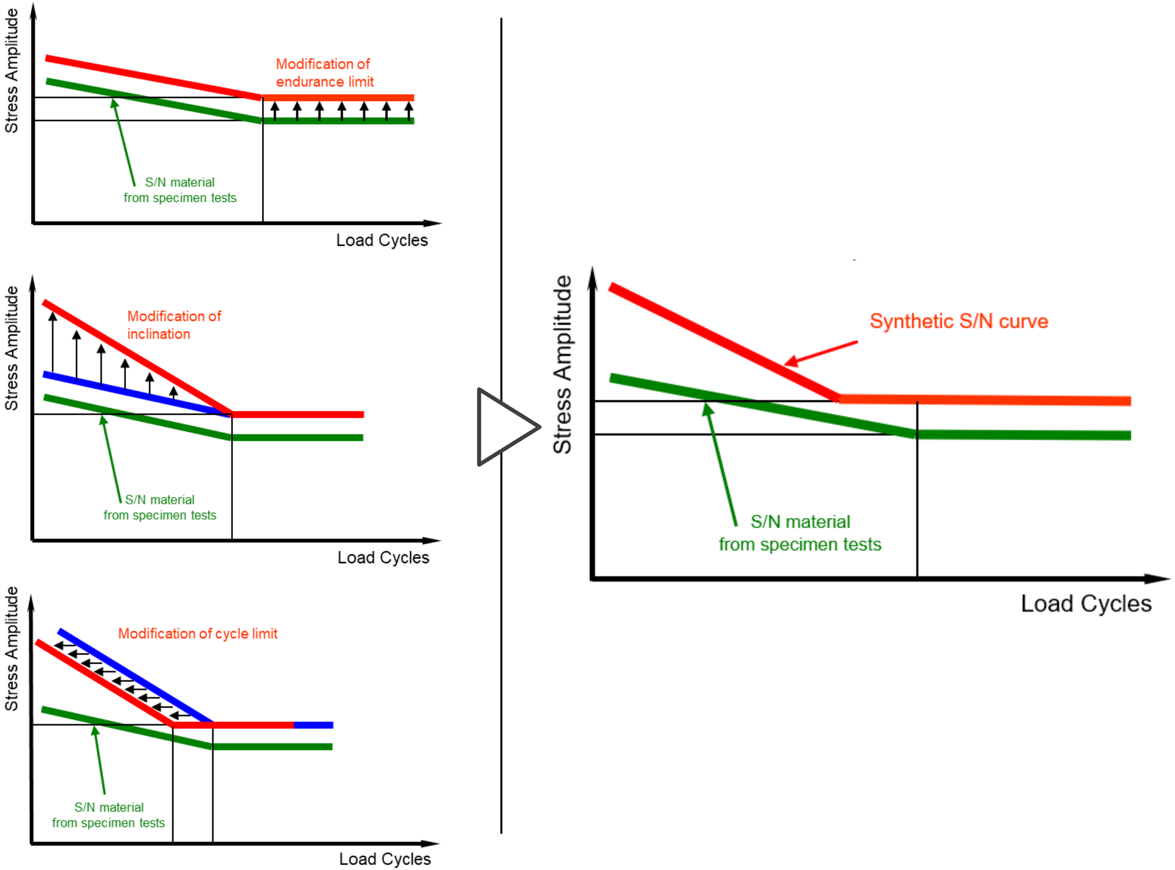
Introduction in Four Questions (3/4)

Why is the gradient such an important influence factor?

The locations of stress concentrations are critical to fatigue life.

The gradient has an influence on the component S/N curve and therefore on all fatigue results.

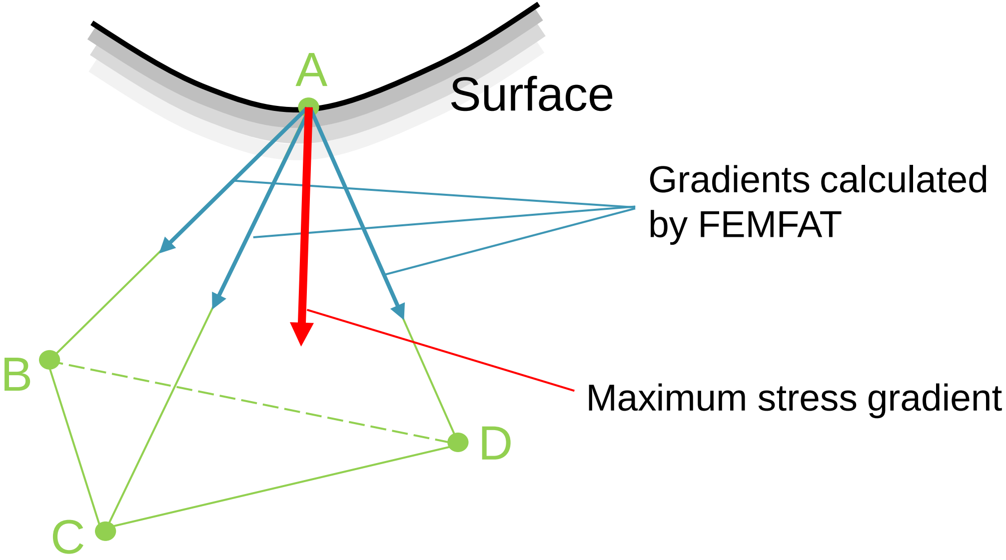
Therefore, you want to compute the stress gradient as accurate as possible.



Introduction in Four Questions (4/4)

Why is there a new method, what does it make better than the default gradient?

- A complex shaped structure is usually meshed automatically with parabolic tetrahedrons
- FEMFAT calculates the stress gradient along Finite Element edges
- The maximum stress gradient is usually perpendicular to the surface
- But often there are no Finite Element edges perpendicular to the surface
  → inaccurate results!



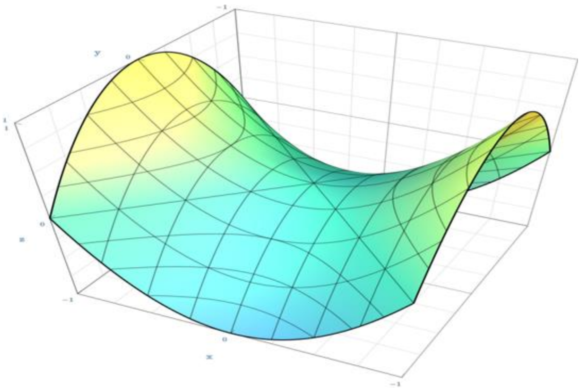
New Gradient Method

Date: May 2021 / Author: Gerhard Spindelberger

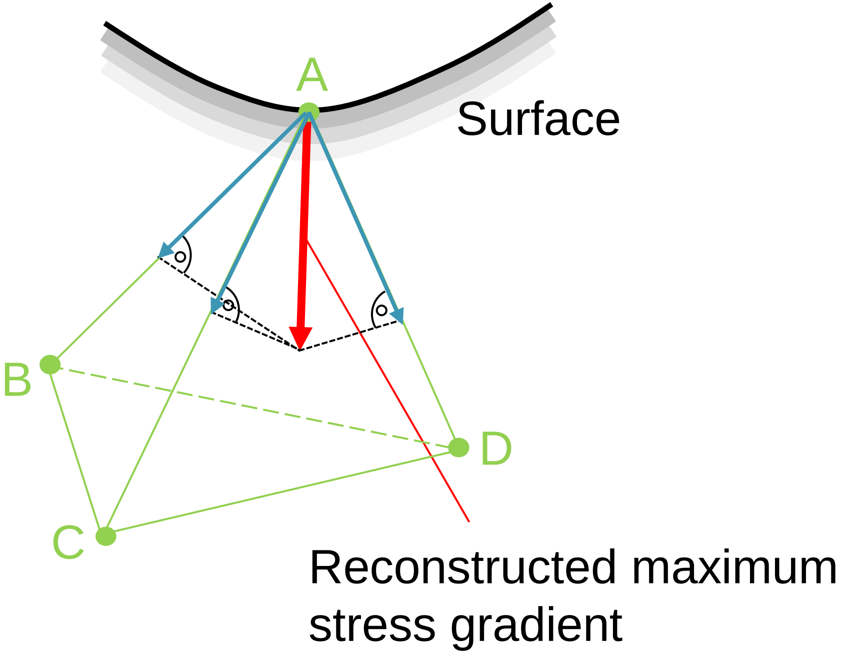
The new Gradient Method explained

A stress gradient is a vector pointing in the direction of the largest stress decrease.

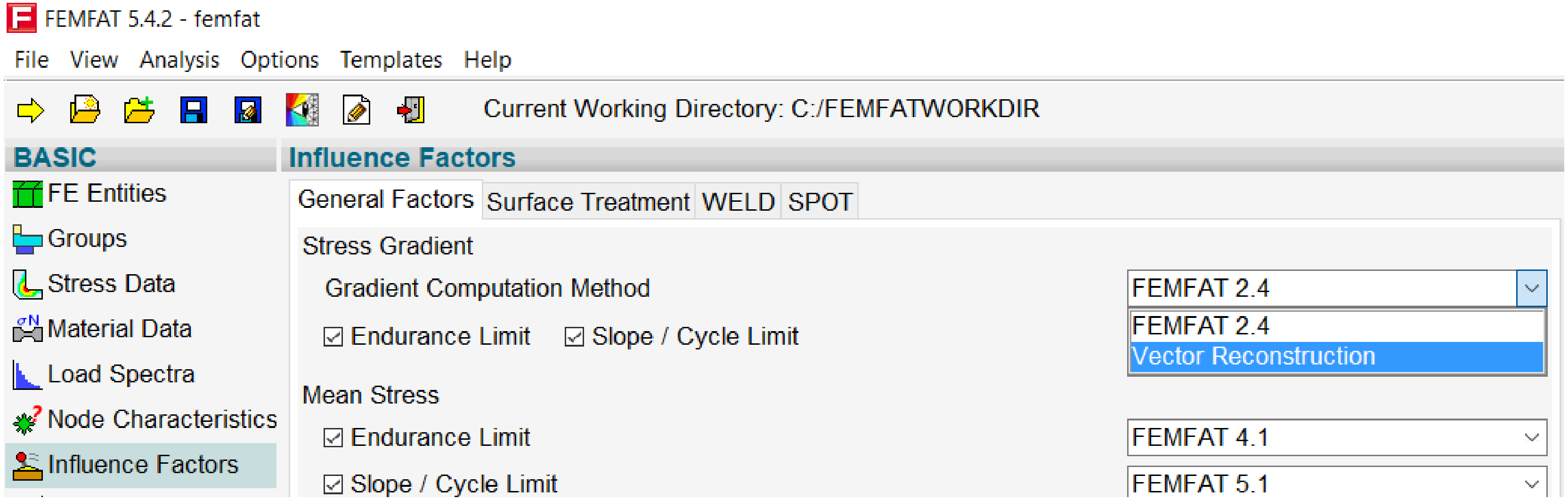
$$\vec{\chi} = -\vec{\nabla}\sigma_{Mises} = -\begin{pmatrix} \dfrac{\partial\sigma_{Mises}}{\partial x} \\ \dfrac{\partial\sigma_{Mises}}{\partial y} \\ \dfrac{\partial\sigma_{Mises}}{\partial z} \end{pmatrix}$$



It can be reconstructed by its components along the Finite Element edges.



New Stress Gradient Analysis Method



Stress Gradient

Gradient Computation Method: FEMFAT 2.4

FEMFAT 2.4

Vector Reconstruction

☑ Endurance Limit ☑ Slope / Cycle Limit

Mean Stress

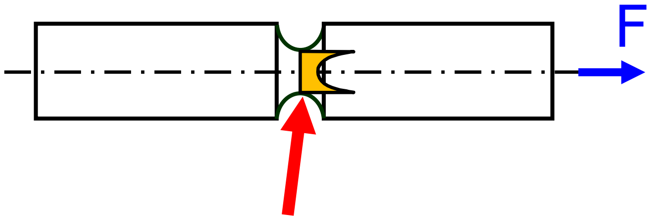
☑ Endurance Limit: FEMFAT 4.1

☑ Slope / Cycle Limit: FEMFAT 5.1

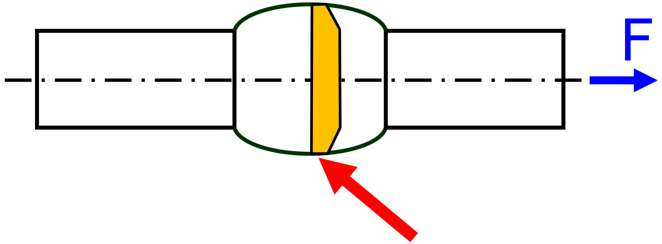
The new option “Vector Reconstruction“ can be activated from the “Influence Factors“ menu. “FEMFAT 2.4“ method is still the default setting.

New Stress Gradient Analysis Method

Only Finite Element edges with decreasing stresses are considered for gradient reconstruction, because there is no support effect for bulges („negative“ notches).



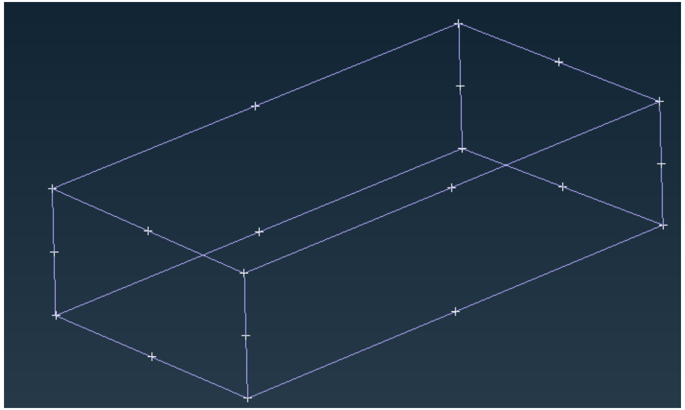
Decreasing stress → gradient influence ✓

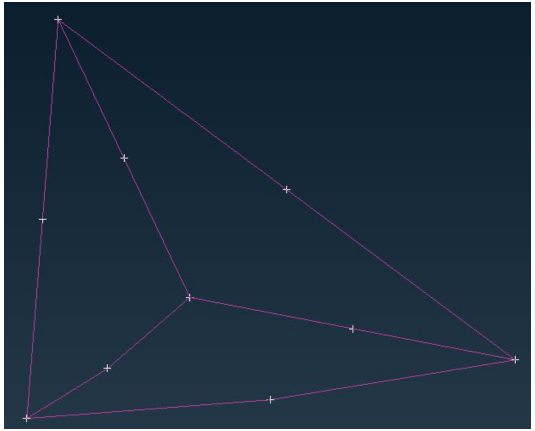


Increasing stress → NO gradient influence ✗

Different Handling for Middle Nodes of parabolic Elements

With activated “Vector Reconstruction” the gradients at middle nodes of parabolic elements are calculated directly, i.e. like corner nodes.

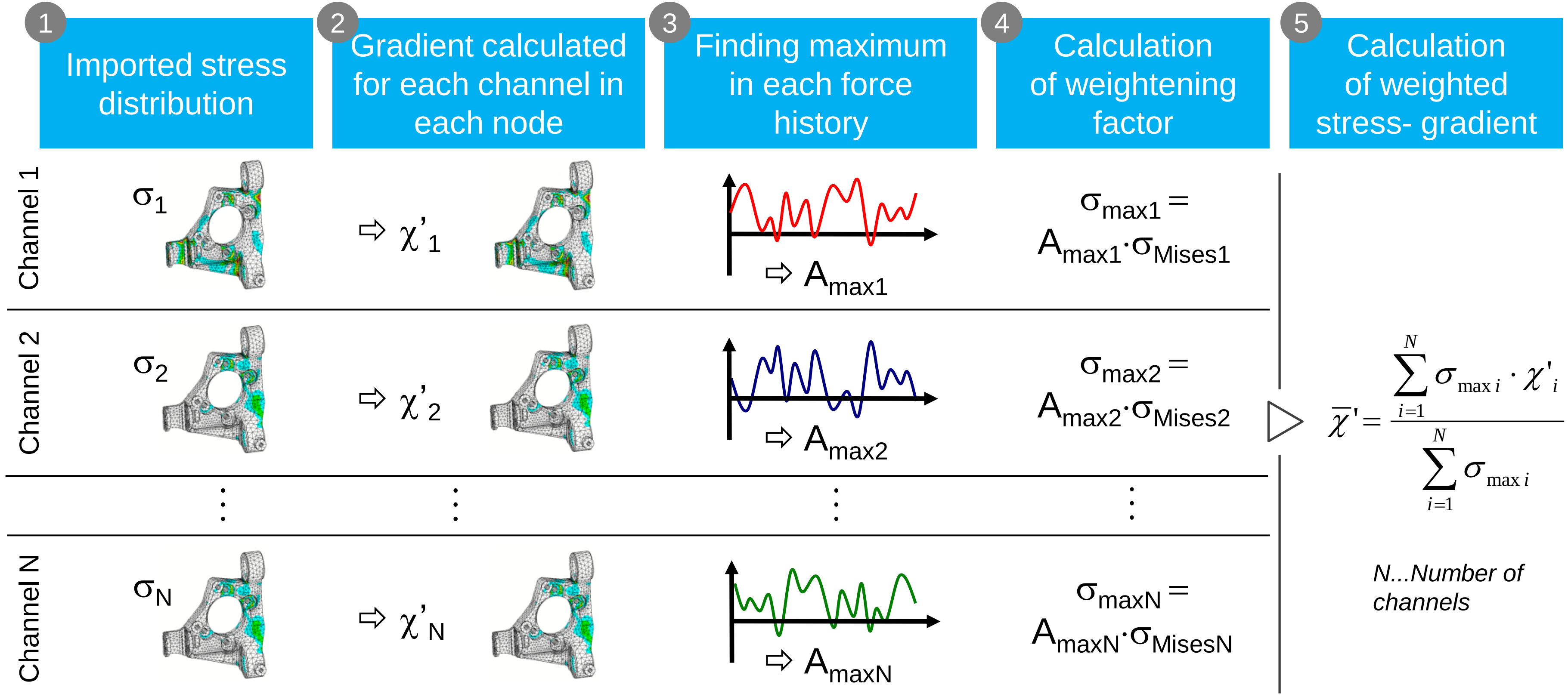




For the default setting “FEMFAT 2.4” the gradients at middle nodes are computed from the averaged gradients of the adjacent corner nodes.

Special Aspects in ChannelMAX

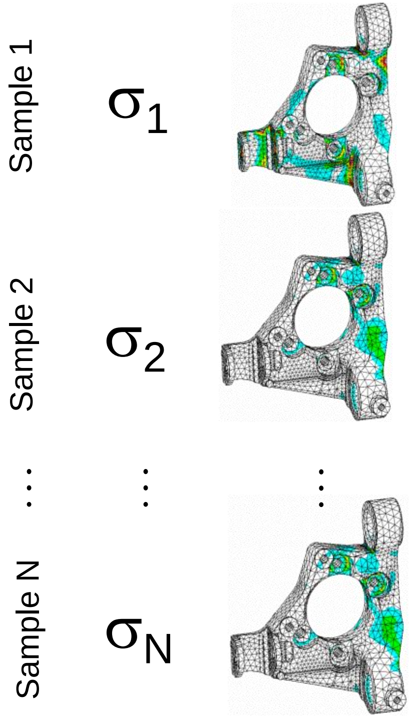
ChannelMAX Gradient Analysis Old Method (“FEMFAT 2.4”)



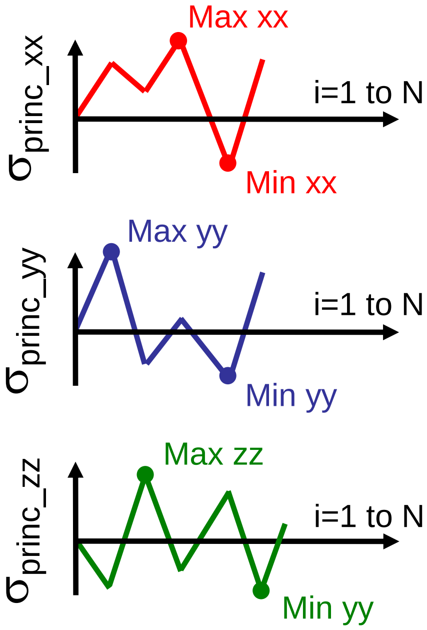
	1 Imported stress distribution	2 Gradient calculated for each channel in each node	3 Finding maximum in each force history	4 Calculation of weighting factor	5 Calculation of weighted stress- gradient
Channel 1	σ_1	⇨ χ'_1	⇨ A_{max1}	$\sigma_{max1} = A_{max1} \cdot \sigma_{Mises1}$	▷ $\bar{\chi}' = \dfrac{\sum_{i=1}^{N} \sigma_{\max i} \cdot \chi'_i}{\sum_{i=1}^{N} \sigma_{\max i}}$ *N...Number of channels*
Channel 2	σ_2	⇨ χ'_2	⇨ A_{max2}	$\sigma_{max2} = A_{max2} \cdot \sigma_{Mises2}$	
	⋮	⋮	⋮	⋮	
Channel N	σ_N	⇨ χ'_N	⇨ A_{maxN}	$\sigma_{maxN} = A_{maxN} \cdot \sigma_{MisesN}$	

ChannelMAX Gradient Analysis New Method (“Vector Reconstruction“)

1 Superimposed stresses



2 Calculation of principal stress histories



3 Find 3 σ_{Max} and 3 σ_{Min}, one for each principal stress history

4 From nine possible combinations of 3 σ_{Max} and 3 σ_{Min} …

5 … calculate Nine „Difference-Tensors“ $\Delta\sigma = \sigma_{Max} - \sigma_{Min}$

6 Calculation of nine Mises stress amplitudes

Gradient is calculated for the two time steps that cause the biggest Mises stress amplitude.

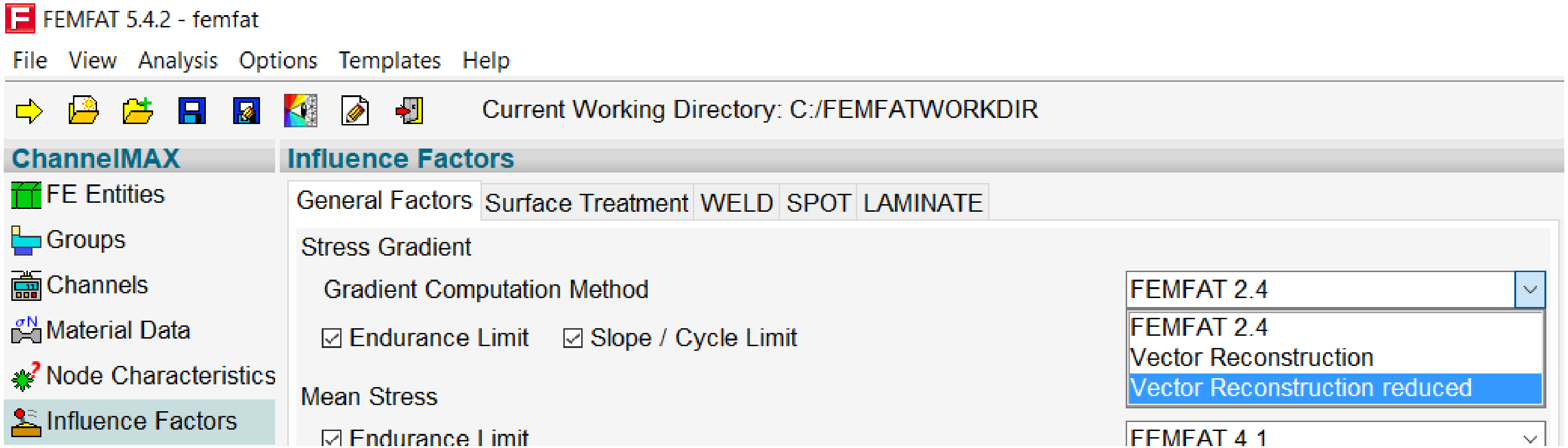
Consequences of the “Vector Reconstruction” in ChannelMAX

- Usage of superimposed stresses **before** gradient computation & cutting plane analysis ensures the invariance of the Stress Gradient with respect to the analysis type (inertia relief or statically determined boundary conditions)

- Equivalent method to TransMAX and therefore identical results for identical loading.

- “Vector Reconstruction reduced” for an accelerated analysis with less time steps considered for superposition, but mostly same accuracy.

“Vector Reconstruction reduced“ for accelerated Gradient Computation



Current Working Directory: C:/FEMFATWORKDIR

Influence Factors

Stress Gradient

Gradient Computation Method: FEMFAT 2.4

☑ Endurance Limit ☑ Slope / Cycle Limit

Mean Stress

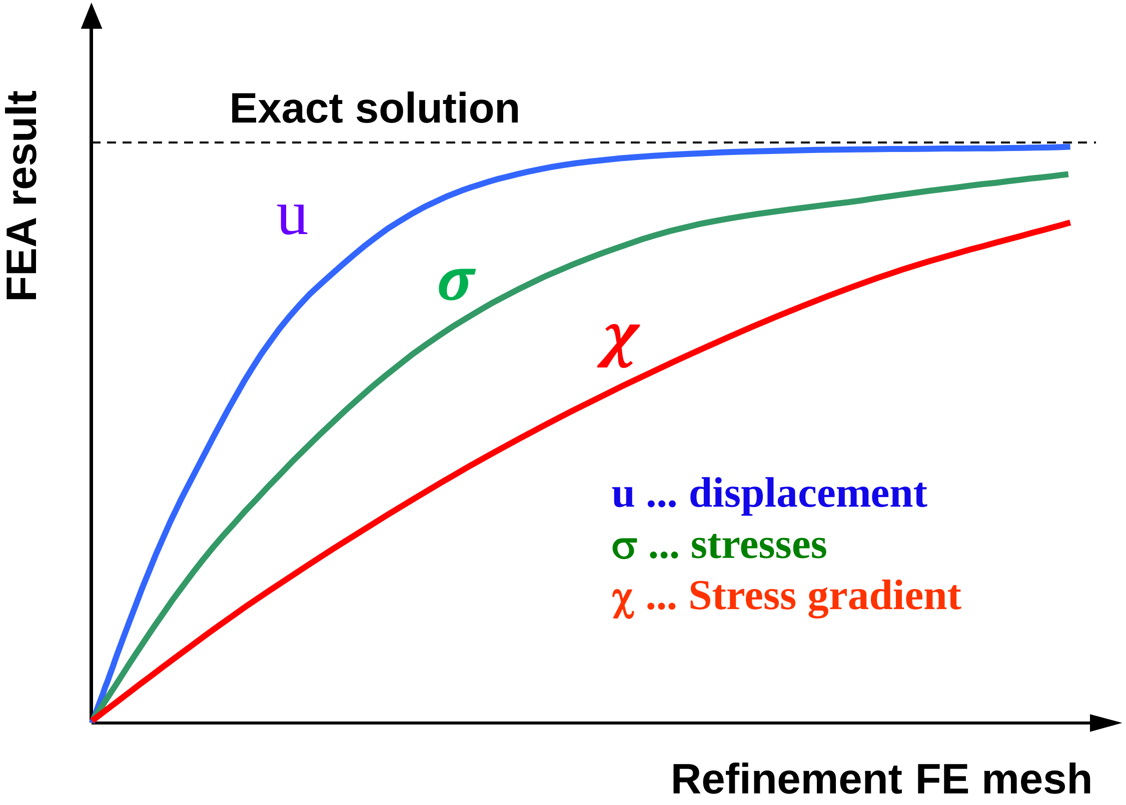
☑ Endurance Limit: FEMFAT 4.1

The “Vector Reconstruction reduced” method takes only the maximum and minimum points in time of the load history records into account (i.e. a maximum of 2x number of channels).

Comparison of Methods

Date: May 2021 / Author: Gerhard Spindelberger

Correlation between Accuracy and Type of Result

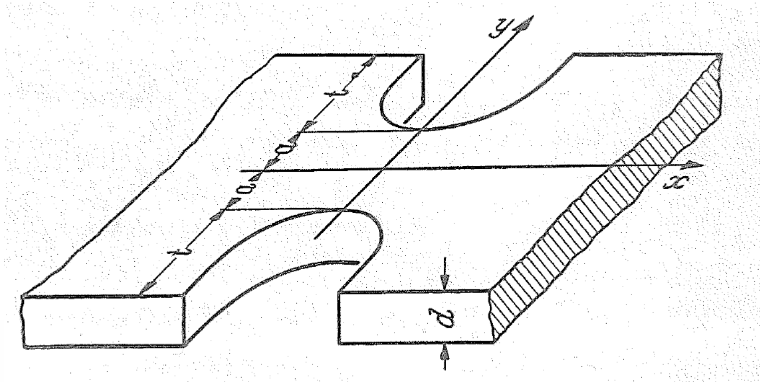


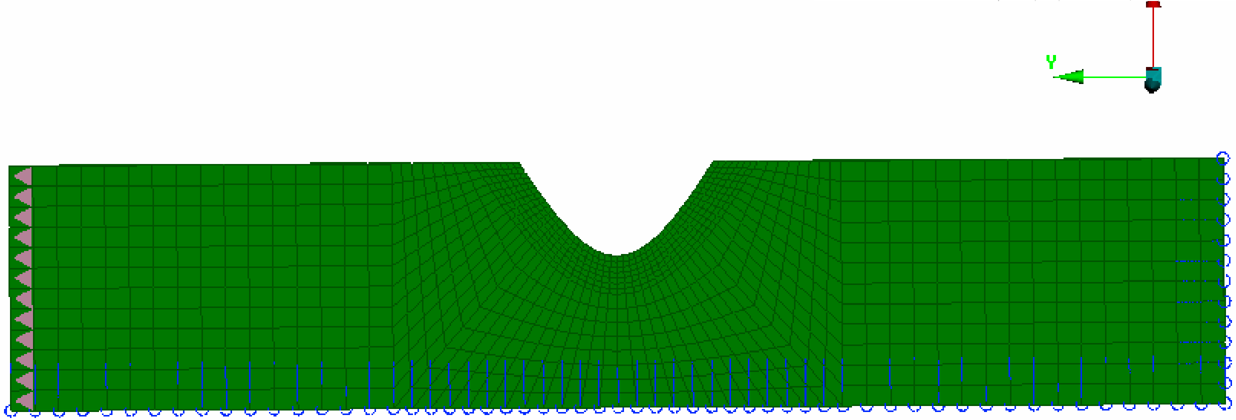
u ... displacement
σ ... stresses
χ ... Stress gradient

As a derived quantity (from displacements), stress is always less precise!

First Example: Hyperbolic Notch

We consider a specimen with hyperbolic notch under tensile loading for which analytical expressions for the stresses* are available. The focus is on the comparison of the different gradient methods in FEMFAT for several discretization levels.

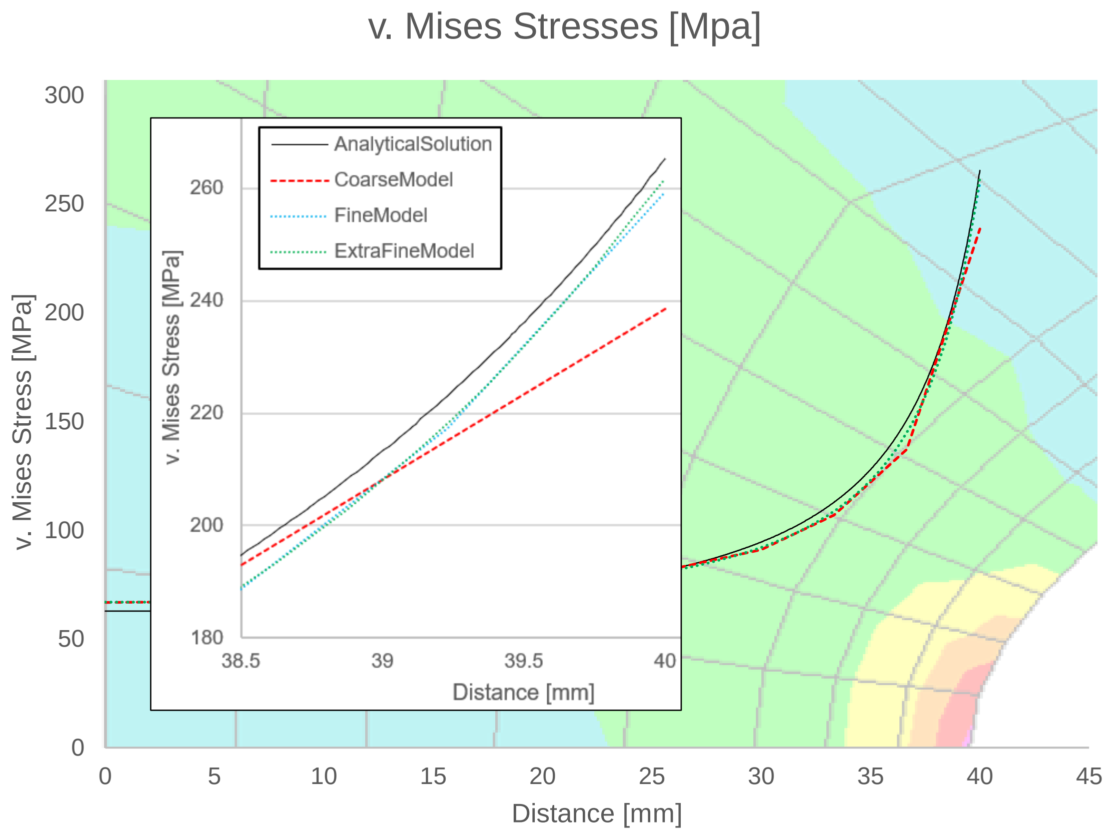


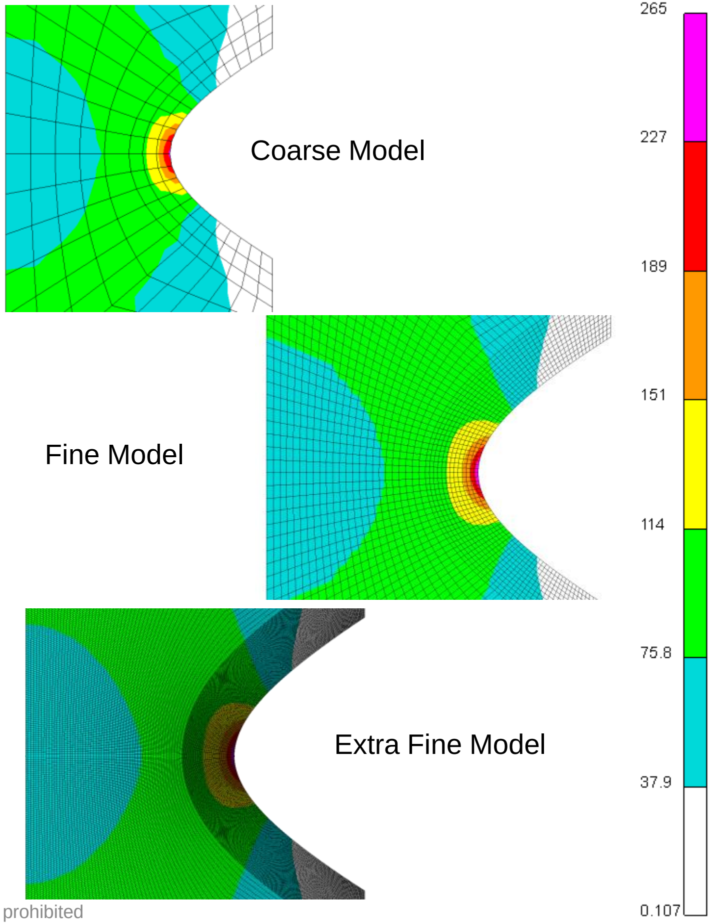


---

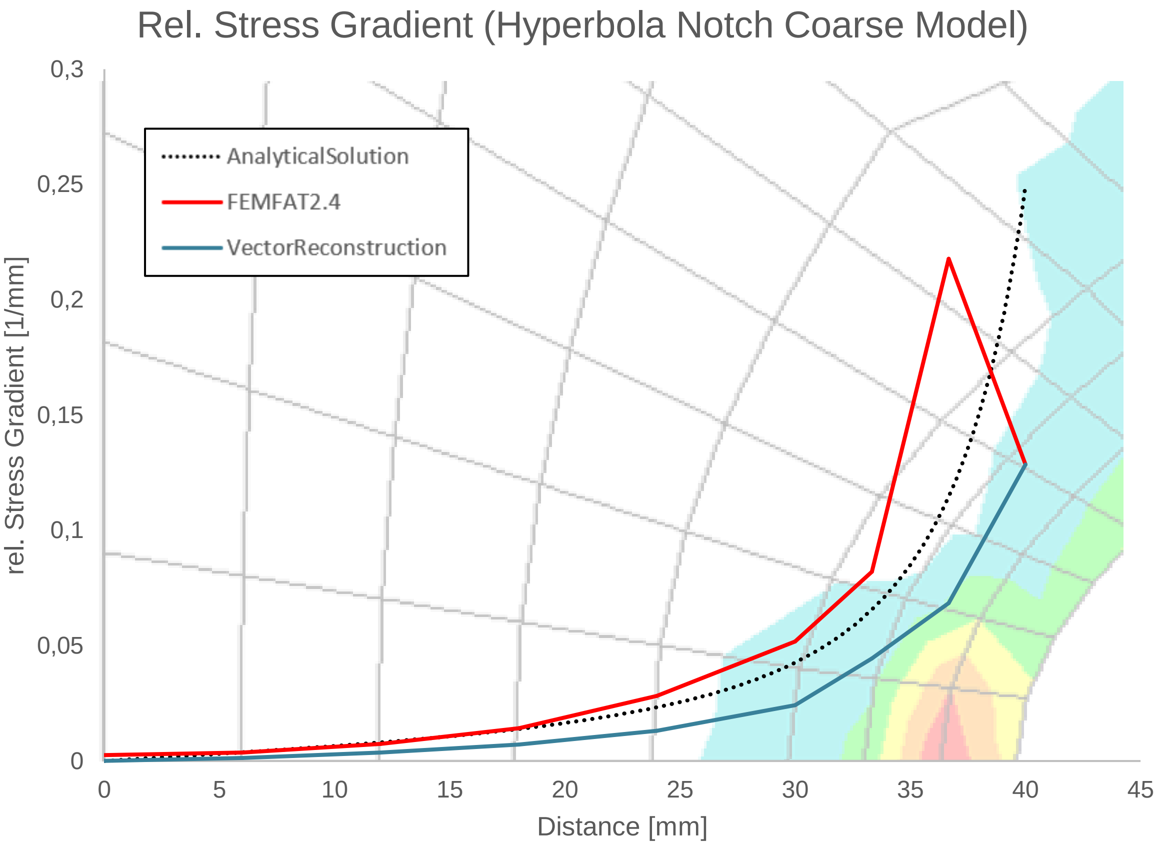
*Neuber H.: Kerbspannungslehre, 2. Auflage, Springer Verlag, Berlin / Göttingen / Heidelberg, 1958

Convergence Study

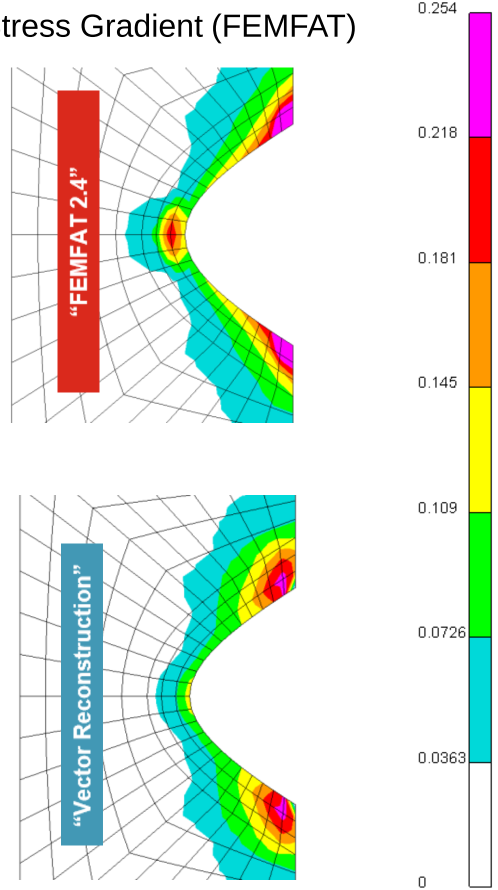




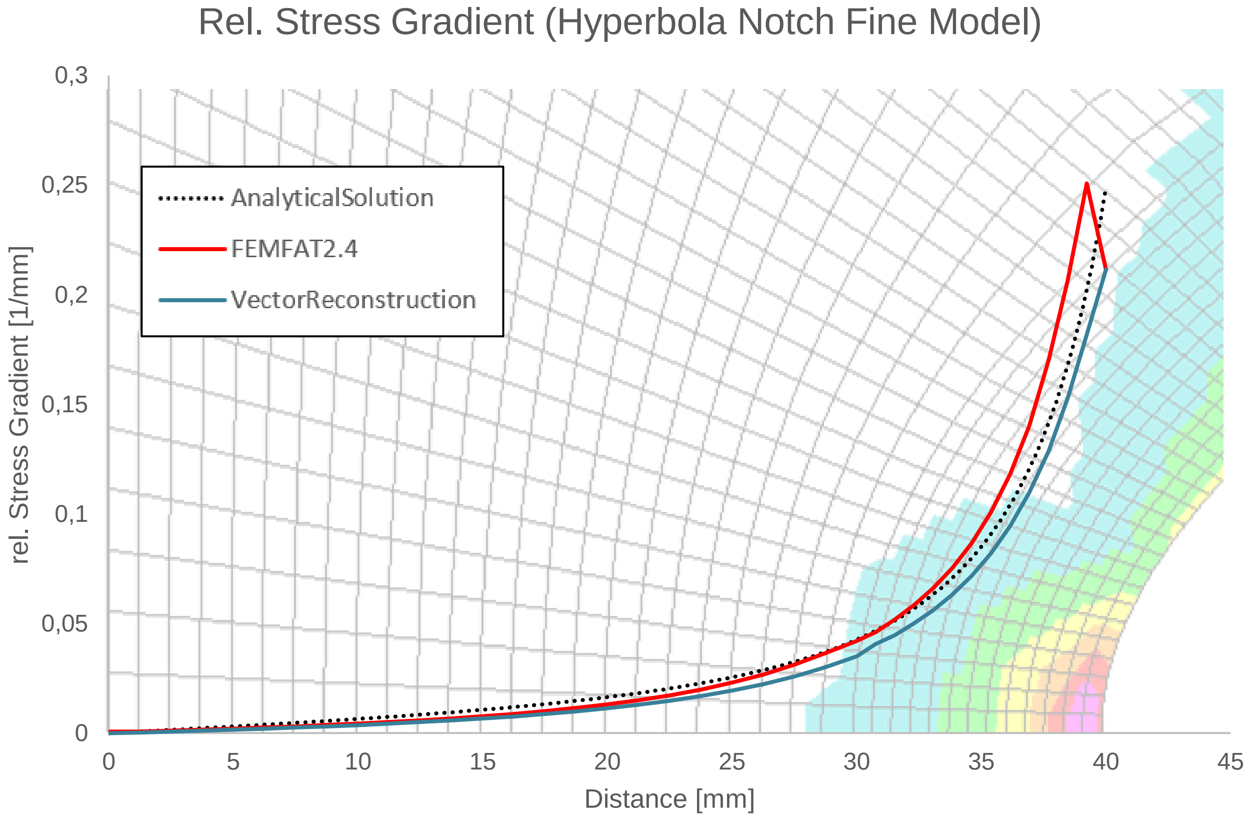
Gradient Comparison for Coarse Model

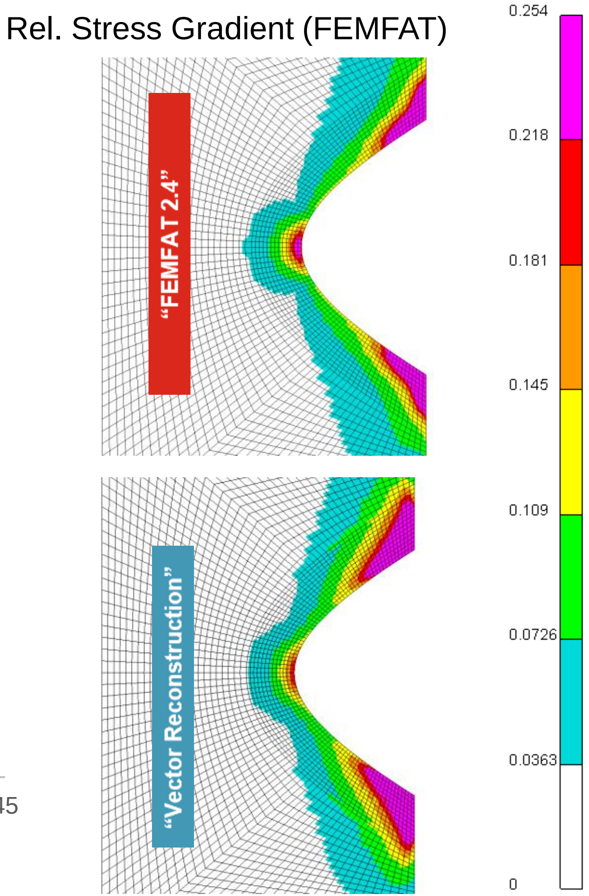


Rel. Stress Gradient (FEMFAT)

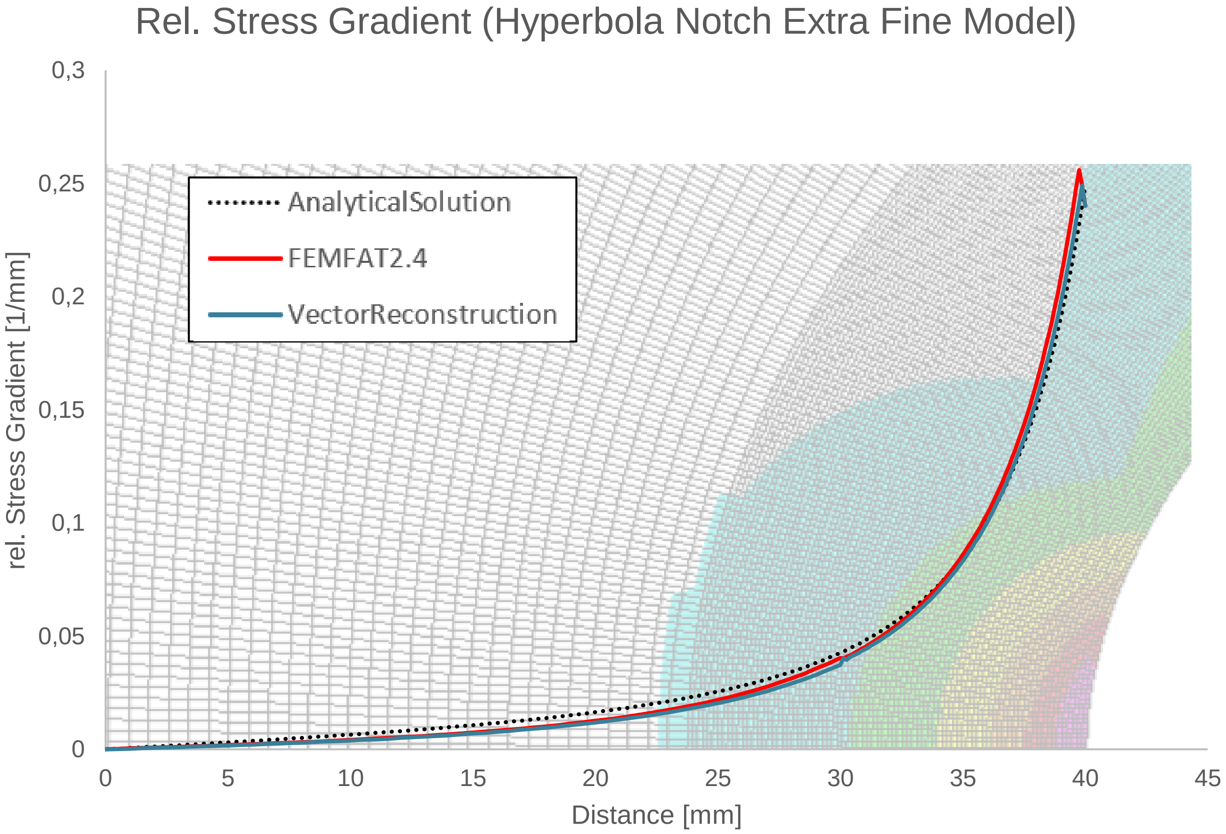


Comparison for Fine Model

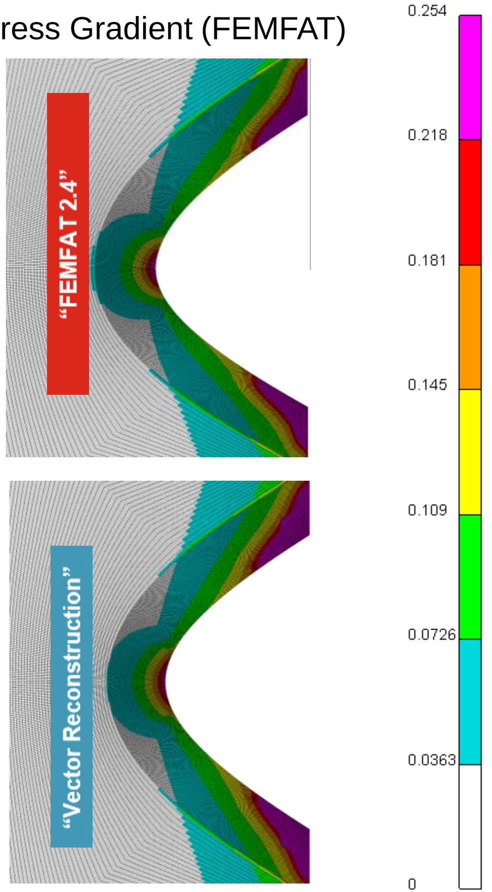




Comparison for Extra Fine Model


Rel. Stress Gradient (Hyperbola Notch Extra Fine Model)

Rel. Stress Gradient (FEMFAT)



Case Study

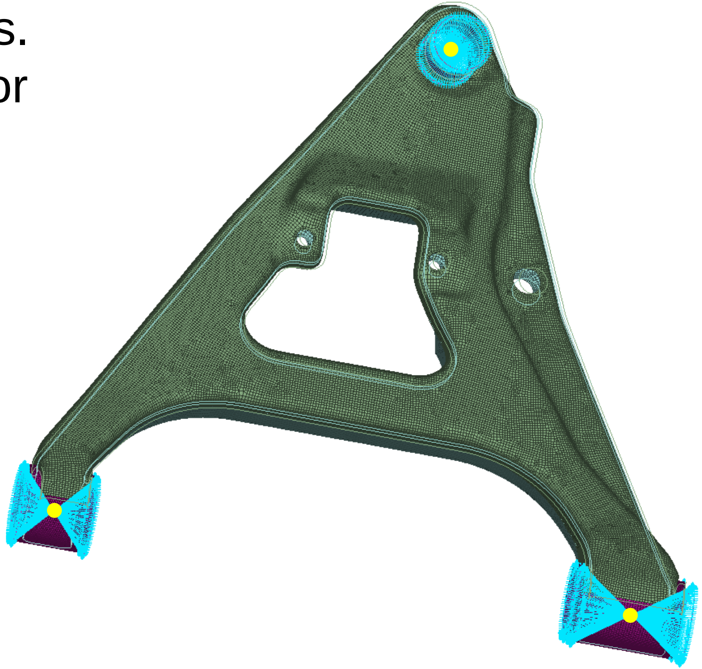
Date: May 2021 / Author: Gerhard Spindelberger

Control Arm Case Study

Task:
We consider a control arm modeled from shell elements. In FEA we analyse a total of 18 unit load cases (i.e. 6 for each interface node).

The subsequent fatigue analyses are carried out in ChannelMAX using random load histories for each channel.

The focus is on the comparison of damage results for different gradient methods (default “FEMFAT 2.4” and “Vector Reconstruction” resp.)



Number of Elements	~84000
Number of Nodes	~86000

Control Arm Case Study

Since in ChannelMAX the gradient is now calculated based on the superposed stress tensors, we also want to investigate the influence of the simulation method.

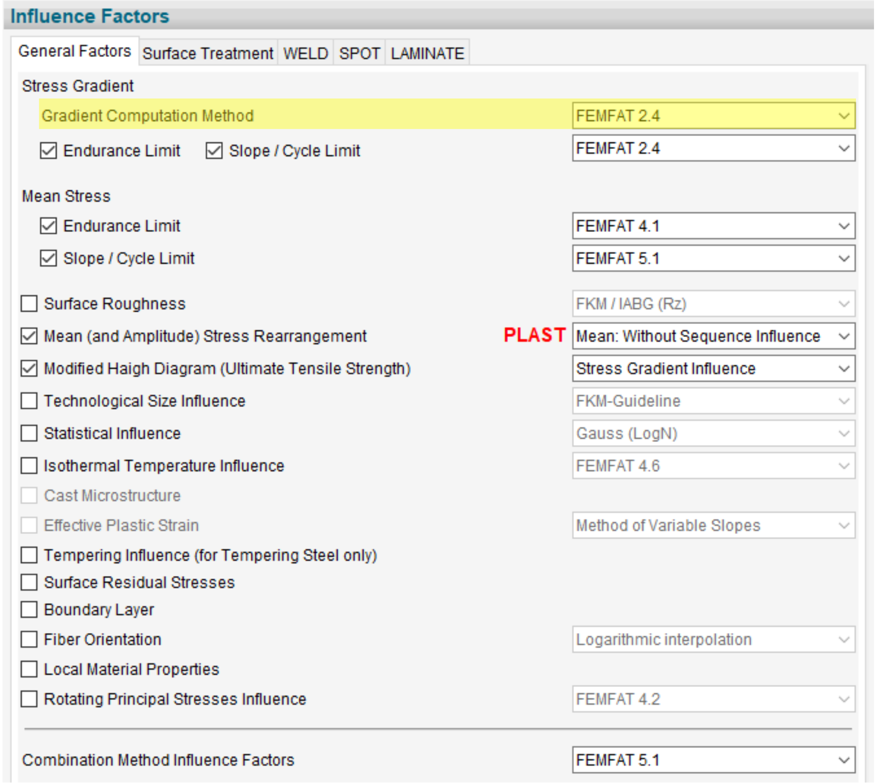
For this purpose, we use two different approaches in finite element analysis: Inertia Relief and Statically Determined Boundary Conditions.

Therefore we get four different fatigue analyses in ChannelMAX:

	“FEMFAT 2.4”	“Vector Reconstruction”
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4

ChannelMAX Settings

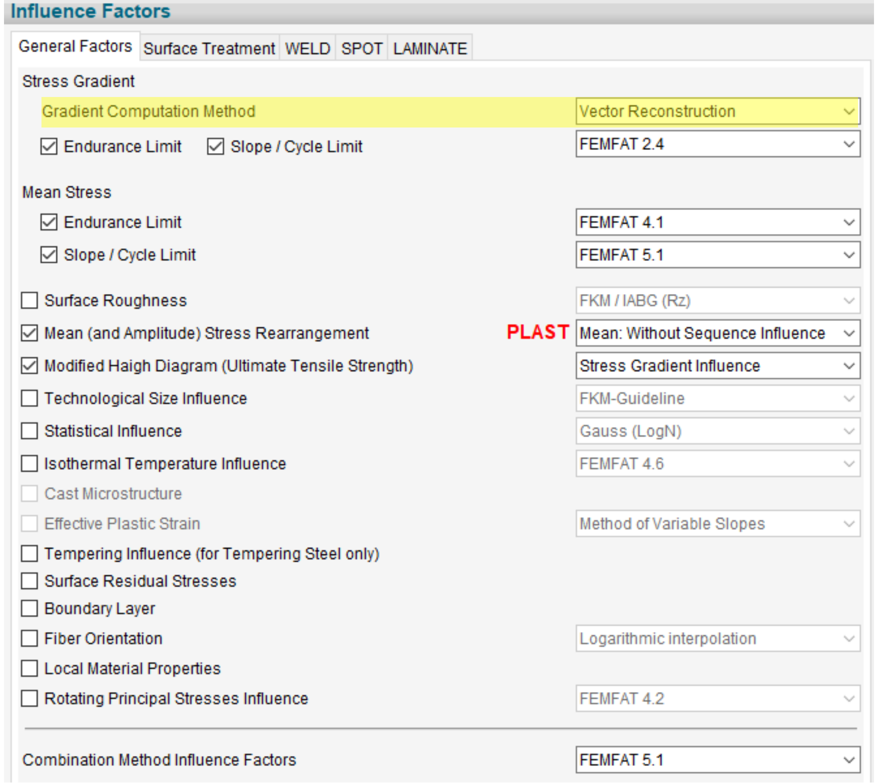
“FEMFAT 2.4”



Influence Factors

Stress Gradient	
Gradient Computation Method	FEMFAT 2.4
☑ Endurance Limit ☑ Slope / Cycle Limit	FEMFAT 2.4
Mean Stress	
☑ Endurance Limit	FEMFAT 4.1
☑ Slope / Cycle Limit	FEMFAT 5.1
☐ Surface Roughness	FKM / IABG (Rz)
☑ Mean (and Amplitude) Stress Rearrangement **PLAST**	Mean: Without Sequence Influence
☑ Modified Haigh Diagram (Ultimate Tensile Strength)	Stress Gradient Influence
☐ Technological Size Influence	FKM-Guideline
☐ Statistical Influence	Gauss (LogN)
☐ Isothermal Temperature Influence	FEMFAT 4.6
☐ Cast Microstructure	
☐ Effective Plastic Strain	Method of Variable Slopes
☐ Tempering Influence (for Tempering Steel only)	
☐ Surface Residual Stresses	
☐ Boundary Layer	
☐ Fiber Orientation	Logarithmic interpolation
☐ Local Material Properties	
☐ Rotating Principal Stresses Influence	FEMFAT 4.2
Combination Method Influence Factors	FEMFAT 5.1

“Vector Reconstruction”



Influence Factors

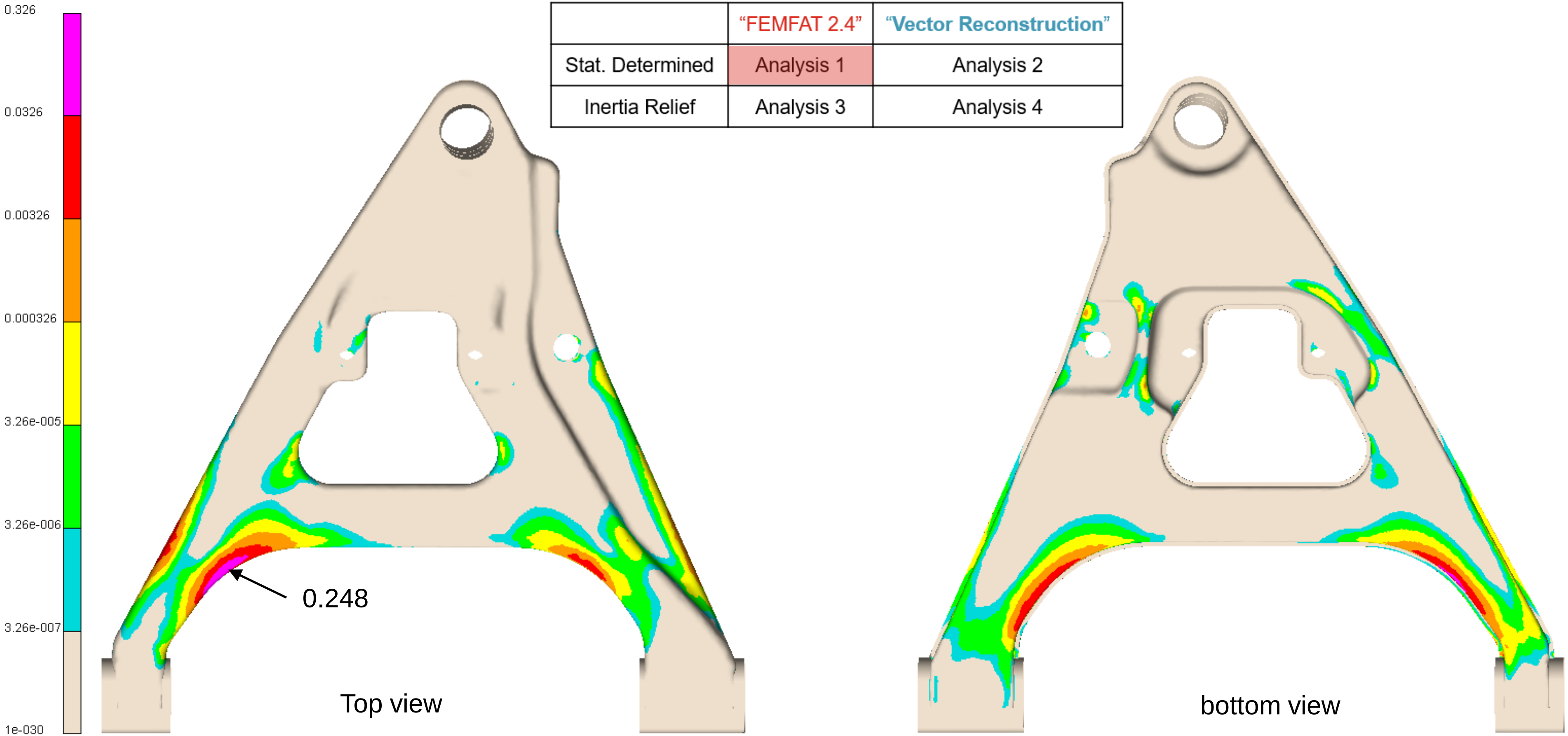
Stress Gradient	
Gradient Computation Method	Vector Reconstruction
☑ Endurance Limit ☑ Slope / Cycle Limit	FEMFAT 2.4
Mean Stress	
☑ Endurance Limit	FEMFAT 4.1
☑ Slope / Cycle Limit	FEMFAT 5.1
☐ Surface Roughness	FKM / IABG (Rz)
☑ Mean (and Amplitude) Stress Rearrangement **PLAST**	Mean: Without Sequence Influence
☑ Modified Haigh Diagram (Ultimate Tensile Strength)	Stress Gradient Influence
☐ Technological Size Influence	FKM-Guideline
☐ Statistical Influence	Gauss (LogN)
☐ Isothermal Temperature Influence	FEMFAT 4.6
☐ Cast Microstructure	
☐ Effective Plastic Strain	Method of Variable Slopes
☐ Tempering Influence (for Tempering Steel only)	
☐ Surface Residual Stresses	
☐ Boundary Layer	
☐ Fiber Orientation	Logarithmic interpolation
☐ Local Material Properties	
☐ Rotating Principal Stresses Influence	FEMFAT 4.2
Combination Method Influence Factors	FEMFAT 5.1

Results Comparison for Different Gradient Methods

Damage Results

“FEMFAT 2.4”

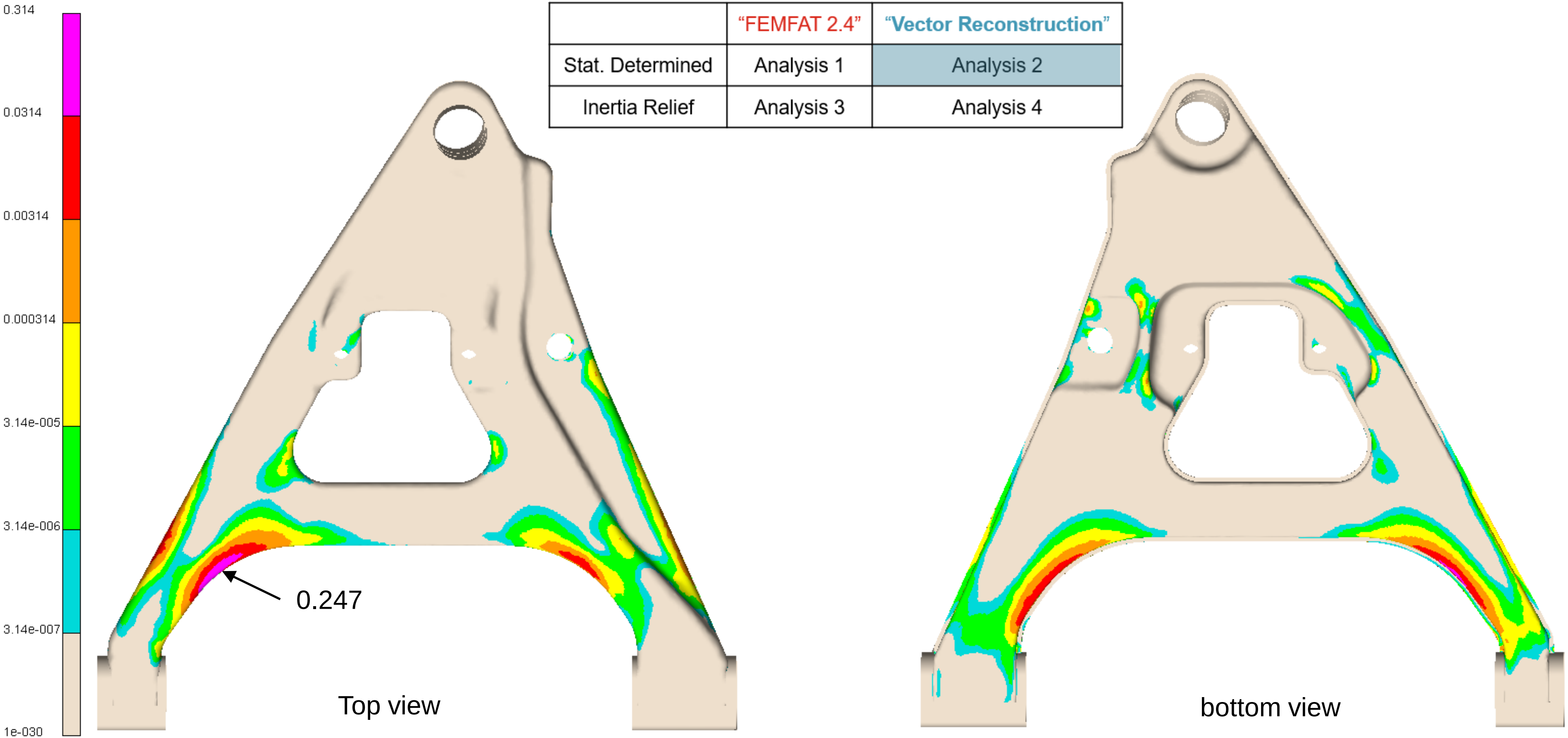
	“FEMFAT 2.4”	“Vector Reconstruction”
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4



Damage Results

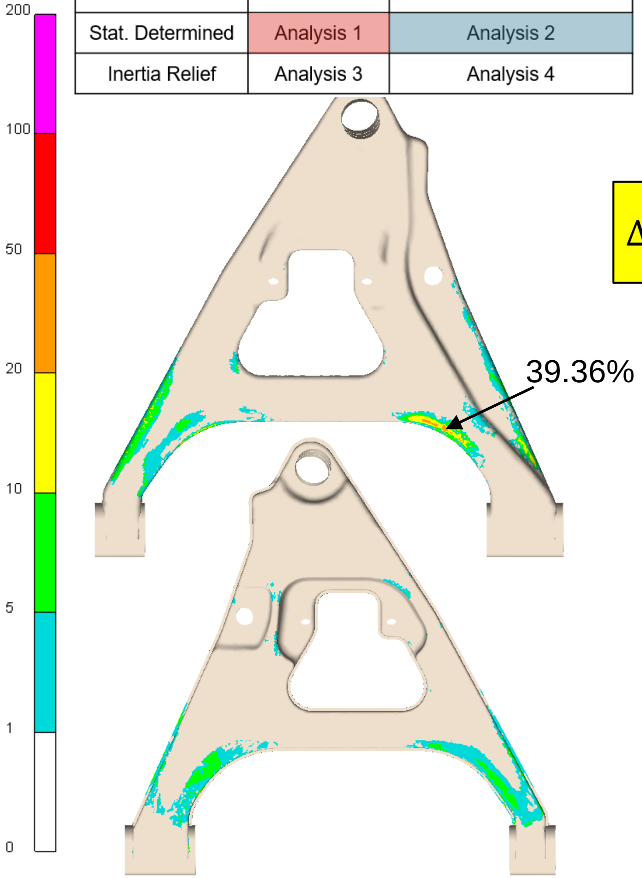
“Vector Reconstruction”

	“FEMFAT 2.4”	“Vector Reconstruction”
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4



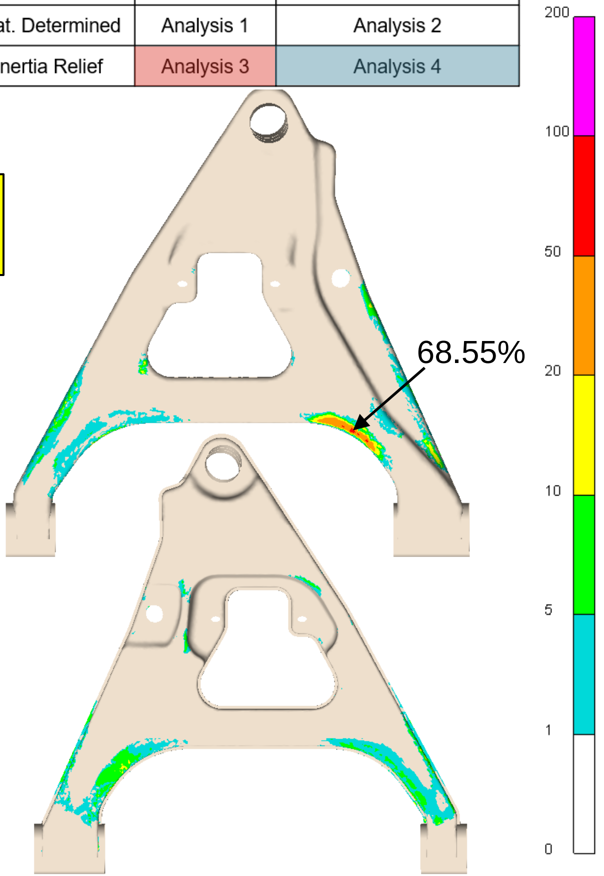
Damage Discrepancy Δ_{Damage}

	"FEMFAT 2.4"	"Vector Reconstruction"
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4



$$\Delta_{Damage} := 100 * \left|\frac{D_{Femat24} - D_{VectorRec}}{D_{Femat24}}\right|$$

	"FEMFAT 2.4"	"Vector Reconstruction"
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4



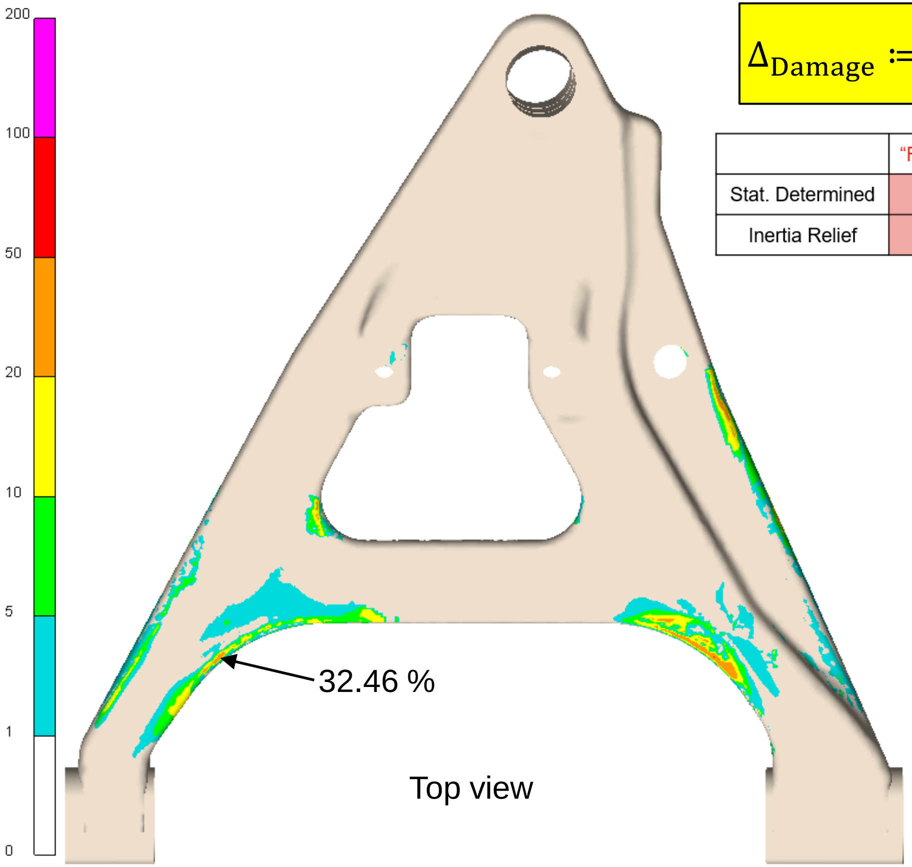
Results Comparison for FEA Simulation Methods

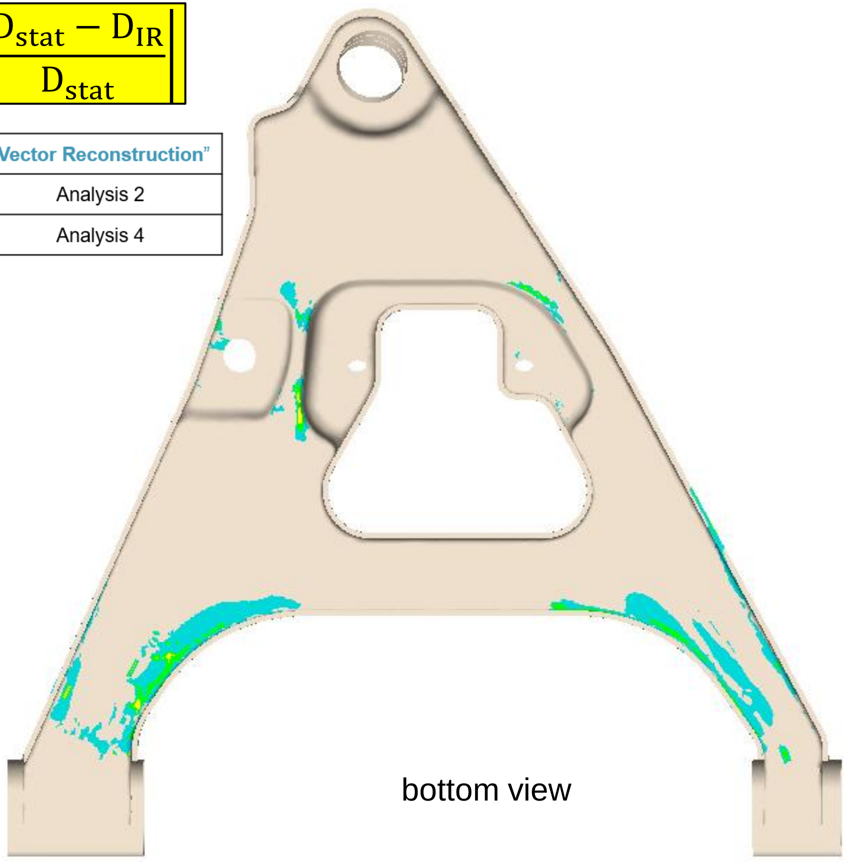
Damage Discrepancy Δ_{Damage}

”FEMFAT 2.4“

$$\Delta_{\text{Damage}} := 100 * \left|\frac{D_{\text{stat}} - D_{\text{IR}}}{D_{\text{stat}}}\right|$$

	“FEMFAT 2.4”	“Vector Reconstruction”
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4

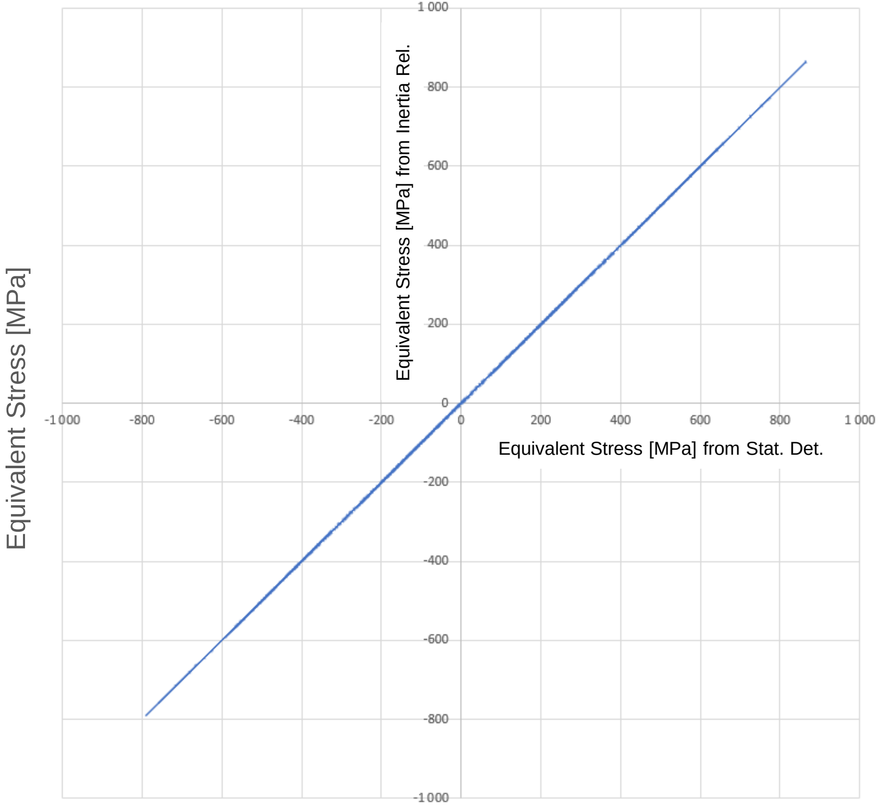




Results Node 1 (max. Damage)

”FEMFAT 2.4“

Local Equivalent Stress History



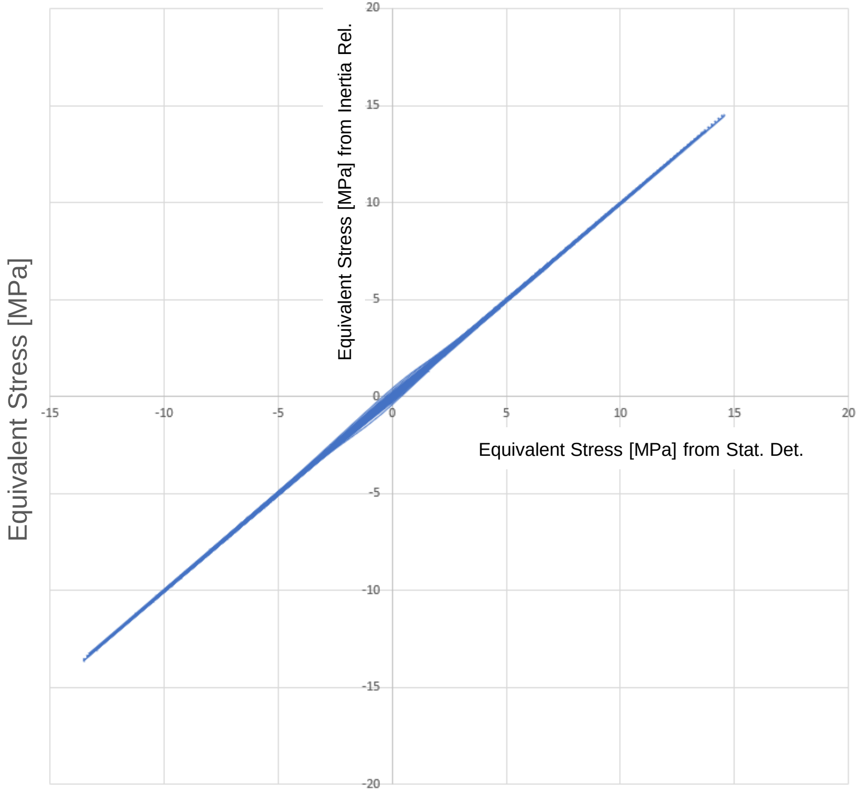
Detailed Local Results

	Inertia Relief	Statically Determined	
Damage [-]	0.1672	0.248	✗
Rel. Stress Gradient [1/mm]	0.0677	0.048	✗
Stress Ampl. [MPa]	835.1	835.1	✓
Mean Stress [MPa]	5.32	5.32	✓
Local Fatigue Limit [MPa]	290.9	288.7	✗
Local Slope [-]	10.96	11.31	✗
Local Cycle Limit [-]	1.903E06	1.935E06	✗

Results Node 2 (max. Gradient)

”FEMFAT 2.4“

Local Equivalent Stress History



Detailed Local Results

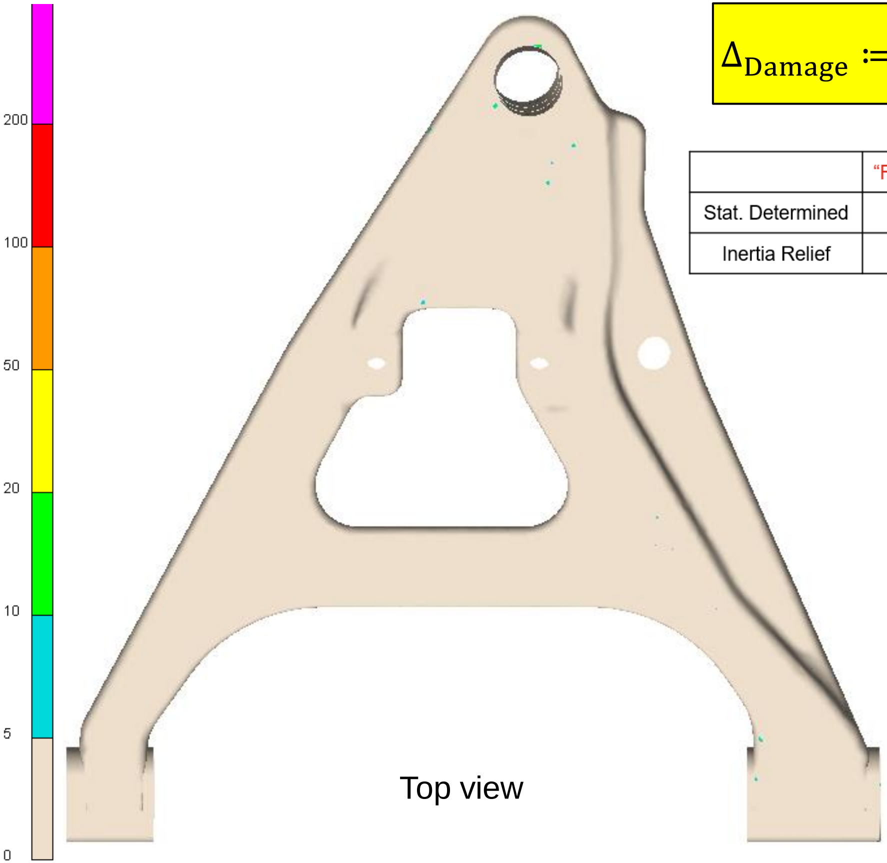
	Inertia Relief	Statically Determined	
Damage [-]	1.566E-13	5.074E-13	✗
Rel. Stress Gradient [1/mm]	2.616	5.455	✗
Stress Ampl. [MPa]	14.27	14.08	✓
Mean Stress [MPa]	0.46	0.46	✓
Local Fatigue Limit [MPa]	383.4	440.8	✗
Local Slope [-]	3.34	3.095	✗
Local Cycle Limit [-]	5.757E05	5.029E05	✗

Date: May 2021 / Author: Gerhard Spindelberger

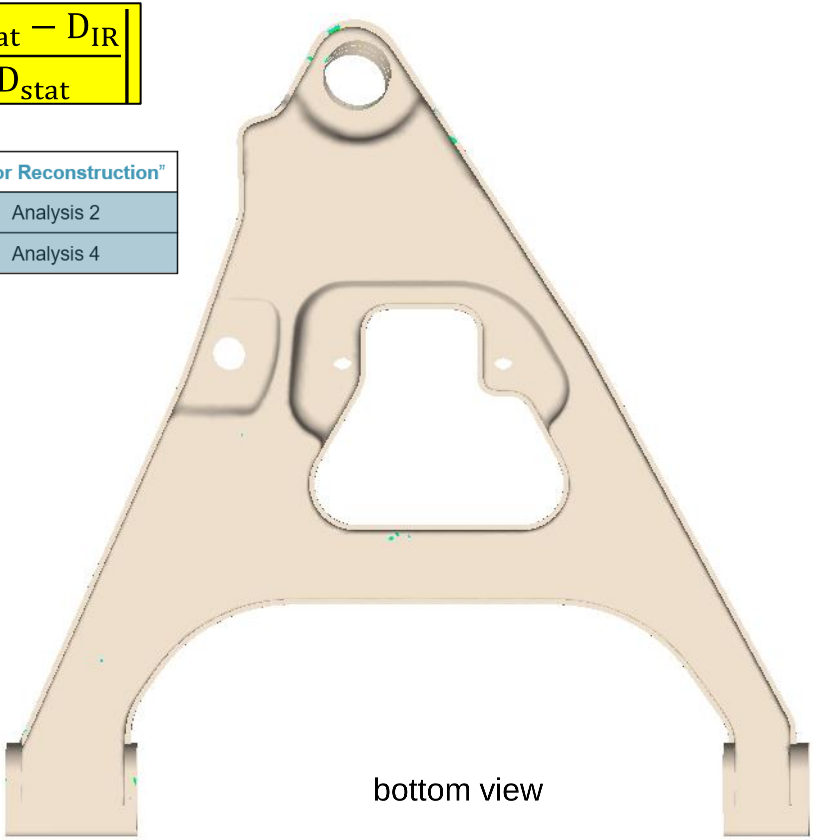
Damage Discrepancy Δ_{Damage} "Vector Reconstruction"

$$\boxed{\Delta_{\text{Damage}} := 100 * \left| \frac{D_{\text{stat}} - D_{\text{IR}}}{D_{\text{stat}}} \right|}$$

	"FEMFAT 2.4"	"Vector Reconstruction"
Stat. Determined	Analysis 1	Analysis 2
Inertia Relief	Analysis 3	Analysis 4



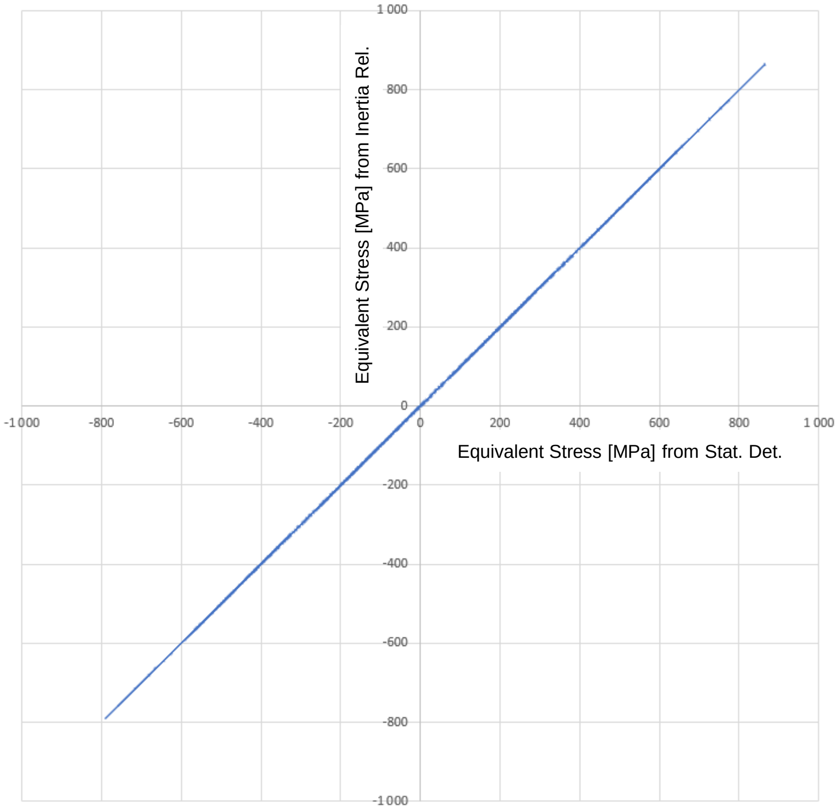
Top view



bottom view

Results Node 1 (max. Damage) “Vector Reconstruction”

Local Equivalent Stress History

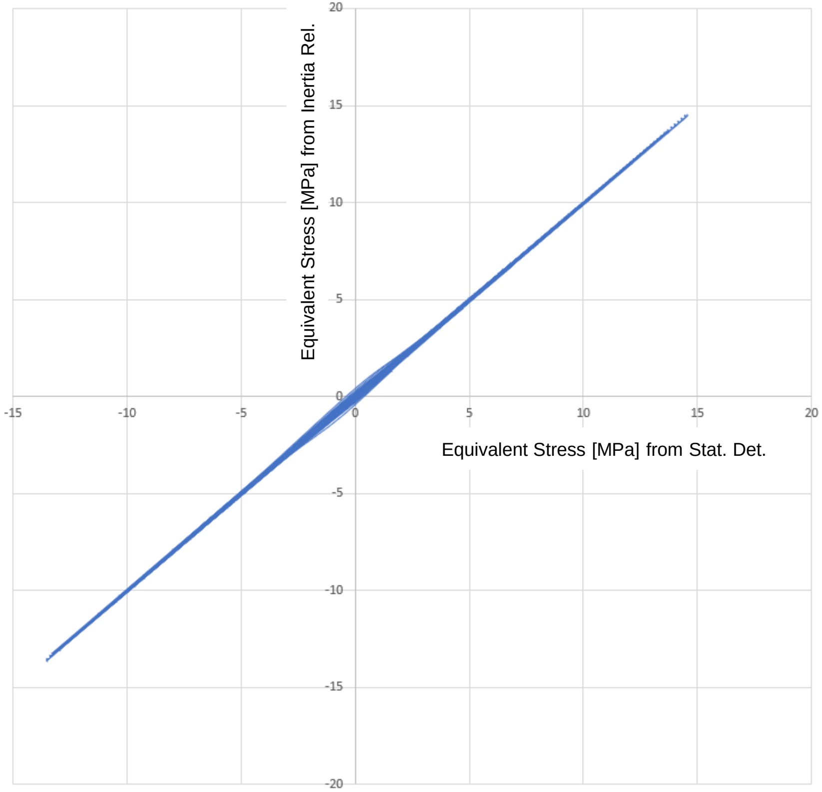


Detailed Local Results

	Inertia Relief	Statically Determined	
Damage [-]	0.247	0.247	✓
Rel. Stress Gradient [1/mm]	0.047	0.047	✓
Stress Ampl. [MPa]	825.9	825.9	✓
Mean Stress [MPa]	9.62	9.62	✓
Local Fatigue Limit [MPa]	288.1	288.1	✓
Local Slope [-]	11.39	11.39	✓
Local Cycle Limit [-]	1.936E06	1.936E06	✓

Results Node 2 (max. Gradient)“Vector Reconstruction”

Local Equivalent Stress History



Detailed Local Results

	Inertia Relief	Statically Determined	
Damage [-]	4.82E-13	4.83E-13	✓
Rel. Stress Gradient [1/mm]	7.51	7.51	✓
Stress Ampl. [MPa]	14.05	14.03	✓
Mean Stress [MPa]	0.67	0.72	✓
Local Fatigue Limit [MPa]	474.7	474.7	✓
Local Slope [-]	3.055	3.055	✓
Local Cycle Limit [-]	4.906E05	4.906E05	✓

Performance of “Vector Reconstruction” Method

Control Arm example, single CPU run:

Analysis Duration	**“Vector Reconstruction”**	**Method “FEMFAT 2.4“**	**“Vector Reconstr. Reduced”**
Inertia Relief	650 sec	489 sec	477 sec
Statically Determined	561 sec	431 dec	429 sec

▶ The ratio seen here also applies in general: the “Vector Reconstruction” method leads to approximately 30% longer analysis running time.

Summary

Date: May 2021 / Author: Gerhard Spindelberger

Summary

- As of FEMFAT 5.4.2 a completely new method for relative stress gradient calculation (“Vector Reconstruction“) is available.

- The new method can be used in all modules with gradient computation (BASIC, MAX, SPECTRAL).

- Big advantage: identification of max. gradient, unified method for all modules, invariant for different simulation techniques (Inertia Relief or Statically Determined Boundary conditions).

- Two additional aspects for ChannelMAX:
  - Gradient is computed on basis of superimposed stress tensors (analoguous to TransMAX)
  - third method „Vector Reconstruction Reduced“ for improved performance

MAGNA

DRIVING **EXCELLENCE.**
INSPIRING **INNOVATION.**

Date: May 2021 / Author: Gerhard Spindelberger