New method for assessing the failure of adhesive bonds under cyclic loading

Date: 20th May 2021

Manuel FRANK, Magna Powertrain

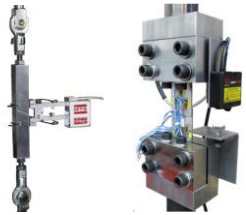
Agenda

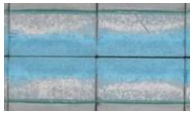
1) Fatigue Analysis in Adhesive Joints
   - Analysis Concept & Strength Data
   - Validation
   - Correlation for Stress Concentrations
2) Adhesive Failure for Stress Concentrations
3) New Method for Adhesive Assessment
4) Case Study: Vehicle Body
   - Fatigue Analysis (incl. FE Mesh Generation)
   - Damage Assessment (incl. Definition of Adhesives)
   - Results
   - Detailed Investigation
5) Conclusion

Fatigue Analysis in Adhesive Joints

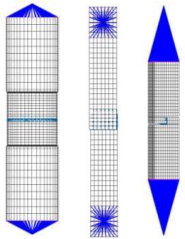
Way to Assessment of Bonded Joints

1. Analysis Concept & Strength Data

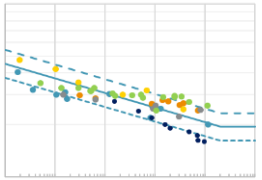




FOSTA [1] [2] [3] [4]

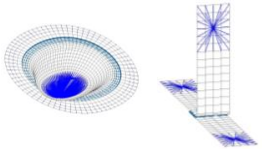


Master S-N curve:

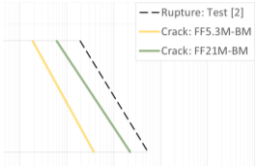


2. Validation

FOSTA [1] [2] [3] [4]



Validation S-N curves:



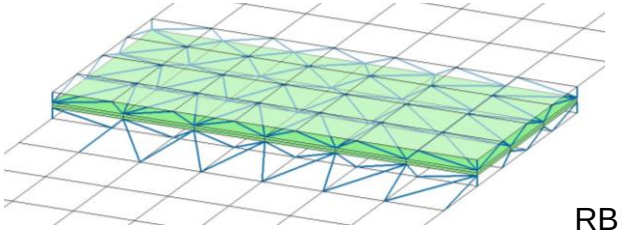
3. Calibration (+ Method Improvement, if nec.)

Analysis Concept & Strength Data

Master S-N Curve Generation: Betamate 1496V

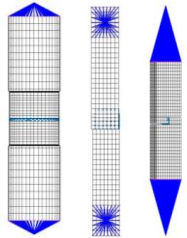
MAGNA

FE Modelling Guideline:



3 Stripes,
2 Coats,
hexa8

RBE3-hexa-RBE3



Influence Factors:

Stress Gradient

- Endurance Limit

Mean Stress

- Endurance Limit
- Slope/ Cycle Limit

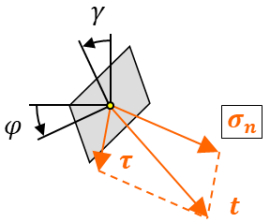
Stress Rearrangement

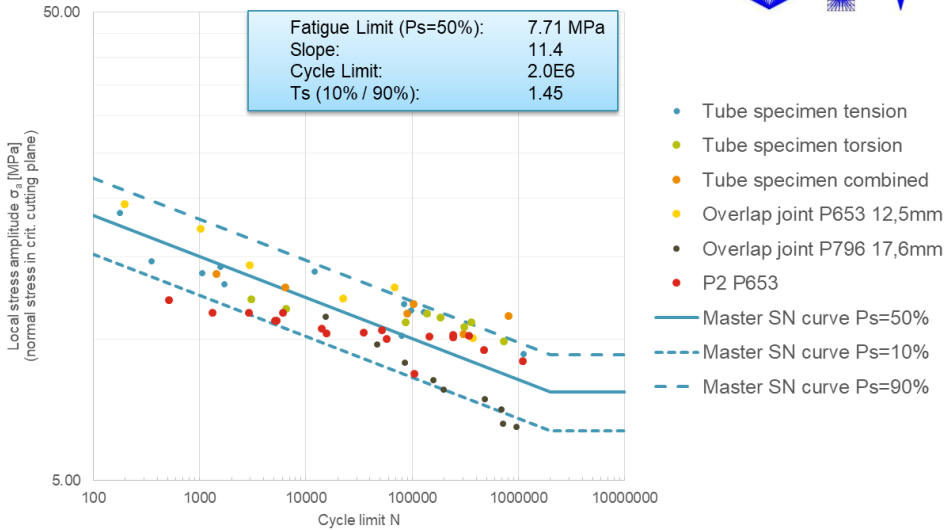
- Mean

Analysis Parameters:

MINER Elementary

Normal Stress in Critical Plane

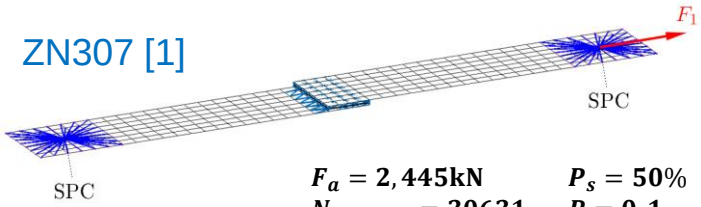




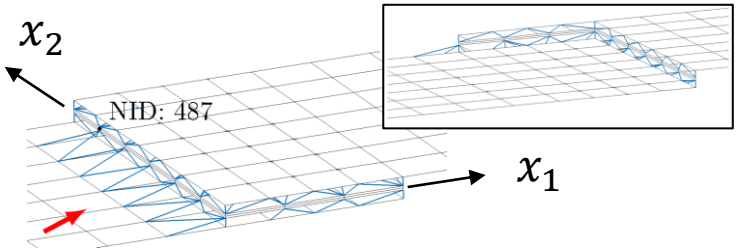
Middle Plane Assessment

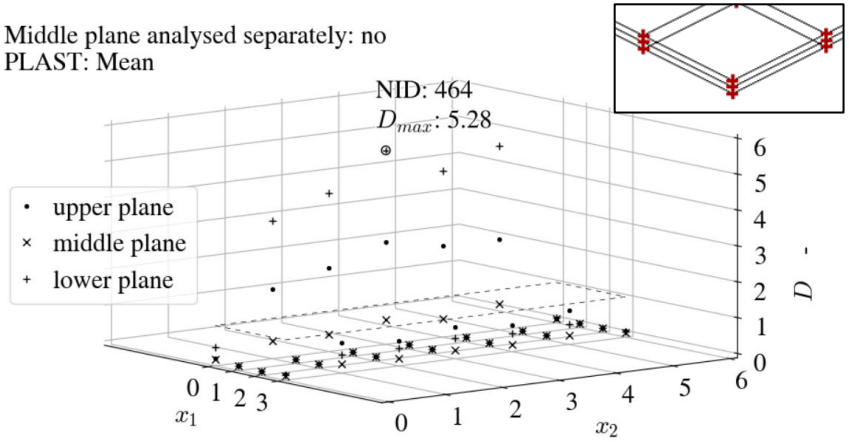
Reduction of high coupling sensitivity through assessment of middle plane

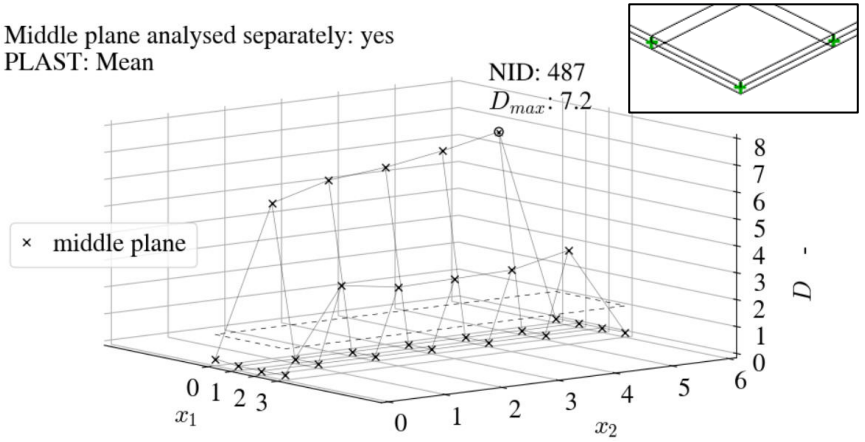
ZN307 [1]



$F_a = 2,445\text{kN}$ $P_s = 50\%$
$N_{Rupture} = 30631$ $R = 0.1$

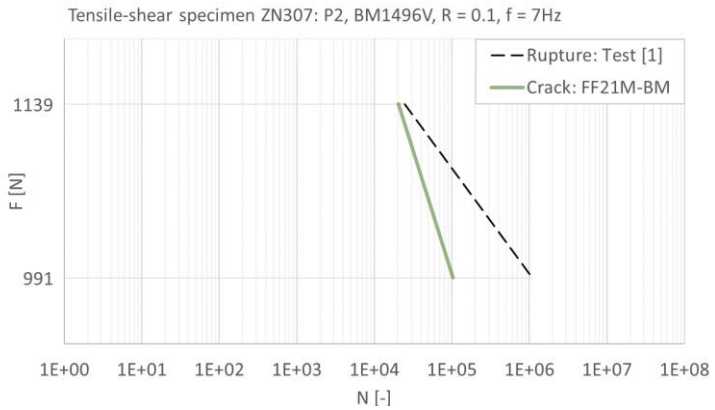


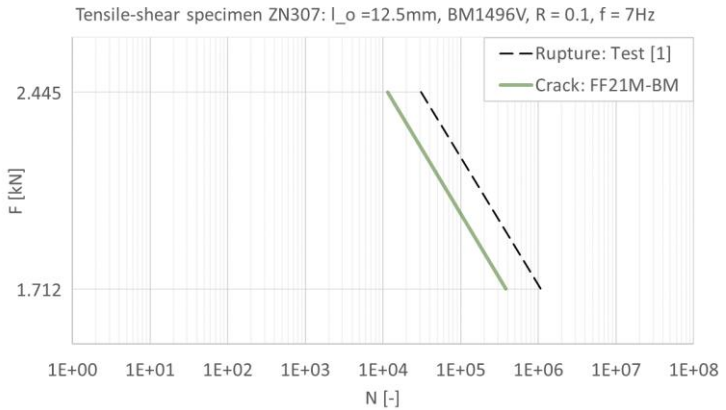


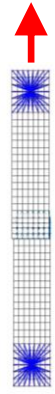


Validation

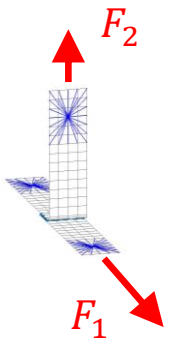
Validation: Betamate 1496V *Examples*

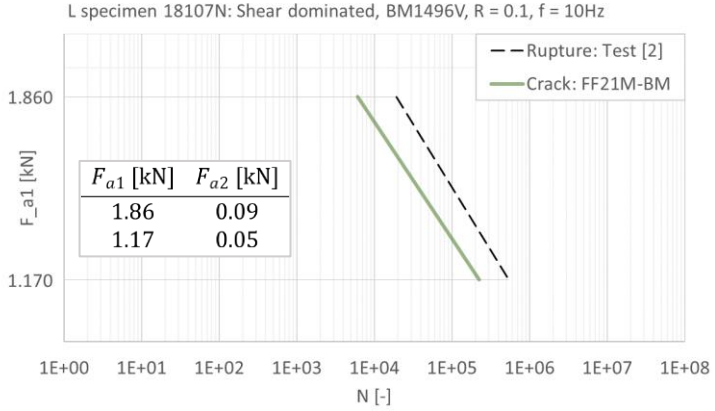




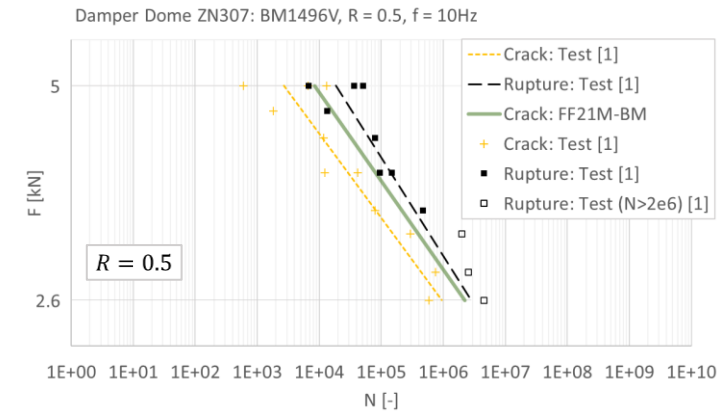


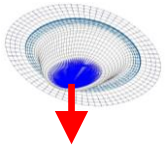
$P_S = 50\%$





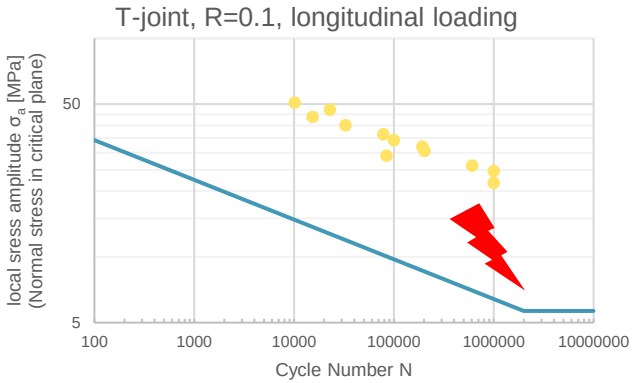
F_{a1} [kN]	F_{a2} [kN]
1.86	0.09
1.17	0.05

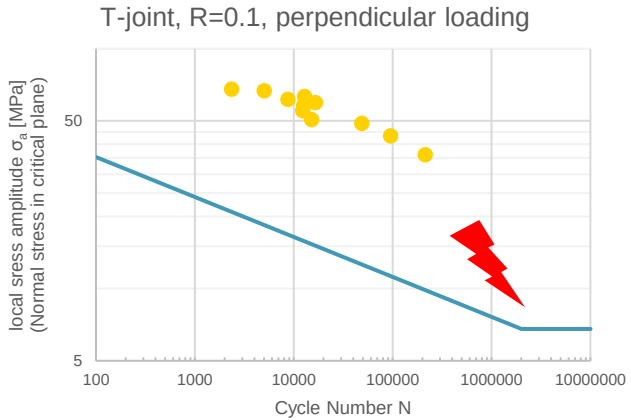


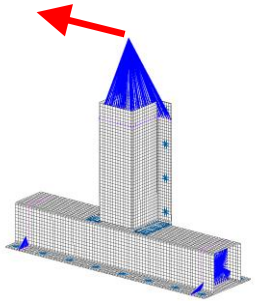


Correlation for Stress Concentrations

Correlation for Stress Concentrations



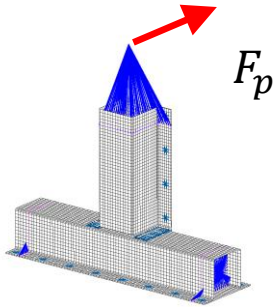




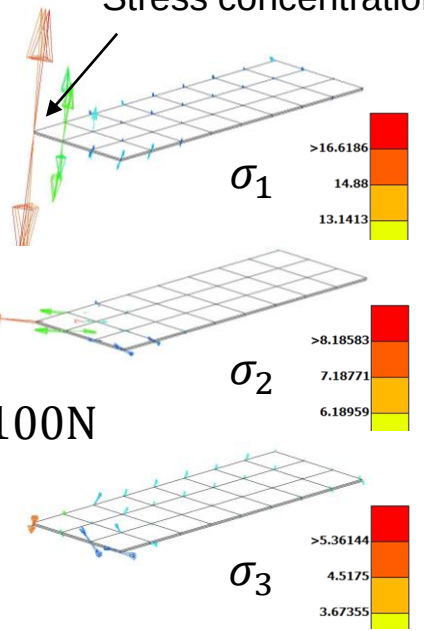
Rupture in test

FEMFAT result

$P_S = 50\%$



Stress concentration



$F_p = 100\text{N}$

→ *New MP1 specimen tests*

→ *New assessment approach?*

Failure for Stress Concentrations

… by tests on MP1 specimen

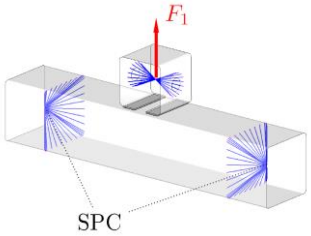
Test MP1 Specimen: Crack Propagation

SikaPower 493

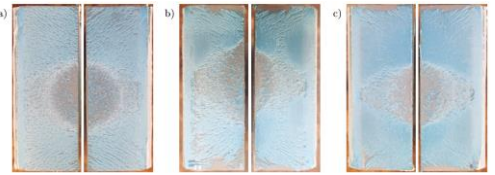
Small bead

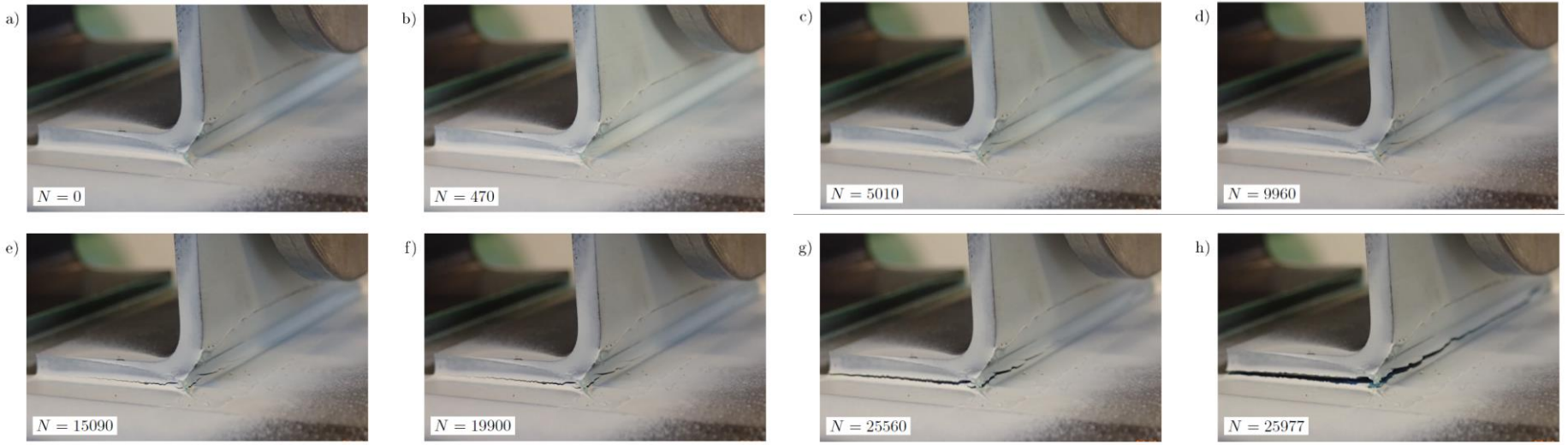
Force perpendicular

$R = 0$



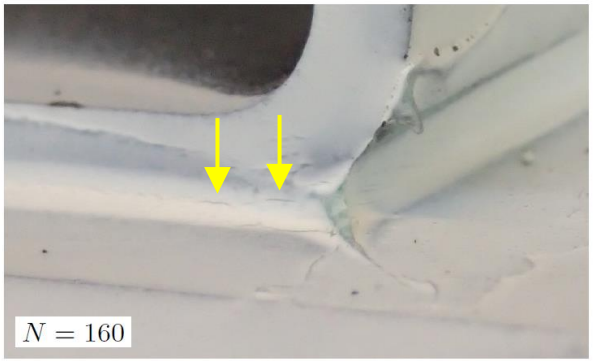
Cohesive Fatigue Failure

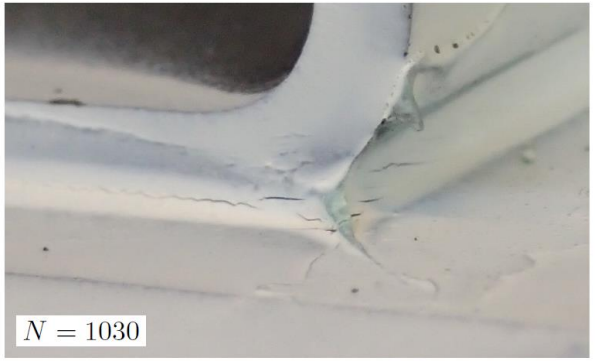


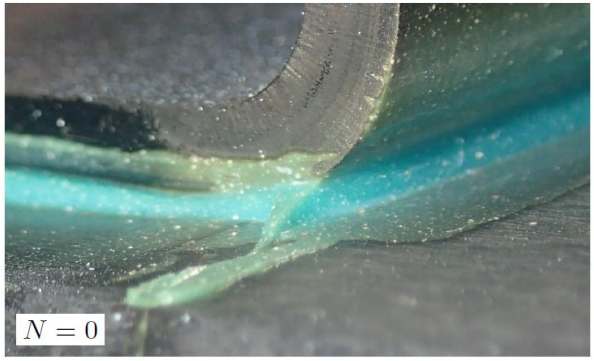


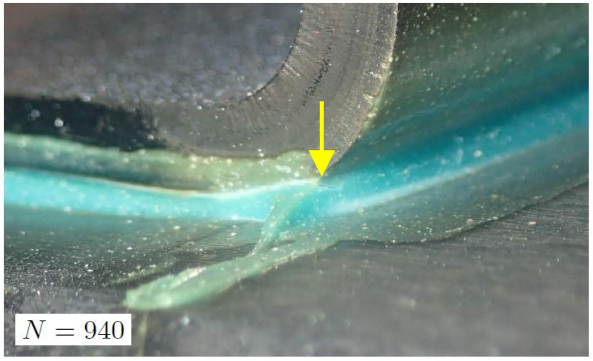
Test MP1 Specimen: Failure Criterion

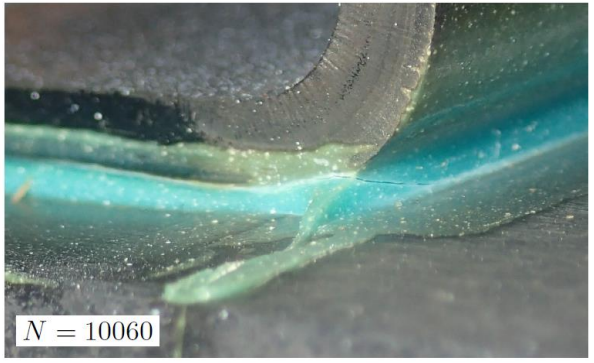
Crack Initiation: Zone:





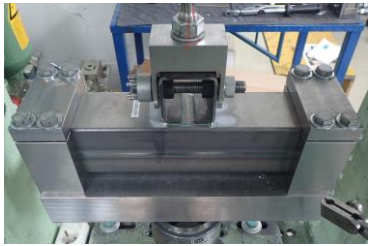


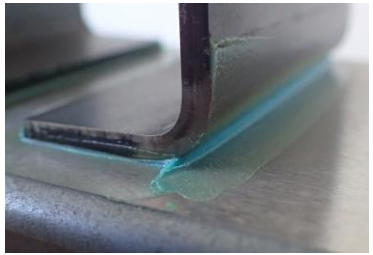


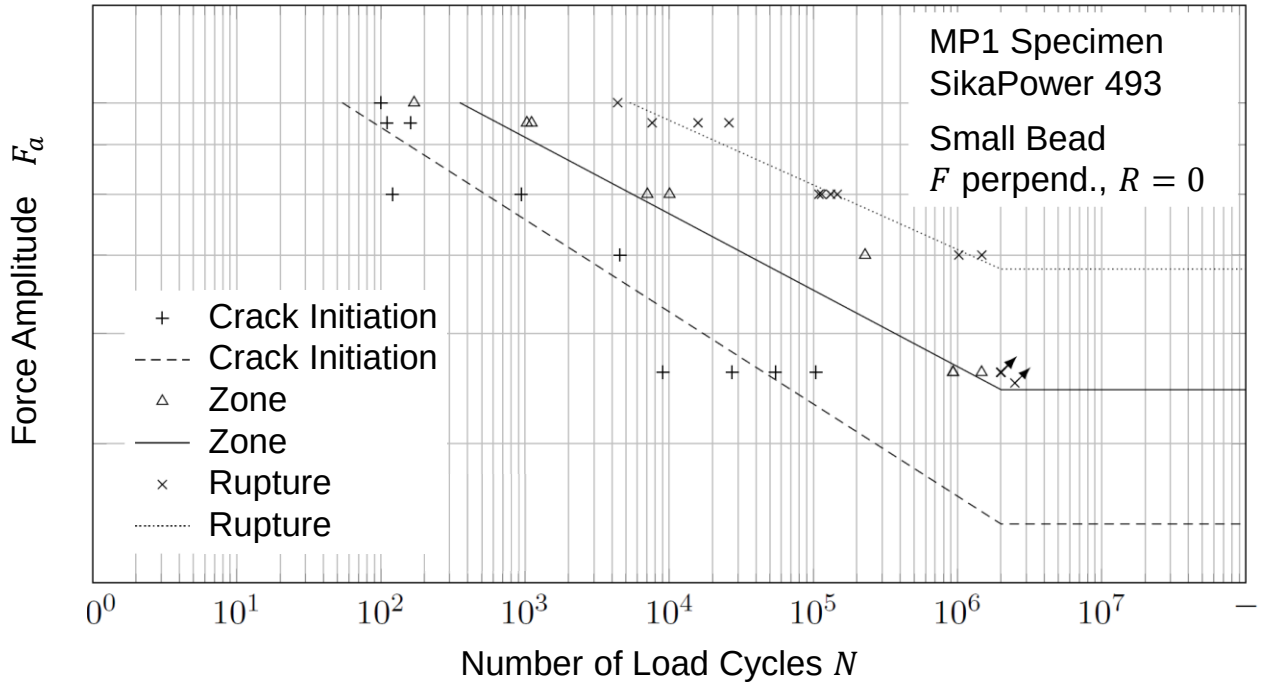


Test MP1 Specimen: S-N Curves

SikaPower 493, Small bead, Force perpendicular, $R = 0$







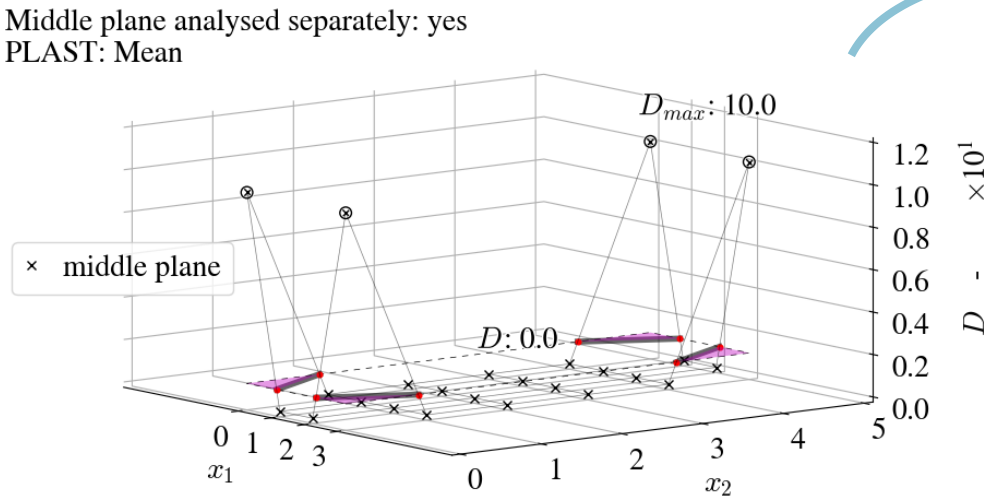
New Method for Adhesive Assessment

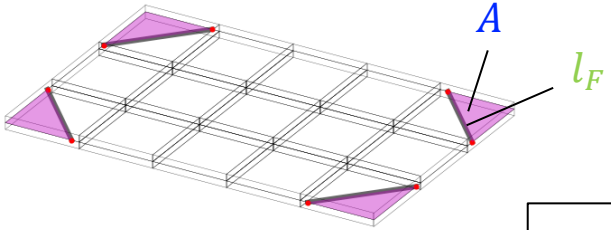
… against Zone Failure

New Method for Adhesive Assessment

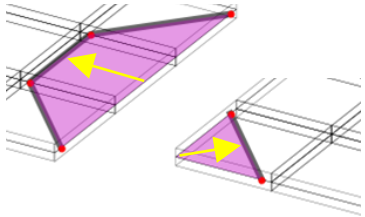
Determination of Equivalent Length l_V from Intersection Area A and Front Length l_F of **Virtual Cracked Zones**

→ *Result of Interest: Degree of Utilization* a_V



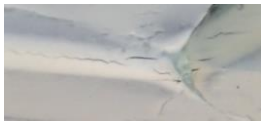


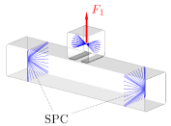
$$l_V = \frac{A}{l_F}$$

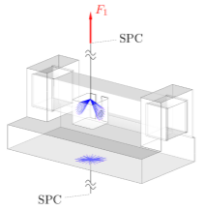


$$a_V = \frac{l_V}{l_{Vcrit}}$$

Critical Length l_{Vcrit} calibrated by Zone S-N curves:

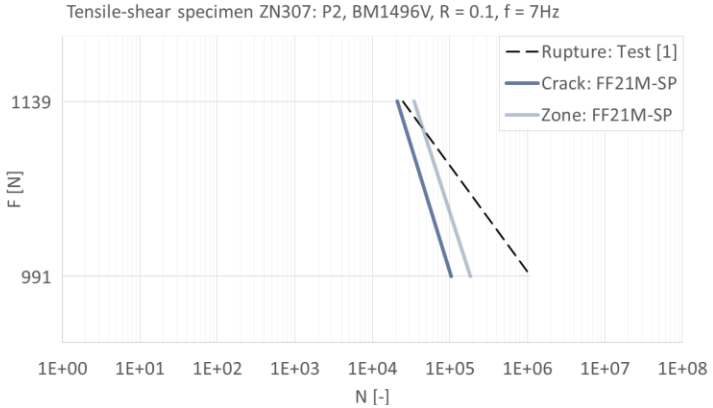


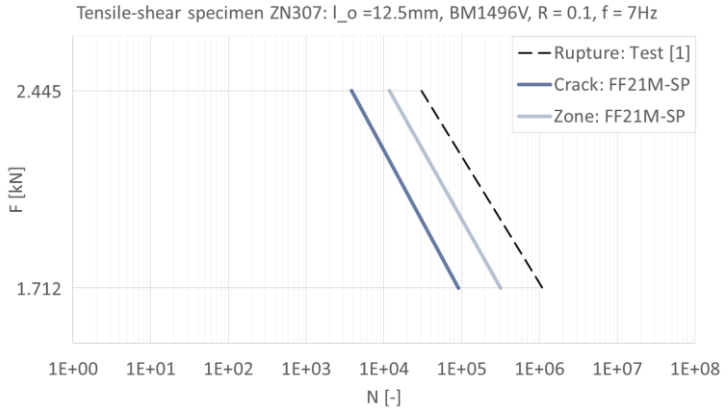


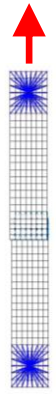


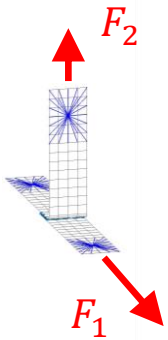
✓ *Method implemented in Standalone Tool* **ClaRP**

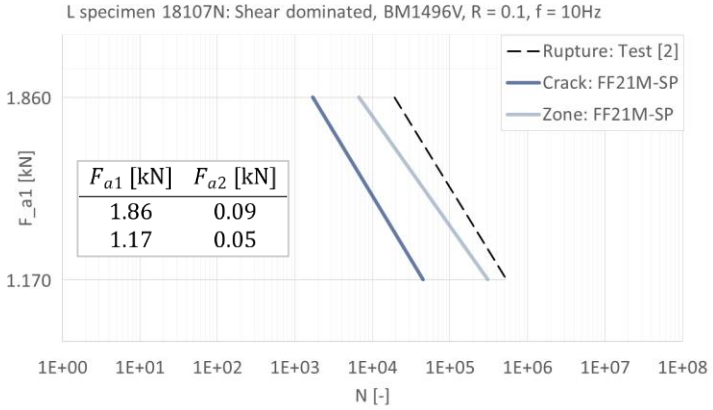
Validation: SikaPower 493 *Examples*











F_{a1} [kN]	F_{a2} [kN]
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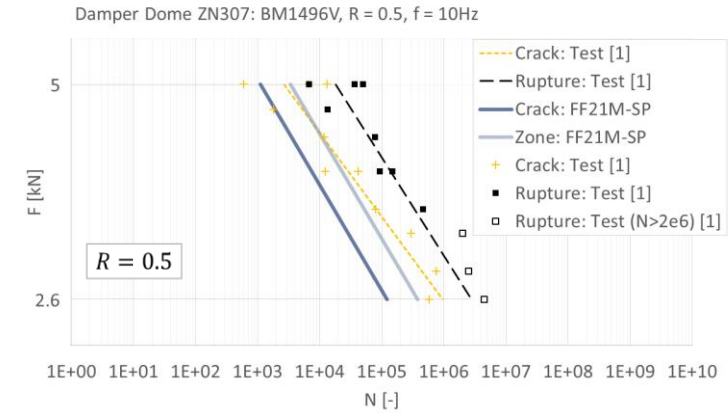
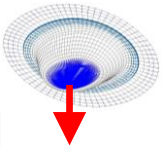


$P_S = 50\%$



Case Study – Vehicle Body

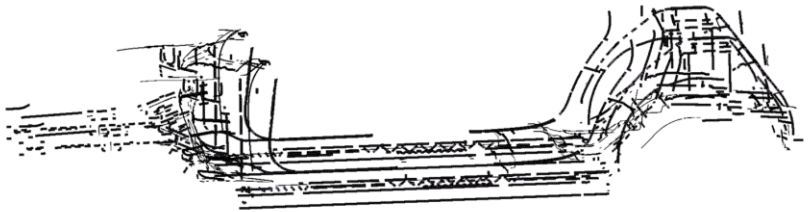
Case Study – Vehicle Body

FE Model

FE Analysis

Fatigue Analysis

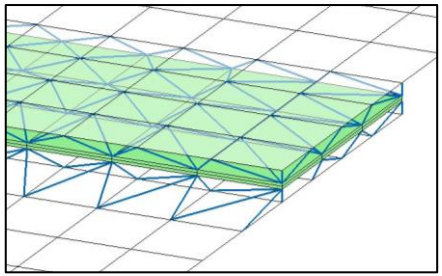
Damage Assessment



BIW with 1310 Adhesive Joints

FEMFAT

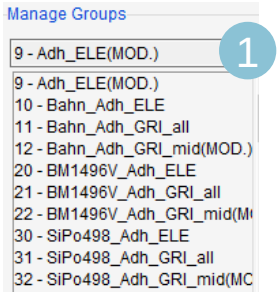
ClaRP



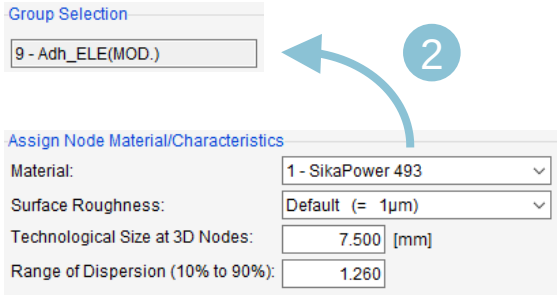
Fatigue Analysis

FEMFAT – Minimum Input & Analysis Run

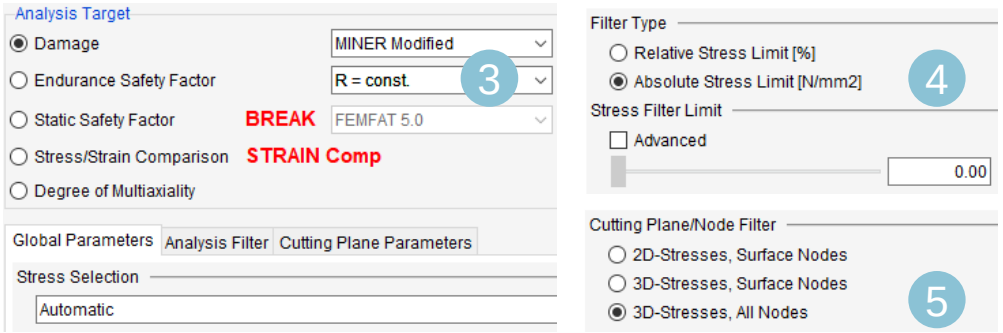
Groups:



Node Characteristics:



Analysis Parameters:



1. Add Nodes of *_Adh_GRI_mid to Elements of Adh_ELE to create the Analysis Group

   *Add *_Adh_ELE to *_Adh_GRI_mid for separate analysis of the adhesives*

2. Assign the available Material SP493_FEMFAT54_ClaRP211.ffd to the Analysis Group

3. Select R = const

4. Set Abs. Str. Limit to 0 N/mm2

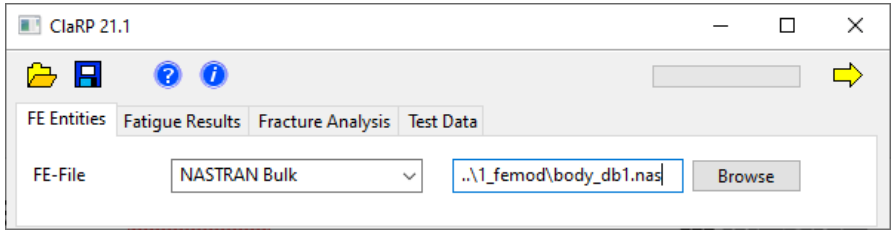
5. Select 3D-Stresses, All Nodes (for MAX only)

Damage Assessment

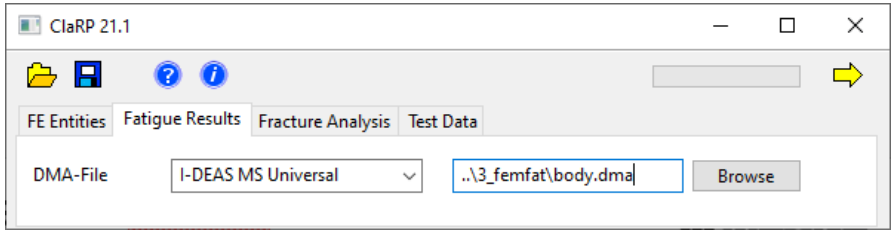
ClaRP – Minimum Input & Analysis Run

GUI Mode:

1. *Select FE Entities:*



2. *Select Fatigue Results:*



3. *Save 💾 & Run ➪ the job*

Batch Mode:

Job File (.crp):*

```
Version: ClaRP 21.1

# FE
FE_File: ..\..\1_femod\example.nas         # file path

# FF
FF_File: ..\..\3_femfat\max\example.dma         # file path
```

Run the job (.bat, *.que, …):*

```
rem  ------------------------------------------------------
set CP=CALL "C:\path2\software\clarp\win\ClaRP.exe"
rem  ------------------------------------------------------
%CP% --crp C:\path2\projects\project1\job1.crp
%CP% --crp C:\path2\projects\project2\job1.crp
```

ClaRP – Database (*.drp)

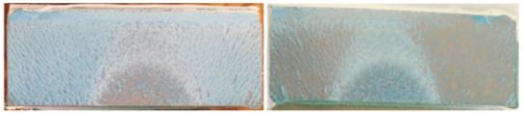
Standard Database:

```
# Database              : Adhesive Layer Assessment on FE-Structures
# Content               : Critical Lengths of Virtual Cracked Zones

# Program               : ClaRP
# Version               : 21.1




# Material Data         : SikaPower 493
# ====================================

# Source                : ECS - Test MP1 specimen: Zone, EP1_k_s0, Mid_M_a3250_R0
# Last Modification     : Mar 14 2021
Identifier              : SP493
Critical Length         : 2.12044

# Requirements for validity of Critical Length
#   Material Data in FEMFAT Analysis ................. SikaPower493_FEMFAT54_ClaRP211.ffd
#   Last Modification of ffd-File .................... Mar 14 2021



# Material Data         : Betamate 1496V
# ====================================

# Source                : ECS - Test MP1 specimen: Zone, EP2_k_s0, Mid_M_a3250_R0
```

If your Material is not included, choose an available with similar properties (before FE Analysis):

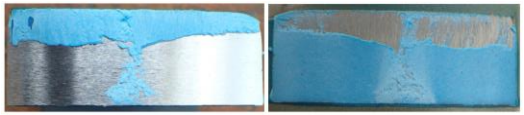
SikaPower 493

Long cohesive crack propagation phase for grinded + degreased parts



Betamate 1496V

Small cohesive crack propagation phase for grinded + degreased parts



Results

Results: SikaPower 493 $P_S = 50\%$

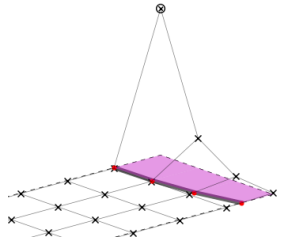
Assessment result in the report file (*.rrp):

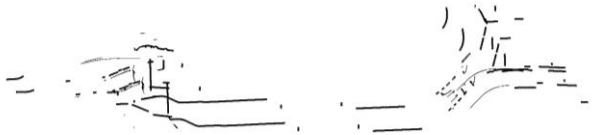
Computation time: 14s

```
---------------------------
A N A L Y S I S   R E P O R T
---------------------------

Program              : ClaRP
Version              : 21.1
Date                 : Di Apr 13 16:31:22 2021
Analysis Content     : Adhesive Layer Assessment on FE-Structures
                       ... based on Fatigue Analysis Results from FEMFAT
Notice               :
Comment              :


General Input Data
==================

ClaRP Input
  C:\FEMFAT\body\4_clarp\body.crp

ClaRP Database
  C:\FEMFAT\body\4_clarp\body.drp

ClaRP Allocation Table
  C:\FEMFAT\body\4_clarp\body.drpa

FE Input
  C:\FEMFAT\body\1_femod\body_db1.nas

FEMFAT Result
  C:\FEMFAT\body\3_femfat\body.dma

Status
  Analysed Adhesive Layer Planes
    Fatigue Analysis ..................... Middle Plane
    Fracture Assessment .................. Middle Plane
  Scaling ..........................................  Linear
  Report
    Zones per Layer ....................................  All
    Sorting ..........................................  Utili. Deg.
  Number of Load Cycles ..............................  1

Limits
  Damage from Crack Initiation .....................  1.0 [-]
```

```
Virtual Cracked Zones Data
==========================

Virtual Cracked Zones Types      ... combined types are possible
  ci ... D > 1 at i corner nodes
  ei ... D > 1 at i edge nodes
  mi ... D > 1 at i middle nodes


In Scope
```

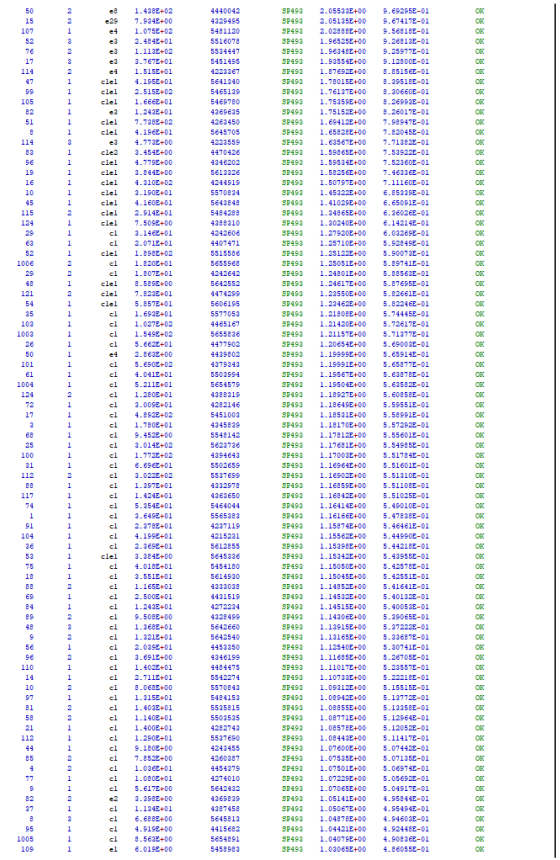
Adh. ID	Zone ID	Zone Type	Dmax	Node ID(Dmax)	Asse. Mat.	Equiv. Len.	Utili. Deg.	ClaRP Res.
85	3	c2e3	1.578E+04	4260471	SP493	3.53003E+00	1.66476E+00	not OK
117	3	c2e3	1.057E+04	4363734	SP493	3.51498E+00	1.65767E+00	not OK
2	1	c2e2	2.378E+02	4398927	SP493	3.33234E+00	1.57153E+00	not OK
121	1	c2e2	4.228E+02	4474239	SP493	3.22838E+00	1.52250E+00	not OK
86	1	c2e2	2.752E+01	5477385	SP493	3.21192E+00	1.51474E+00	not OK
12	1	c2e3	4.935E+03	5572658	SP493	3.14312E+00	1.48229E+00	not OK
42	1	c2e3	3.153E+03	5570711	SP493	3.13976E+00	1.48071E+00	not OK
89	3	c2e2	2.231E+02	4328595	SP493	3.01723E+00	1.42293E+00	not OK
118	1	c2e2	8.232E+01	4435071	SP493	2.90110E+00	1.36816E+00	not OK
40	1	c2e2	1.911E+01	5616679	SP493	2.89957E+00	1.36744E+00	not OK
116	1	c2e2	1.083E+01	4356714	SP493	2.77718E+00	1.30972E+00	not OK
33	1	c2e2	1.967E+01	5643278	SP493	2.76410E+00	1.30355E+00	not OK
7	1	c2e5	4.102E+02	5641541	SP493	2.75993E+00	1.30159E+00	not OK
46	1	c2e5	1.902E+02	5643488	SP493	2.42202E+00	1.14222E+00	not OK
15	3	c1e2	3.098E+02	4329963	SP493	2.36398E+00	1.11485E+00	not OK
49	1	c2e2	4.111E+01	5570918	SP493	2.36396E+00	1.11484E+00	not OK
124	3	c2e2	7.393E+02	4388406	SP493	2.35127E+00	1.10886E+00	not OK
50	5	c1e2	3.005E+01	4440378	SP493	2.26355E+00	1.06749E+00	not OK
45	2	c1e4	7.585E+01	5643932	SP493	2.18922E+00	1.03244E+00	not OK
6	1	c2e6	9.527E+01	5642828	SP493	2.18041E+00	1.02828E+00	not OK
50	3	e4	1.598E+02	4440198	SP493	2.05837E+00	9.70725E-01	OK

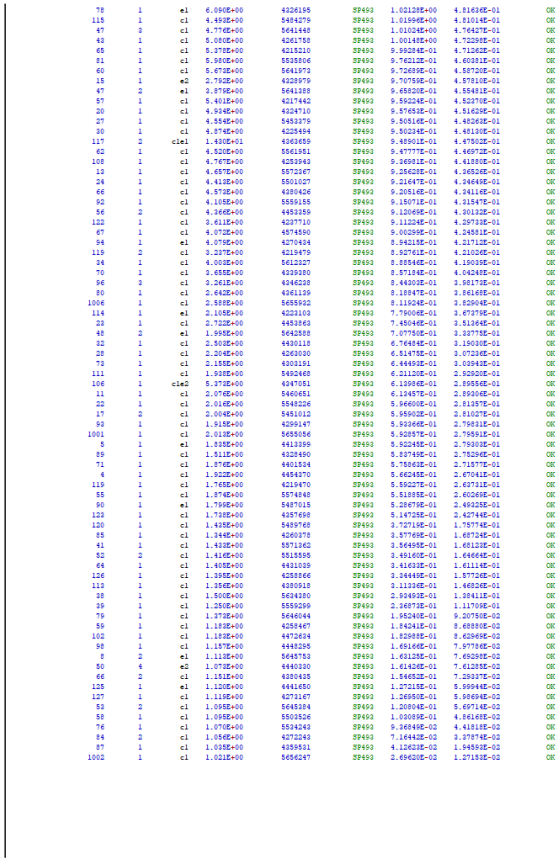




20 critical Zones with $a_V > 1$

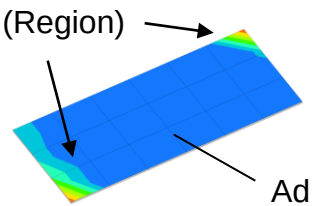
Results: SikaPower 493 $P_S = 50\%$





1310 Adhesives in BIW

180 Virtual Crack Zones (VCZ) at 133 Adhesives with $D_{max} > 1$

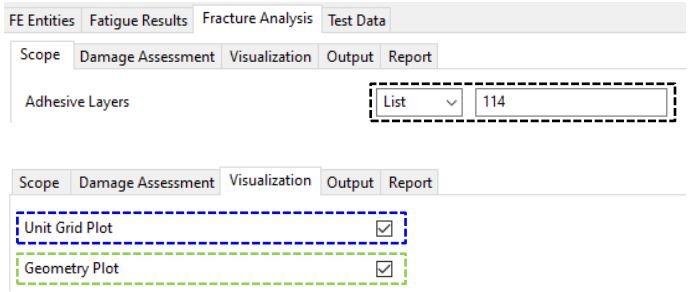


20 critical VCZ with $a_V > 1$

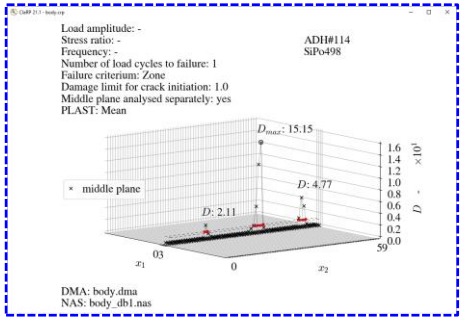
Detailed Investigation

Detailed Investigation: SikaPower 493 $P_S = 50\%$

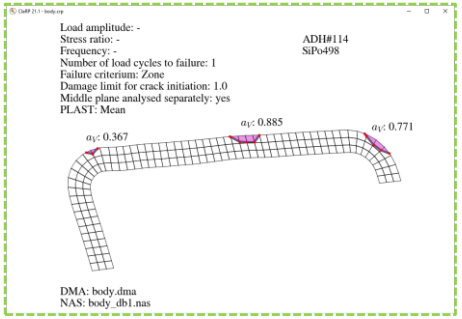
ClaRP – Visualization:



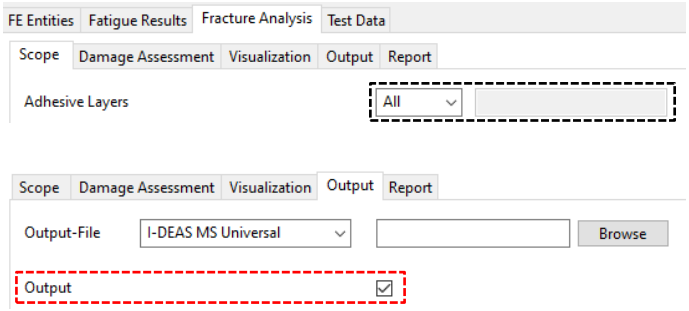
Unit Grid Plot:



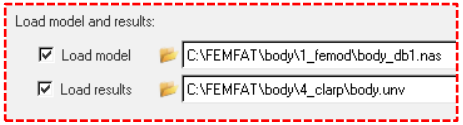
Geometry Plot:

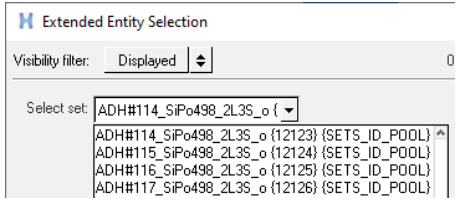


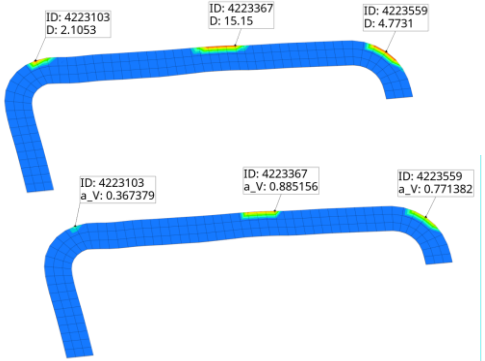
ClaRP – Output:



HyperView:







Conclusion

Conclusion

- The new method for the assessment of adhesives calibrated by test results
  - provides with the Degree of Utilization a_V a further result in addition to Damage D
  - consider nodes with damage maxima and their neighboring nodes
  - enables a clear comparison of highly damaged areas
  - limits the number of critical cracked zones significantly
- The assessment of adhesives by the new Standalone Tool ***ClaRP***
  - is applied to damage results in a post-processing step
  - is directly applicable to complex structures
  - requires low computational effort
  - enables the visualization for detailed investigation
  - be executed in Batch Mode and thus automated
  - can be used to locate critical adhesive layers for sub-model analyses
  - uses an open Universal format for the input of node-based results
  - uses an open database, that can be extended
- The focus is now on gaining experience & the improvement of usability

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

Acknowledgment

With many thanks to FOSTA (Forschungsvereinigung Stahlanwendung e.V.), which has cooperated with MAGNA for many years in IGF research projects.

The funding of the IGF projects was provided by the AiF (Arbeitsgemeinschaft industrieller Forschungsvereinigungen e.V.) as part of the Program for the Promotion of the IGF (Industrielle Gemeinschaftsforschung) by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Government.

Special thanks go to the universities, institutes and people involved in the IGF projects for the great research. Same to all MAGNA development partners from industry who continuously support the ECS (Engineering Center Steyr) in method development.

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