Numerical Framework of Weld Residual Stress

&

its Integration in Fatigue Life Assessment using FEMFAT

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Development of Residual stress in Welding

Welding Between Two Plates

Temperature & Residual stress Distribution Across c/s

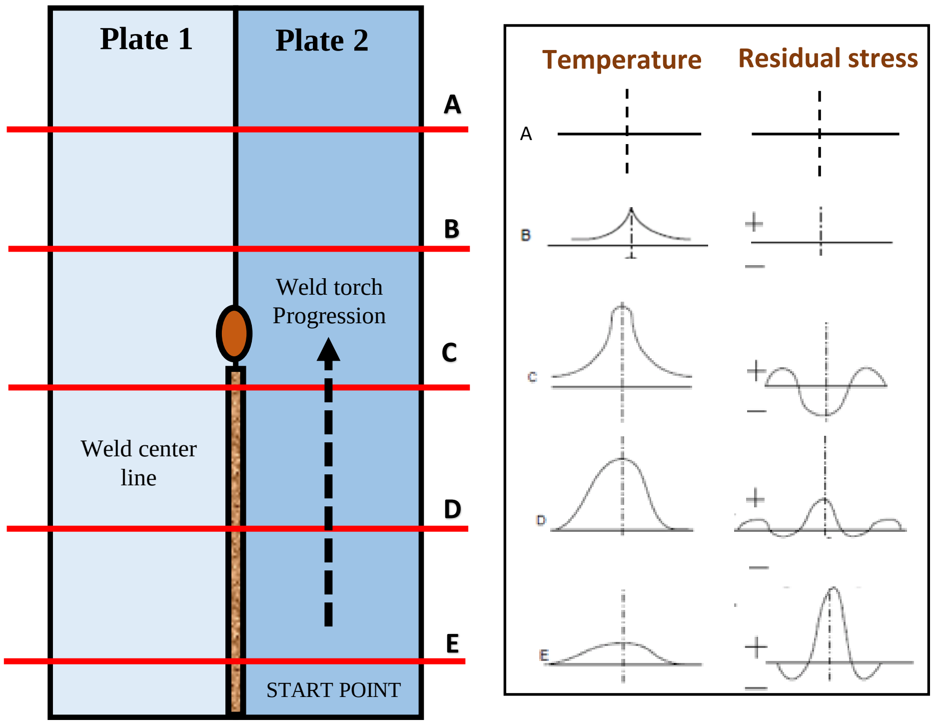


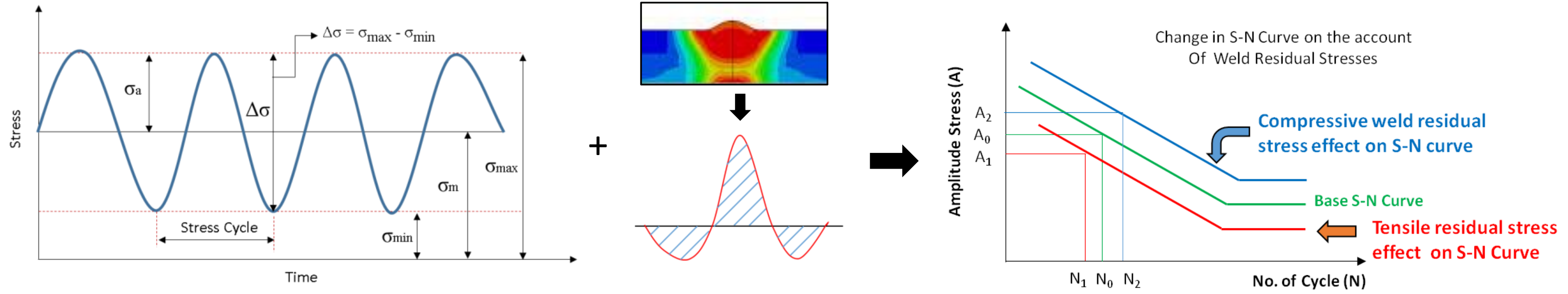
Figure 1. Temperature and Stress distribution during welding process

Welding Progression & Effects

Temperature	Residual Stress
At cold end before welding (Location : A)	
• No Temperature rise	• No Residual stress
Near to weld torch (Location : B)	
• Temperature start rising	• No Residual stress
Just after passing welding torch (Location : C)	
• Maximum Temperature	• At center - Compressive stresses • Adjacent zone - Tensile stress
Intermediate state after welding (Location : D)	
• Temperature drops	• At center - Tensile stresses • Adjacent zone - Compressive stresses
At cold end after welding (Location : E)	
• Temperature drops further	• At center – Max. Tensile stresses • Adjacent zone - Compressive stresses

Effects of Weld Residual Stress on fatigue life

Operating Loading Cycle | **Residual Stress** | **S-N Curve**



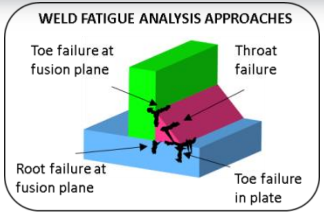
Influencing factors for change in S-N curve in fatigue line estimation

- Stress Range (Δσ)
- Mean Stress (σmean)
- Rate of cyclic loading
- Stress concentration
- Weld Size / Geometry
- Material
- Environmental conditions

Residual stress causes change in mean stress

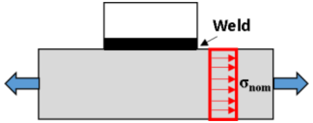
Figure 2. Combined effect of Fatigue load & Residual stress

Fatigue Analysis Approaches



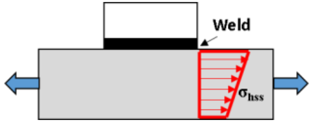
CLASSICAL APPROACH (S-N Curve)

NOMINAL STRESS



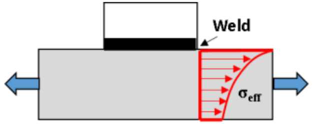
- Based on extensive test sample data
- Classified as weld type, Load & Shape.
- Assumption - S-N curve of test specimen of particular class applicable for practical case
- Do not consider Complex geometrical configurations & local stress effects.

STRUCTURAL/HOT SPOT STRESS



- Based on specific test of real field data
- Measured stresses extrapolation for toe/root area.
- Fewer S-N test curves are Considers macro geometrical stress concentration effects.

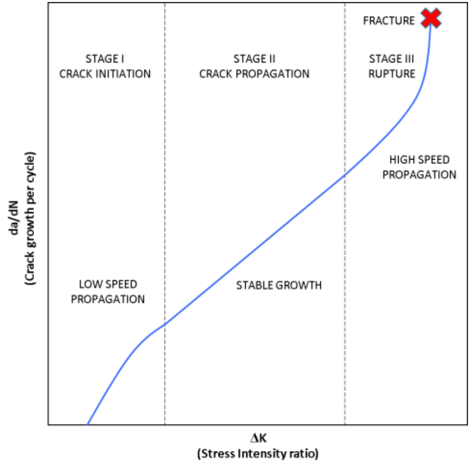
LOCAL/EFFETIVE STRESS



- Involves computation of highest stresses at weld discontinuities
- Single S-N test curves
- Consider both geometrical & local stress concentration effects

Residual stress effects are considered as local stresses

FRACTURE MECHANICS APPROACH



$$\frac{da}{dN} = f(\Delta K, R) \rightarrow N = \int_{a_0}^{a_f} \frac{da}{f(\Delta K, R)}$$

Case Study - Trailing arm of Rear Twist Beam (RTB) suspension

Rear Twist Beam :

- Semi-independent suspension
- Structural simplicity, durable and lightweight design
- Main components : Coil spring, shock absorber & brackets, trailing arms, hub, wheel mounting bracket, trailing arm plates.
- Loading : Absorbs the cyclic road loads through the wheels attached to the ends of beam through twisting and hence serve as an anti-roll bar mechanism.
- Trailing arm : Fabricated part of RTB comprising of lower & upper arms joined together through welding.
- Failure causes : Repetitive cyclic nature of load on RTB Suspension makes it imperative to assess trailing arm in fatigue point of view.

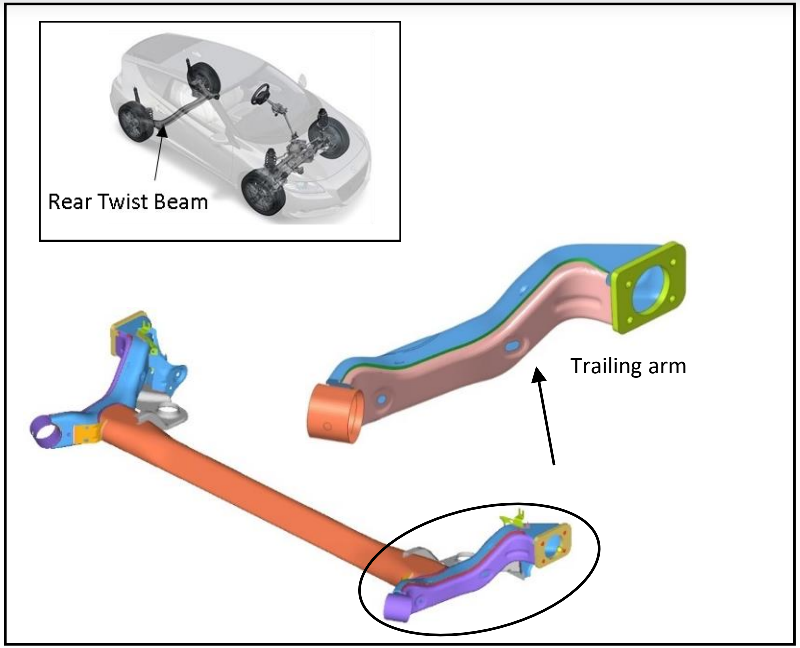
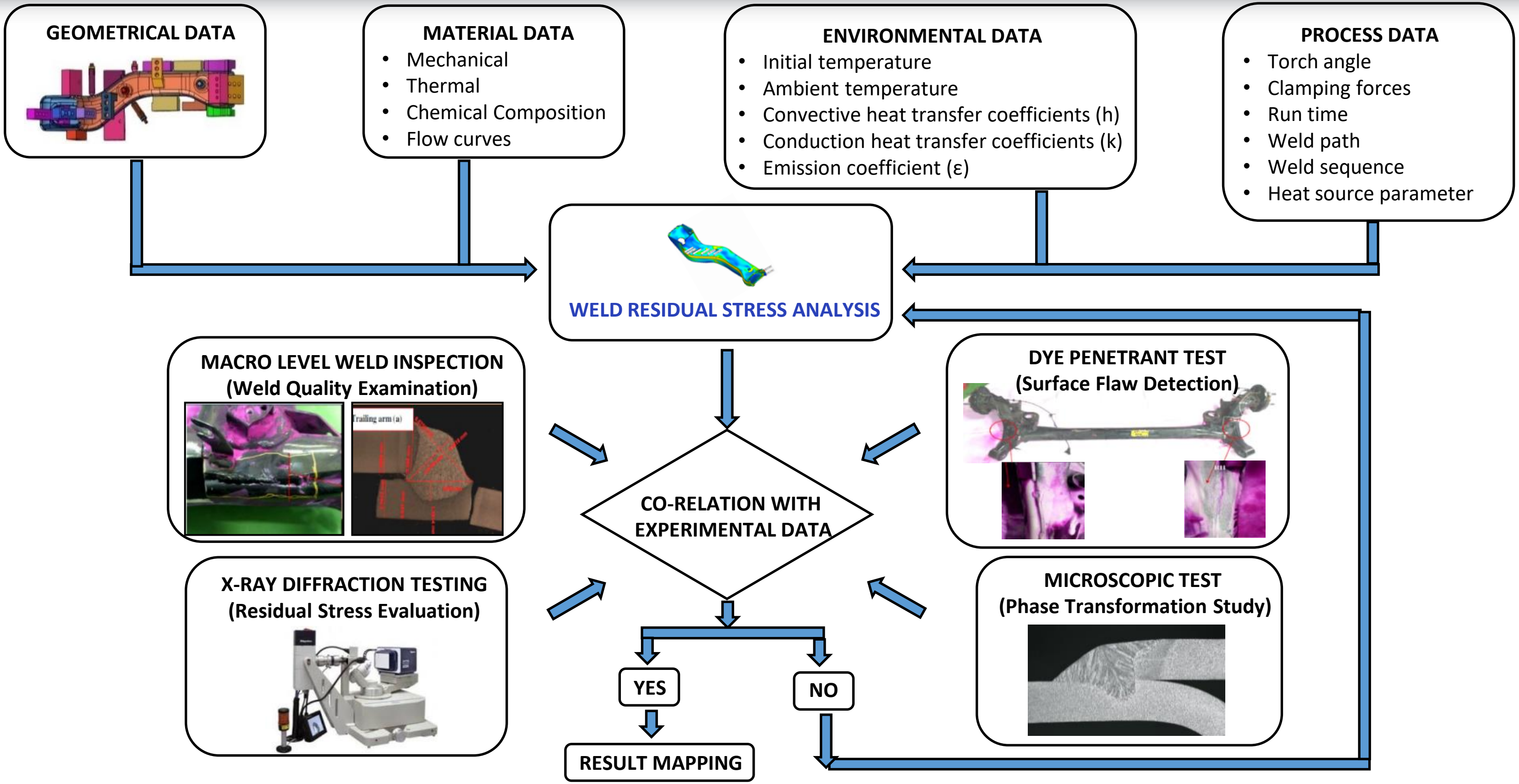


Figure 6. Rear Twist Beam

Comprehensive study during Weld manufacturing followed by fatigue simulation in FEMFAT makes design safe & ensures that the vehicle has good handling and stability.

Welding Analysis Methodology



Welding Simulation Results

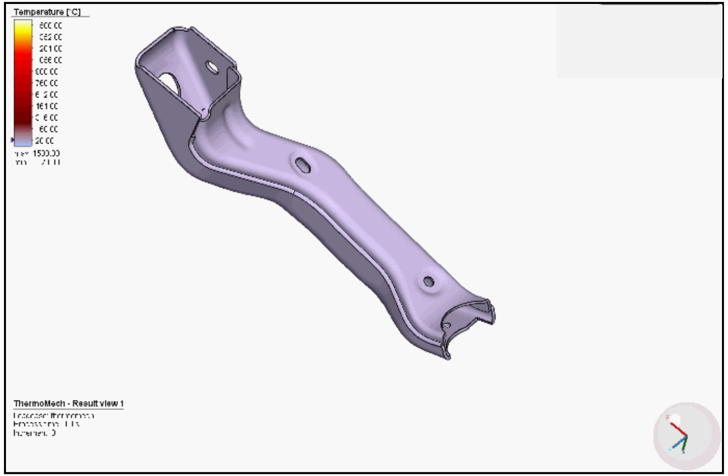


Figure 9. Temperature vs Time

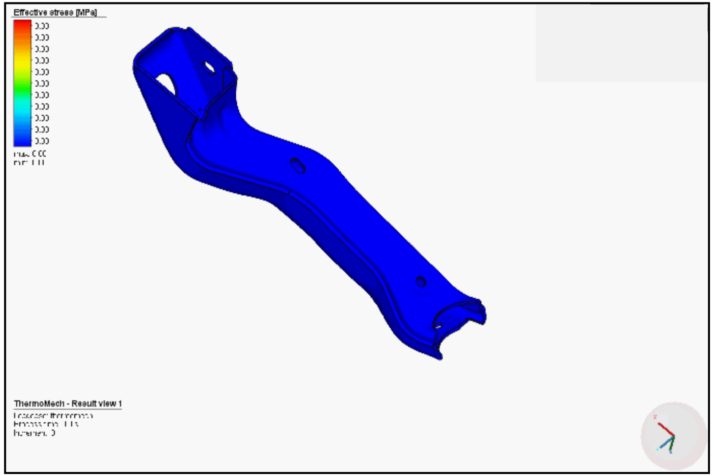
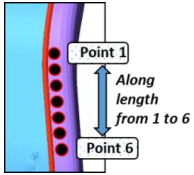


Figure 10. Residual Stress vs Time

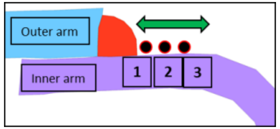
Comparison of Residual stresses FEA Vs Test results

Top side of Trailing arm near Welding HAZ (Heat affected zone)



Along Length of Trailing arm						
CAE Results (Mpa)						Test Results (Mpa)
Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	293 to 366
298	309	338	350	360	370	

Figure 11. Residual Stress along Length



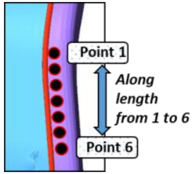
Along C/s of Trailing arm			
CAE Results (Mpa)			Test Results (Mpa)
Pt 1	Pt 2	Pt 3	293 to 366
281	309	358	

Figure 12. Residual Stress along cross section

Observation :

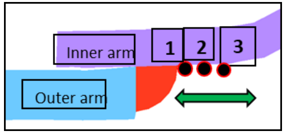
1. **Residual stress pattern :** The stresses on top side of trailing arm are tensile in nature & resembles the stress pattern measured in x-ray diffraction testing.
2. **Residual stress quantification analysis :** On top side, the stresses are within range of the experimental data.

Bottom side of Trailing arm near Welding HAZ (Heat affected zone)



Along Length of Trailing arm						
CAE Results (Mpa)						Test Results (Mpa)
Pt 1	Pt 2	Pt 3	Pt 4	Pt 5	Pt 6	-85 to -332
-108	-198	-270	-325	-335	-367	

Figure 13. Residual Stress along Length



Along C/s of Trailing arm			
CAE Results (Mpa)			Test Results (Mpa)
Pt 1	Pt 2	Pt 3	-158 to -92
-137	-96	-82	

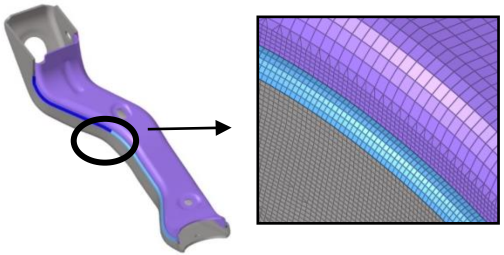
Figure 14. Residual Stress along cross section

Observation :

1. **Residual stress pattern :** The stresses on bottom side of trailing arm are compressive in nature & resembles the stress pattern measured in x-ray diffraction testing.
2. **Residual stress quantification analysis :** On bottom side, the stresses are within range of the experimental data.

Result Mapping

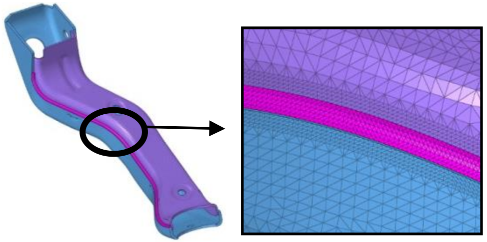
Meshing in Weld Residual stress analysis
RTB - Trailing arm Mesh



Element size : 1 mm to 5 mm
Element Type : Hexa 8 & Penta 6 Solid Mesh

Figure 15. Weld Residual Stress mesh

Meshing in Durability analysis
RTB - Trailing arm Mesh



Element size : 1 mm to 5 mm
Element Type : Tetrahedral Solid Mesh

Figure 16. Durability mesh

Mesh Mapping

Mesh Mapping steps comprises of Extraction of Welding Residual stresses on Durability Mesh

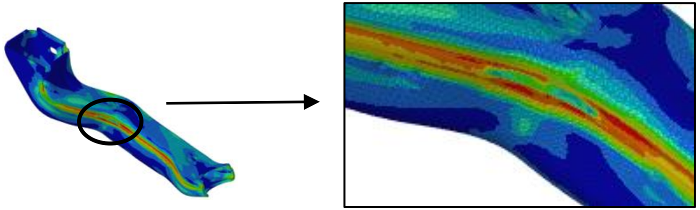


Figure 17. Residual stress on Durability mesh

Fatigue Analysis Methodology

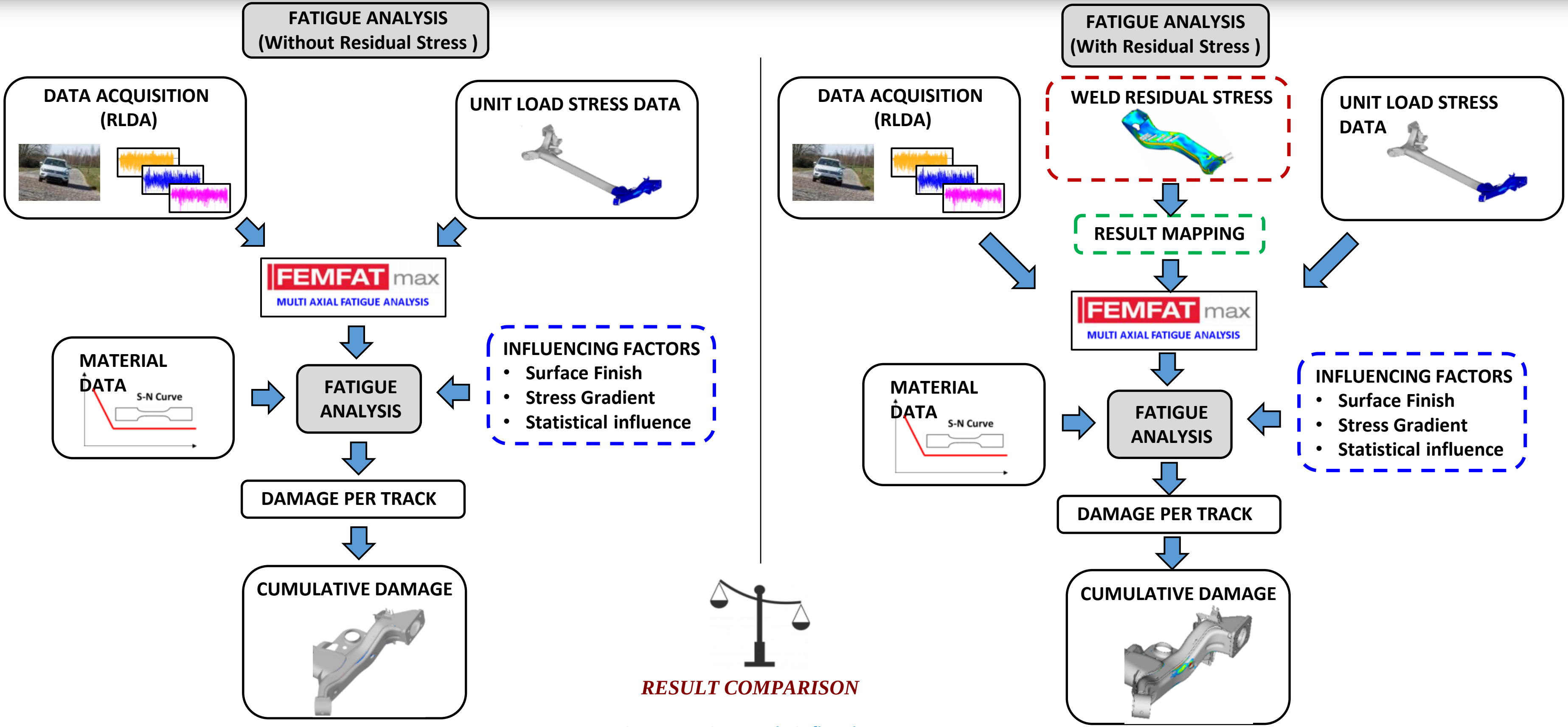


Figure 7. Fatigue analysis flowchart

Unit Load Inertia Relief Analysis

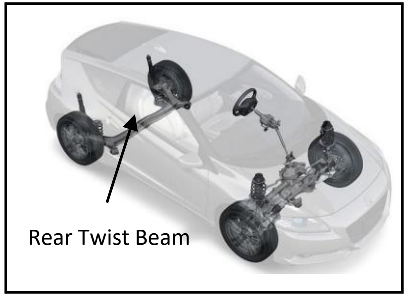


Figure 18. RTB Suspension in Vehicle

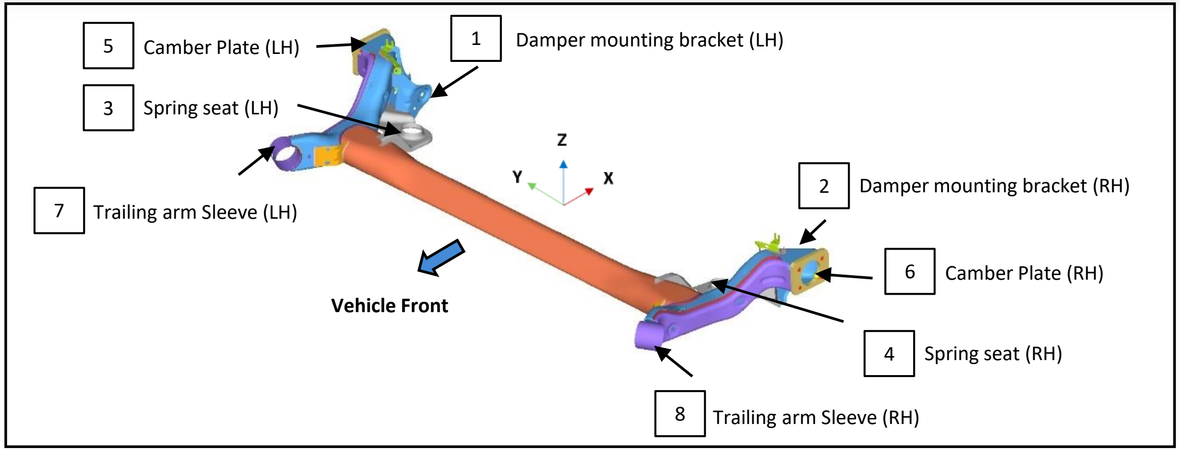


Figure 19. Rear Twist Beam (RTB)

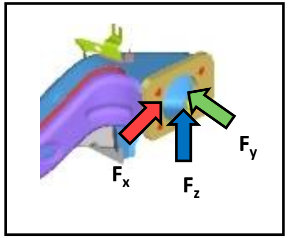


Figure 20. Unit Load Application on Camber Plate
Unit Load at all 8 locations of RTB

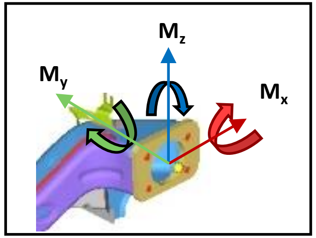


Figure 21. Unit Moment Application on Camber Plate
Unit Load at all 8 locations of RTB

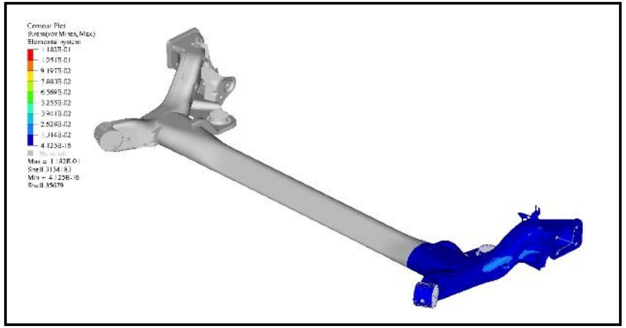


Figure 22. Unit Load Stress Output

Road Load Data Acquisition (RLDA)

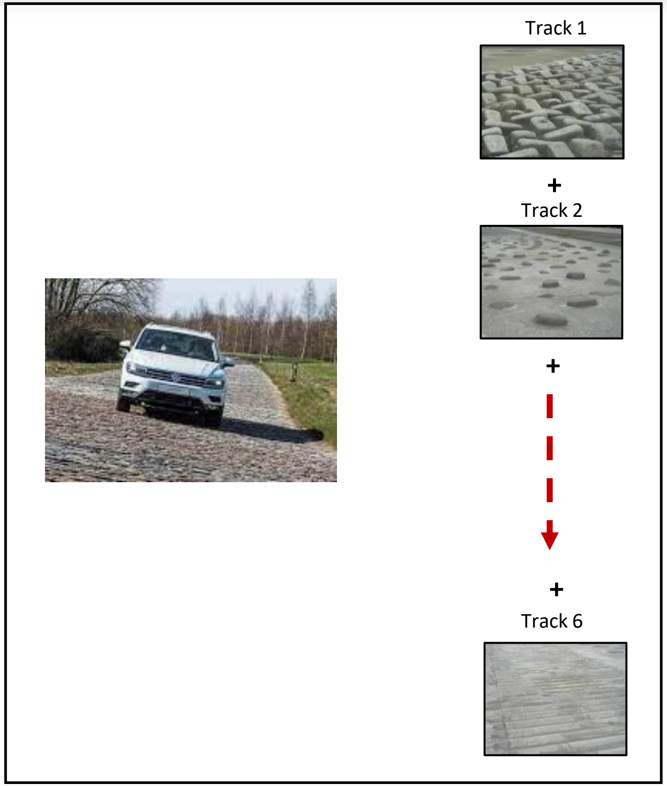


Figure 23. Test tracks

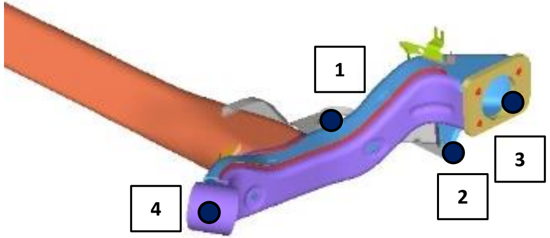


Figure 24. Trailing arm Measurement RLDA points

RLDA Measurement Location (LH & RH side)

1. Damper mounting bracket
2. Camber Plate
3. Spring seat
4. Trailing arm Sleeve

Vehicle Programme - RLDA Loading cycle																			
Sr. No.	Event/Track	Loading Condition																	
		Unladen						Partial Loading						Laden					
		X		Y		Z		X		Y		Z		X		Y		Z	
		F_x	M_x	F_y	M_y	F_z	M_z	F_x	M_x	F_y	M_y	F_z	M_z	F_x	M_x	F_y	M_y	F_z	M_z
1	Track 1																		
2	Track 2																		
↓	↓	Road Load Data Acquisition (RLDA) ↔																	
5	Track 5																		
6	Track 6																		

Figure 25. RLDA Loading details

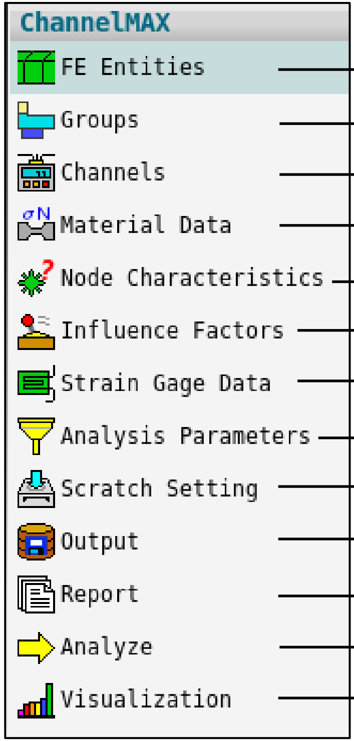
Summary - Road Load Data Acquisition

- Data Locations
  4 (LH) + 4 (RH)
- RLDA Test tracks
  6 Tracks
- Loading condition
  3 Loadings

FEMFAT ChannelMAX Definition

FEMFAT max

MULTI AXIAL FATIGUE ANALYSIS



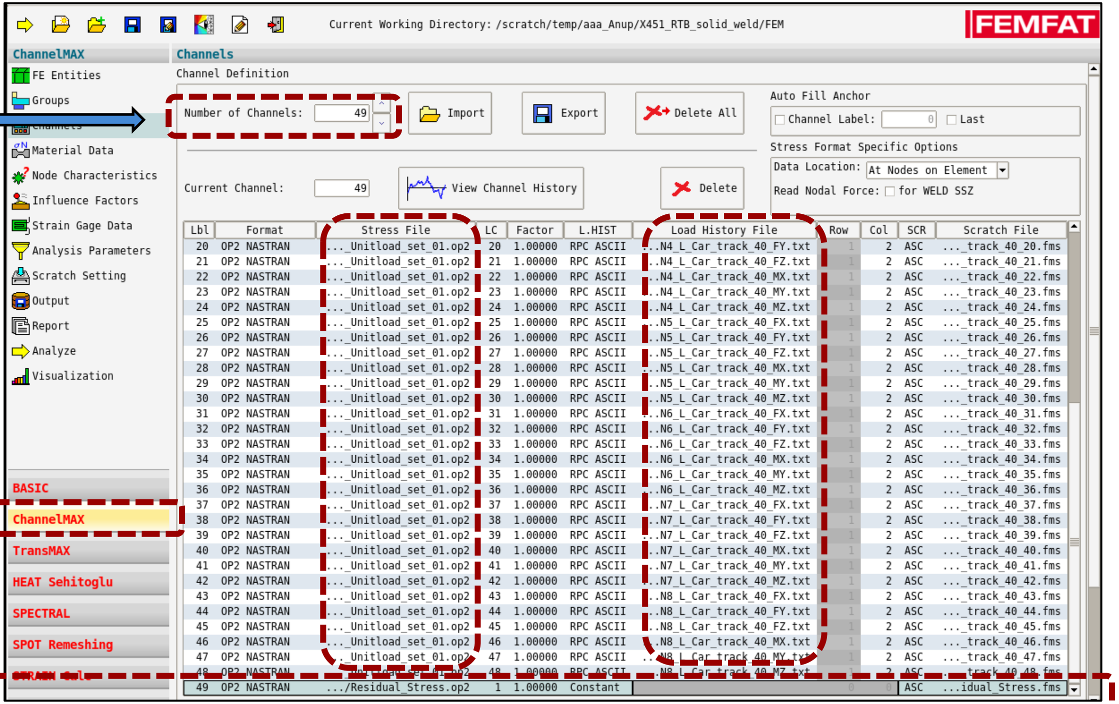
- FE Entities → Bulk data file (RTB file in *.bdf Nastran format)
- Groups → Only Trailing arm elements group submitted for evaluation of damage
- Channels → Total channels = 49 (6 tracks x 8 locations = 48 channels + 1 Residual stress channel
- Material Data → Measured test data of material
- Node Characteristics → Single node characteristics to single group
- Influence Factors → Definite influence factor Stress Gradient, Surface roughness Statistical Influence, Mean & Amplitude stress rearrangement
- Strain Gage Data → Not applicable
- Analysis Parameters → Damage – Miner modified & Relative stress defined
- Scratch Setting → Individual scratch file for each load channel will be generated in scratch directory
- Output → Hyper view Output file format selected
- Report → Not defined
- Analyze → Fatigue Analysis
- Visualization → Hyperview post-processing tool is used

Figure 26. ChannelMAX definition in FEMFAT

FEMFAT ChannelMAX Load History

Total No. of channels = 49

ChannelMAX Module



Residual Stress as a 'Constant' history data

Figure 33. Load History

Unit Load Stress data

Load & Moment history data

Linear Damage Accumulation by Miners Rule

Cumulative Damage factor by Miner's Rule

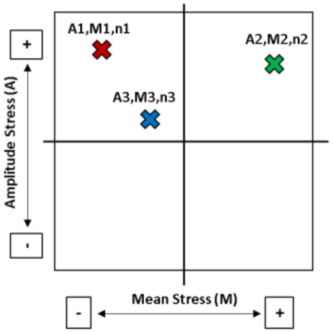


Figure 27. Different Load cycles

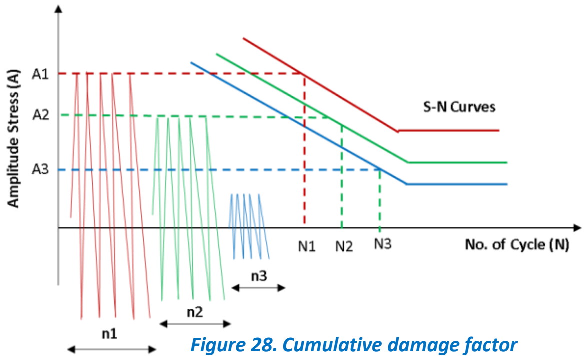


Figure 28. Cumulative damage factor

Damage factor by Miners Rule					
Load Cycle	Amplitude stress	Mean Stress	Cumulative cycle	Equivalent load cycle	Individual Damage factor
1	A1	M1	n1	N1	d1 = n1/N1
2	A2	M2	n2	N2	d2 = n2/N2
3	A3	M3	n3	N3	d3 = n3/N3
n	A_n	M_n	n_n	N	dn = n_n/N
Cumulative Damage Factor (D) = ∑ (di) = d1 + d2 +d3 + ----- + dn					

When ∑di =1, the fatigue failure occurs

Derived Loadcase for Damage calculation

Loadcases

Selective Load cases & Multiplying factor

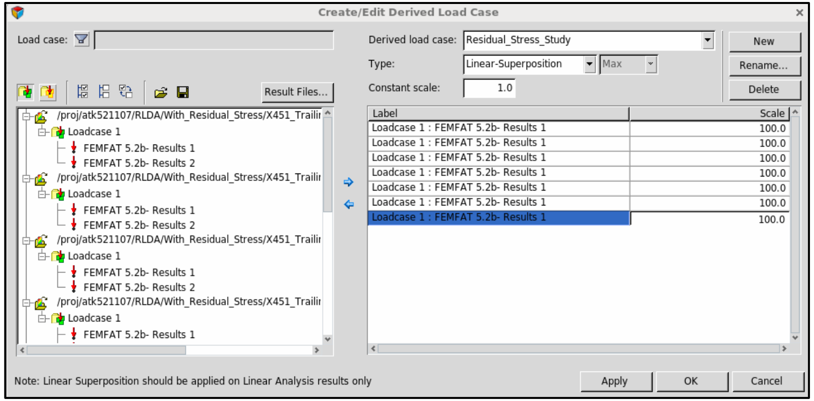


Figure 29. Derived Loadcase

By Linear Superposition of different load cases Cumulative damage factor is calculated

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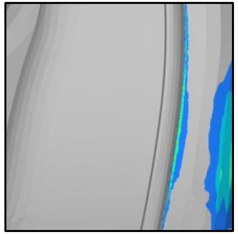
Damage factor Comparison on Trailing arm With & W/o Residual Stress
(At Different Location)

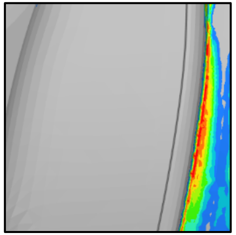
TATA

Location 1 : Top side of Trailing arm near toe

Without Residual Stress

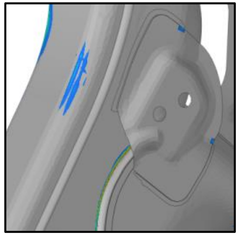


With Residual Stress

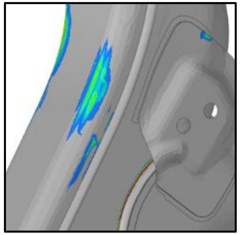


Location 3 : Bottom side of Trailing arm near toe

Without Residual Stress



With Residual Stress



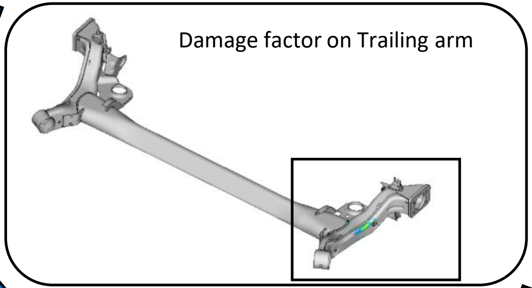
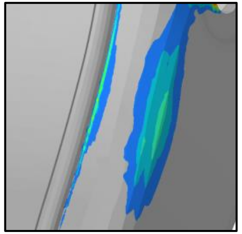


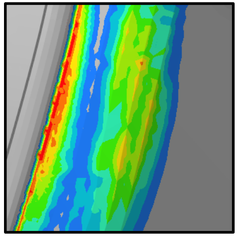
Figure 30. Damage factor at different location on Trailing arm

Location 2 : Top side of Trailing arm on curvature

Without Residual Stress

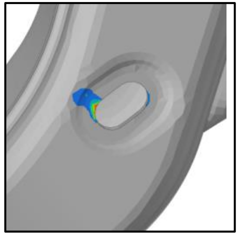


With Residual Stress

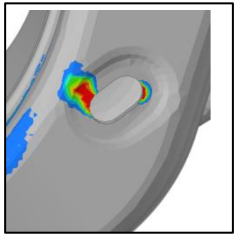


Location 4 : Hole on Trailing arm

Without Residual Stress



With Residual Stress



Quantitative analysis of Damage factor
(At Top & Bottom side of Trailing arm)

Location : Top side of Trailing arm near toe

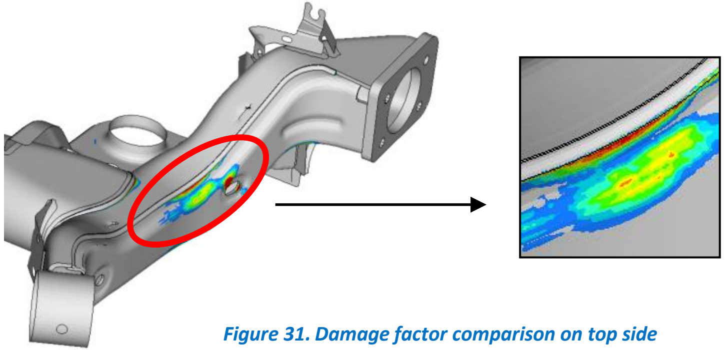


Figure 31. Damage factor comparison on top side

Location : Bottom side of Trailing arm near toe

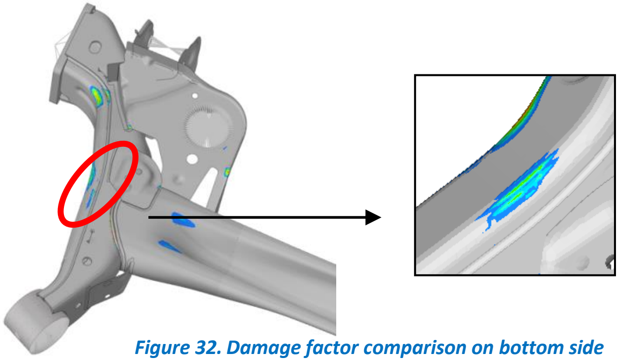


Figure 32. Damage factor comparison on bottom side

Damage factor Comparison (Top Side)				
Sr. No.	Node ID	Without Residual stress effect	With Residual stress effect	Change in Damage factor
1	1752655	1.06E-01	2.32E-01	119.51%
2	1752676	1.24E-01	2.87E-01	131.59%
3	1752697	1.43E-01	3.15E-01	120.76%
4	1752719	1.26E-01	3.04E-01	141.01%
5	1752742	1.23E-01	2.70E-01	119.12%
6	1752753	1.26E-01	2.81E-01	123.35%
7	1752771	1.84E-01	3.86E-01	109.95%

Damage factor Comparison (Bottom Side)				
Sr. No.	Node ID	Without Residual stress effect	With Residual stress effect	Change in Damage factor
1	1065818	7.69E-08	1.58E-08	-79.49%
2	1065859	3.68E-07	3.54E-08	-90.37%
3	1065872	4.60E-07	2.09E-08	-95.46%
4	1065887	1.28E-06	7.07E-08	-94.43%
5	1065896	1.31E-06	1.22E-07	-90.69%
6	1065914	1.79E-06	2.20E-07	-87.72%
7	1065908	3.34E-06	3.07E-06	-8.15%

Results & Discussions :

- Welding process generates most of the time unfavourable residual stresses & affects structural performance.
- These stresses have a significant impact on fatigue life.
- Conventional approach in fatigue assessment accounts residual stress in generic way.
- Comprehensive inclusion of residual stresses & its association in fatigue life assessment is more precise approach for robust product development.
- Manufacturing processes leads the component in pre-stressed condition. Without capturing those, there are chances of pre-mature failures.

Way Forward :

- Effect of Phase transformation also leads to generate the residual stresses & needs to be studied.
- Distortion due to welding affects fatigue life & needs to be studied.
- Optimized weld process parameters will minimize the residual stresses & improve fatigue life of component.

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- MSc. Simufact Welding 8.0 - ARC Welding Users Guide
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!!! THANK YOU !!!

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Question & Answer Session