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Thermo-Mechanical Coupled Simulation with LS-DYNA

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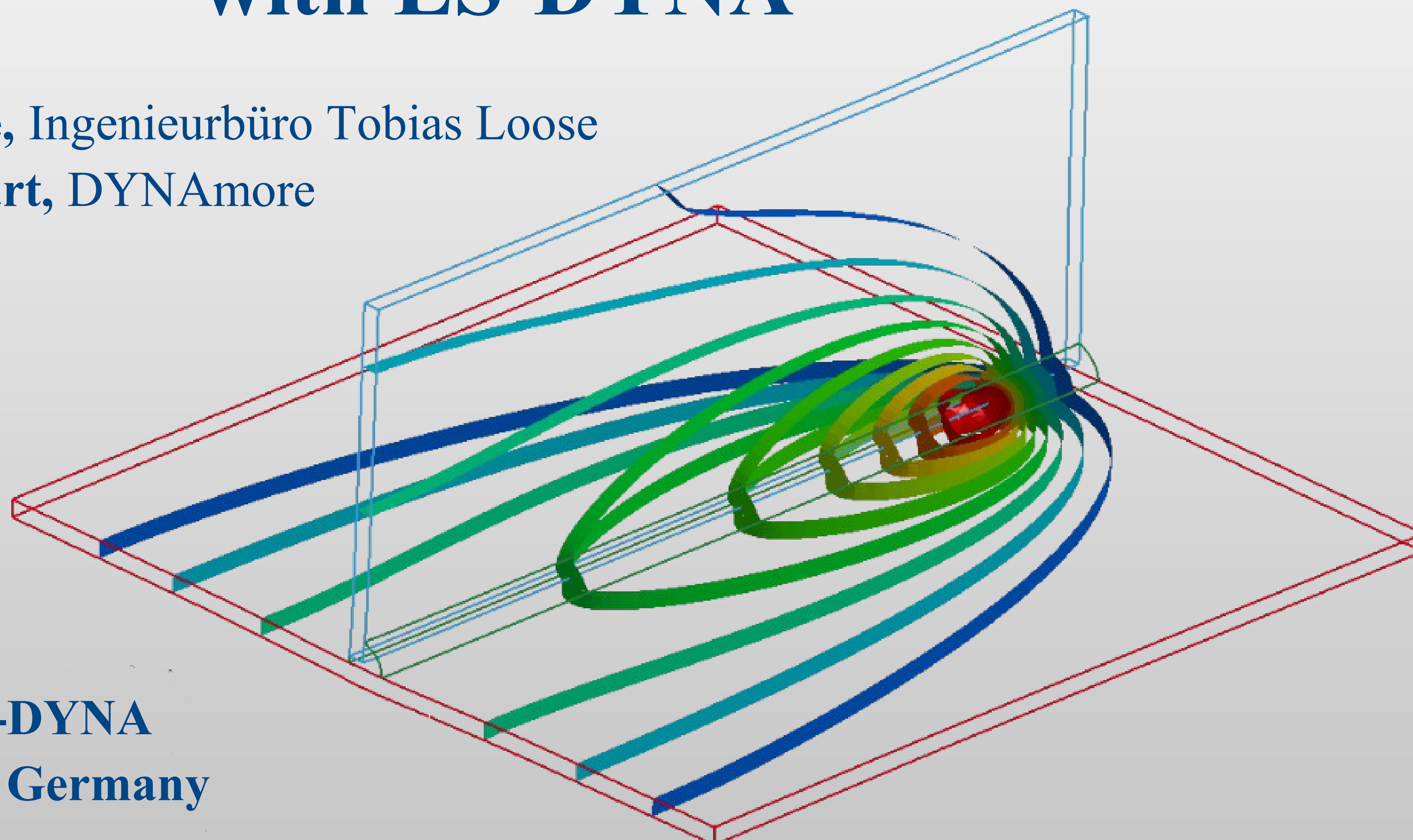


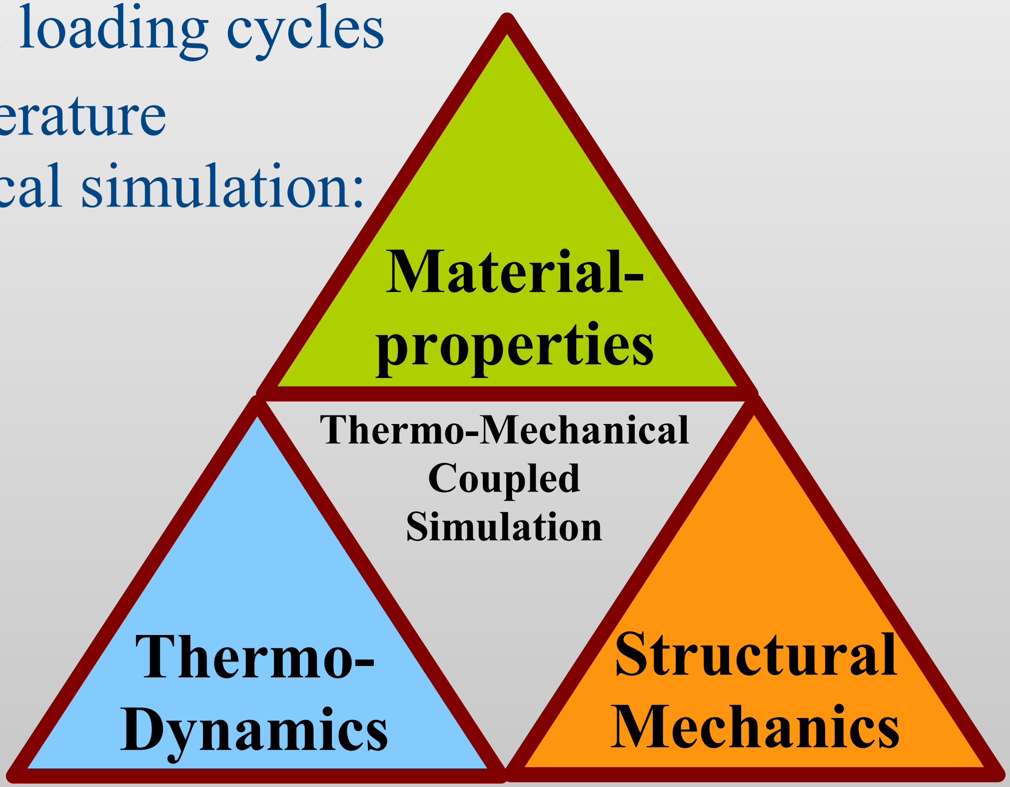
Multiphysics with LS-DYNA
17.03.2014, Stuttgart, Germany

Introduction

Basement of variables: DISPLACEMENT, TIME and TEMPERATURE

Real nature:

- material properties depend on temperature
- material properties change in thermal loading cycles
- thus all processes with variable temperature need a coupled temperature-mechanical simulation:



- **Hot Forming**
- **Forging**
- **Heat Treatment**
- **Welding**
- **Post Weld Heat Treatment**

1976

- Lawrence Livermore National Laboratory:
- Thermo-dynamical **FEM code** for **stress analysis of structures subjected to impact loading**
- explicit short time analysis, nonlinear material, large deformations

1987

- **metal forming simulations** and composite analysis

1988

- Livermore Software Technology Corporation (LSTC) was founded by John Hallquist
- Development of **LS-DYNA** for problems in **crashworthiness**
- **one-code strategy**

1990

- **ALE** (Arbitrary Lagrane Eulerian) for Airbags
- constraint technique for **contact**, friction in the contact
- **parallel implementation**

1992

- Springback analysis (after forming), Barlats anisotropic plasticity
- Adaptivity
- First MPP (Massively Parallel) version

1996

- LS-DYNA Version 940:
- **Boundary element method (BEM)** for incompressible fluid dynamics and fluid-structure interaction

1998

- LS-DYNA Version 950:
- **implicit** solution scheme

2000

- LS-DYNA Version 960:
- **Incompressible flow solver**,
- layered shell theory, nonlocal failure theory, thick shell element

2002

- LS-DYNA Version 970:
- particle gas airbags (*AIRBAG_PARTICLE)
- **SPH (Smooth Particle Hydrodynamics)**
- **Element Free Galerkin method (EFG)**

2005

- LS-DYNA Version 971:
- *MAT_MUSCLE (human modelling)
- heat flow through shell elements

2011

- LS-DYNA Version 971 R6:
- **Discrete Element Method (DEM)**
- vibration and **acoustic problems: Boundary Element Method (BEM)**
- soil-structure interaction analysis under earthquake ground motion

2012

- LS-DYNA Version 971 R6.1:
- isogeometric shells
- *MAT_UHS (phase transformations, metal hot forming)

2013

- LS-DYNA R7:
- **EM (Electromagnetic solver)**
- **CESE (Compressible CFD solver), ICFD (incompressible CFD solver)**
- *MAT_THERMAL_CWM for welding simulations

Basics

Brief description of main Keywords

Thermo-dynamic material parameters:

- density
- heat capacity or latent heat
- conductivity

***MAT_THERMAL_ISOTROPIC_TD_LC**

- TRO: density
- HCLC: heat capacity, temperature depended, defined by curve
- TCLC: conductivity, temperature depended, defined by curve

***MAT_THERMAL_CWM**

similar to *MAT_THERMAL_ISOTROPIC_TD_LC but extended for multilayer welding by activation features:

- TLSTART, TLEND: temperature interval for activation
- TISTART, TIEND: time interval for activation
- HGOHST: heat capacity for deactivated material (*)
- TGHOST: thermal conductivity for deactivated material (*)

(*) valid for activation by temperature

Thermal boundary conditions:

- Heat conductivity or radiation on surface or at contact faces
- Surface or volume heat-source
- Thermal constrained nodes by fixed temperature or temperature variable in time (thermal cycle)

***BOUNDARY_CONVECTION**

- HLCID: heat transfer coefficient, temperature depended, defined by curve
- TMULT: temperature of environment

***BOUNDARY_FLUX** (Surface heat source on segments)

***LOAD_HEAT_GENERATION** (Volume heat source on solid elements)

***BOUNDARY_TEMPERATURE**

- LCID: heat flux or temperature as a function of time

***BOUNDARY_THERMAL_WELD**

- Special heat source for welding according to Goldak ellipsoidal heat source
- free movement of this heat source can be defined in the simulation model

Contact and Initial conditions

Thermal contact conditions:

- Heat conductivity in case of open gap
- Heat conductivity in case of closed gap
- Heat radiation on contact surfaces

***CONTACT_..._THERMAL_...**

- K: Heat conductivity in case of open gap
- H0: Heat conductivity in case of closed gap
- FRAD: Heat radiation on contact surfaces
- LMIN, LMAX: Limit distance of the gap LMIN: gap closed, LMAX: no contact

Initial conditions

- Information about temperature at each node at simulation start is needed

***INITIAL_TEMPERATURE**

- TEMP: initial temperature

Mechanical material Parameters

All mechanical material parameters have to be defined **temperature** depended.

In case of materials with phase transformations during thermal loading cycle, for example low alloyed steel, mechanical parameters have to be defined for each **phase** and **temperature** depended.

To take influence of strain rate on hardening additionally into account, the flow curve has to be defined dependend on **phase, temperature** and **strain rate**.

***MAT_UHS_STEEL**

- for shell and solids
- provides phase transformation, properties depend on phase and non-linear flow curve depends on phase, temperature and strain rate

***MAT_CWM**

- for solids
- provides activation of filler elements with temperature (for welding simulation)
- single phase model with linear strain hardening and no strain rate dependance

Coupled implicit thermal and mechanical analysis

***CONTROL_SOLUTION**

- SOLN: switches between thermal (1), mechanical (0) and coupled (2) simulation

***CONTROL_IMPLICIT**

***CONTROL_THERMAL**

- drives solver settings for mechanical implicit solver and thermal implicit solver resp.

***CONTROL_THERMAL_TIMESTEP**

- TIP: choose numerical solution method of thermal solver
  - 0: forward difference
  - 0,5: Crank-Nicolson
  - 2/3: Gallerkin
  - 1: backward difference → for transient problem as welding

Time step size should be adapted to the thermal gradients. Small time step for heating, welding or quenching. Increasing time steps during cooling. Time step size can be defined as time depended curve

Application

on welding simulation

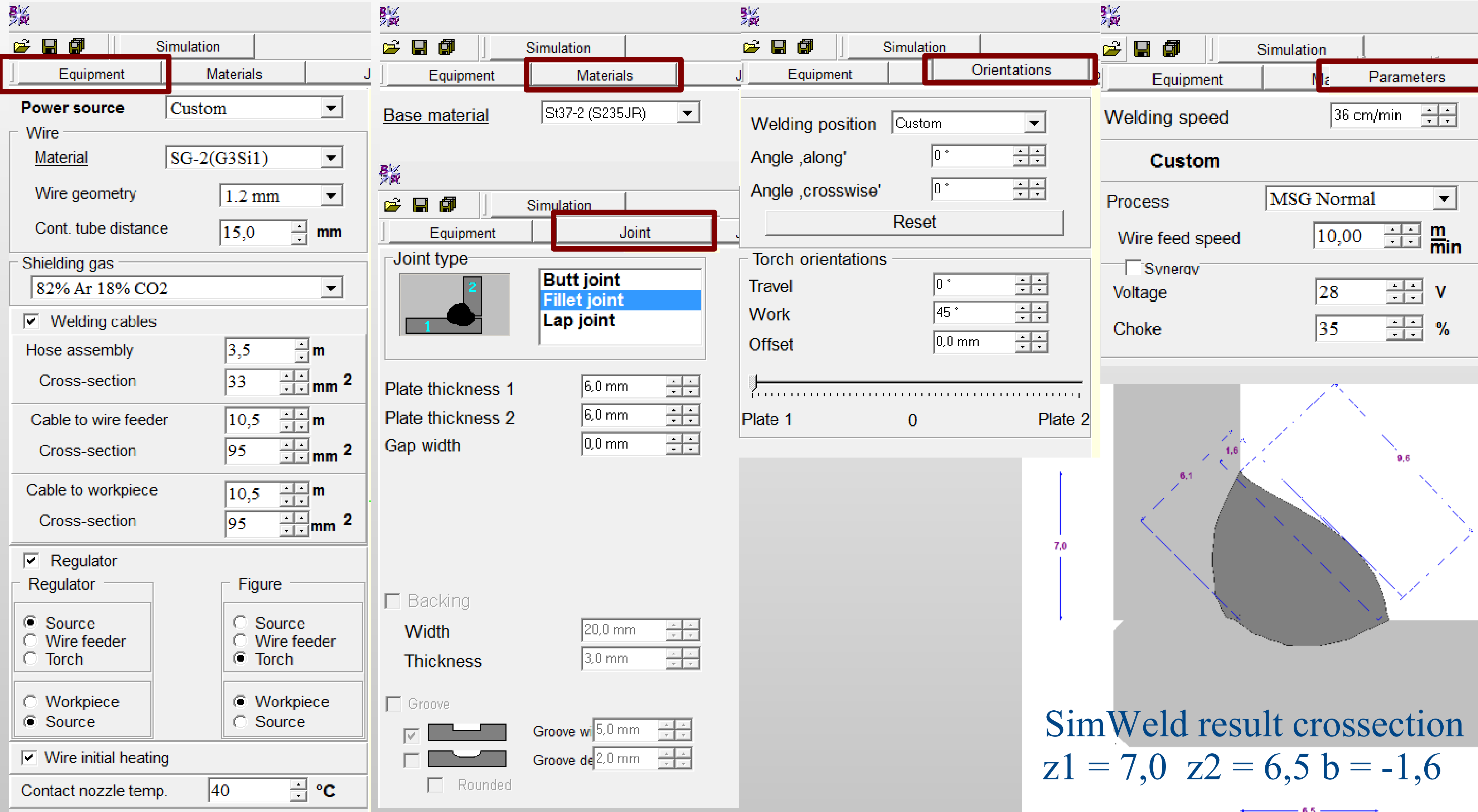
HSS - Heat Source from SimWeld

How to extract the
Equivalent Heat Source
from process simulation
with SimWeld

Dr.-Ing. Tobias Loose

06.03.2014

Process simulation with SimWeld
Input Parameter

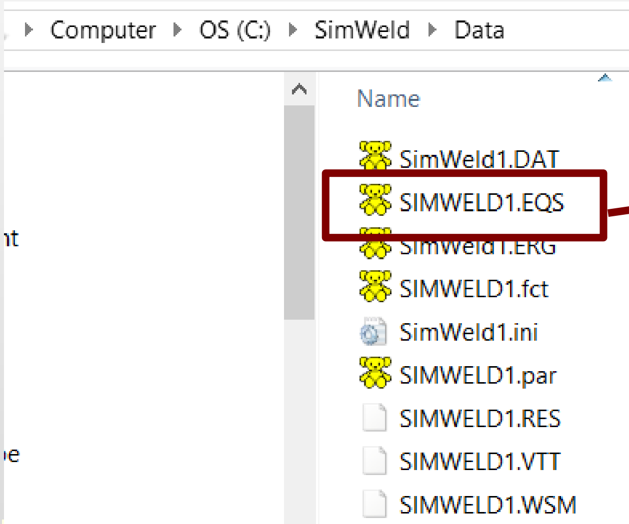


SimWeld result crossection

z1 = 7,0 z2 = 6,5 b = -1,6

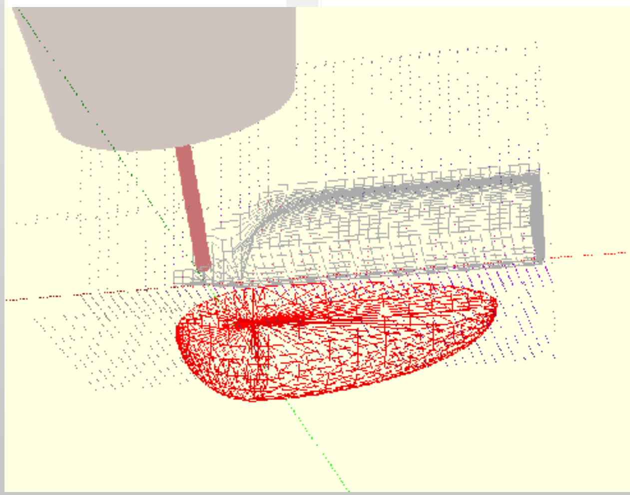
Equivalent Heat Source Goldak is one output of SimWeld Process Simulation

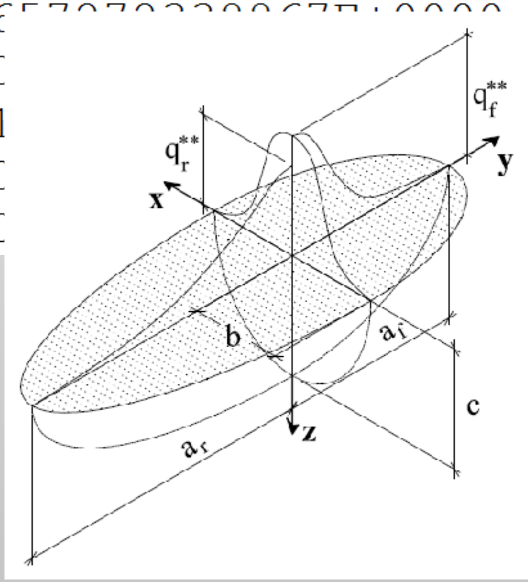
- **SimWeld1.EQS**



SIMWELD1.EQS Zeile 1 von 14 Spalte 1

```
3D double ellipsoid source
 6.5908271484375OE+0003   //Q  (W)
 5.6667651367187 5E+0003  //Qf  (W)
 9.2406213378906 3E+0002  //Qr  (W)
 1.0643688201904 3E+0002  //q0_front  (W/mm3)
 5.5540285110473 6E+0000  //q0_rear  (W/mm3)
 5.9028053283691 4E+0000  //af  (mm)
 1.8446266174316 4E+0001  //ar  (mm)
 5.6049914360046 4E+0000  //b  (mm)
 6.006                    //c  (mm)
 3.260                    //x0  (mm)
 3.521                    //z0  (mm)
 4.720                    //ay  (degree)
 3.600                    //vy  (cm/min)
```





LS-DYNA input *BOUNDARY_THERMAL_WELD

```
SIMWELD1.EQS     Zeile 1 von 14     Spalte 1
3D double ellipsoid source
  6.5908271484375OE+0003   //Q  (W)
  5.6667651367187 5E+0003  //Qf  (W)
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  1.8446266174316 4E+0001  //ar  (mm)
  5.6049914360046 4E+0000  //b  (mm)
  6.0065727233886 7E+0000  //c  (mm)
  3.2608697414398 2E+0000  //x0  (mm)
  3.5217392444610 6E+0000  //z0  (mm)
  4.7202598571777 3E+0001  //ay  (degree)
  3.6000000000000 0E+0001  //vy  (cm/min)
```

SimWeld → LS-DYNA

a → c
b → a
c → b

0,76 = 5,7*2/(5,7+9,2)

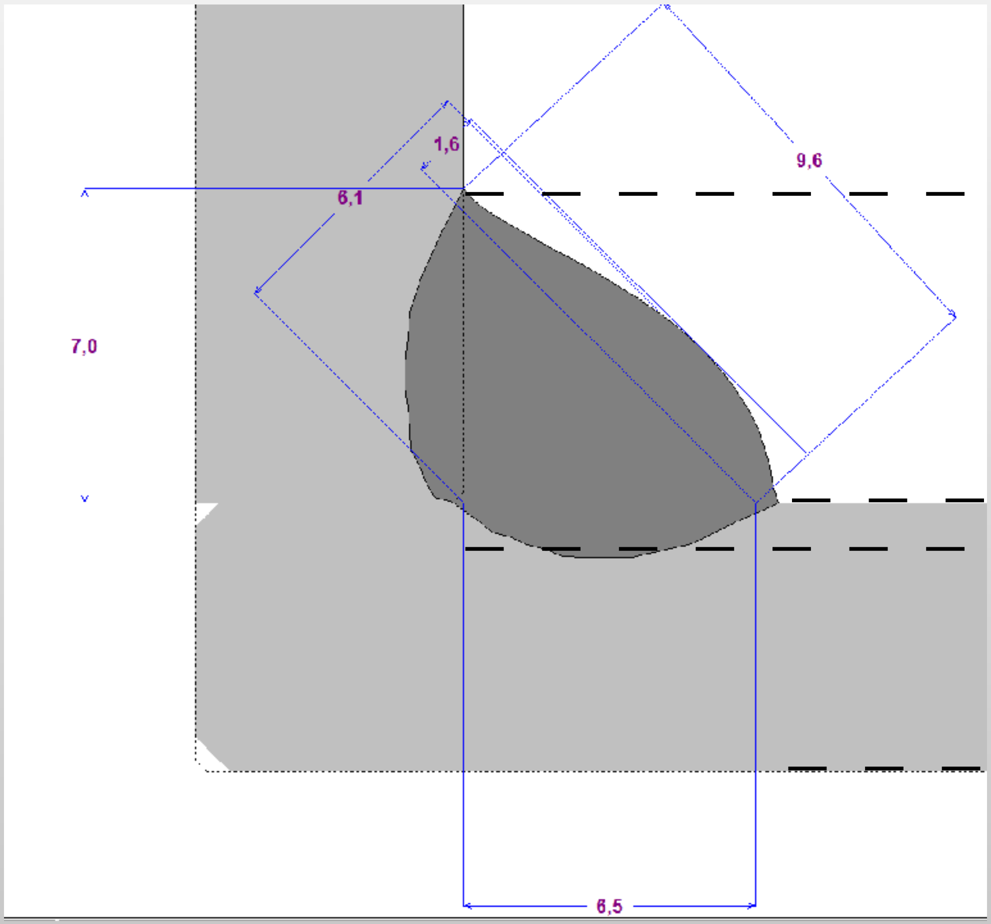
1,24 = 2 - 0,76

```
*BOUNDARY_THERMAL_WELD
$#     pid      ptyp       nid     nflag        x0        y0        z0      n2id
      1001         2    900001         1     0.000     0.000     0.000    800001
$#     b=a       c=b     af=cf     ar=cr      lcid         q        ff        fr
$#      mm        mm        mm        mm                  mW
       5.6       6.0       5.9      18.0         5  -6591000.     0.760     1.240
```

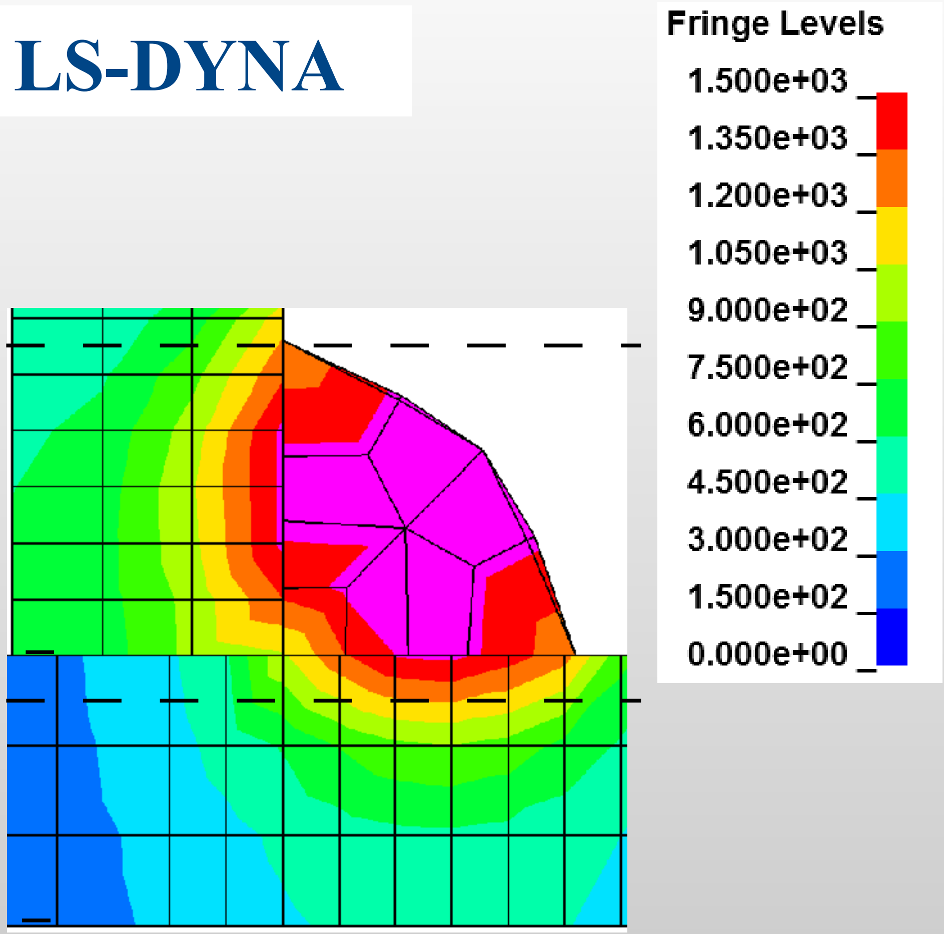
LSDYNA puts n = 3 and defines the heat-source geometrically unlimited.

Check of Weld-Pool

- SimWeld

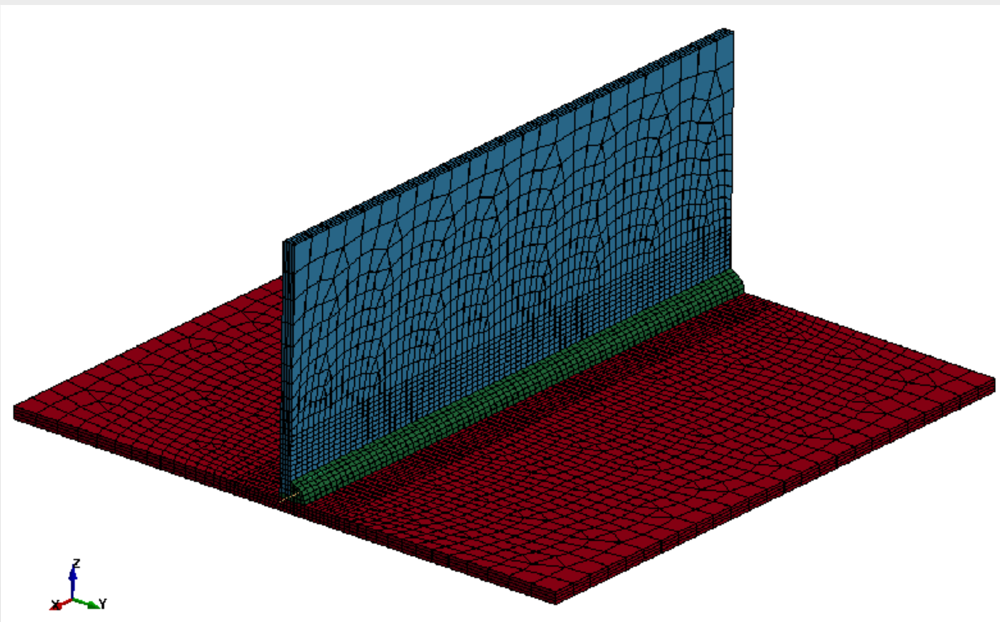


- LS-DYNA

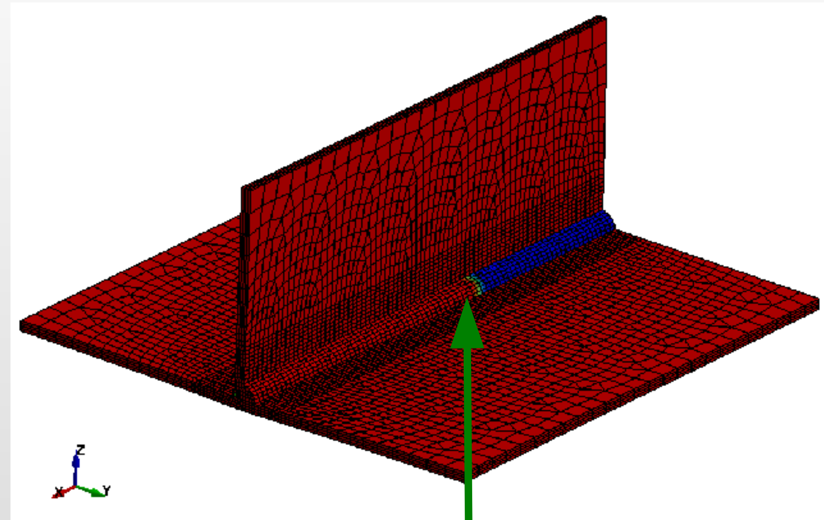


T-Joint with filled weld

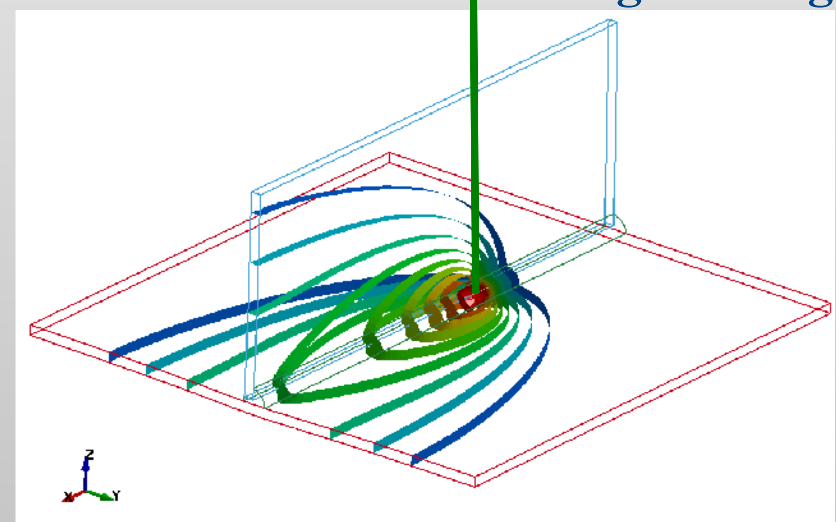
Plate: 200 x 200 x 4 mm
Stiffener: 200 x 80 x 4 mm
Fillet: a = 4 mm
Material: 1.4301



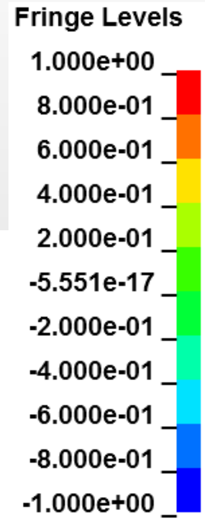
The plate is clamped in z-direction during welding and cooling



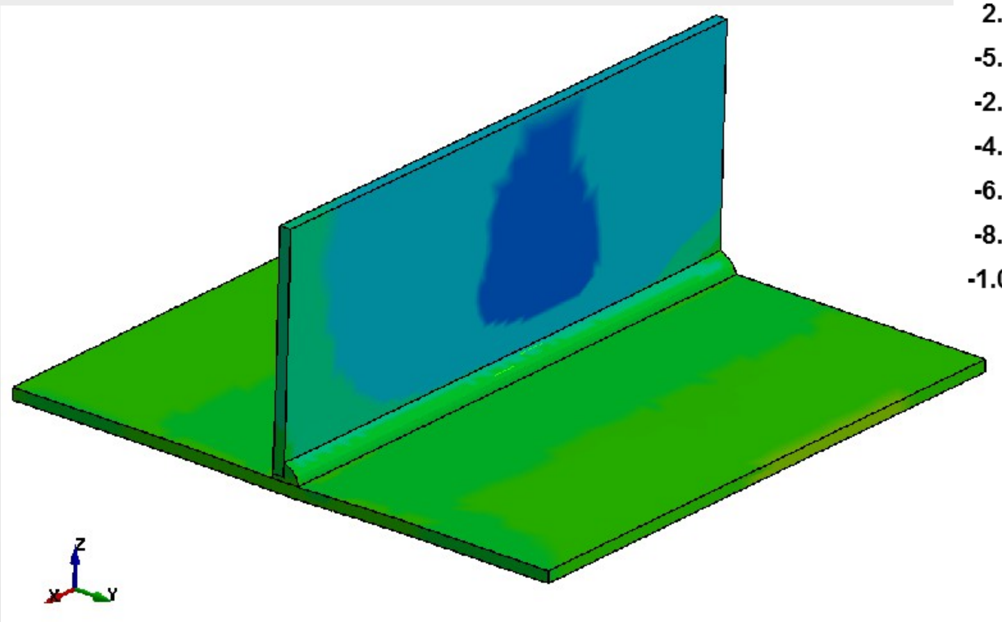
Activation of filler during welding



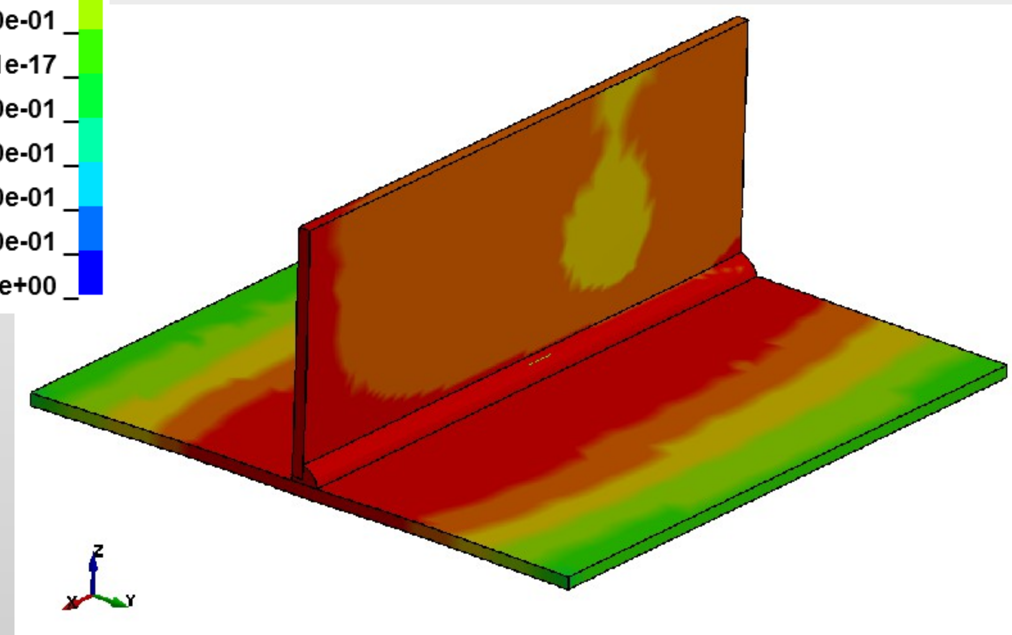
Distortion in z-Direction



before unclamping

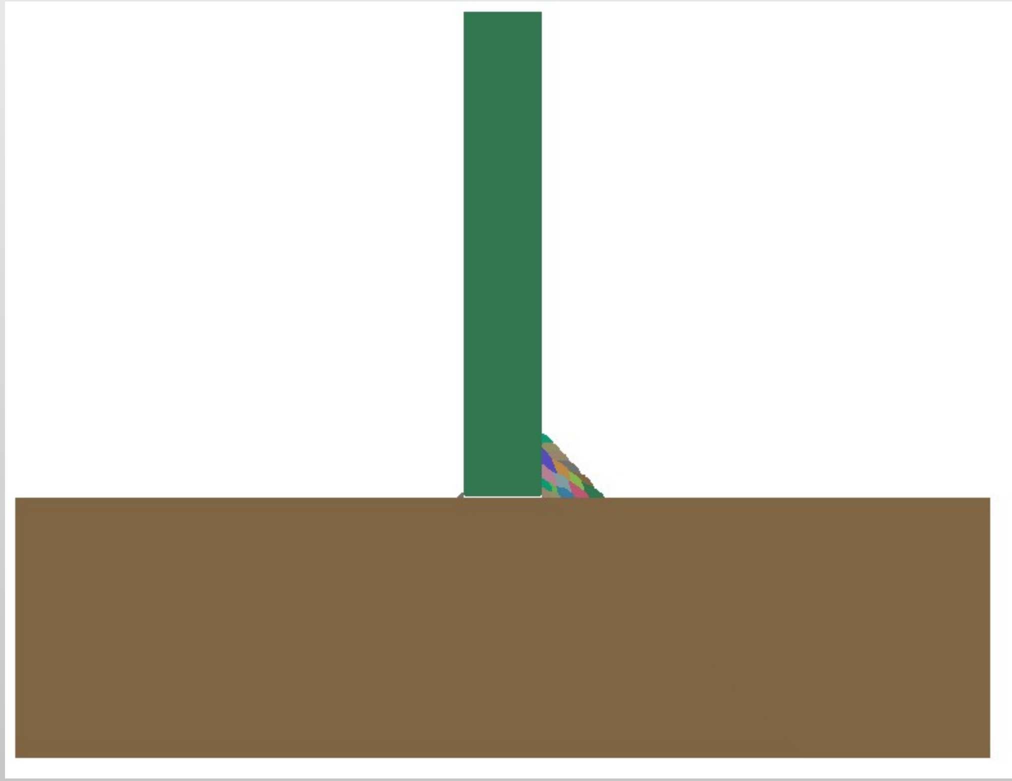


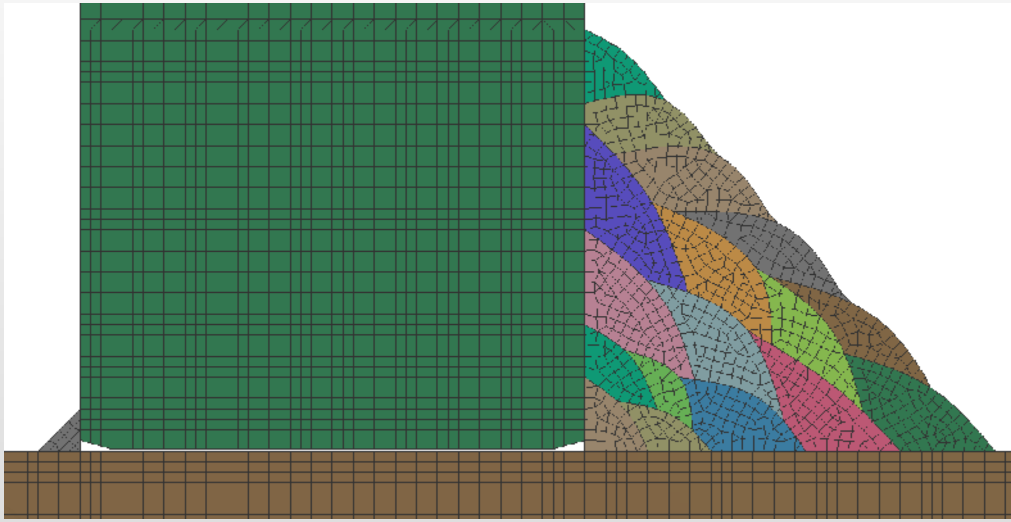
after unclamping



T-Joint of thick Plate with 17-layered fillet weld

2D plain strain analysis
Plate: 300 x 80 mm
Stiffener: 150 x 24 mm
Fillet: a = 13 mm
Material: 1.4301



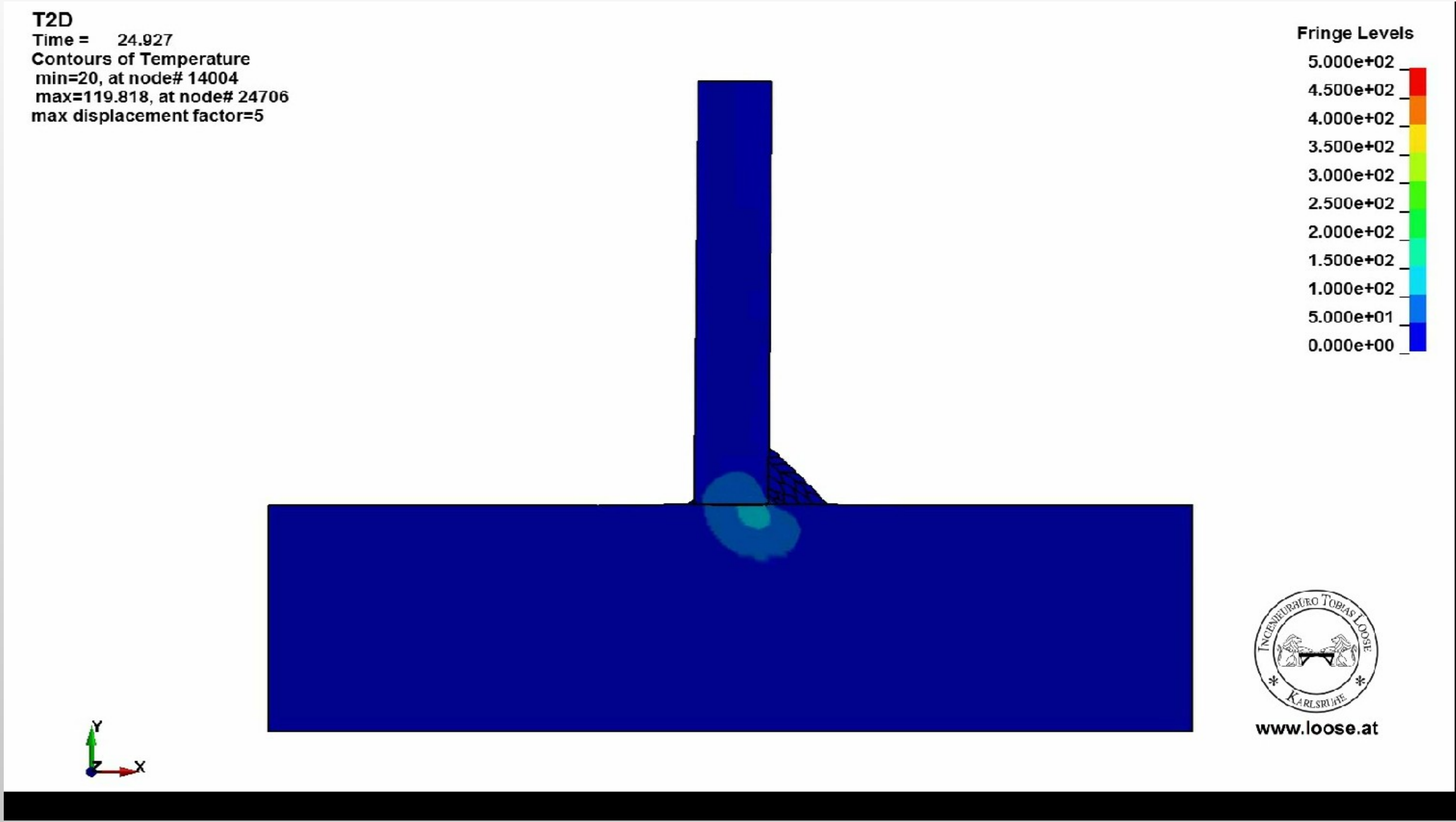


Tack weld a = 1,4 mm
with KFAIL = 0,25

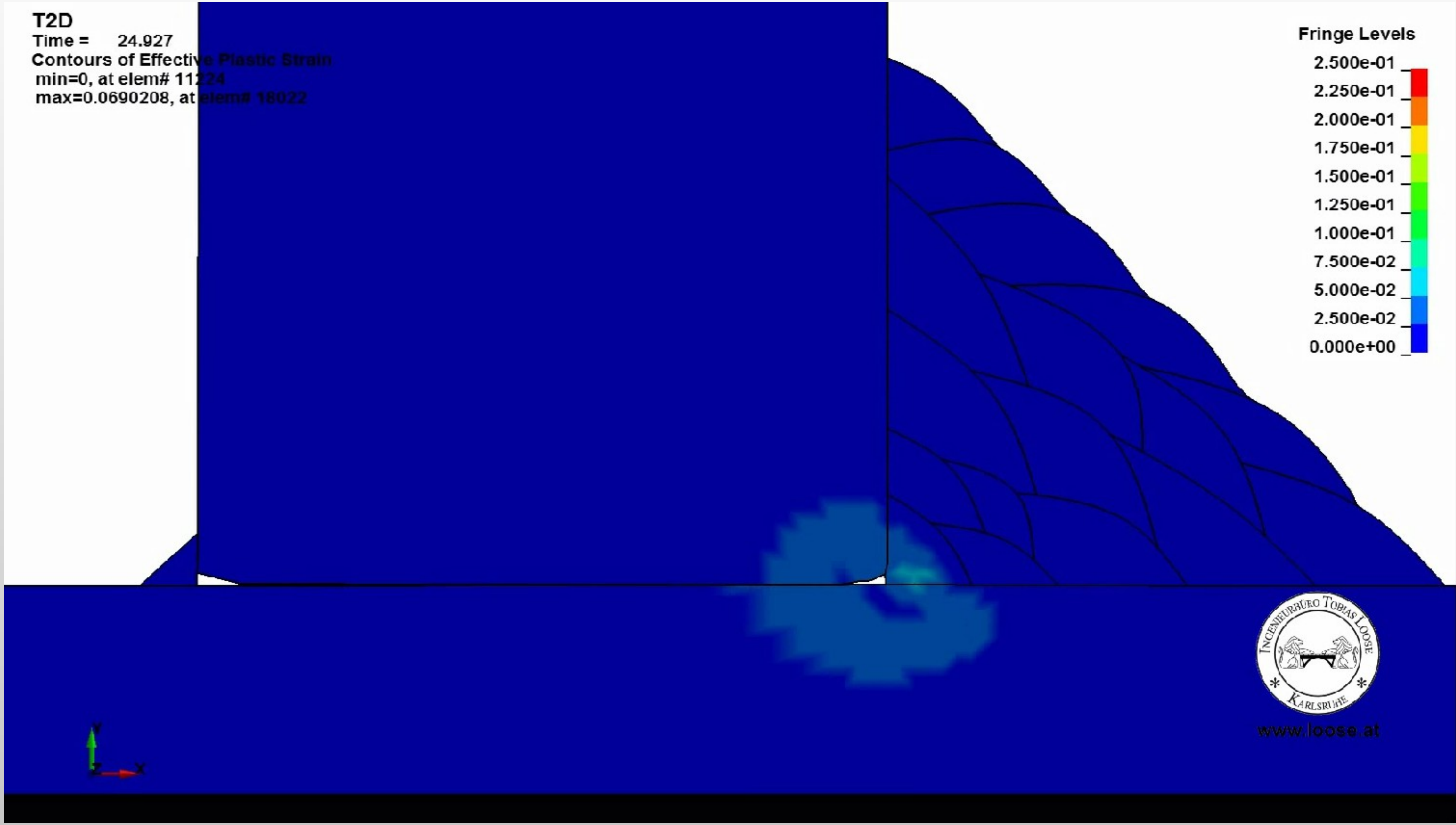
Initial gap between stiffener and plate: 0,1 mm

The plate is contrained with symmetry conditions at the left and right end.

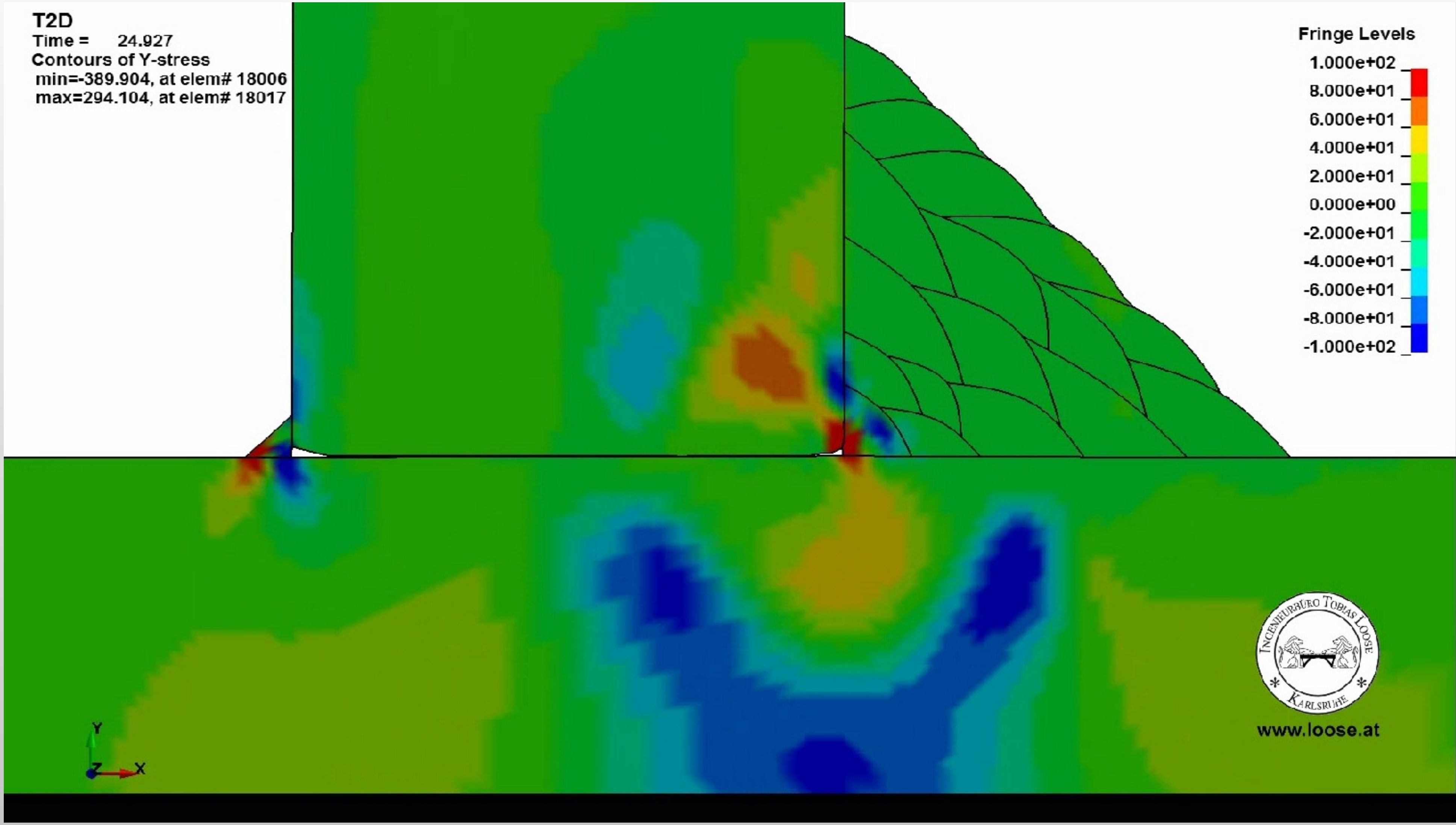
Temperature 0 .. 500 °C
Distortion scaled 5 times



Plastic strain 0 .. 0,25 m/m



Stress in y-direction -100 .. 100 N/m²



Benefits

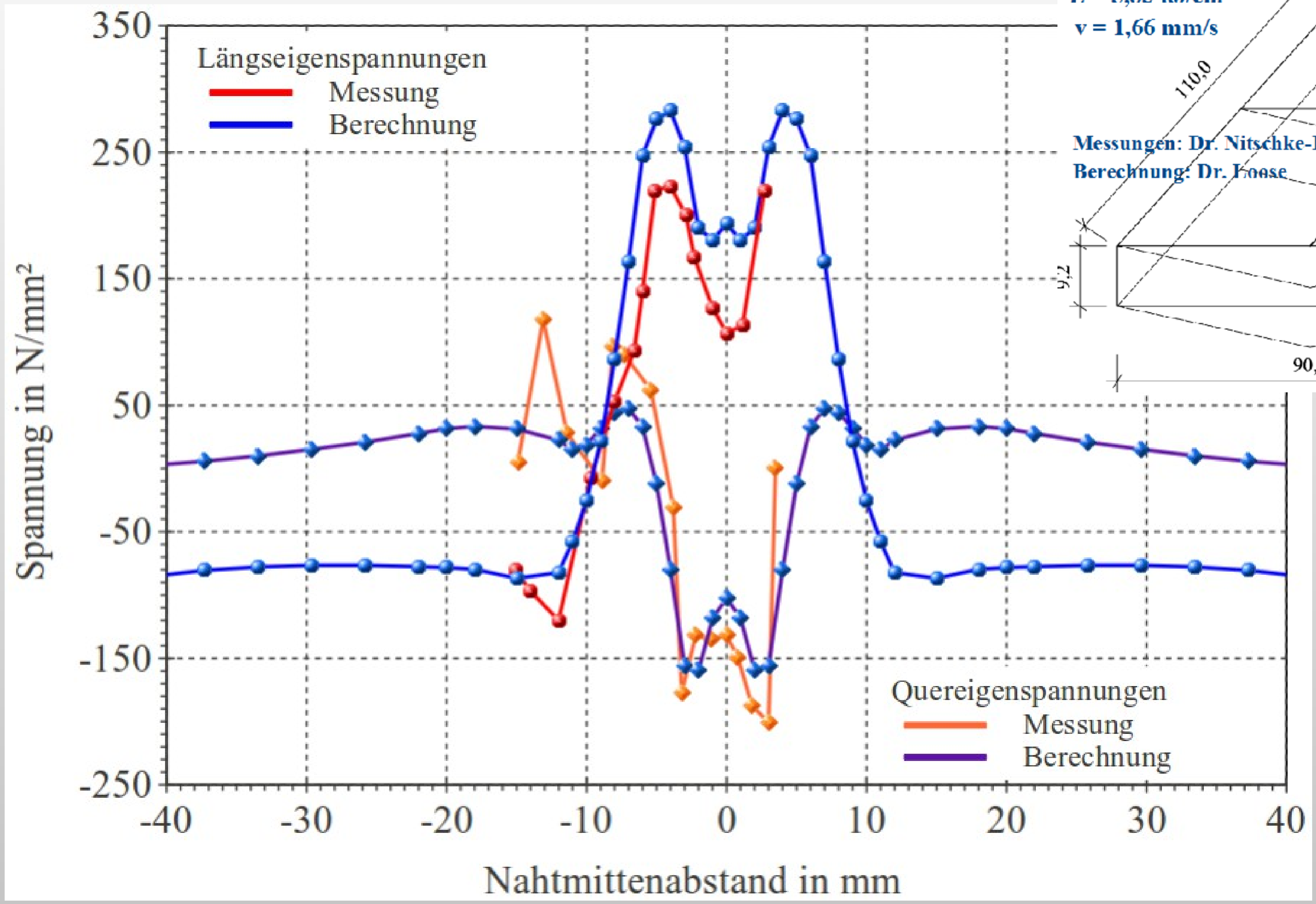
with scope of welding structure simulation

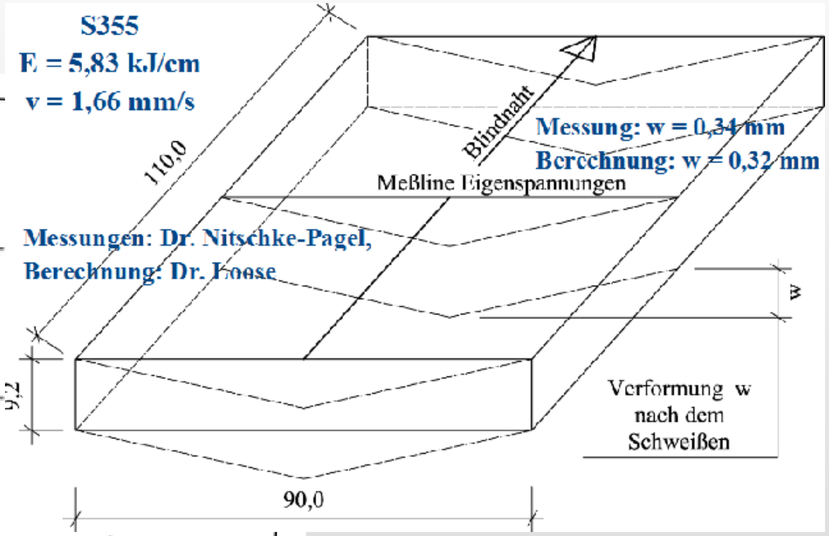
Benefits for welding simulation

- **Distortion check**
  - Critical and too large distortions during assembly?
- **Compensation of distortion**
  - Design of process in order to get the desired geometry after assembly.
  - Cost savings: less straightening and less defective goods.
- **Process design**
  - Achievement of a stable assembly process
  - Prevention of damage induced during heating
  - Decision on the best choice of filler material
  - Decision on pre heating or post weld heat treatment
- **Quality assurance**
  - design of desired mechanical properties or behaviour in the weld zone
- **Design**
  - Determination of ultimate load or behaviour under service load.
- **Answers to many individual questions**

Outlook

Validation of distortion and residual stesses on Nitschke-Pagel test for LS-DYNA





Process chain

- Simulation of various manufactoring steps with
  - one solver
  - consistent material model
- for the manufactoring steps considered:
  - forming
  - heat treatment
  - welding
  - post weld heat treatment
- Analysis of ultimate load or behaviour under service load
  - mechanical analysis
  - buckling analysis
  - crash analysis

Thanks for attention!