



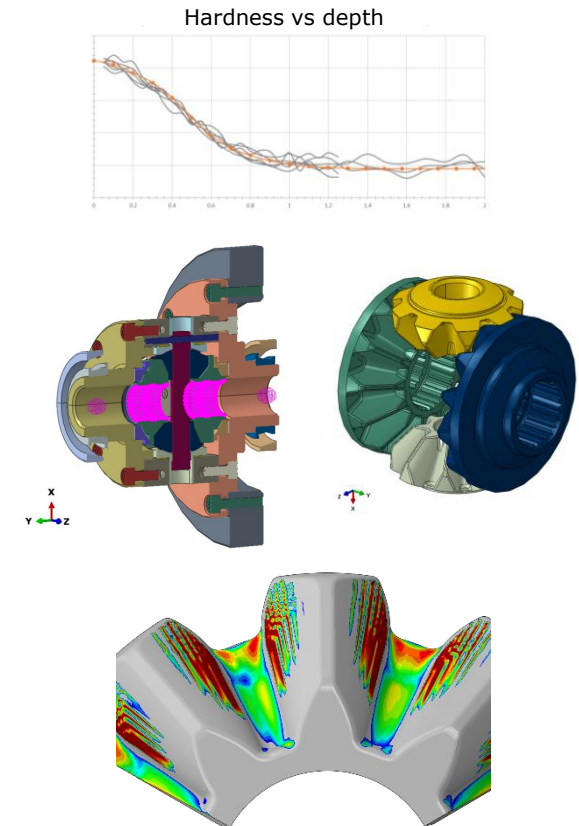
Method for fatigue prediction in differential gears and validation with hardware tests

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Content

- Introduction
- Case carburized material behavior and characterization
- Overview of differential gear FE model
- Diff gear root fatigue life correlation with specialized rig testing
- Diff gear root fatigue life correlation with full axle test
- Summary



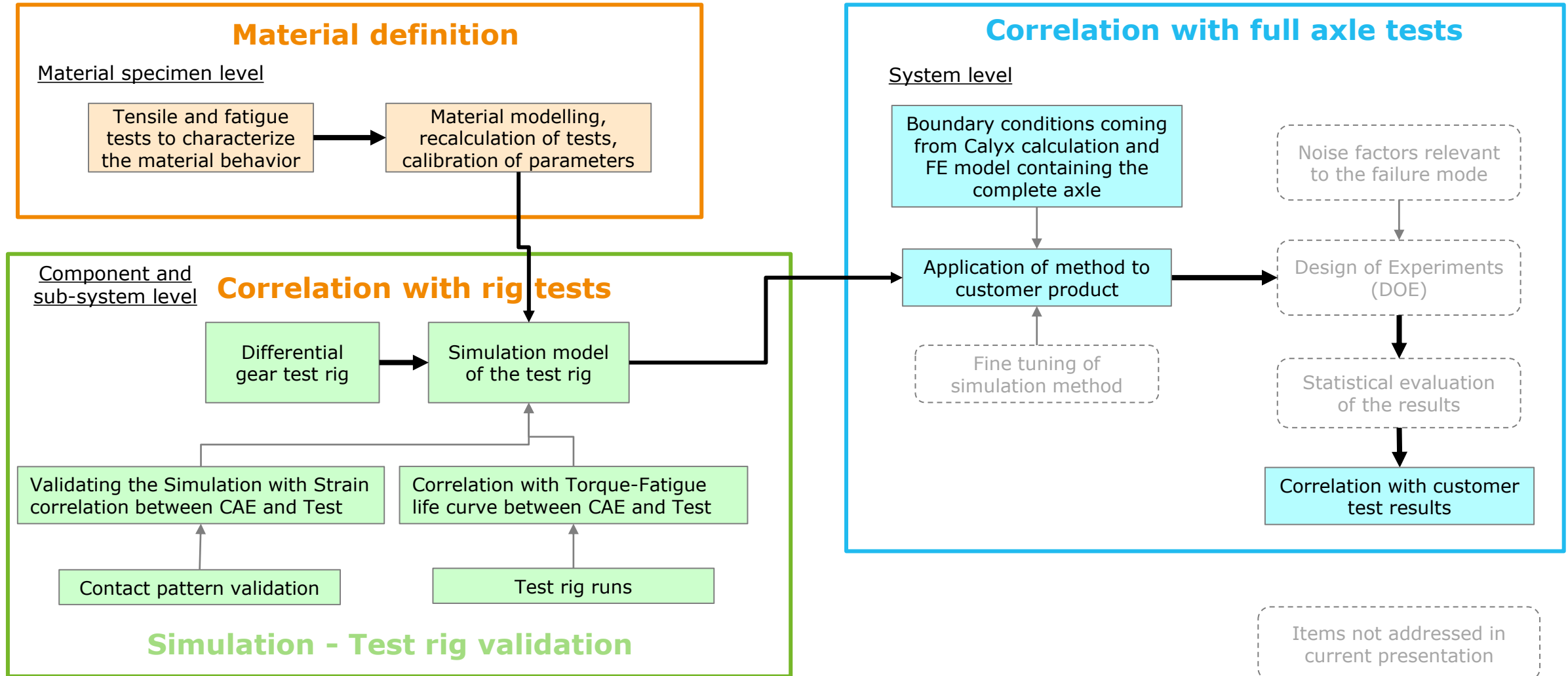
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Introduction

- Objective: Development of an accurate method to predict gear root bending fatigue life over a wide range of loading conditions in differential gear applications.
- Approach:
 - Material testing and development of hardness dependent material models representing conditions in case-carburized and other heat treatment conditions.
 - Development of fatigue models which distinguish crack initiation at case versus core over a wide range of load conditions.
 - Correlation of FE model and differential gear fatigue life predictions with a specialized rig test.
 - Confirmation of method and FE modeling by correlation with full axle tests.

Overview: Process for method development



Content

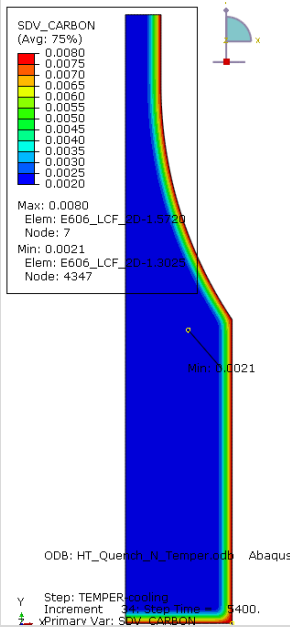
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Case carburized material behavior (inhomogeneous)

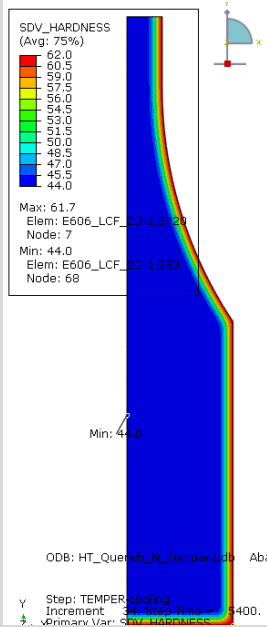
- Case carburizing is a heat treatment process used for gears and other applications where a very hard surface and a high strength case is required (while leaving a softer core).
- The process involves exposure at elevated temperature in atmosphere with high carbon content.
- This produces phase transformations with distinct differences in material behavior between case and core, producing a high gradient of hardness vs depth and residual stresses.

Results shown from simulations of heat treatment process for material test specimens using Dante

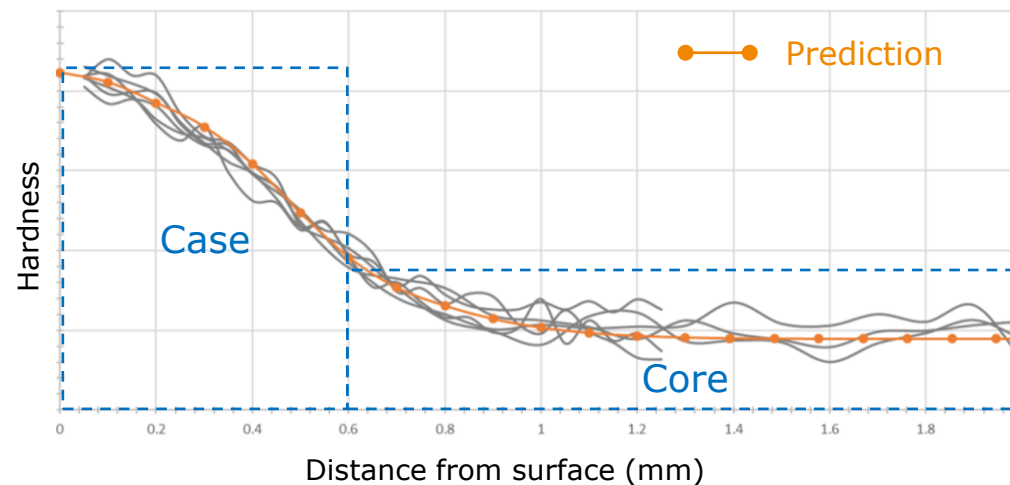
Carbon content



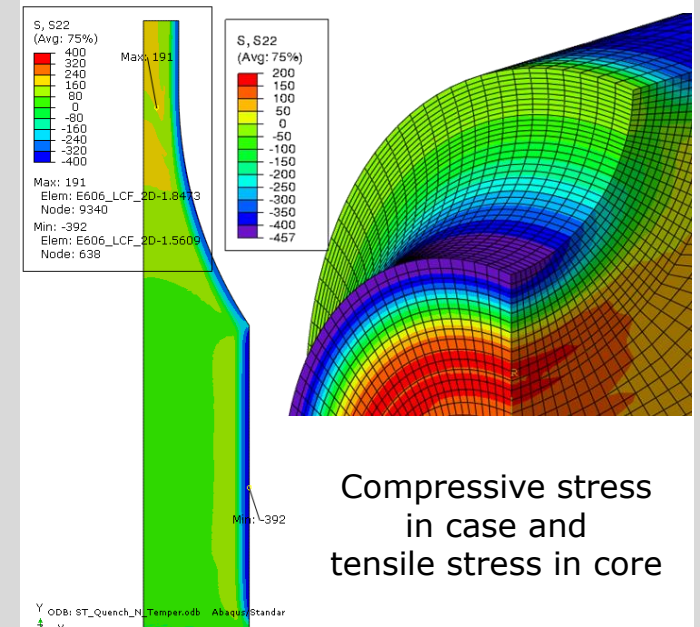
Hardness



Hardness vs Depth
(from simulation and measurements)

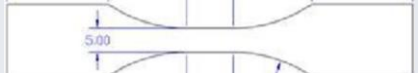
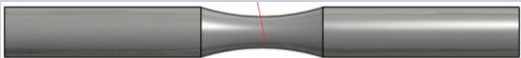


Residual stress (smooth and notched)



Material test program

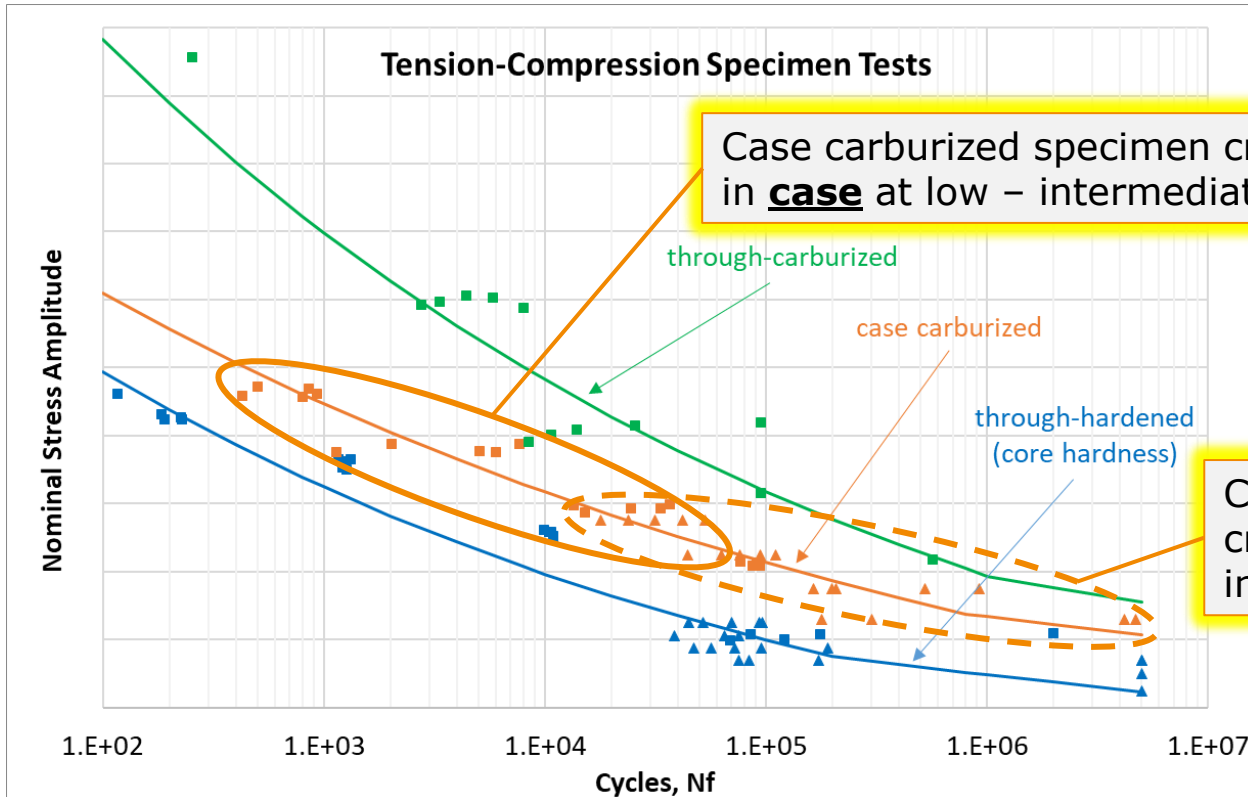
- An extensive material test program has been completed to characterize the material behavior with the goal to provide accurate fatigue life predictions accounting for the gradients in material behavior.
- Detailed FE models have been setup to simulate the tested conditions and characterize material behavior for all tested conditions.

Test condition	Test specimens	Case-carburized	Through-carburized	Through-hardened
Monotonic tension		✓	✓	✓
Tension-compression (strain control & load control)		✓	✓	✓
4-point bending (displacement & load control)		✓		
4-point bending notched (displacement & load control)		✓		
Pulsating tension (strain control & load control)		✓		

Fatigue tests with different heat treatment conditions

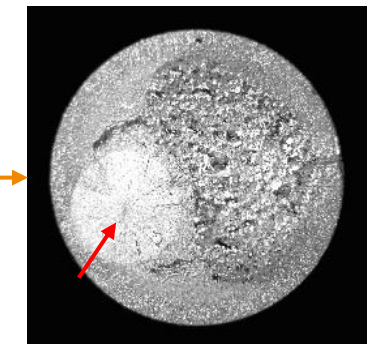
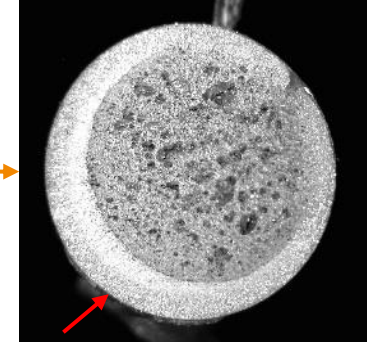
Case carburized fracture initiations at case versus core

Comparison of fatigue S-N behavior with different heat treatment conditions:
(Nominal stress = Force / Area)



Case carburized specimen cracks initiate in **case** at low – intermediate lives

Case carburized specimen cracks initiate in **core** at intermediate – long lives



Inhomogeneous properties for case-carburized condition results in different fracture initiation locations: case versus core (also influenced by inclusions). For notch tests (not shown here), crack origins are in case (at or near surface).

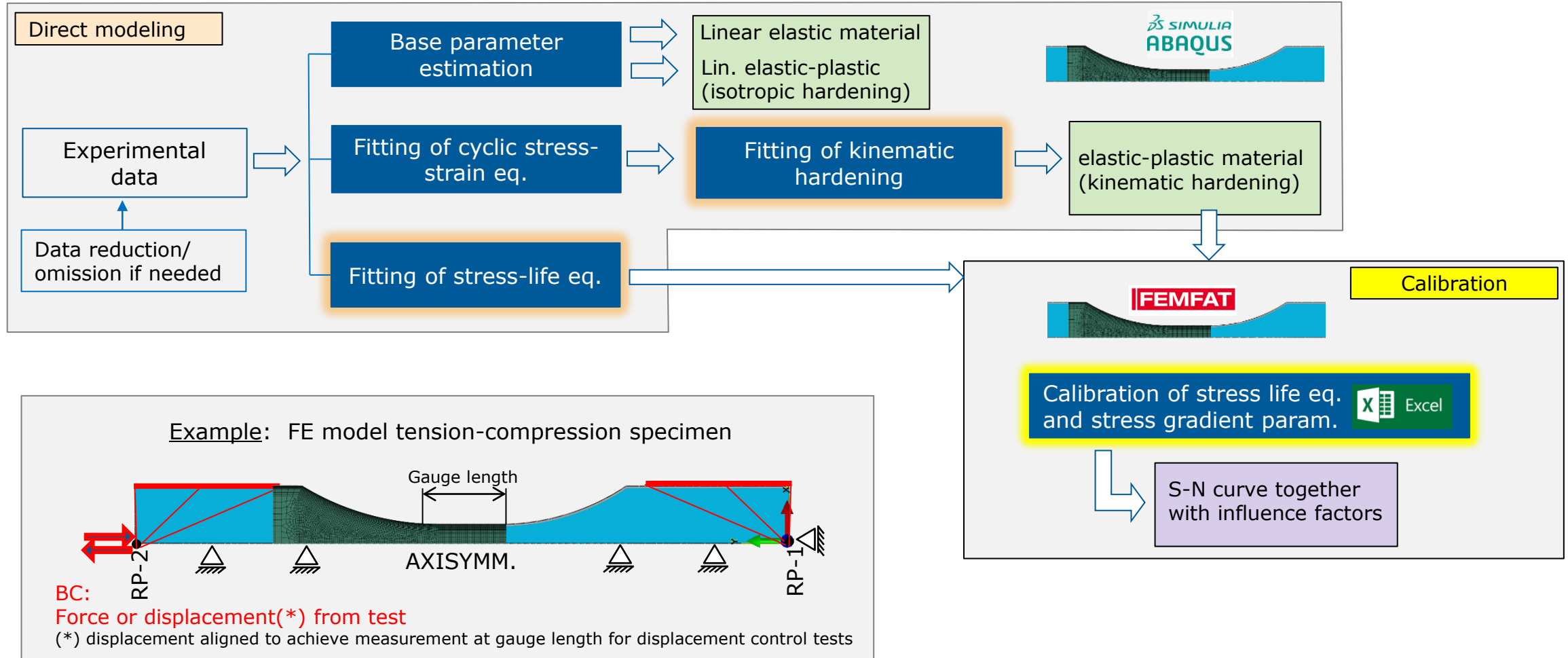
Material modeling workflow

To characterize elastic-plastic and fatigue life behavior

Material models
in ABAQUS

Material models
in FEMFAT

Direct modeling and calibration workflow to develop material models

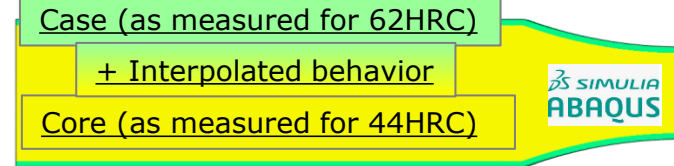


Case carburized material modeling

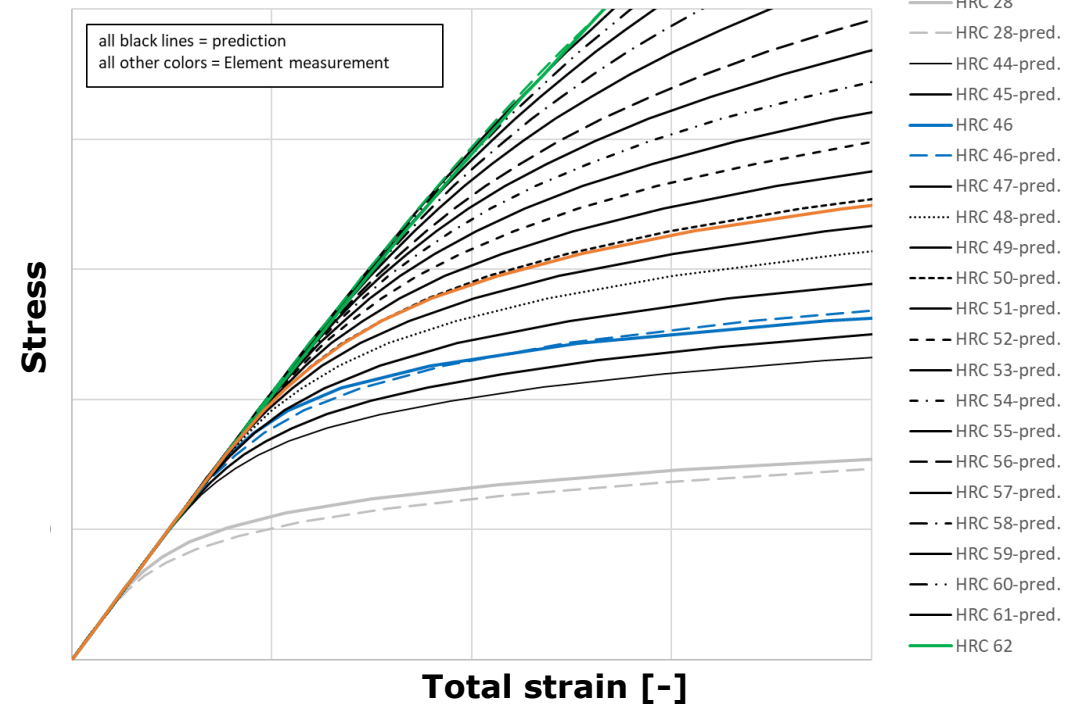
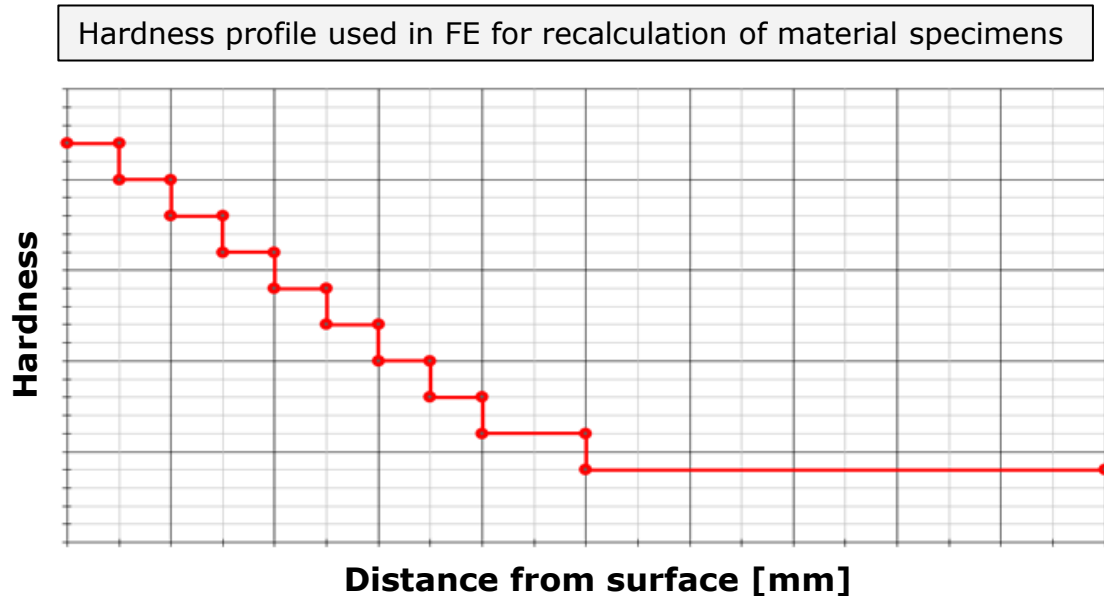
Approach to simulate varying strength behavior

- Multi-layer modeling of varying hardness by depth
- FE model set up with different layers with properties at different hardness aligned with measured hardness profile
- **Simulation of test samples by FE analysis with multi-layer** elastic-plastic material models with kinematic hardening (hardness dependent models) of all specimen loading conditions.

Multi-layer material model



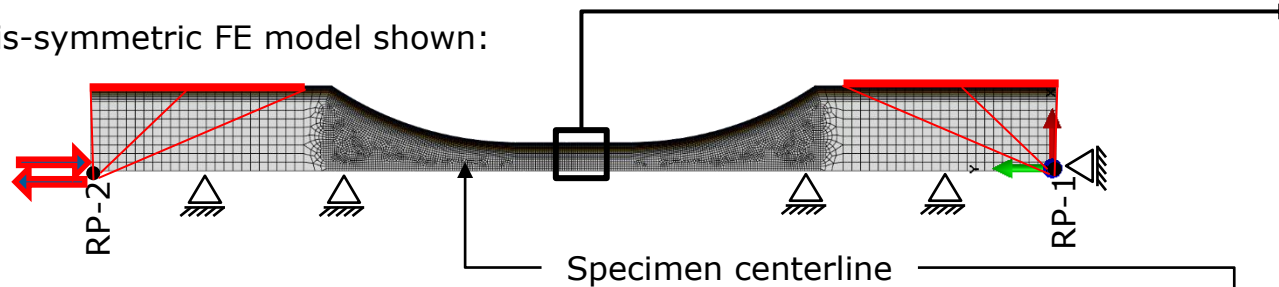
Hardness dependent Stress - Strain behavior (kinematic hardening)



Material specimen FE calculation

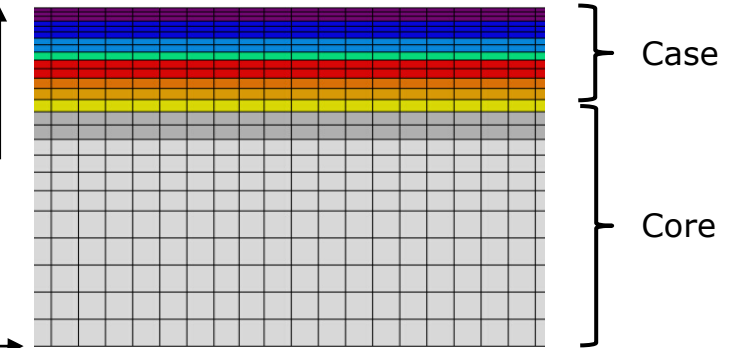
Example: tension-compression specimen

Axis-symmetric FE model shown:



Increasing hardness

Layers in FE mesh with different hardness shown by color

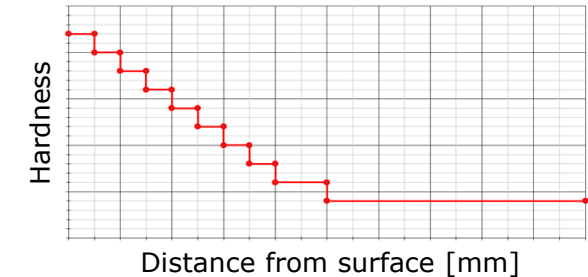


Uniform section stress is generally expected under this test condition:

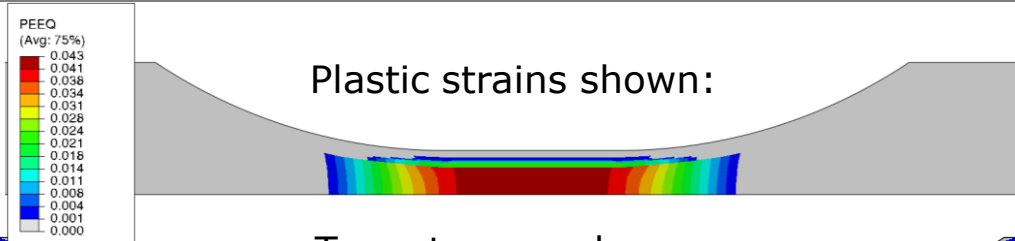
Nominal stress = Force / Area

However, **inhomogeneous material strength results in non-uniform stresses through the section.**

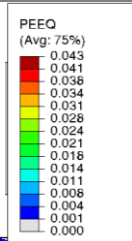
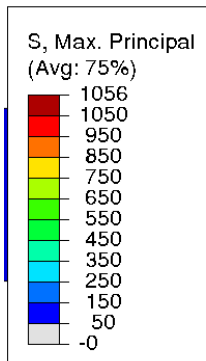
Reason = variation of plastic deformations due to non-uniform strength.



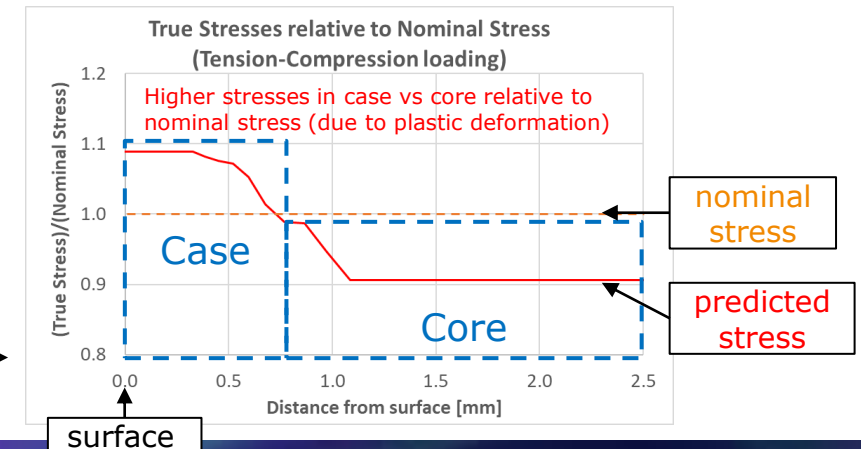
Plastic strains shown:



True stresses shown:
(kinematic hardening model at each layer)



Cross section for stresses in chart:

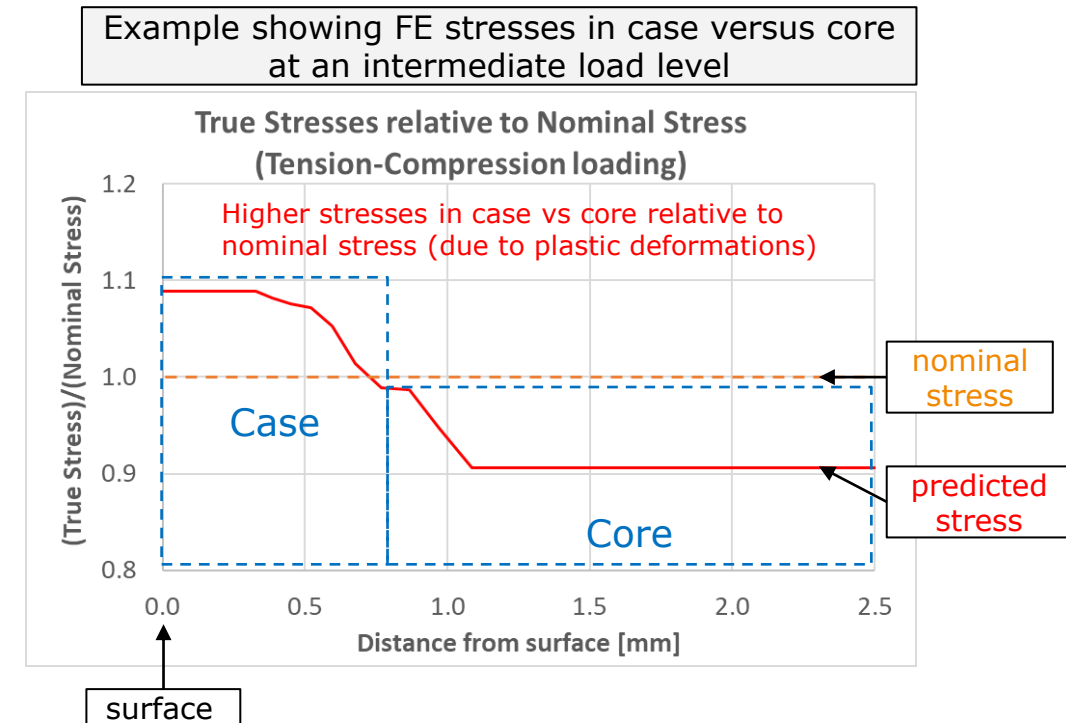
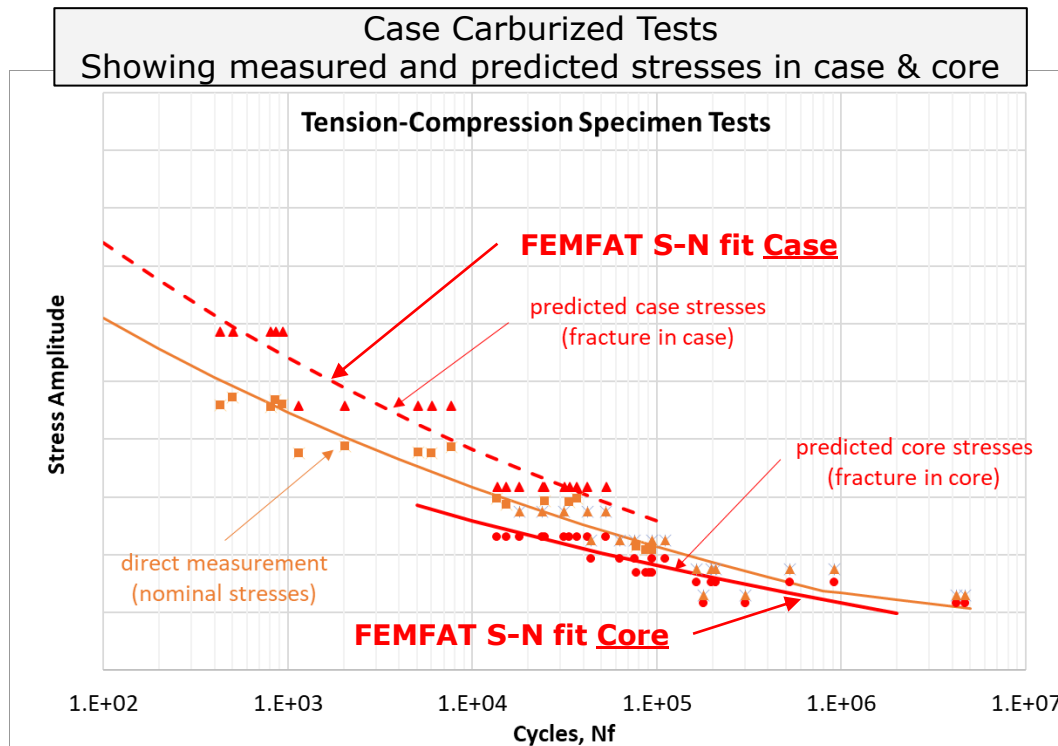


Case carburized material modeling

Fracture in case vs core and calibration of S-N characteristics

▪ Calibration of S-N characteristics

- Plotting of predicted (FE) stresses and measured cycle numbers N_f .
- Calibration of S-N characteristics (k , N_D) based on observed fracture initiation locations (case vs core).
- Under tension-compression loading (uniform nominal stress), there are different stress levels in case versus core at each load level due to gradients in plastic deformations.

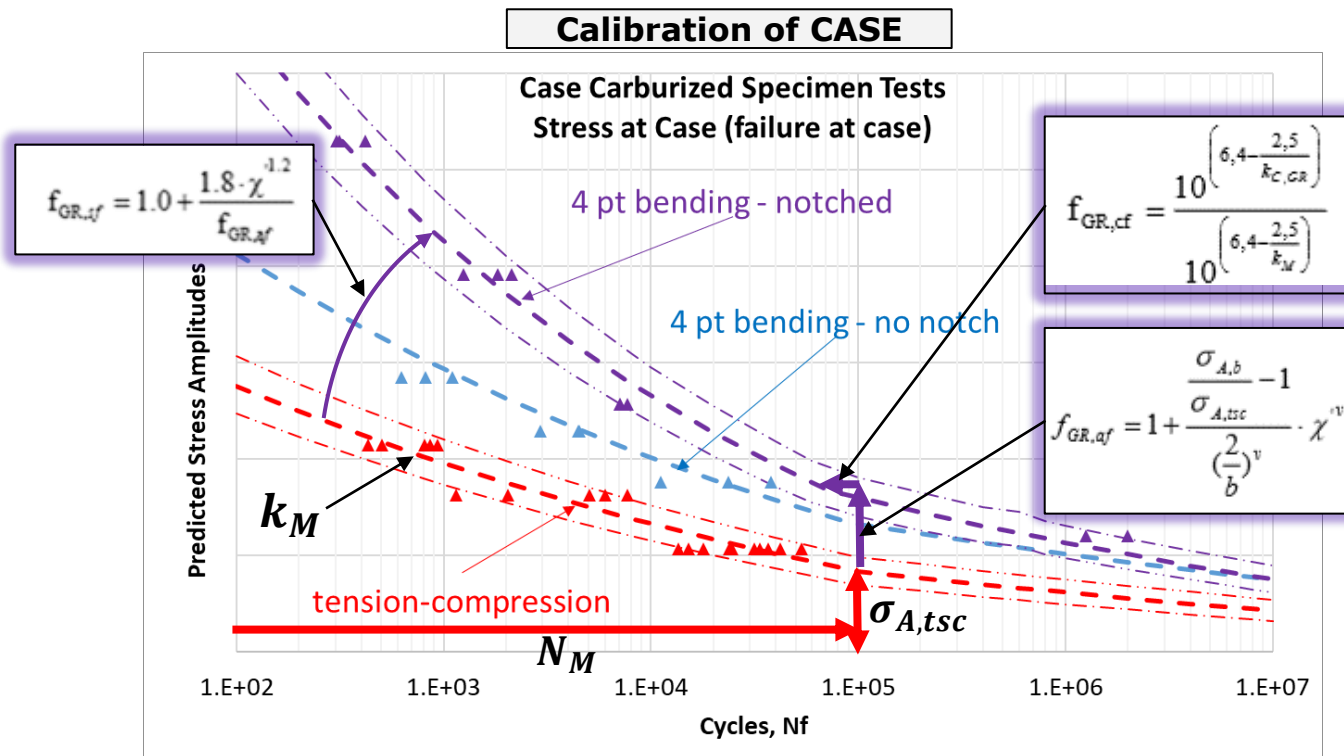


Case carburized material modeling

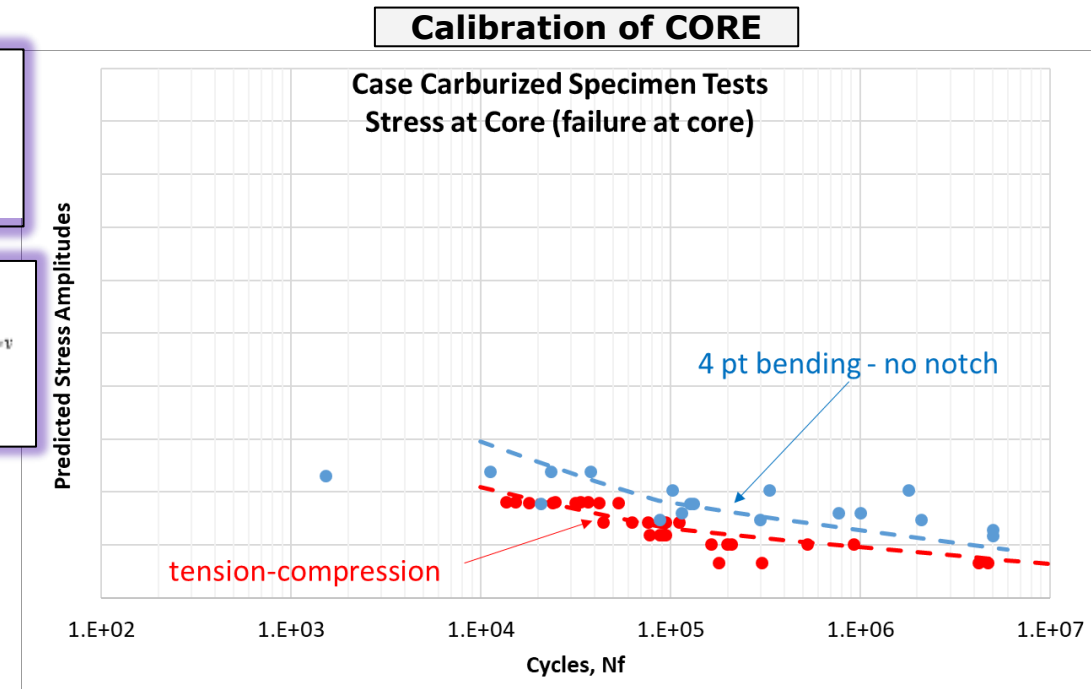
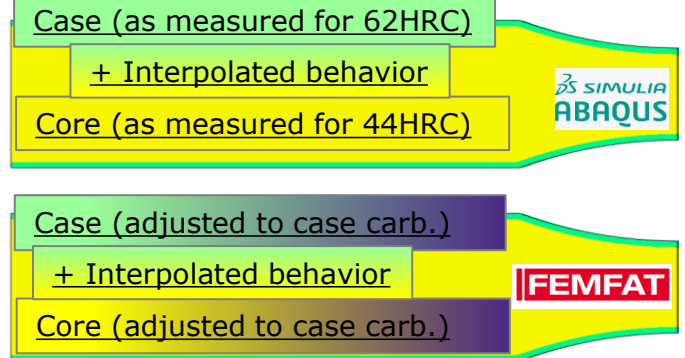
Calibration of stress gradient characteristics

Calibration of stress gradient characteristics

- Plotting of predicted (FE) stresses and measured cycle numbers N_f .
- Manual calibration of v , IFK2, IFK3 for surface and core separately.
- Good agreement of fracture life at case vs core for all tested stress gradient conditions.



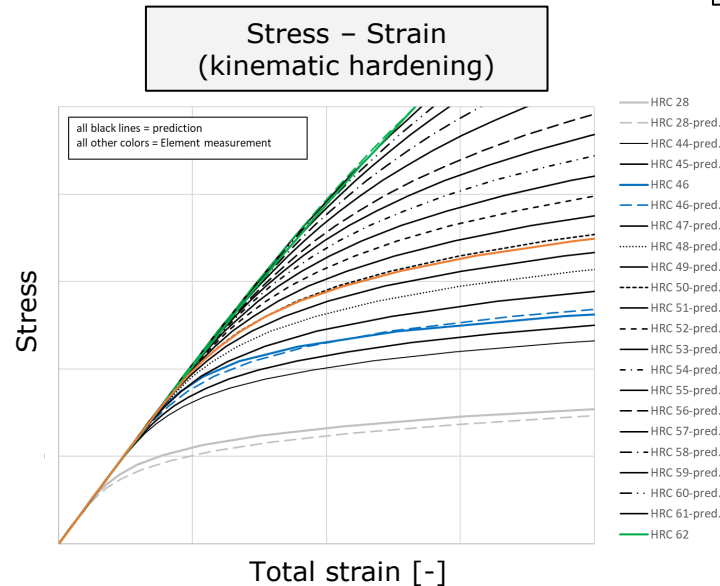
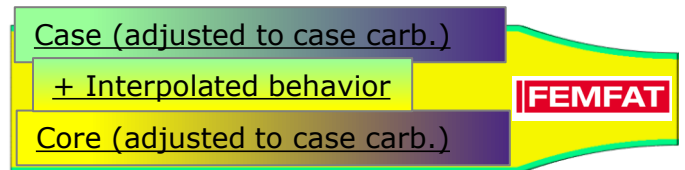
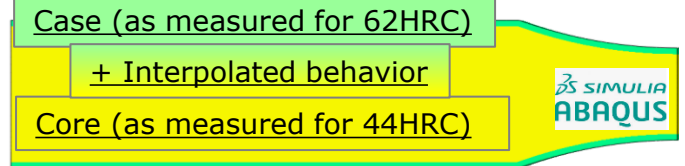
Multi-layer material model



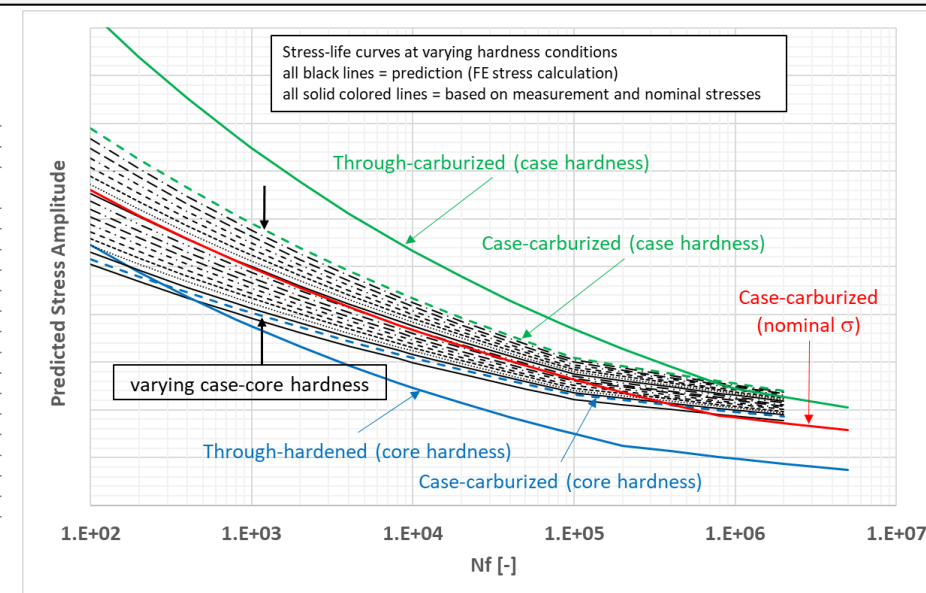
Summary of established material models

- Established material models cover a wide range of heat treatment conditions.
- S-N curves and stress gradient parameters correlate well to a wide range of stress conditions.
- This approach has been used for the next phase of work: correlation with differential gear fatigue tests.

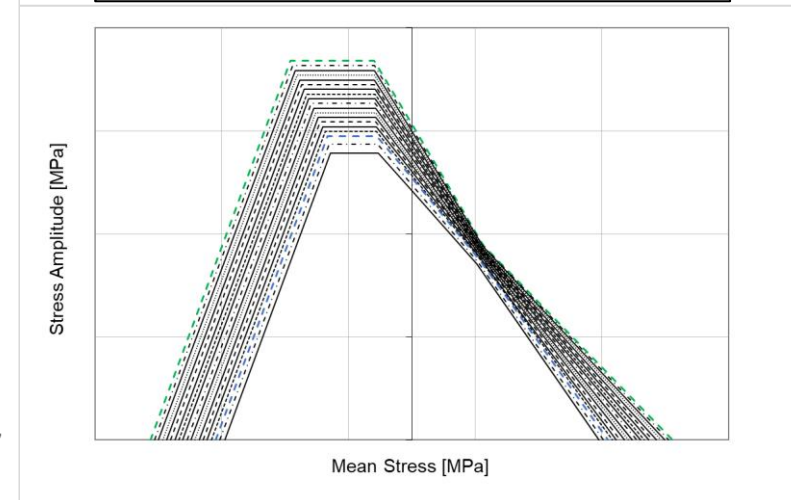
Multi-layer material model



Stress-life curves at varying hardness and heat treatment conditions



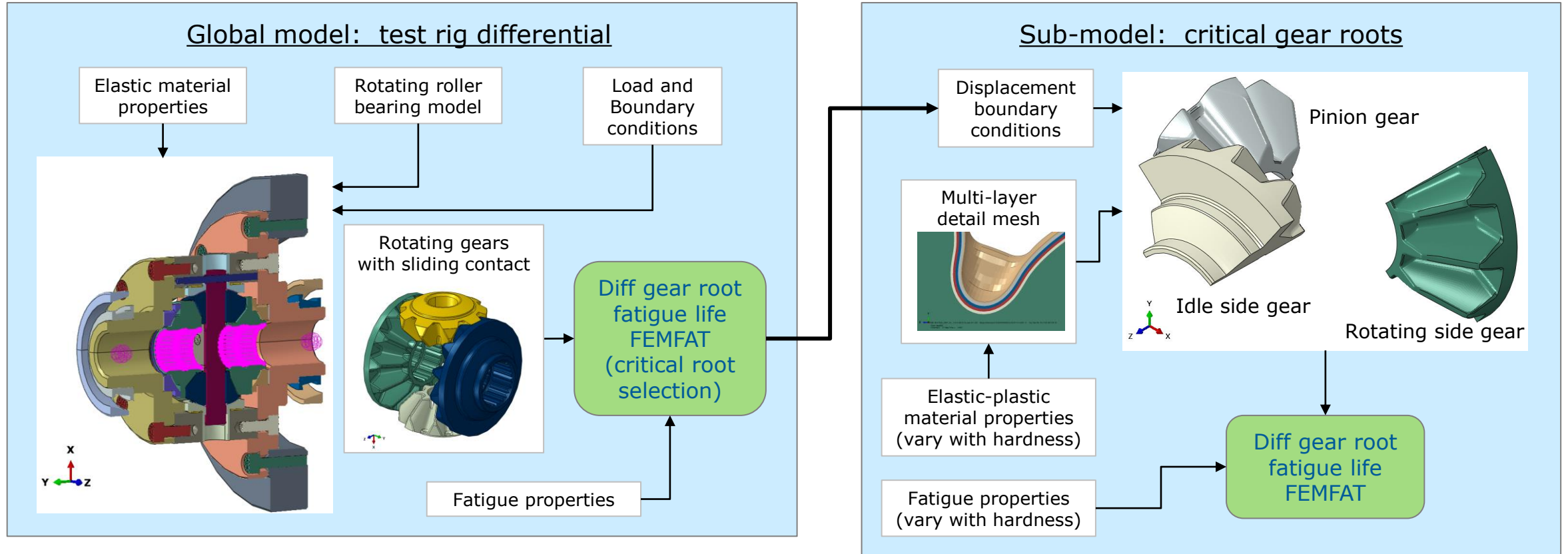
Haigh Diagram
(mean stress influence at varying hardness)



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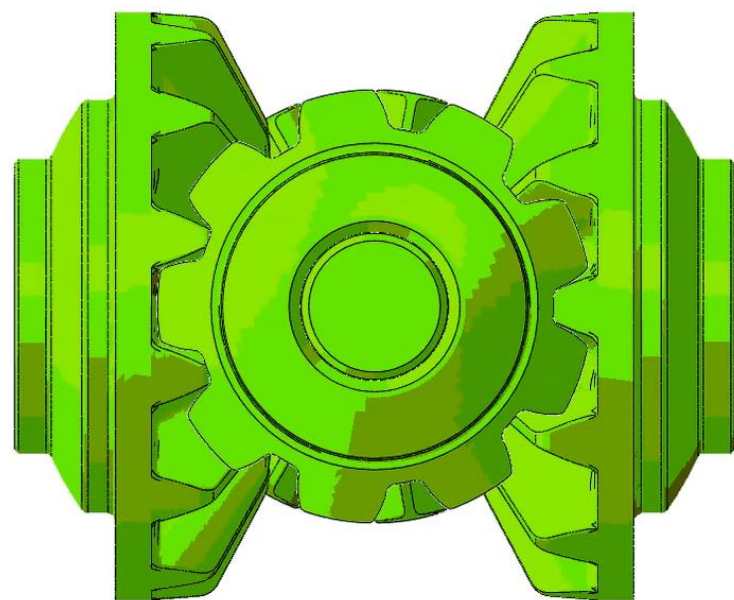
Overview of Workflow: Global model and sub-model



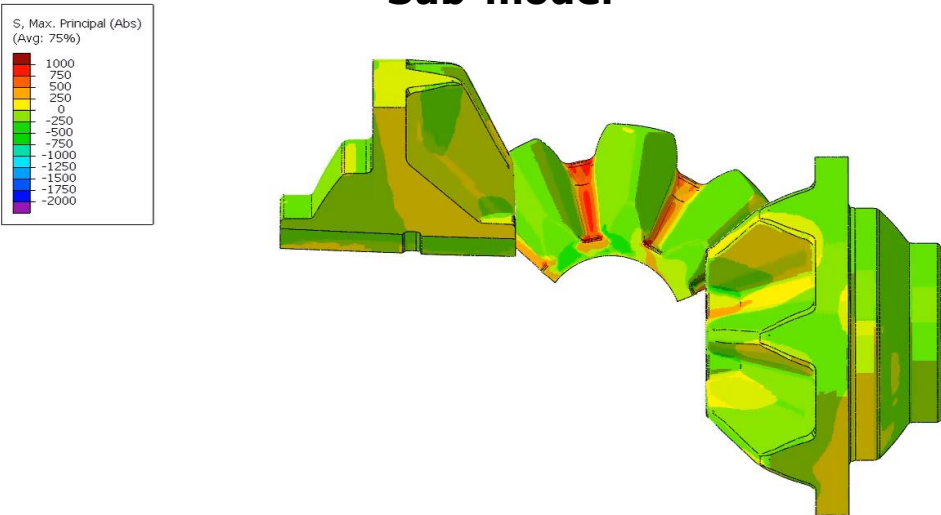
Animations

Showing stress and deformations

Global model

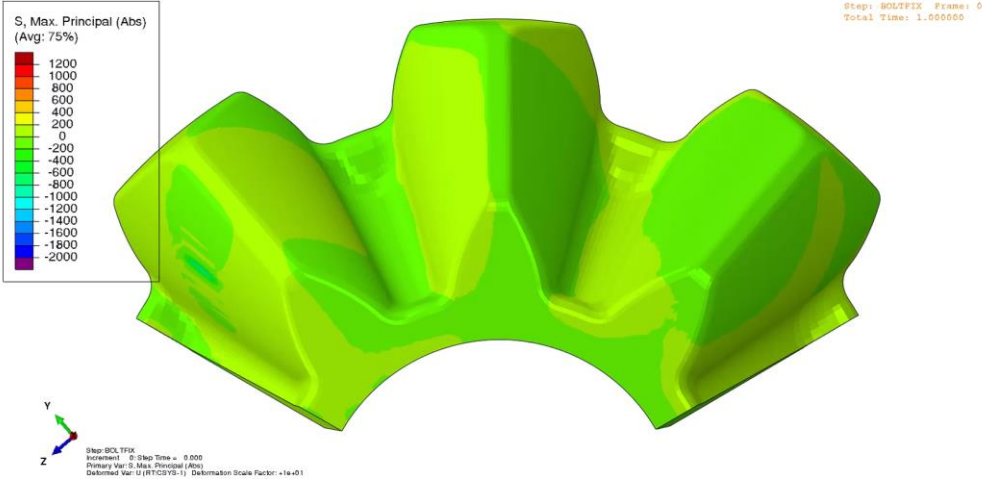


Sub-model



Sub-model

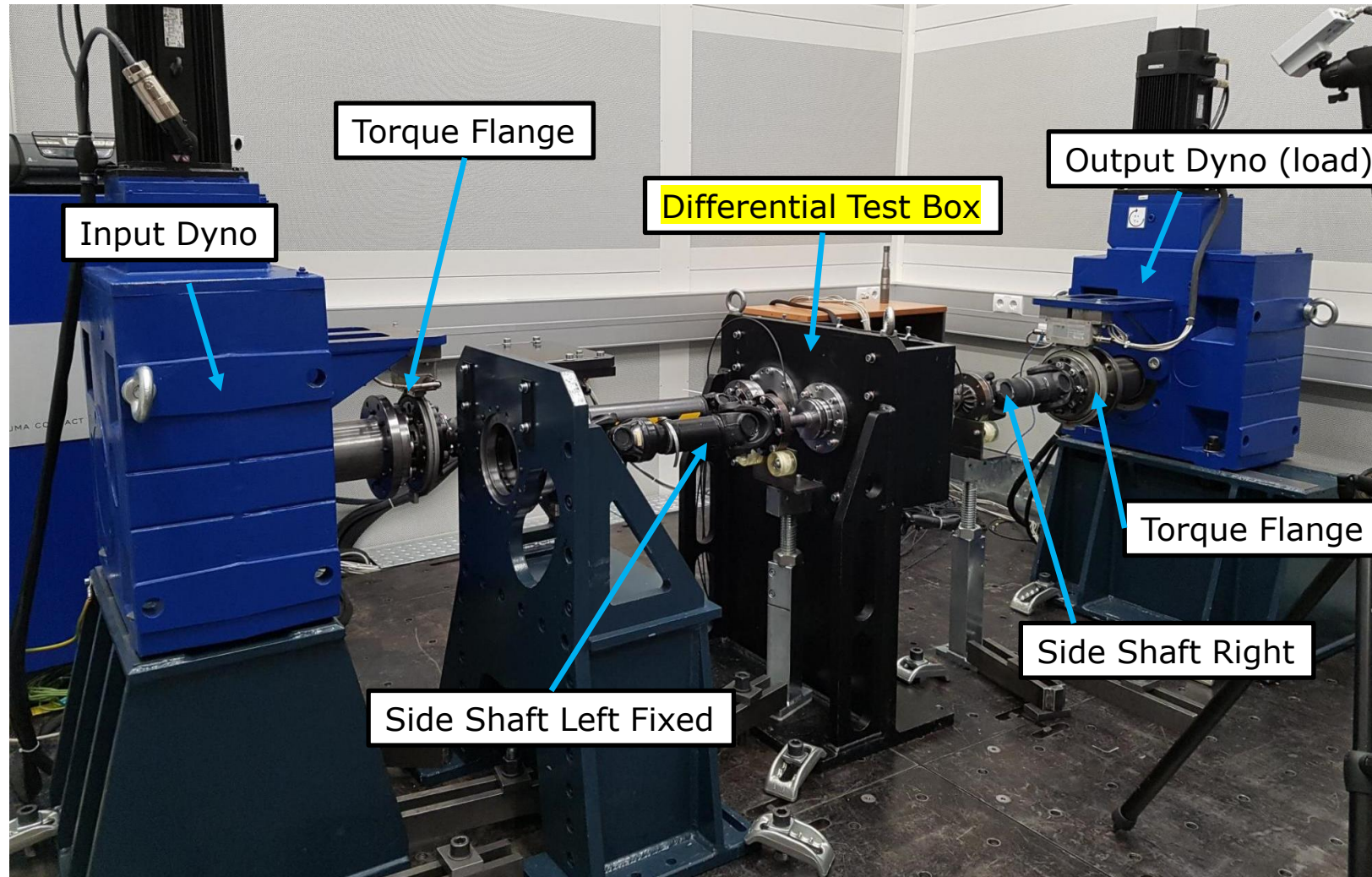
Pinion gear deformations relative to local coord system



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Specialized differential rig test configuration



Differential gear FE model for specialized rig test

- The rig test utilizes a specialized differential case which is stiffened and isolates failures to the gears.
- Bolt preloads, contact clearances, and contact interferences are considered within the differential.
- Preload and stiffness of tapered roller bearings are represented.
- Shim thickness, tolerances, & friction aligned with test.
- Separate simulation carried out at each tested torque level.

Input: Torque

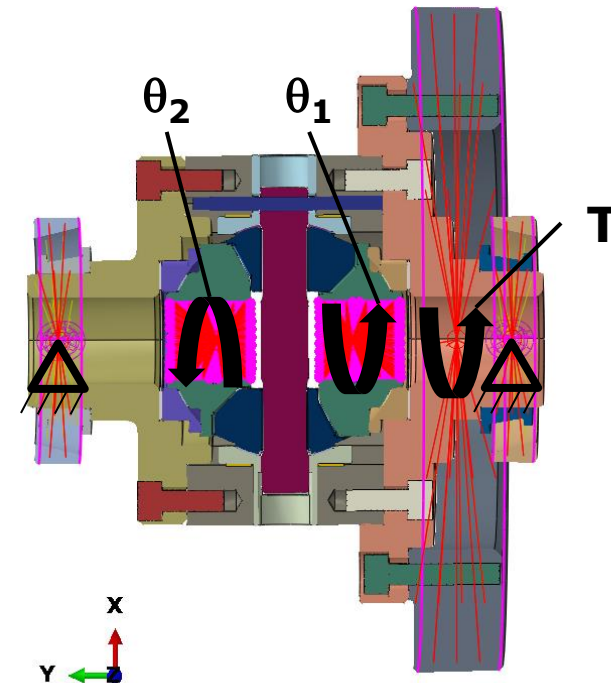
T: constant (at tested level)

Output: angular rotations

θ_1 : constrained (fixed)

θ_2 : incrementally increasing (in time)

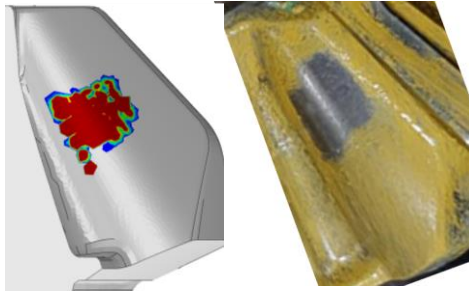
Stiffened differential case



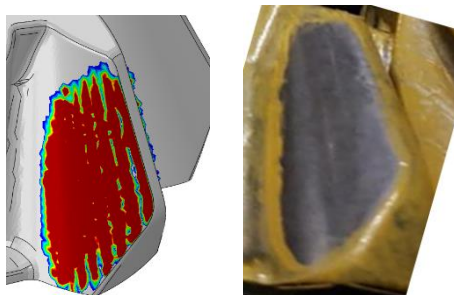
Correlation with contact patterns and strain gages on differential rig test

Contact patterns were tuned during test with shim adjustments. FEA model was aligned with shim thicknesses and tolerances and contact patterns compared with test.

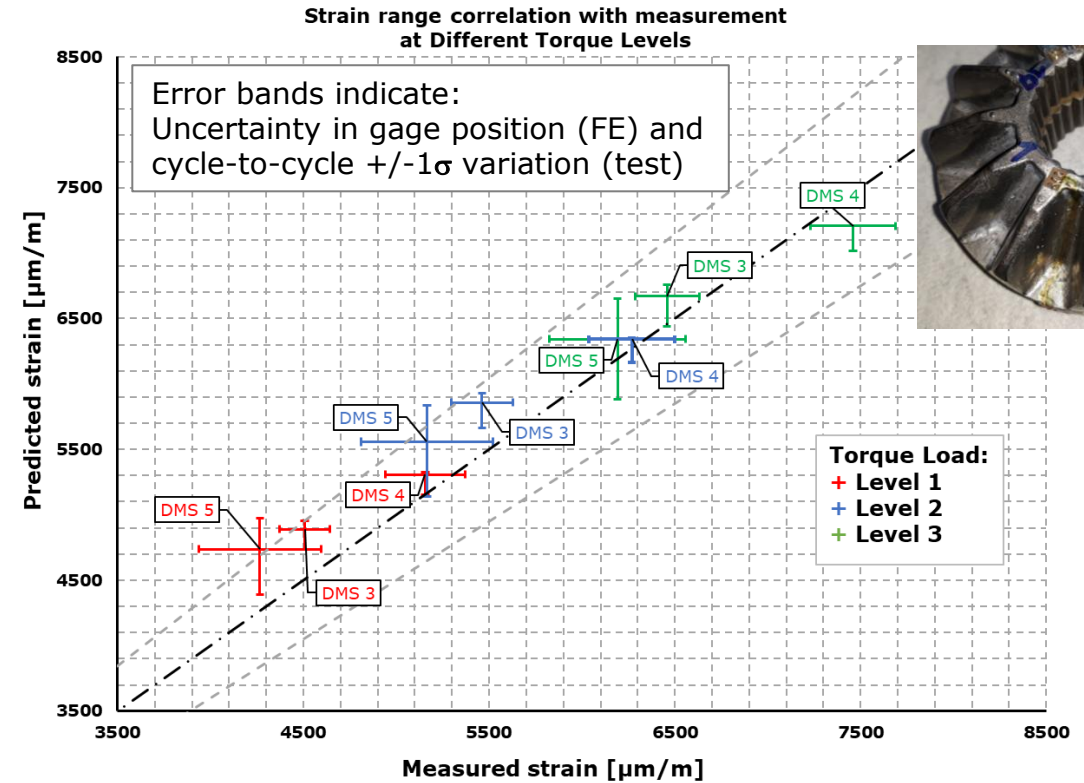
- Light load level:



- Full load level:



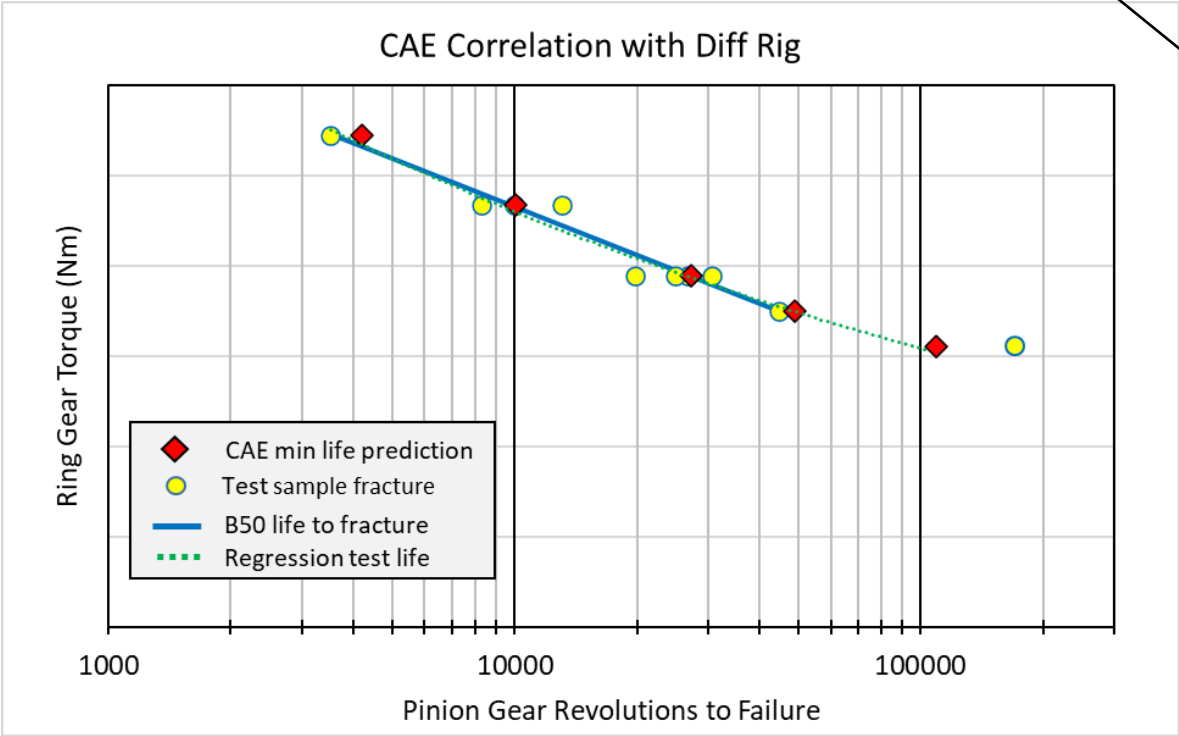
Sufficient agreement with contact patterns.



Good correlation with strain gages achieved (generally within 10%).

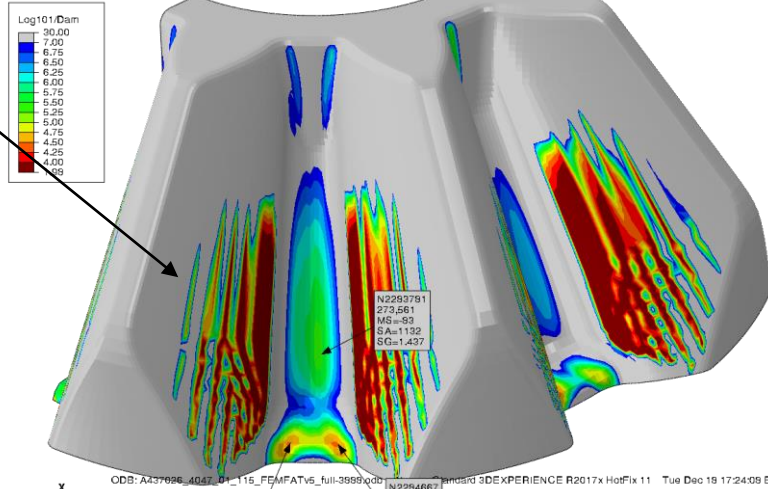
Correlation with fatigue life on differential rig test

Note: high damage areas on flanks are not assessed
(only root areas assessed)



Excellent correlation shown for gear root bending fatigue life with 10 test samples at varying load level from differential rig test.

Scale: Log(Nf)



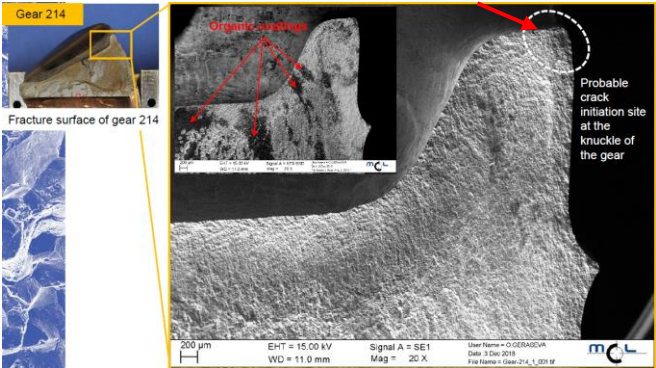
Load level 4



Load level 3



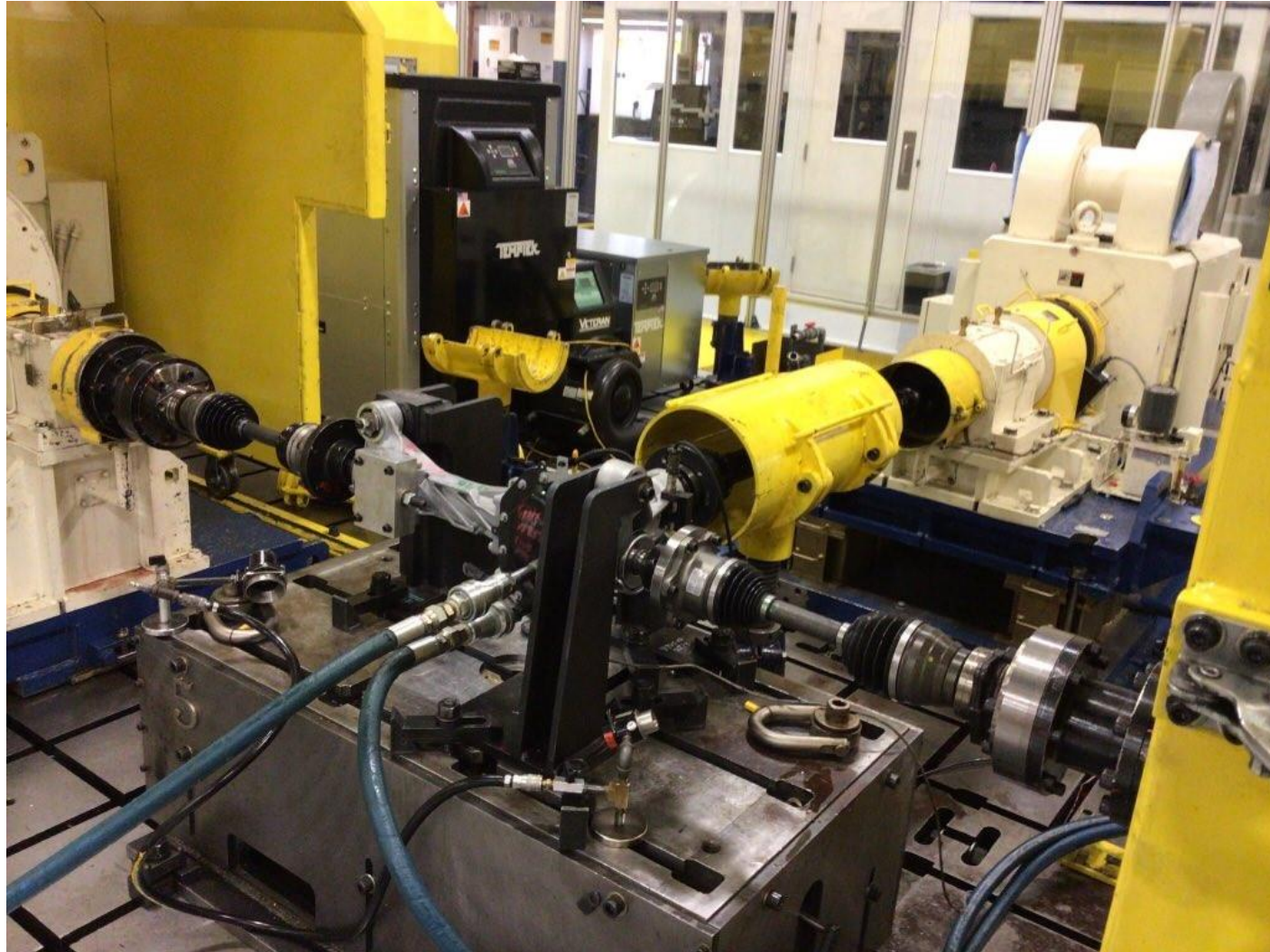
Load level 1



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Example full axle test configuration

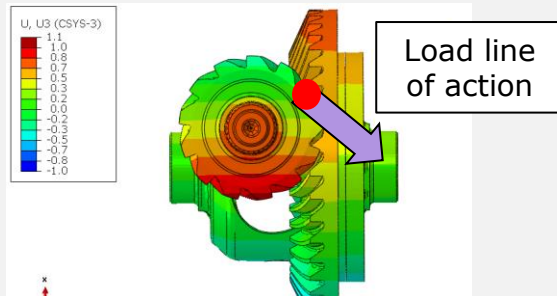


Differential gear FE model for full axle test

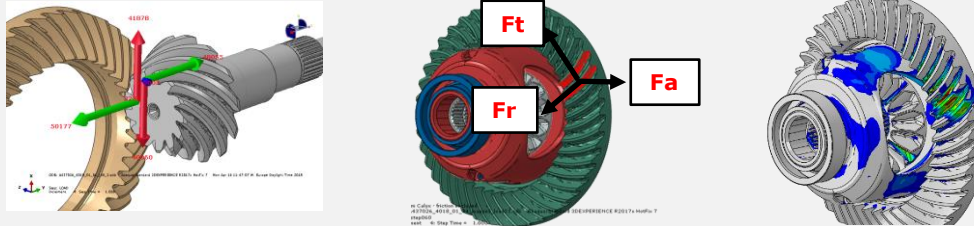
- Similar modeling approach is used as previously described.
- Model is updated, representing customer differential case.
- Rotating roller bearing model is refined for stiffness.

- Ring gear loading is revised:

- Considering deflections in axle assembly:

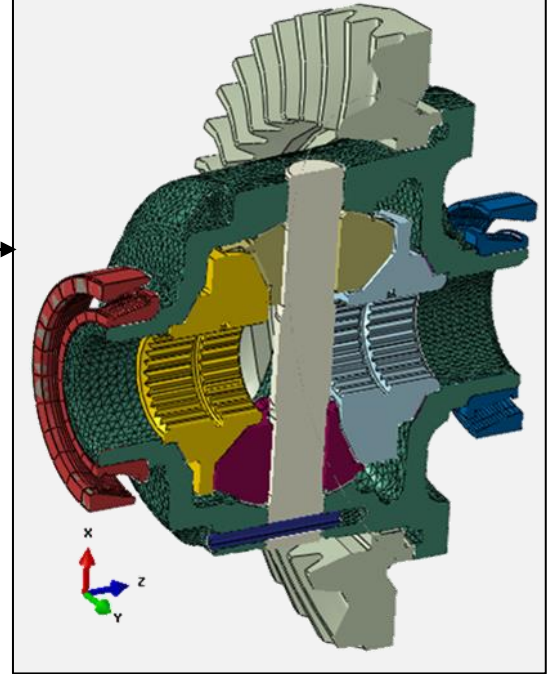


- Time varying loads applied to ring gear from Calyx:

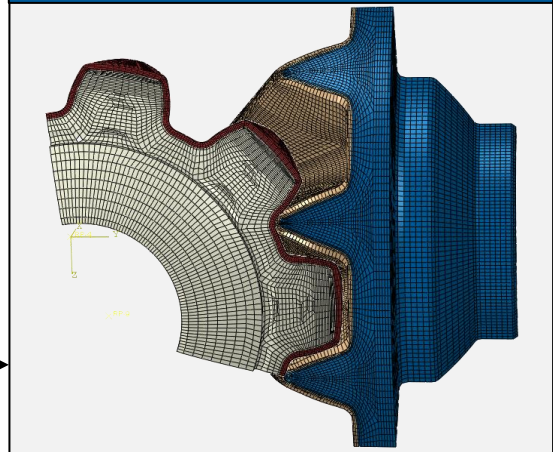


- Same sub-modeling approach is used, based on critical gears identified in global model fatigue calculation.

Differential assembly FEA model



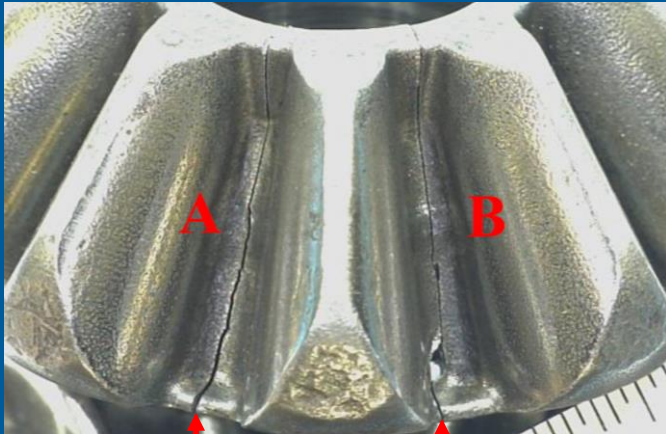
Sub-model of critical meshing teeth



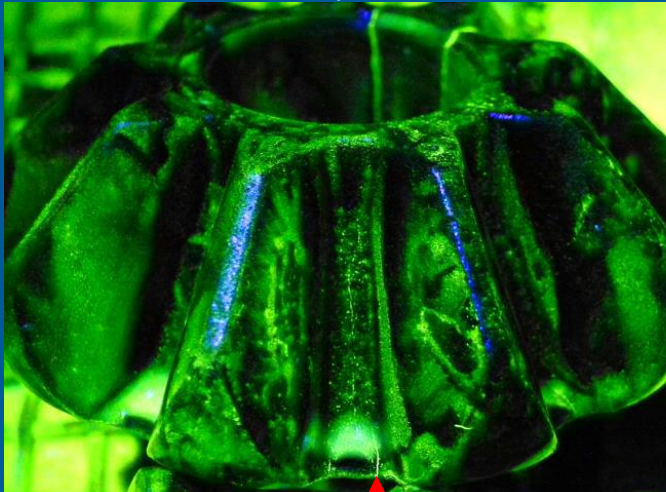
Example correlation with differential full axle test

B50 Test Results: 21,936 pinion revs

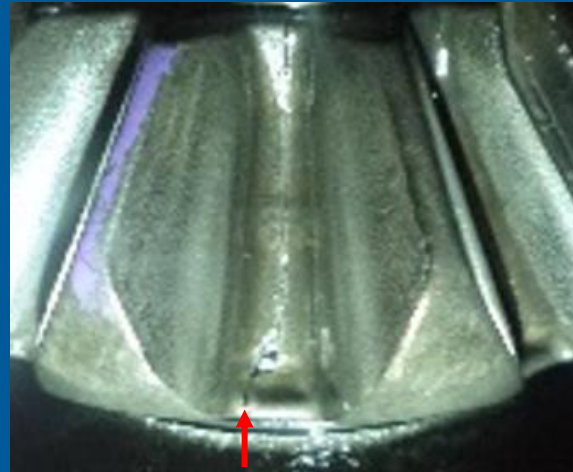
Sample 1



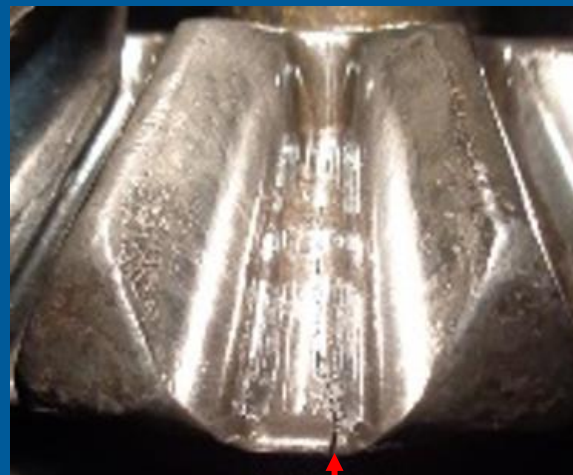
Sample 1



Sample 2

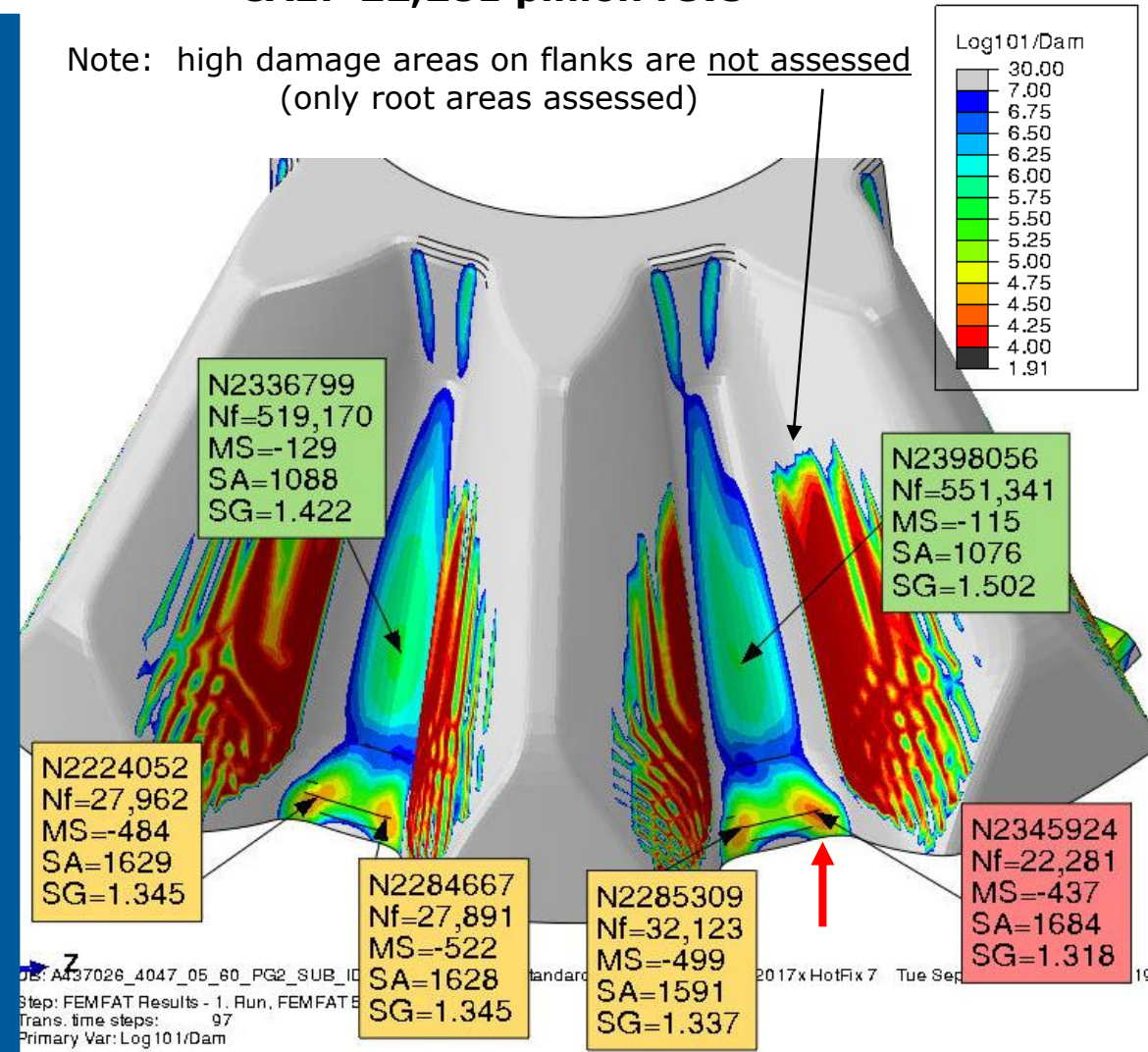


Sample 3



CAE: 22,281 pinion revs

Note: high damage areas on flanks are not assessed
(only root areas assessed)



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Summary

- Case-carburizing produces an inhomogeneous behavior with distinct differences between case and core.
- Established material models characterize the hardness dependent strength for case carburized material test specimens and gears.
- Fatigue models calibrated in FEMFAT correlate with a wide range of stress and stress gradient conditions.
- The established fatigue models can distinguish fracture initiation and fatigue life between case and core.
- Also, a simulation method for FE modeling of differential gears has been established which correctly characterizes rolling contact and transient stresses occurring within the gears.
- The simulation method has been well correlated with a specialized rig test for differential gears (regarding contact patterns and strain) and shows excellent correlation with fatigue life over a wide range of load conditions.
- The simulation method also has been confirmed by fatigue life correlation with full axle tests.
- Similar simulation methods also can be used for:
 - Helical and hypoid gears
 - Differential case fatigue life
 - Development of e-axles as well as conventional drivelines

Acknowledgements: AVL team members and contributors

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