FP6 Program DaToN

Fatigue crack propagation simulation of integrally stiffened structures

Sascha Häusler

28 November 2008

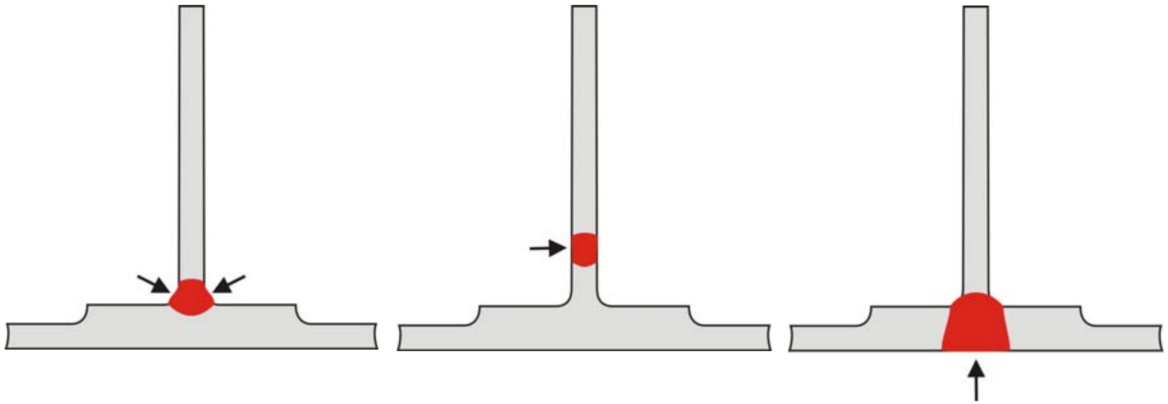
Outline

- FP6 program DaToN – overview
- Pseudo-numerical simulation tool
- Incorporation of residual stress effects
- Model parameters (residual stress module & crack growth)
- Simulation results for two stringer panel in different configurations

FP6 Program DaToN - overview

- DaToN → **Innovative Fatigue and Damage Tolerance Methods for the Application of New Structural Concepts**

- investigation of the damage tolerance behaviour of integrally stiffened metallic structures manufactured from:
  - High speed machining (HSM)
  - Laser beam welding (LBW)
  - Friction stir welding (FSW)



- Project had <u>two major focuses</u>:
  - large **experimental testing program**
  - development and improvement of **simulation tools**

Simulation approach – overview

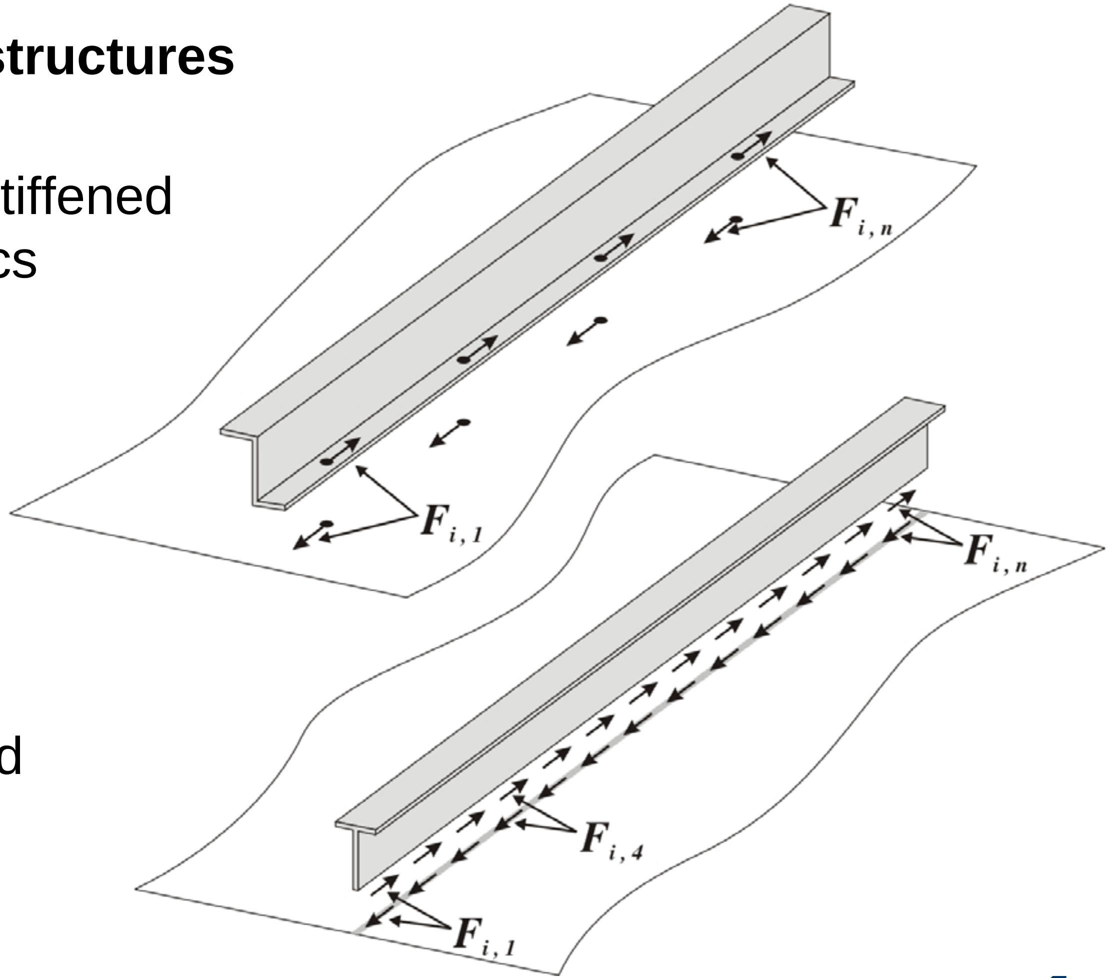
- methodology is based on an analytical approach which demands **compatibility of displacement** between fuselage skin, fasteners and stiffeners in order to determine the stress intensity factors in skin and, if applicable, in stiffeners

- **originally developed for built-up structures**

- **adaptations necessary** to handle stiffened structures with integral characteristics

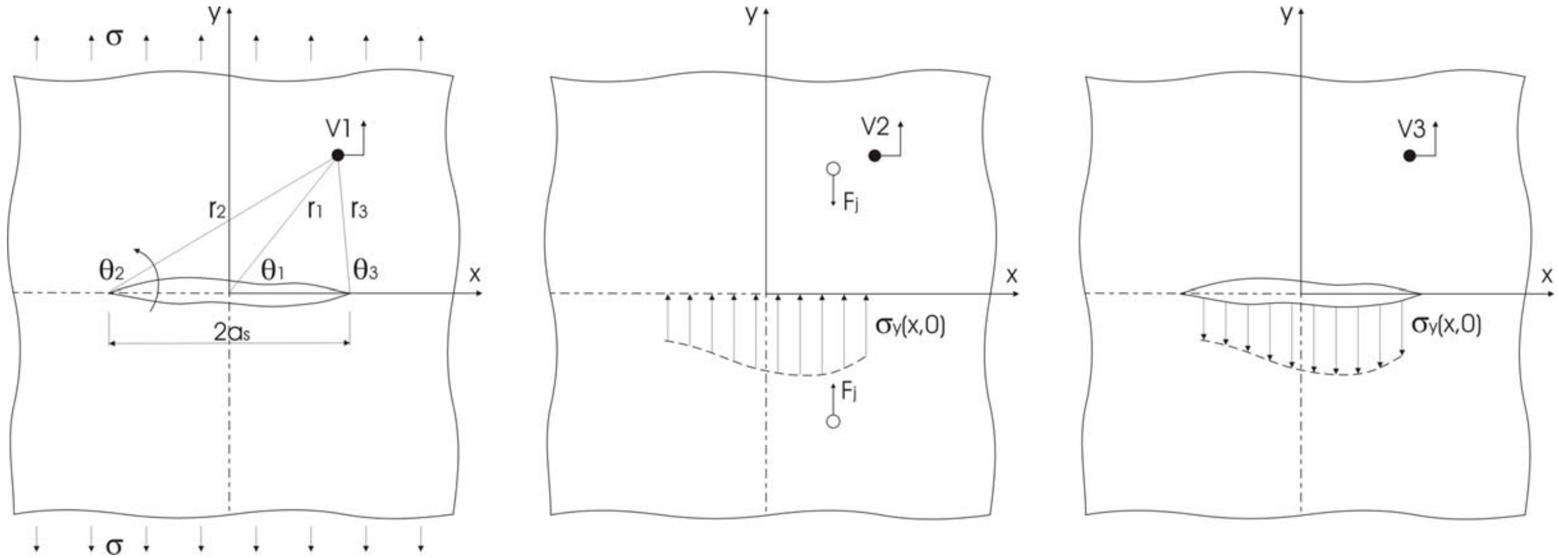
- **unknown local interface forces** along the skin-stiffener interfaces determined by demanding displacement compatibility

- **stress intensity factors** for skin and stiffener cracks calculated by superposition



Simulation approach – skin & stiffener displacements

- **skin displacements** are split up into three different contributions based on complex stress functions



- **stiffener displacements** are split up into two main contributions associated with global stress and local interface forces, which are further differentiated according to the stiffener state

approach by Swift

stiffener displacements:
- intact (*V_g and V_d*)
- broken (*V_g and V_d*)
- contributions due to longitudinal bending (*V_d*)

+

approach by Nishimura

stiffener displacements:
- intact (*V_g and V_d*)
- broken (*V_g and V_d*)
- cracked (*V_g and V_d*)

=

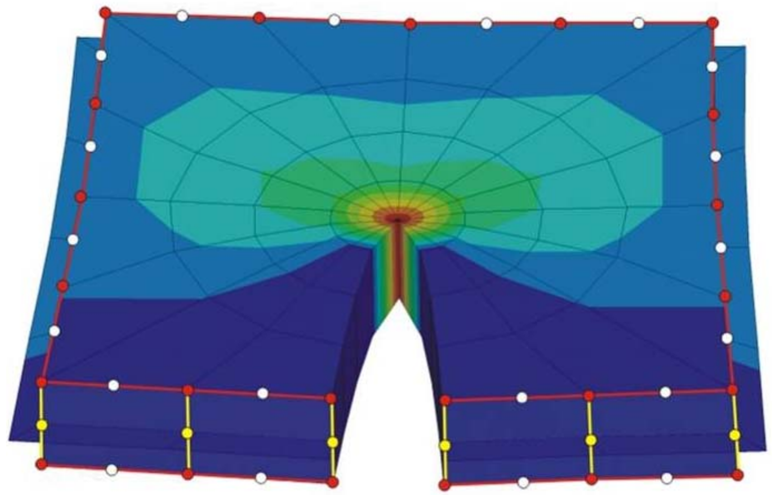
presented approach

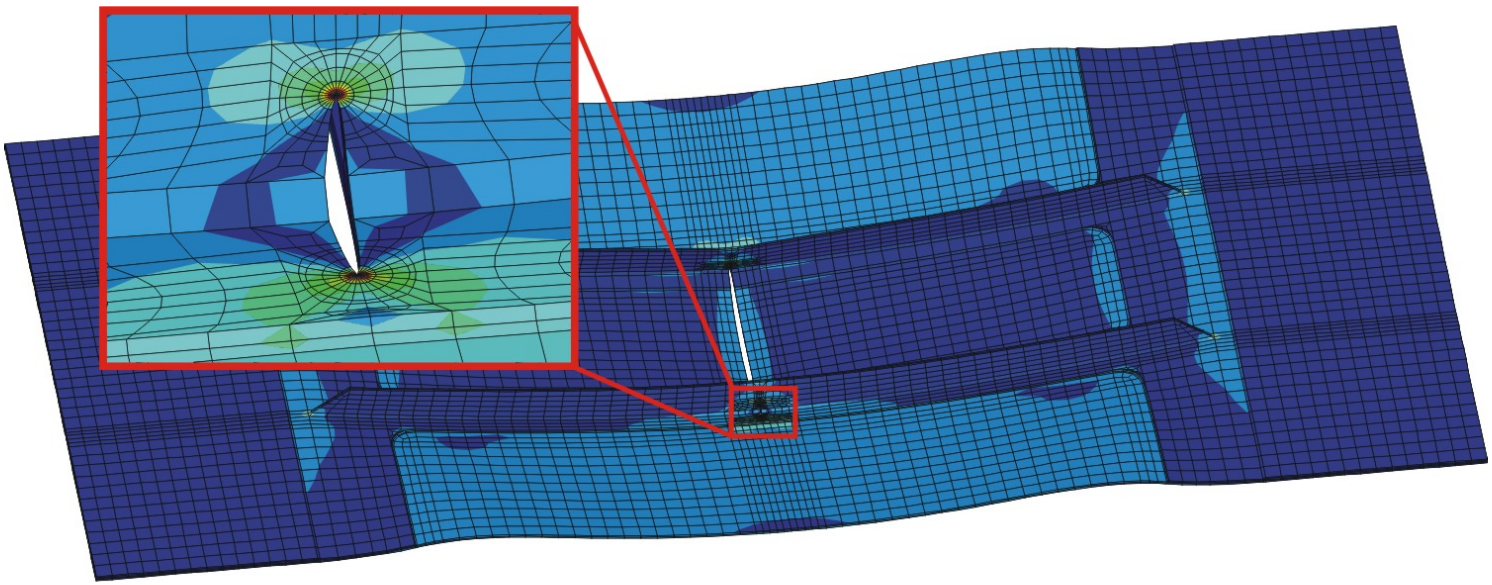
stiffener displacements:
- intact, broken (*V_g and V_d*)
- cracked (*V_g and V_d*)
- contributions due to longitudinal bending (*V_d*)

Model verification – finite element simulations

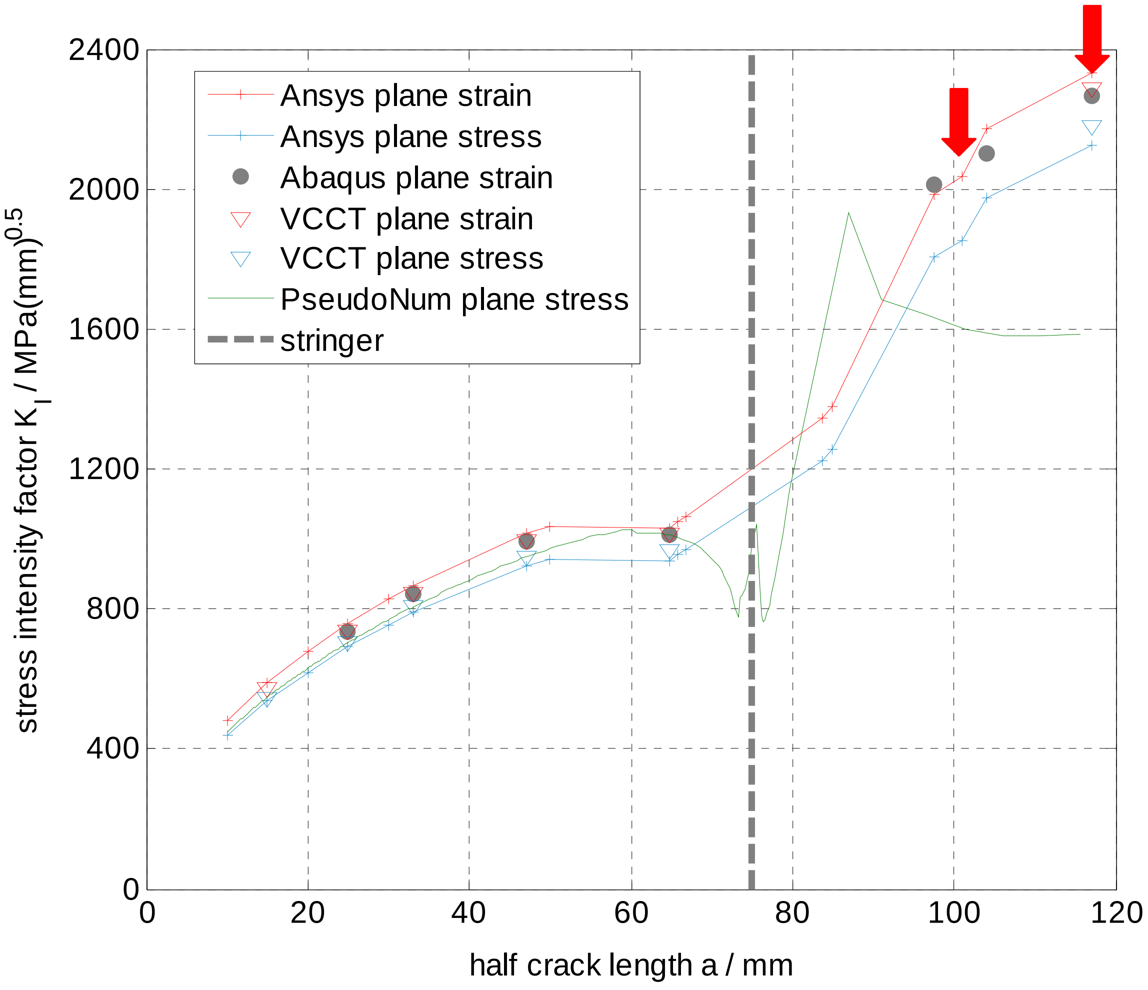
- stress intensity factor (SIF) results from **finite element solutions without** considering **residual stresses** are used to **validate** the **simulation model**

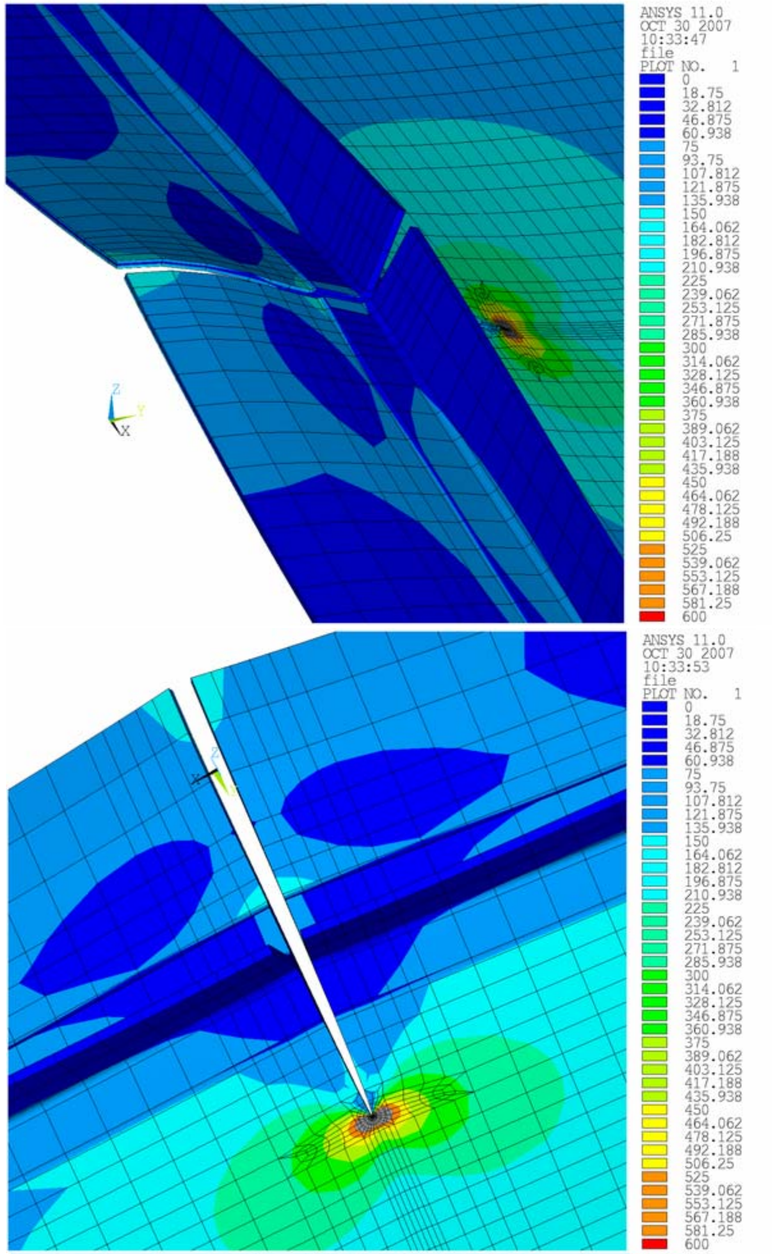
- **3D multilayer crack tip tool**
  offering different extraction methods
  (*J-Integral* and *Virtual Crack Closure Technique - VCCT*)





Model verification – finite element simulation results

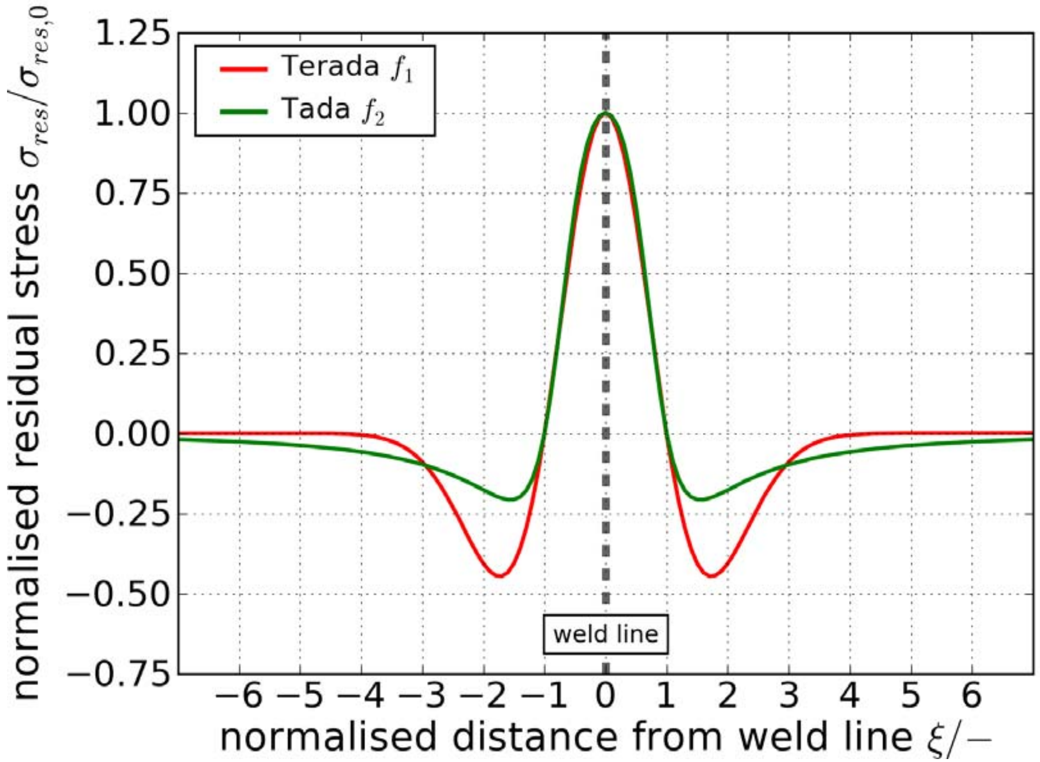


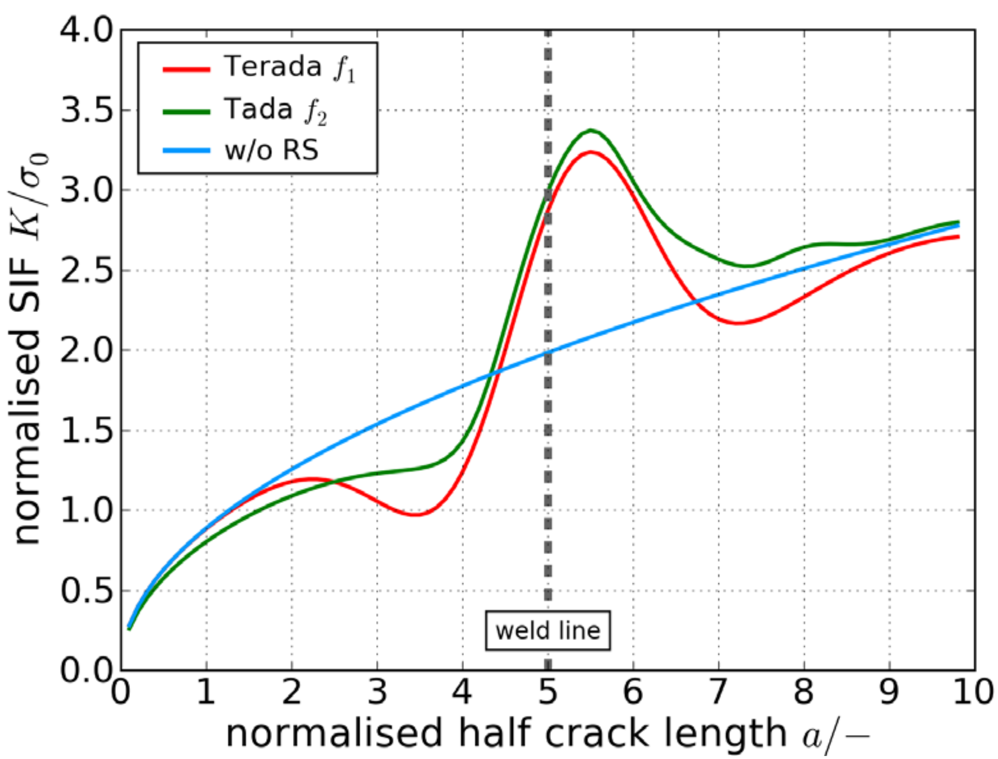


Sascha Häusler
28 November 2008
Institute of Aircraft Design and Lightweight Structures – Technische Universität Braunschweig
IFL

Residual stresses – additional stress intensity factors

- **longitudinal residual stress field** is expressed by **adapted empirical formulations** from Terada and Tada
- residual stress intensity factor is determined by integration of a **weight function**
- **superposition gives overall SIF** $K_{sum} = K_0 + K_{res}$





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Residual stresses – influence on fatigue crack growth rate

- fatigue crack growth (FCG) rate determined using different **crack growth laws**:

Paris: $\frac{da}{dN} = C\Delta K^n$ Forman: $\frac{da}{dN} = \frac{C\Delta K^n}{(1-R)K_c - \Delta K}$ Walker: $\frac{da}{dN} = \frac{C\Delta K^n}{(1-R)^m}$

- with SIF range $\Delta K = K_{max} - K_{min}$ and stress ratio $R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{K_{min}}{K_{max}}$

- **including residual stresses** this leads to

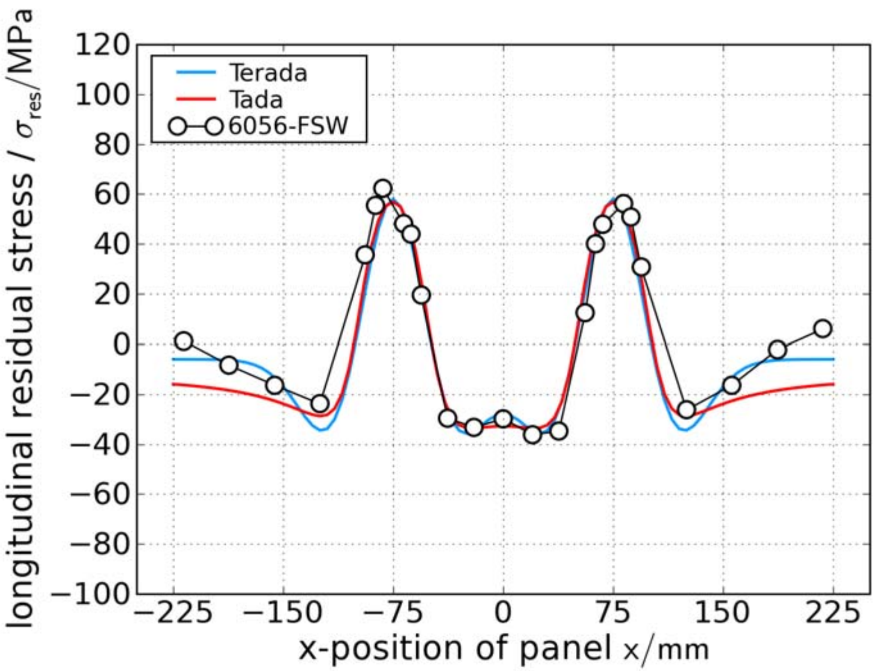
$$\left.\begin{aligned}\Delta K &= (K_{0,max} + K_{res}) - (K_{0,min} + K_{res}) \\ &= K_{0,max} - K_{0,min} \\ R = R_{eff} &= \frac{K_{min}}{K_{max}} = \frac{K_{nom,min} + K_{res}}{K_{nom,max} + K_{res}}\end{aligned}\right\}$$

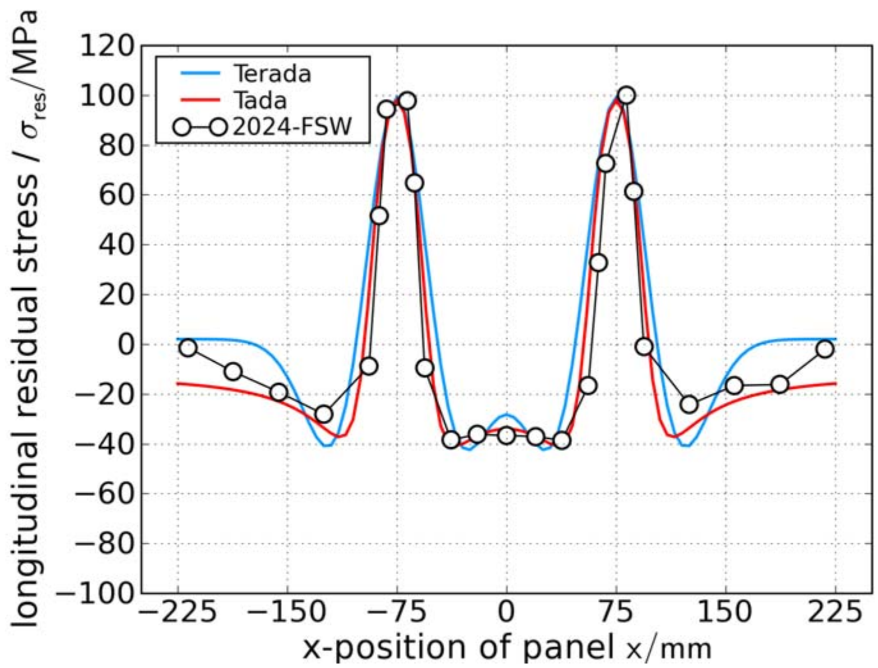
- K_{res} cancels out in ΔK
- use of effective stress ratio R_{eff} essential to include RS effects in FCG calculations

Residual stresses – model adaptation & input parameters

- **interaction of residual stress fields** from welded stiffeners leads to **compressive residual stresses** between the stiffeners → **model adaptation**
  i. shifting parameter $y_{shift} = \sigma_{compr} / n_{stiff}$
  ii. adapted maximum stress $\sigma_0^{\mathrm{mod}} = \sigma_0 - \sigma_{compr} = \sigma_0 - n_{stiff}\, y_{shift}$

→ determined from experimental residual stress field data, provided by project partner at the University of Pisa





Material parameter determination – Al6056

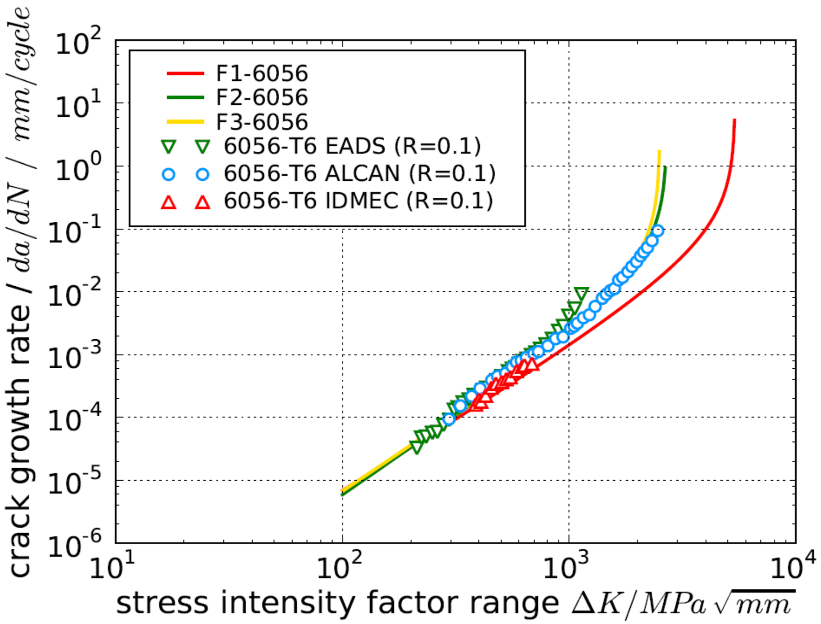
- large sensitivity of the FCG simulation results with respect to crack growth parameters due to the exponential characteristics of the crack growth laws

  → one of the major issues for the simulation tasks throughout project duration

- implemented residual stress module requires the use of effective stress ratio R_{eff}
  → *Forman* Law or *Walker* Law

- determination via curve fitting of experimental crack growth data

	source	law	C	N	K_C	m_W
F1-6056	IDMEC	Forman	1.20E-06	2.240	6000	-
F2-6056	ALCAN	Forman	1.92E-07	2.450	3000	-
F3-6056	ALCAN	Forman	2.81E-07	2.380	2800	-
F5-6056	ALCAN	Forman	1.00E-07	2.490	3000	-
W1-6056	IMPERIAL	Walker	4.42E-12	2.850	3000	1.179

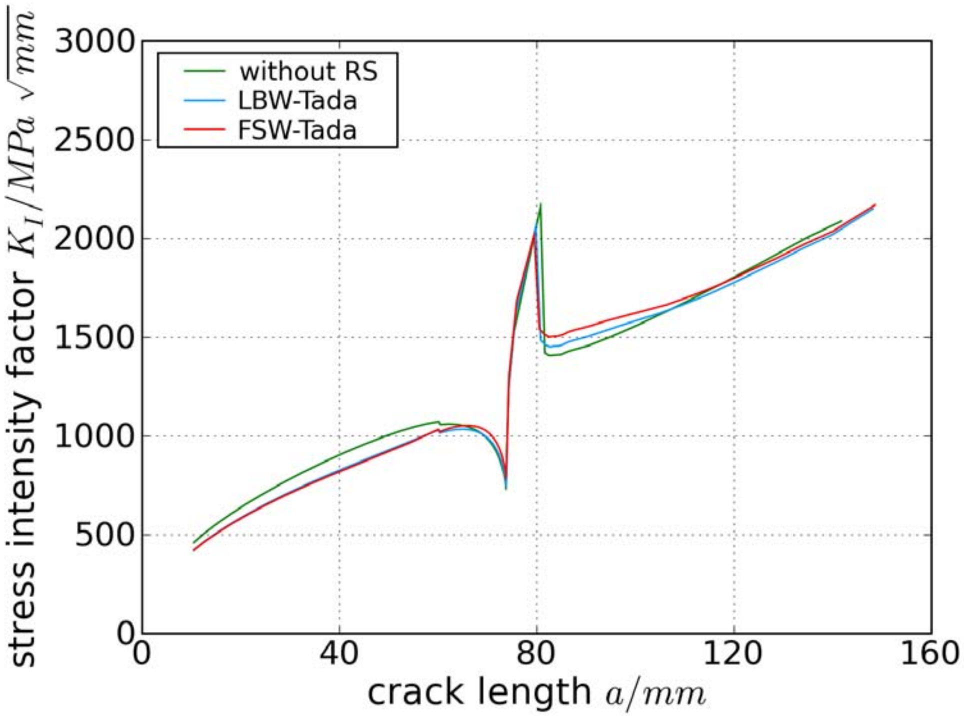


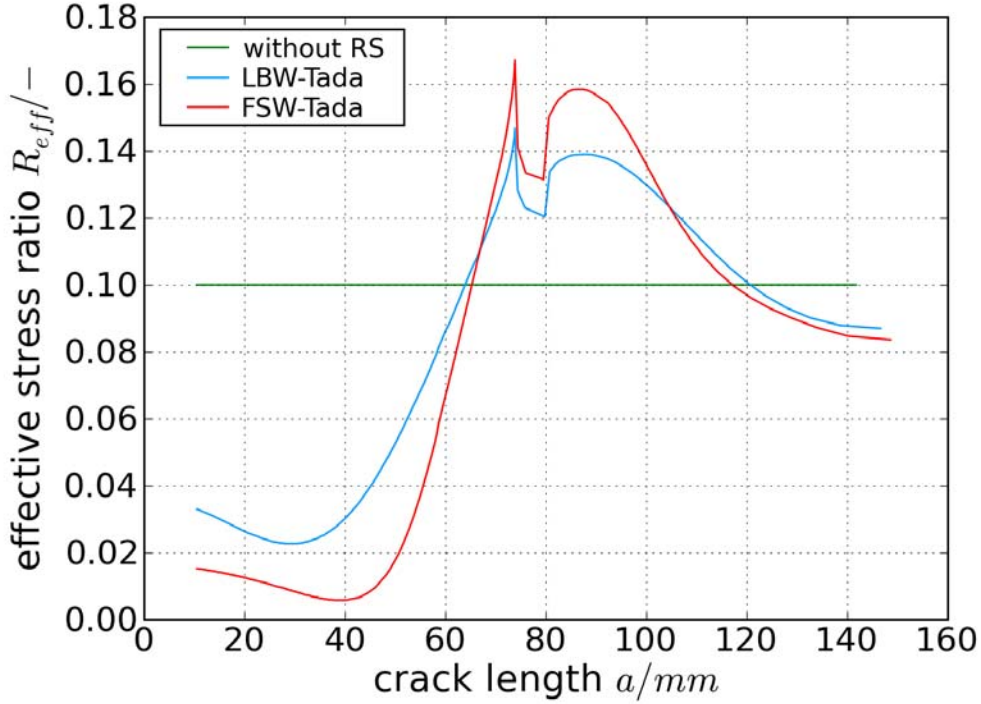
2-stringer panel – influence of residual stress on SIF and FCG solution

- compressive residual stress field between the stiffeners results in decreased overall stress intensity factors K_{sum} approaching the stiffener position

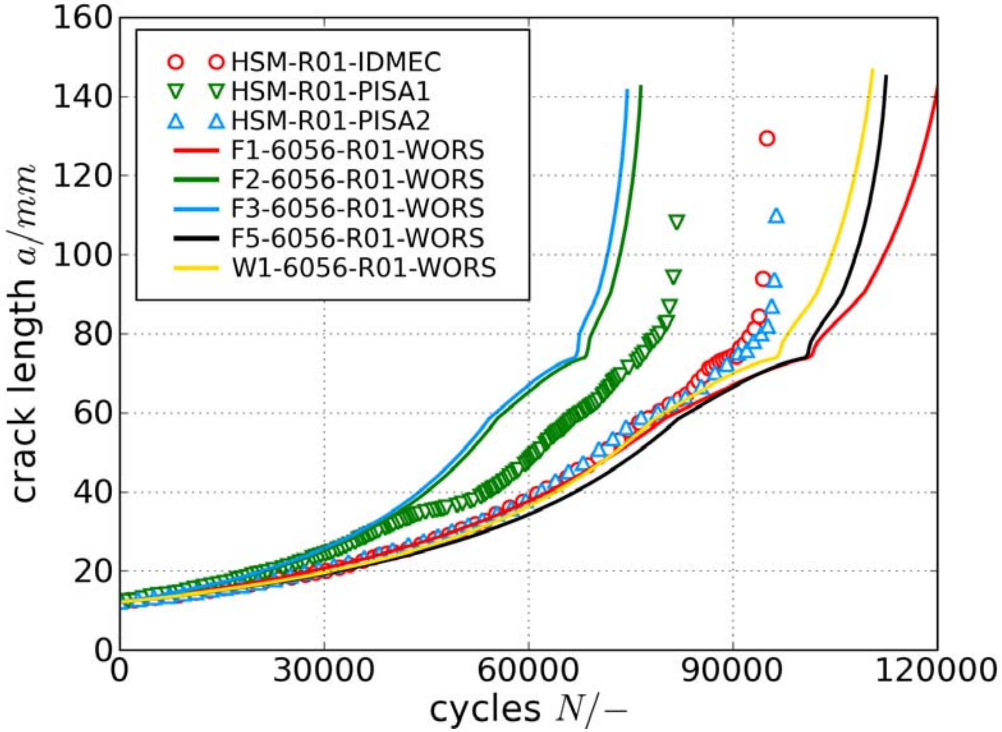
→ effective stress ratio in front of the stiffener is below the applied value of $R_{eff} = 0.1$

→ results in an increased number of bearable load cycles for FCG simulation

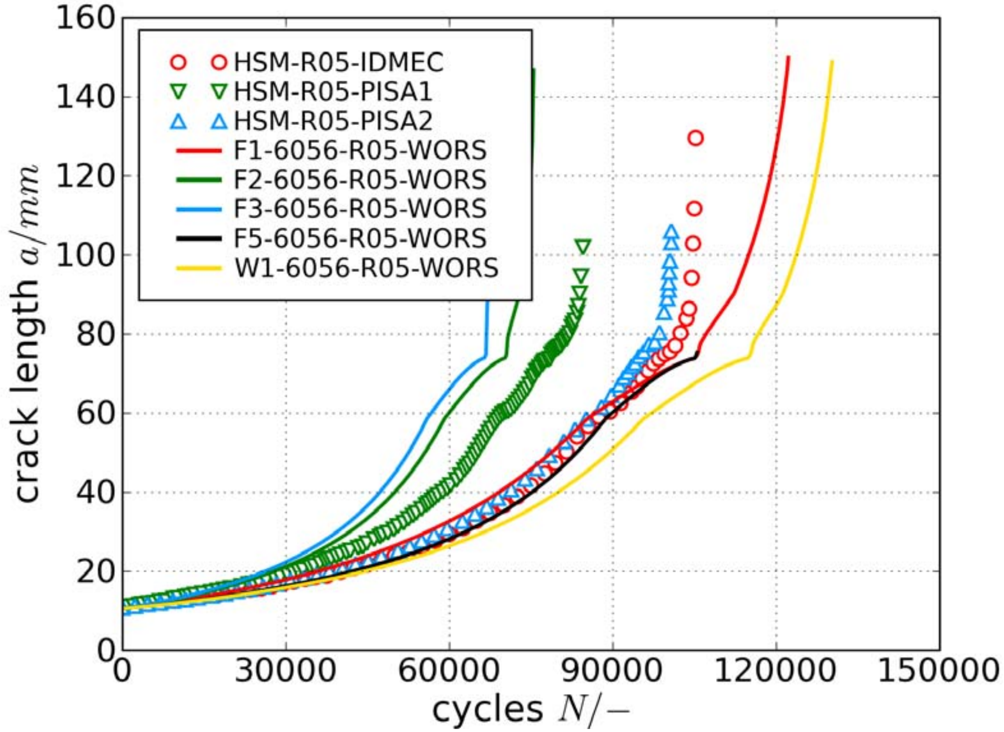




2-stringer panel – simulation results HSM 6056

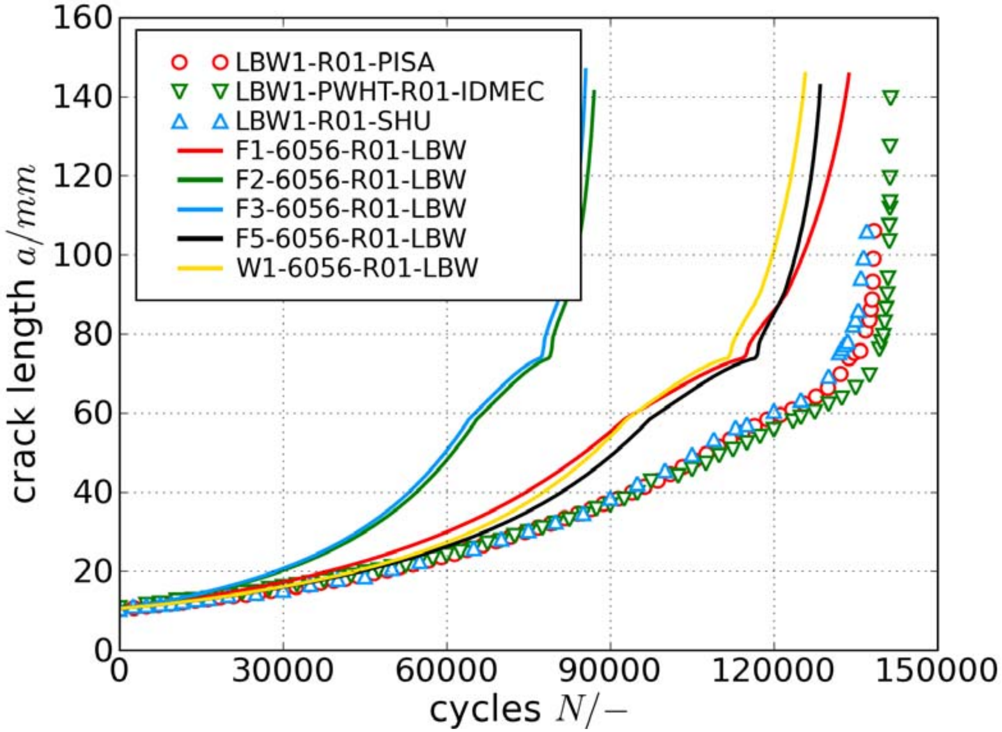


σ_{max}=80MPa , R=0.1



σ_{max}=110MPa , R=0.5

2-stringer panel – simulation results LBW 6056



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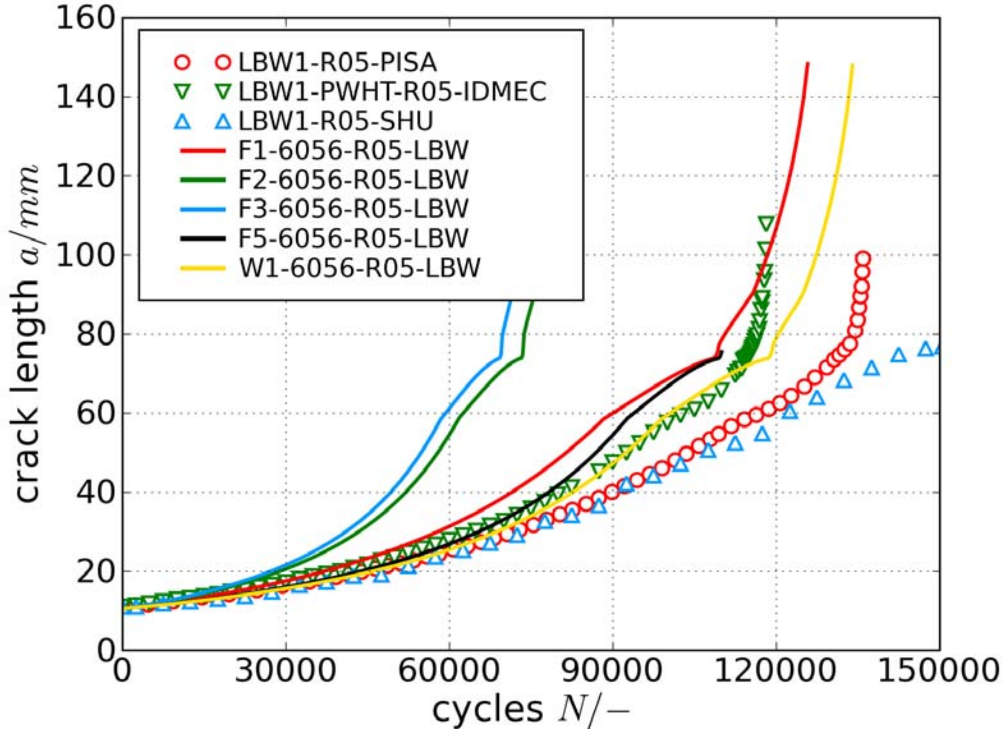

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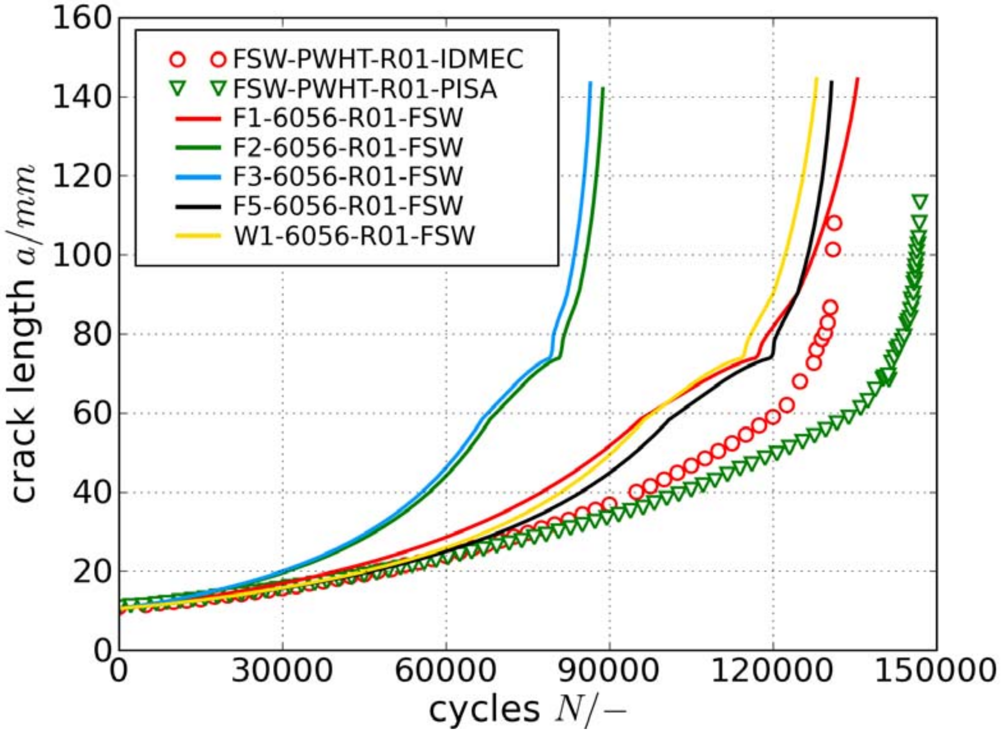
2-stringer panel – simulation results FSW 6056



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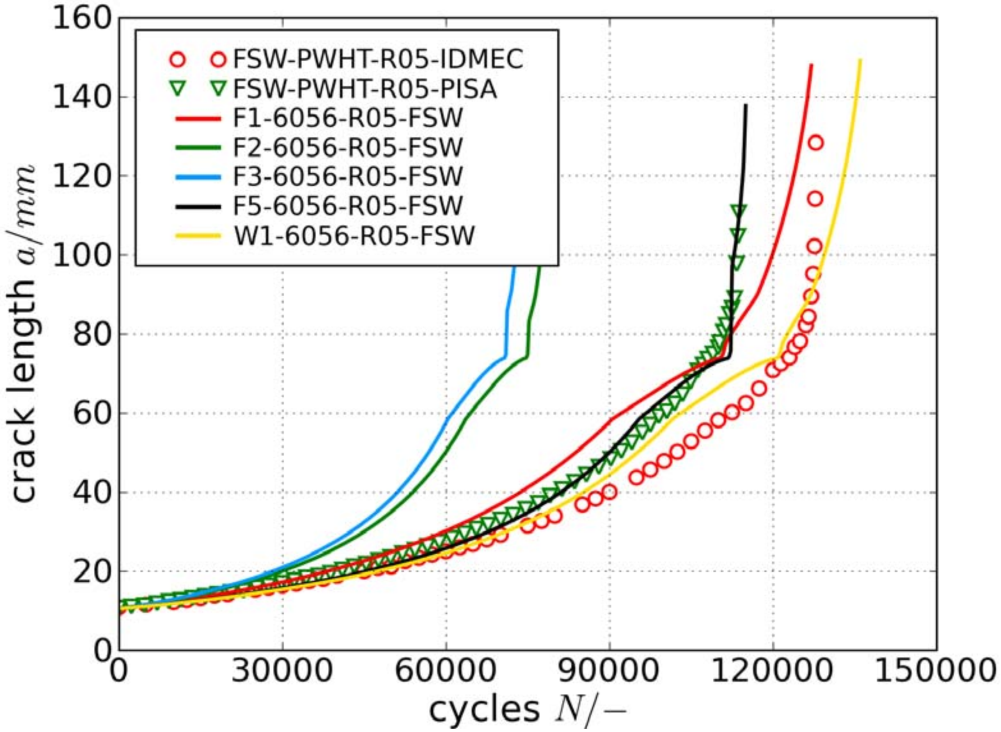
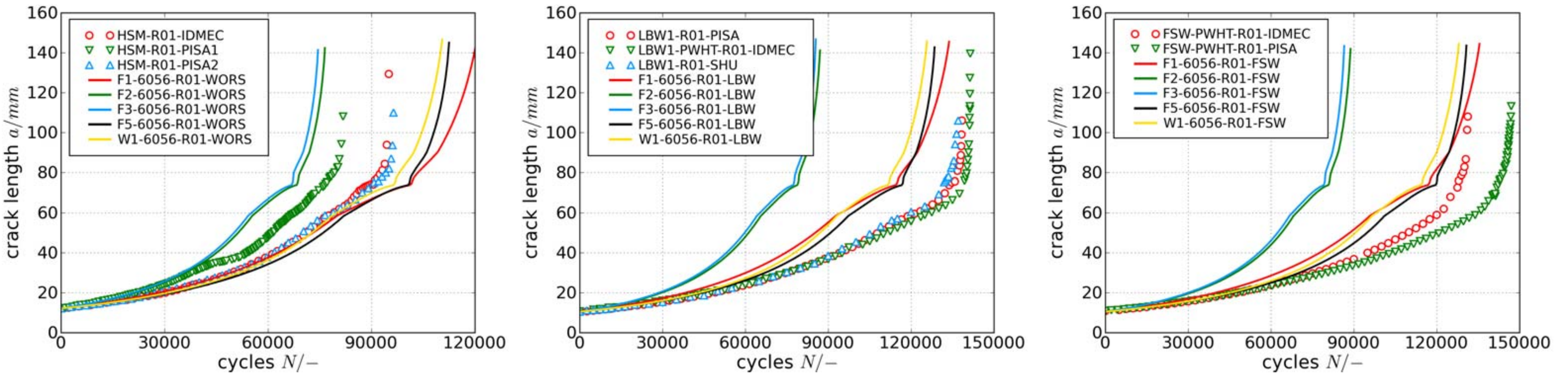
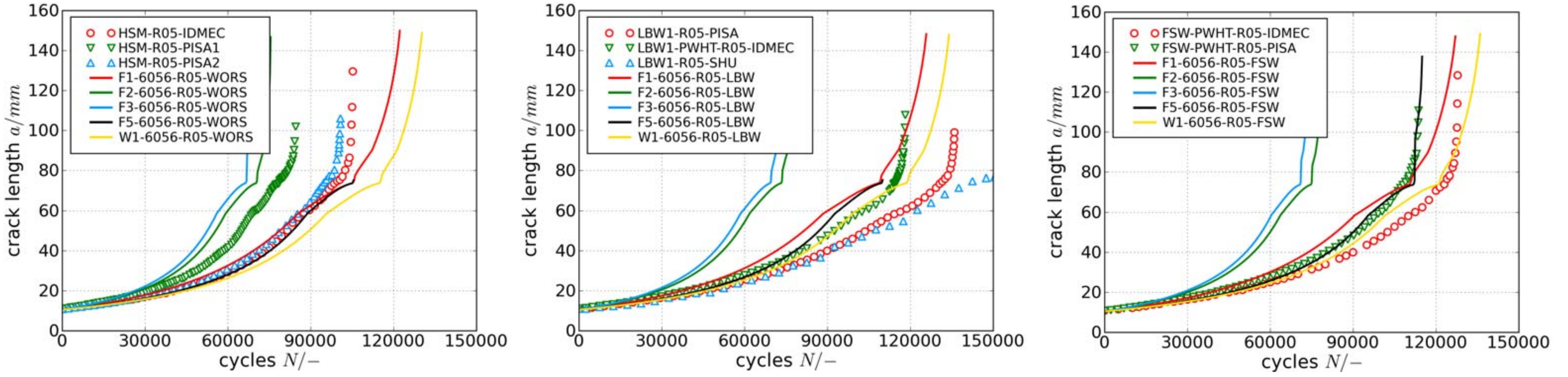


σ_{max}=110MPa , R=0.5

2-stringer panel – result summary Al6056



Al6056 → σ_{max}=80MPa , R=0.1



Al6056 → σ_{max}=110MPa , R=0.5

Sascha Häusler
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Summary

- Accomplished project goals:
  - development and enhancement of pseudo-numerical simulation routine for fast estimations on fatigue crack growth life
  - incorporation of residual stress effects to account for different manufacturing scenarios
  - validation and verification using inputs and results from the large experimental database within the project

- Discussion:
  - despite its simplifications simulation model gives reasonable representation with experimental results for different manufacturing scenarios
  - residual stress module requires experimental residual stress measurements
  - effect on fatigue crack growth seems to be underestimated for certain scenarios
  - fatigue crack growth simulation results are very sensitive with respect to the crack growth parameter set used for simulation

- residual stresses caused by manufacturing do have a significant effect on fatigue crack growth which can be both beneficial as well as detrimental

→ incorporation of residual stress effects essential for crack growth simulation