

# Meeting del Gruppo di Lavoro AIAS Tecniche di Giunzione

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## Il metodo della tensione di picco per l'analisi della resistenza a fatica di giunti saldati tubolari sollecitati a Modo I

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# Outline

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- Description of typical Roller Coaster Structures
- Design Standards
- Fatigue tests on a tubular welded joint & results
- Non conventional approach in Fatigue Strength evaluation of welded joints based on Notch-Stress Intensity Factors: **Peak Stress Method**
- Conclusions

## **REFERENCES:**

**G. Meneghetti, P. Lazzarin**, Significance of the Elastic Peak Stress evaluated by FE analyses at the point of singularity of sharp V-notched components, ***Fatigue & Fracture of Engineering Materials & Structures***, 30, 2006, pp. 95-106.

**G. Meneghetti**, The peak stress method applied to fatigue assessments of steel and aluminium fillet-welded joints subjected to mode-I loading, ***Fatigue & Fracture of Engineering Materials & Structures***, 31 (5), 2008, pp. 346–369.

**G. Meneghetti, B. Atzori, G. Manara**, The Peak Stress Method applied to fatigue assessments of steel tubular welded joints subject to Mode-I loading, ***Engineering Fracture Mechanics***, 2010, *accepted for publication*.



# Typical Roller Coaster Structures



- Welded / bolted steel structures
- Steel quality S235 (yield stress 235 MPa) and S355 (yield stress 355 MPa)



# Design Standards

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- **German Standards:**

- DIN 4112 regulates the amusement ride design
- DIN 15018 regulates the fatigue strength analysis of welded structures

- **European Standards:**

- EN 13814 “Fairground and amusement park machinery and structures - Safety” concerning the general rules
- Eurocode 3 concerning structural assessments of steel structures, including fatigue of welded steel structures

In fatigue design the nominal stress approach is usually adopted.

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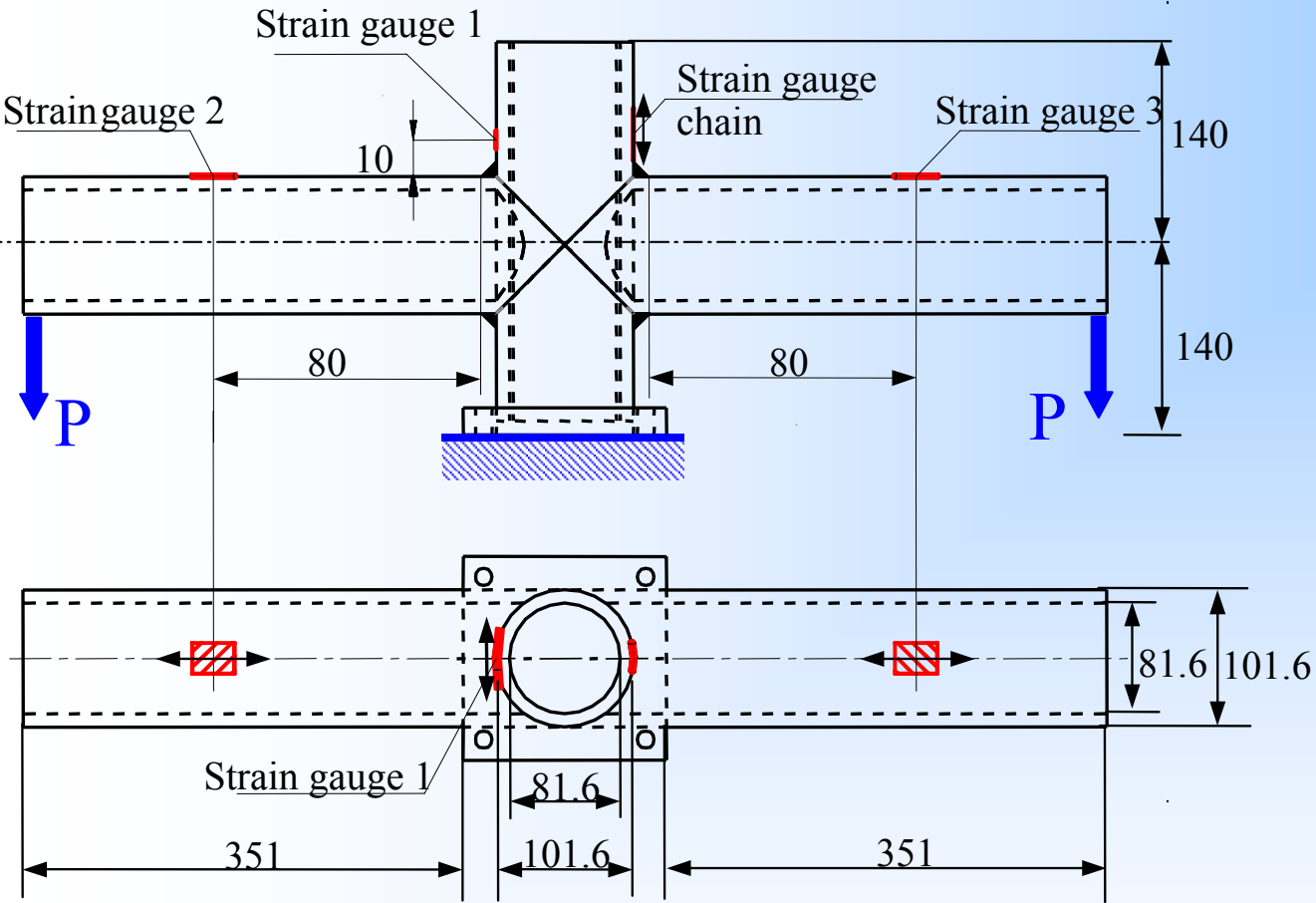
# The analysed tubular joint



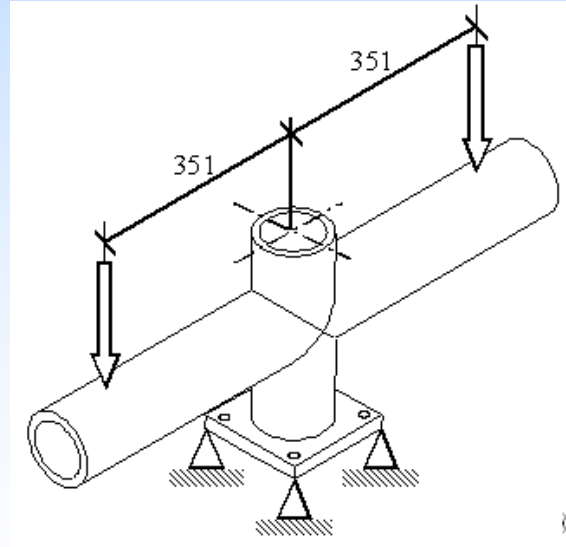
- Considering a welded joint of the steel structure, every time that a wheel of a car approaches the joint and then departs from it, the joint will undergo a stress cycle, with a stress magnitude that initially increases, reaches a peak and then decreases (i.e.  $P$  is a pulsating force)



# Geometry and Material of the tested tubular joint



- SPECIMENS:
- ✓ Material: Fe510
- ✓ Thickness: 10 mm
- ✓ MIG welding
- ✓ As-welded condition
- ✓ 4 specimen tested



- Loading condition: three point bending



# Experimental fatigue tests

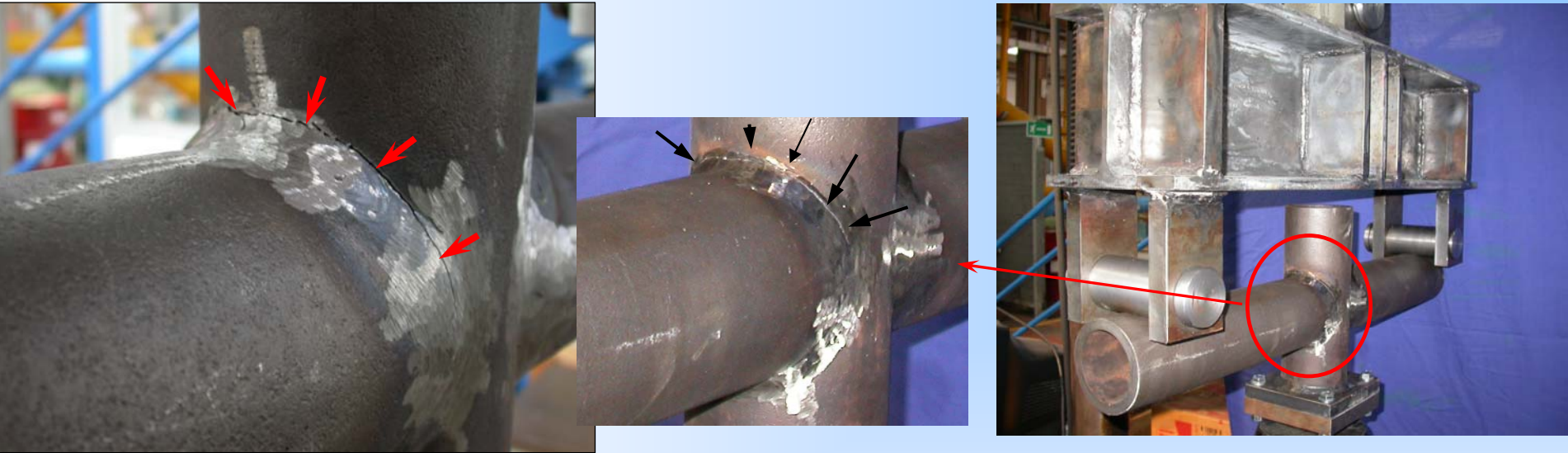


## • FATIGUE TESTS:

- ✓ Bending load
- ✓ Load ratio: 0.1
- ✓ MFL 250 kN test machine / MTS Testar II controller
- ✓ Test frequency: 5÷10Hz
- ✓ Test interrupted after complete stiffness loss



# Observed fatigue damage

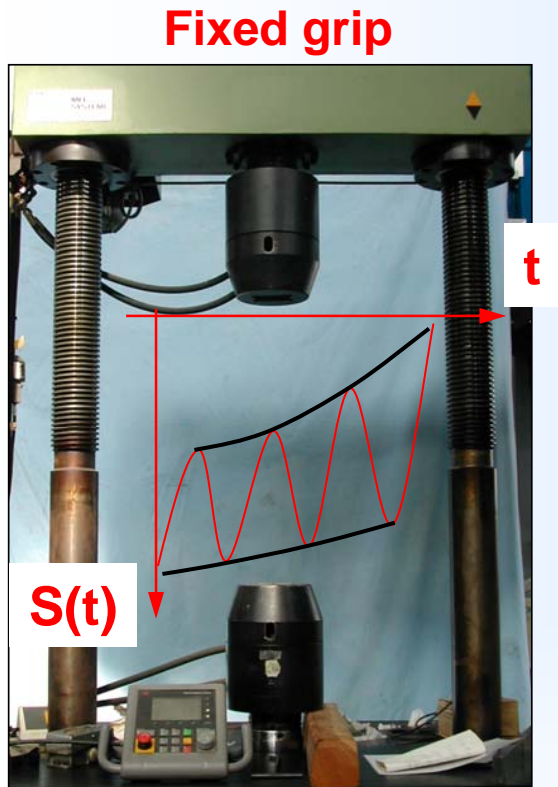


- Crack initiation from weld toe in the chord
- Crack propagation along the weld toe and through the thickness up to complete stiffness loss

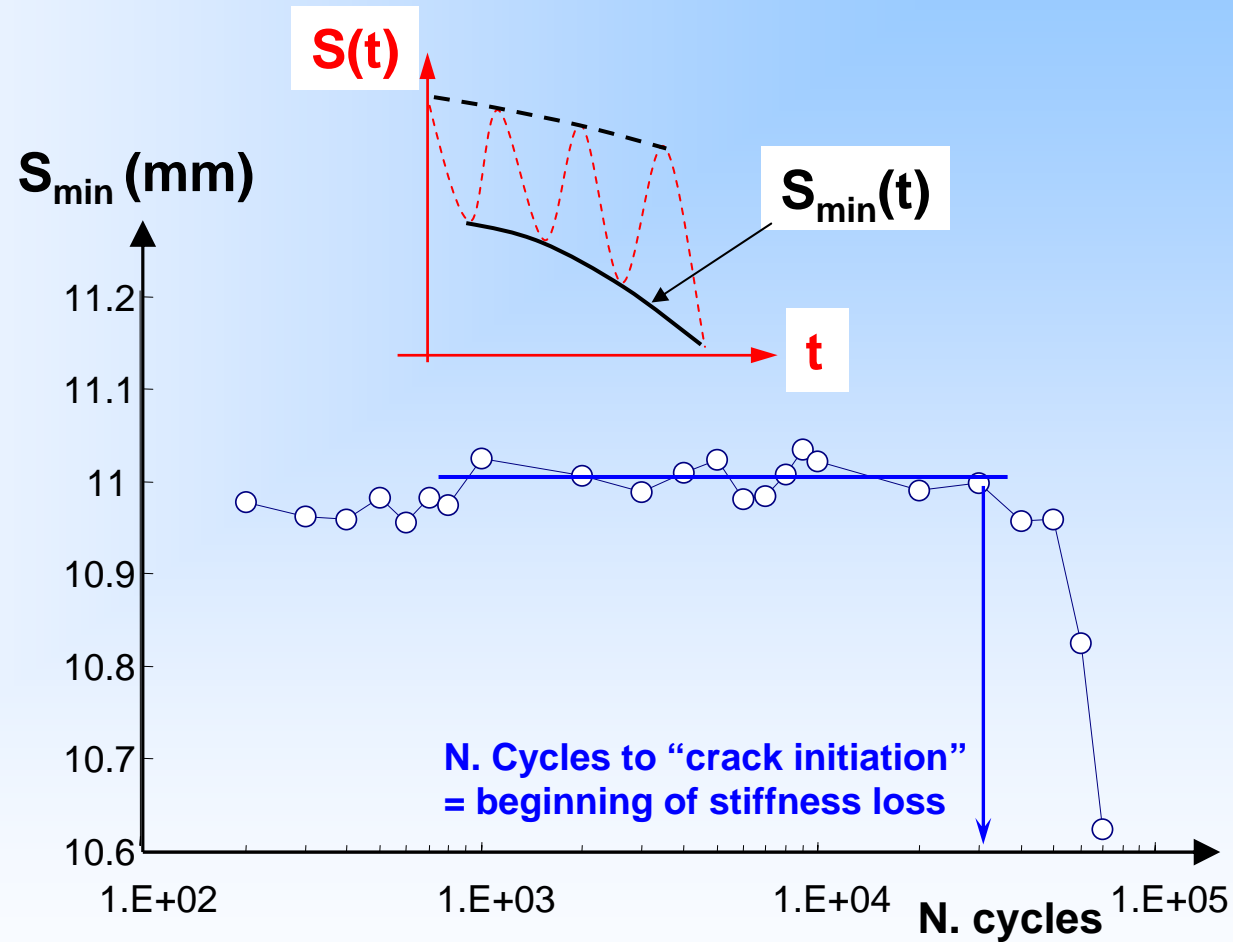


# Fatigue damage monitoring

Crack initiation was defined by analysing the “minimum displacement” vs N. cycles curves



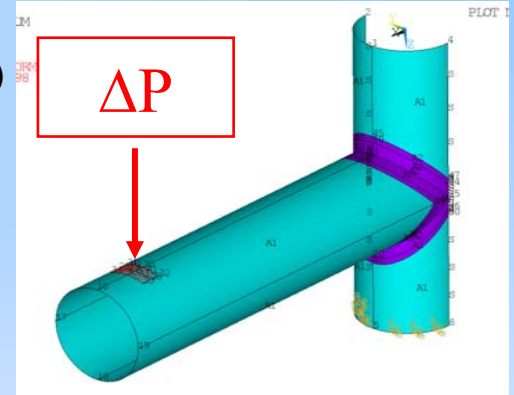
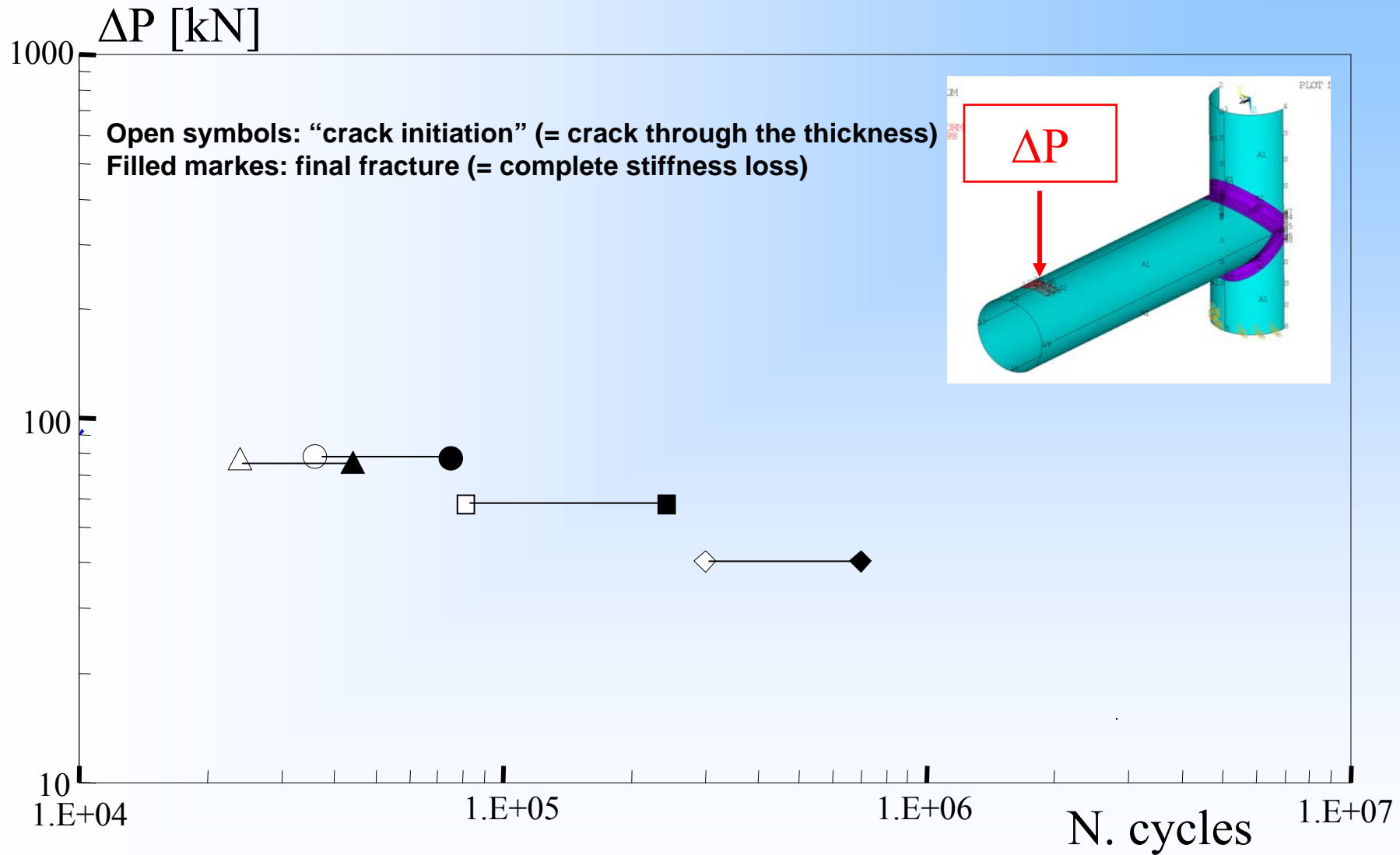
**Moving grip**



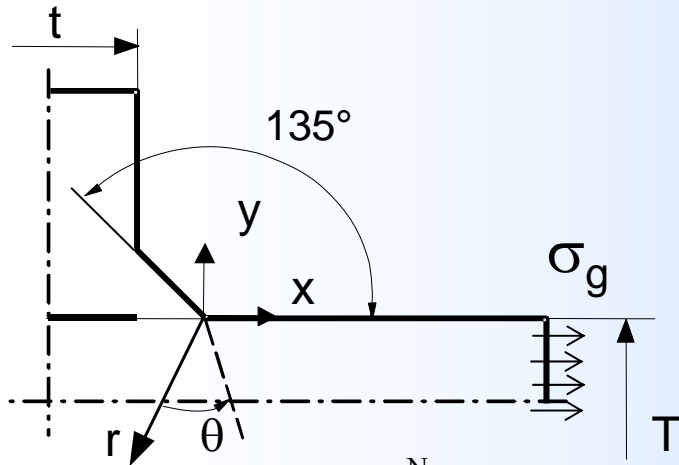
Experimental  $S_{min}$  vs N. cycles curve



# Fatigue test results



# The Notch-Stress Intensity Factor (N-SIF) approach



**Assumed hypothesis:**

- 1) Crack initiation occurs at the weld toe;
- 2) The **weld toe radius** is set equal to **zero**;

**Then:**

The stress field very close to the weld toe can be expressed by Williams equations:

$$\sigma_{\theta\theta} = \frac{K_1^N}{\sqrt{2 \cdot \pi \cdot r^{0.326}}} \cdot f_{\theta}(\theta)$$

$$\sigma_{rr} = \frac{K_1^N}{\sqrt{2 \cdot \pi \cdot r^{0.326}}} \cdot f_r(\theta)$$

where

$$K_1^N = \sqrt{2 \cdot \pi} \cdot \lim_{r \rightarrow 0} \left[ (\sigma_{\theta})_{\theta=0} \cdot r^{1-\lambda_1} \right]$$

**$K_1^N$  = Notch-Stress Intensity Factor**

**The N-SIF range  $\Delta K_1$  can be assumed as a fatigue strength parameter, i.e.:**

**if  $\Delta K_1$  is the same for two welded joint in a fatigue test  $\Rightarrow$  the fatigue life is the same**

**$\Rightarrow$  1 DESIGN CURVE IN TERMS OF  $\Delta K_1$  FOR FILLET WELDS IN STRUCTURAL STEEL, WHATEVER THE JOINT GEOMETRY AND ABSOLUTE DIMENSIONS**

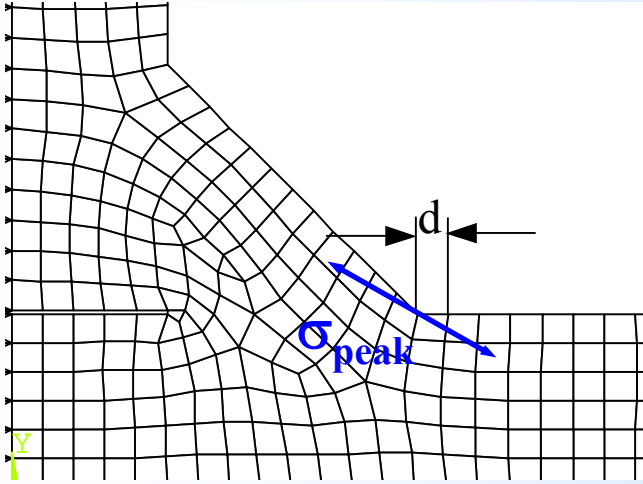
*Lazzarin P., Tovo R., Fatigue Fracture Engng Mater Struct, 1998.*

*Atzori B., Meneghetti G., Int J Fatigue, 2001.*



# The Peak Stress Method (PSM)

The PSM is based on the usefulness of the elastic peak stress calculated by FEM at a V-notch tip.



$$\eta = \frac{K_1^N}{\sigma_{\text{peak}}}$$

$\eta$  depends on : element type, element size

4-node plane  
stress elements

d=1 mm

- $\sigma_{\text{peak}}$  is a 'wild' stress since it is calculated at a point of singularity
- $\sigma_{\text{peak}}$  can substitute the N-SIF  $K_1^N$  in fatigue strength evaluation

Advantages when using  $\sigma_{\text{peak}}$  instead of  $K_1^N$ :

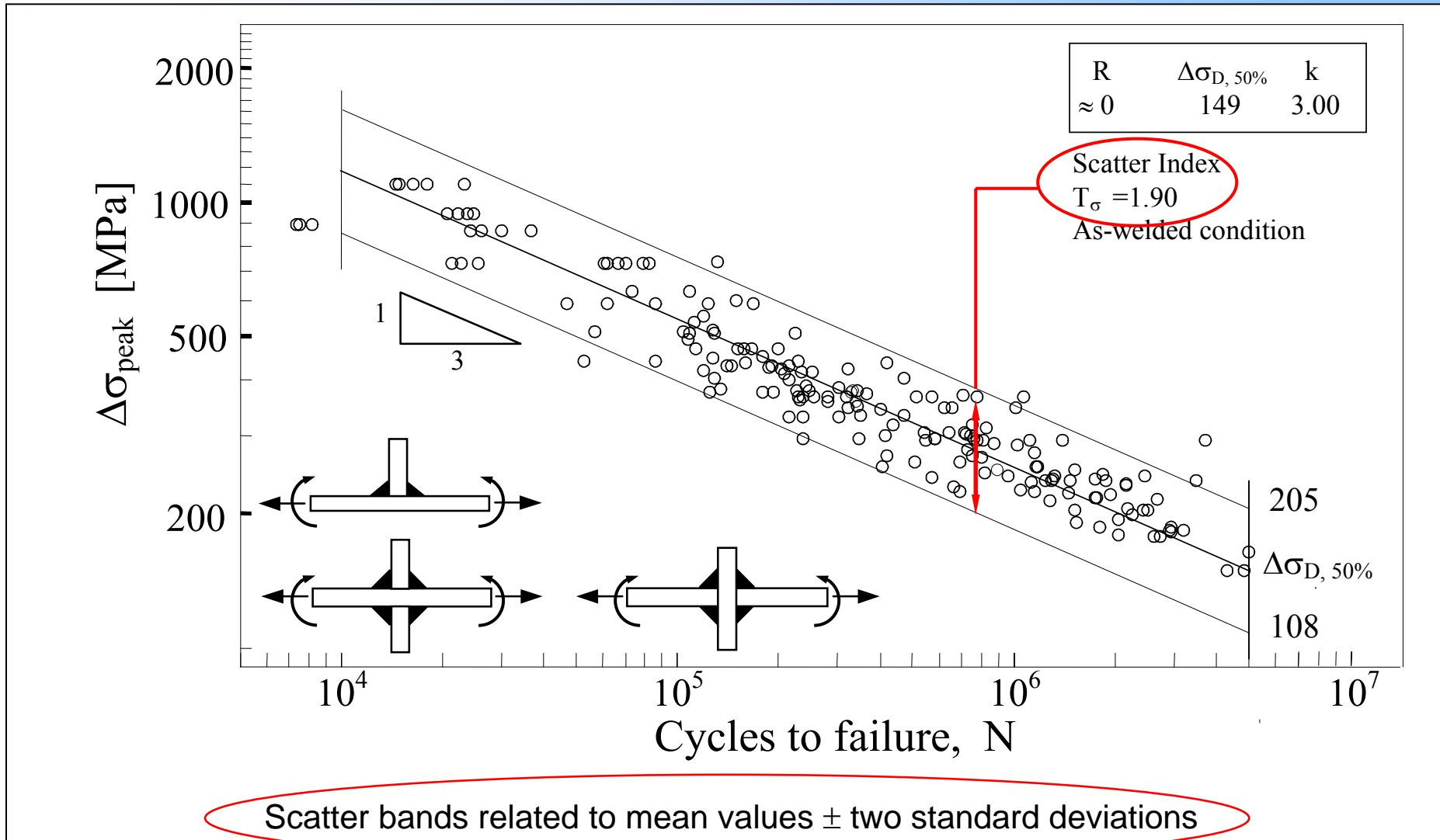
- A coarse mesh is sufficient to assure the applicability of the PSM as compared to that needed to calculate the N-SIF
- The PSM requires just one nodal stress value rather than a set of stress-distance FE data

*G. Meneghetti, Rivista Italiana della Saldatura, 2002.*

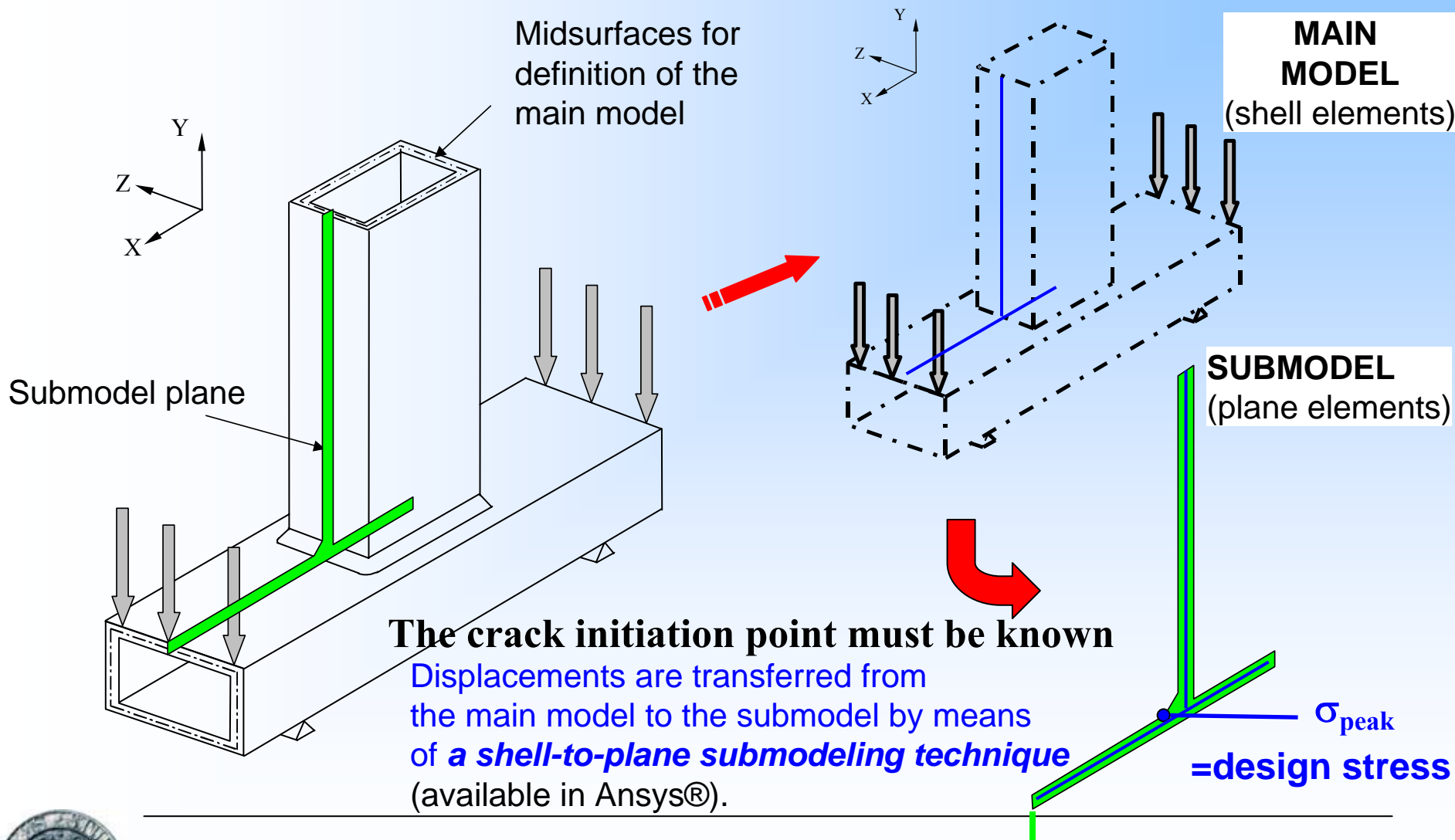
*G. Meneghetti, P. Lazzarin, Fatigue Fract. Engng Mater. Struct., 2006.*



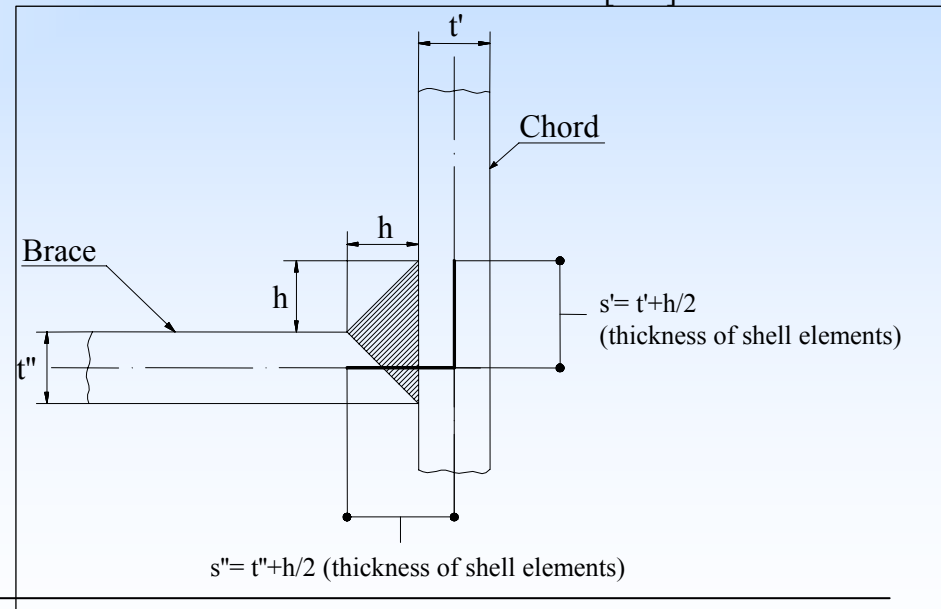
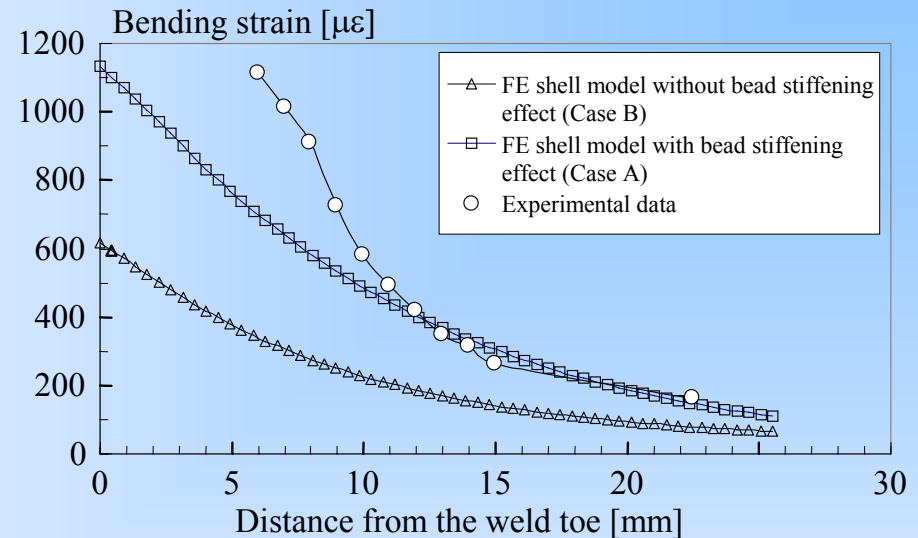
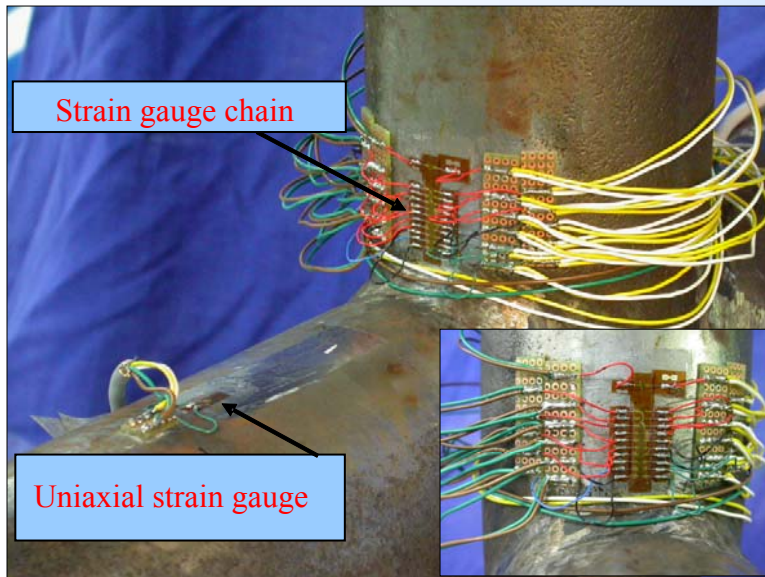
# Design curve for fatigue design of **Steel** fillet-welded joints



# Estimation of $\sigma_{\text{peak}}$ for complex 3-D geometries: a two step analysis



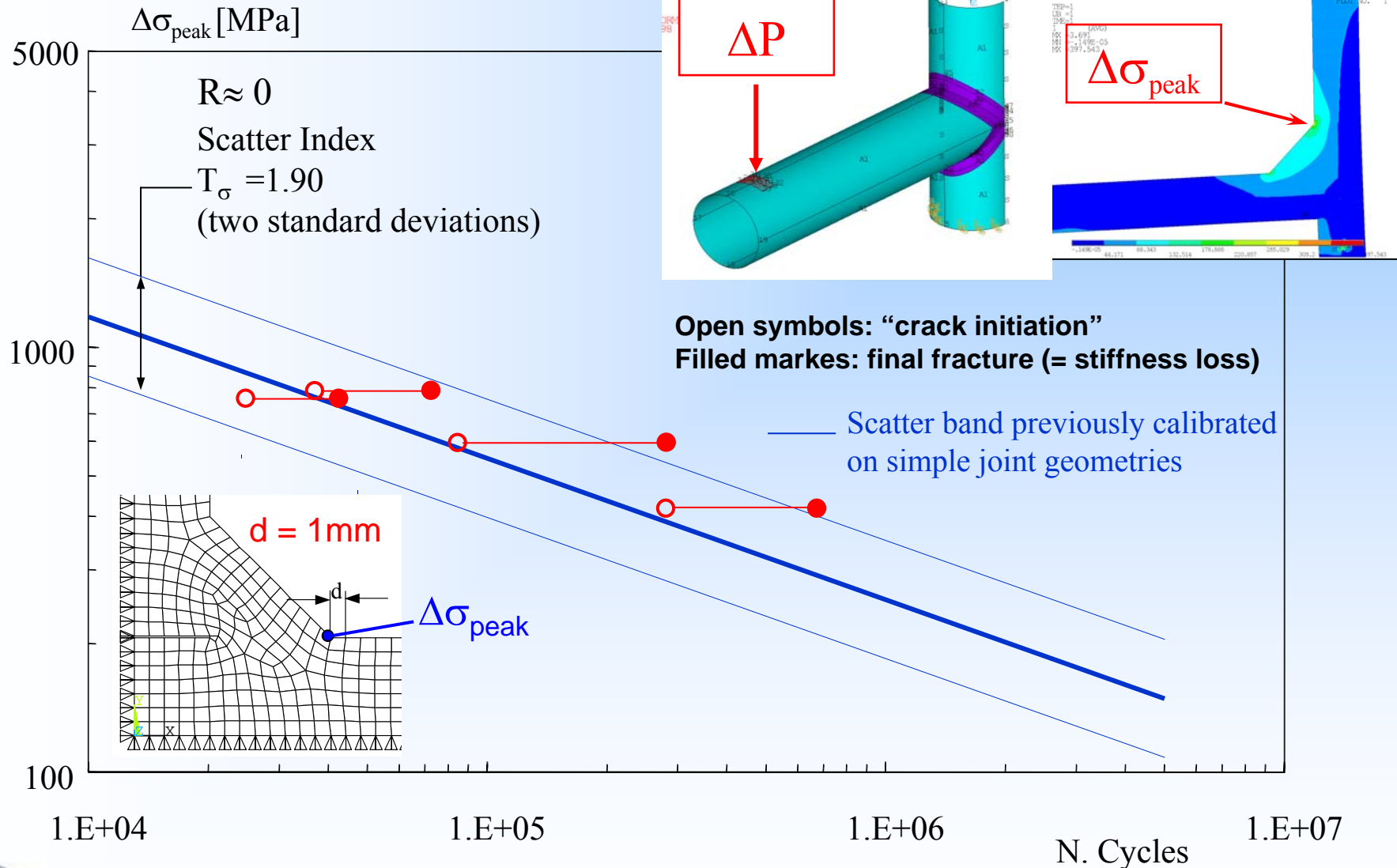
# Influence of the weld bead on *structural* stresses



- One strain gauge chain to check structural stresses
- Two uniaxial strain gauges to check nominal stresses and symmetry loading conditions



# Comparison between design curve and experimental results



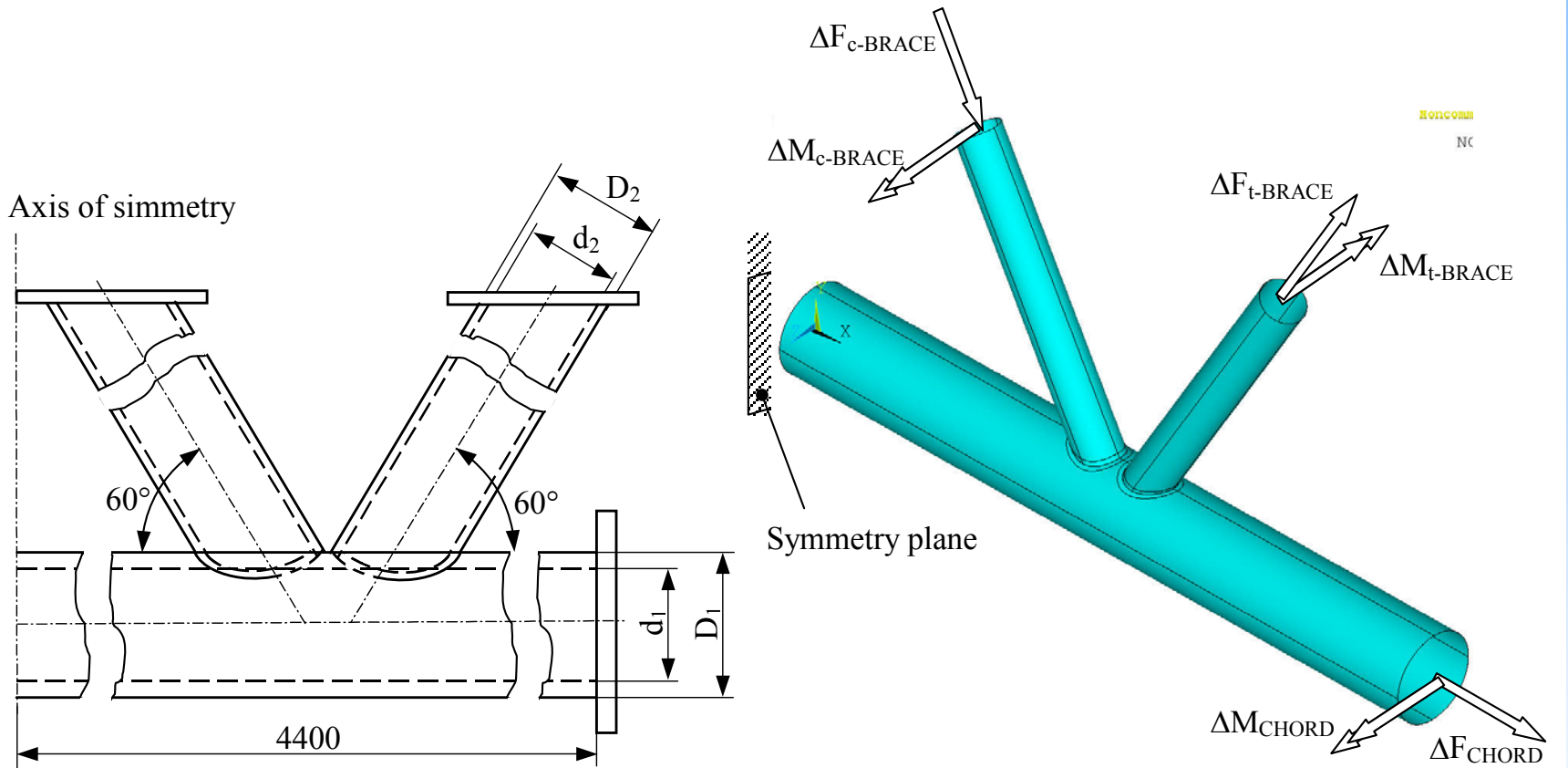
# Additional experimental data taken from the literature

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- [31] **Schumacher A, Nussbaumer A.** Experimental study on the fatigue behaviour of welded tubular K-joints for bridges. *Engineering Structures* 2006; 28: 745-55.
- [32] **Walbridge S, Nussbaumer A.** A probabilistic model for determining the effect of post-weld treatment on the fatigue performance of tubular bridge joints. *Int J Fatigue* 2007; 29: 516-32.
- [33] **Chiew SP, Lee CK, Lie ST, Ji HL.** Fatigue behaviours of square-to-square hollow section T-joint with corner crack. I: experimental studies. *Eng Fract Mech* 2007; 74: 703-20.
- [34] **Chiew SP, Lie ST, Lee CK, Huang ZW.** Fatigue performance of cracked tubular T joints under combined loads. I: experimental. *J Struct Eng* 2004; 130 (4): 562-71.
- [35] **Gandhi P, Berge S.** Fatigue behaviour of T-joints: square chords and circular braces. *J Struct Eng* 1998; 399-404.
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# Circular Hollow Section K-joints



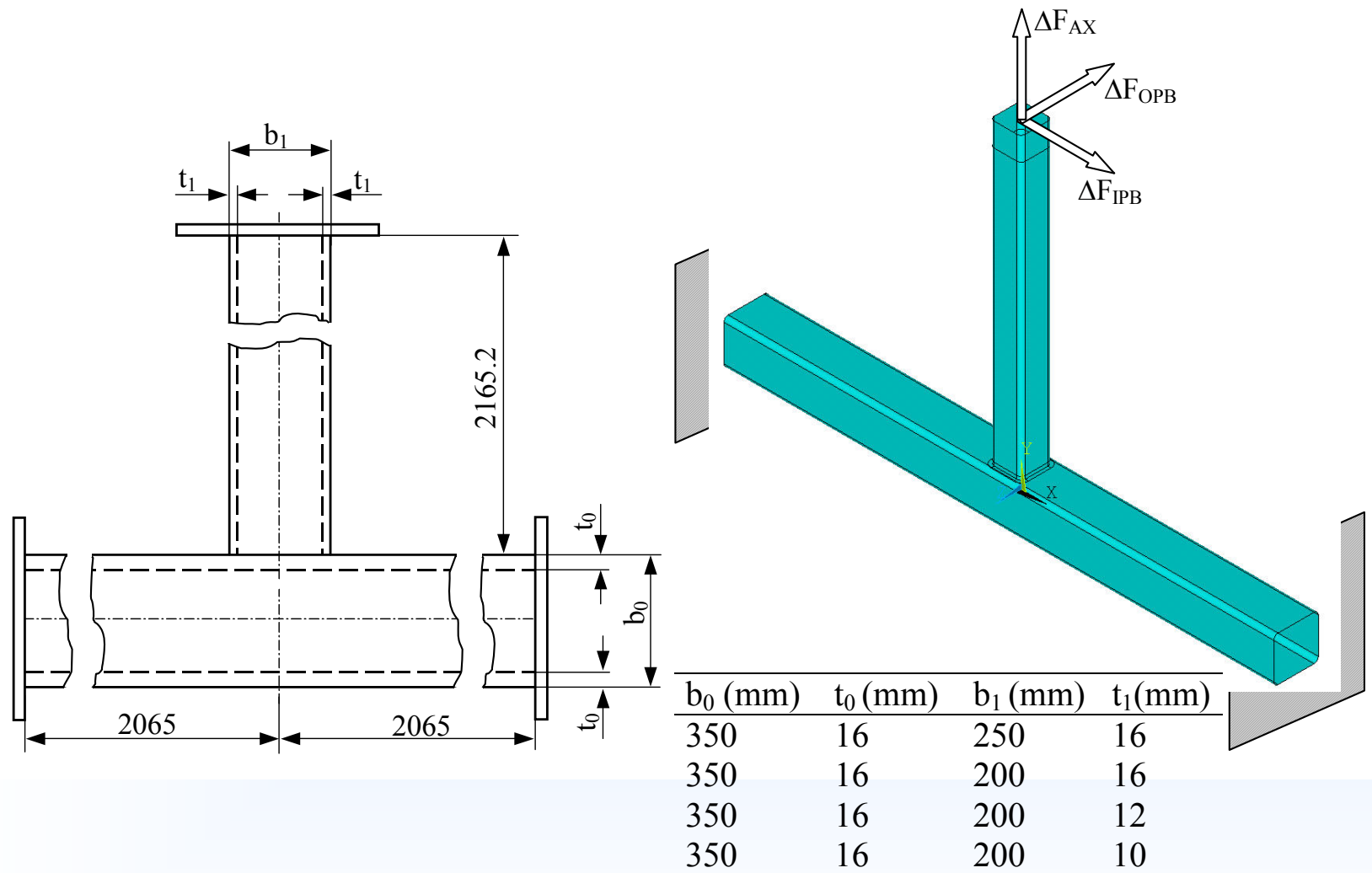
$D_1$ (mm)	$d_1$ (mm)	$D_2$ (mm)	$d_2$ (mm)
273	233	139.7	114.7
168.3	143.3	88.9	72.9

[31] Schumacher A, Nussbaumer A. *Engineering Structures* 2006.

[32] Walbridge S, Nussbaumer A. *Int J Fatigue* 2007.



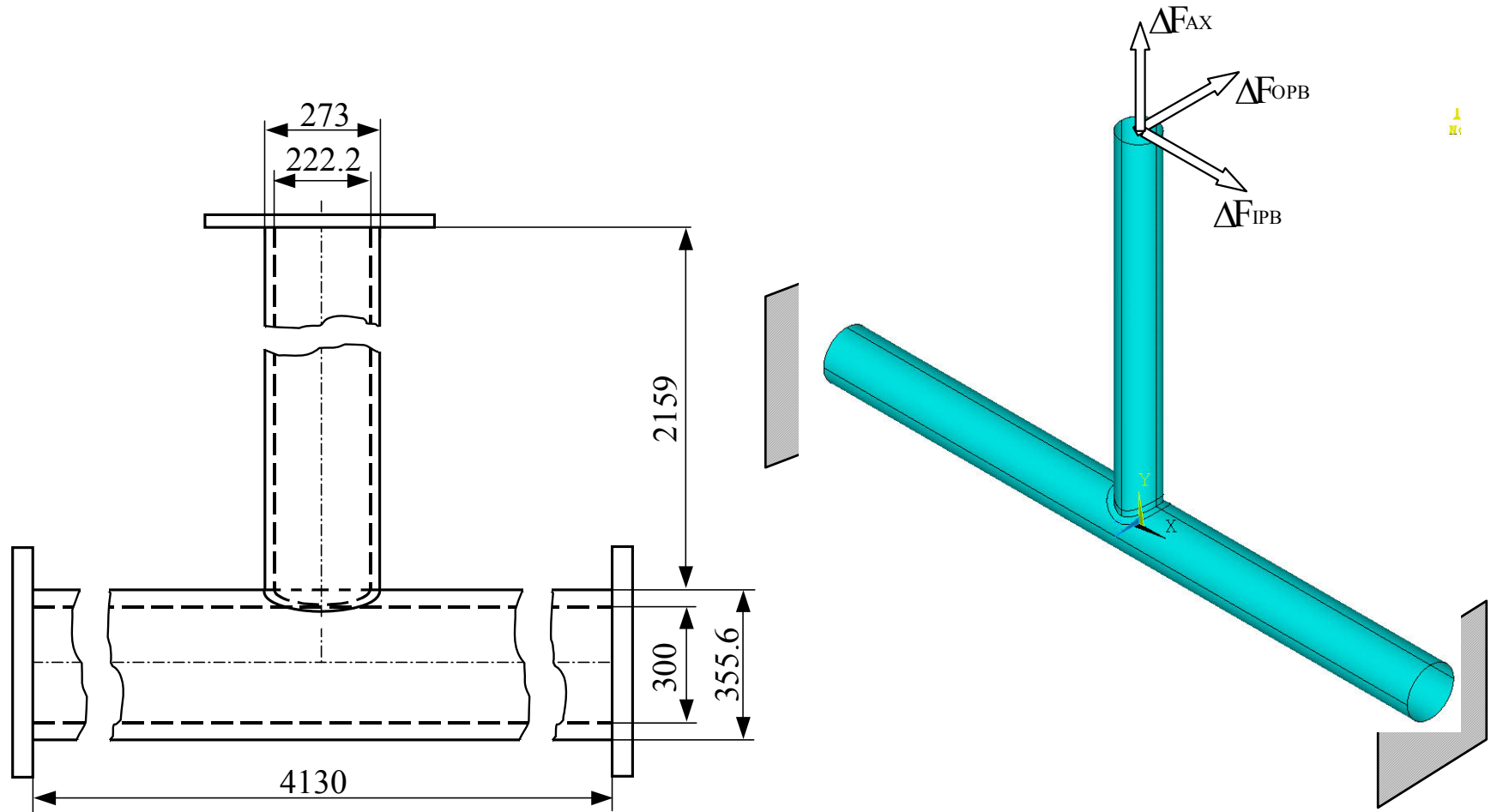
# Square Hollow Section T-joints



[33] Chiew SP, Lee CK, Lie ST, Ji HL. *Eng Fract Mech* 2007.



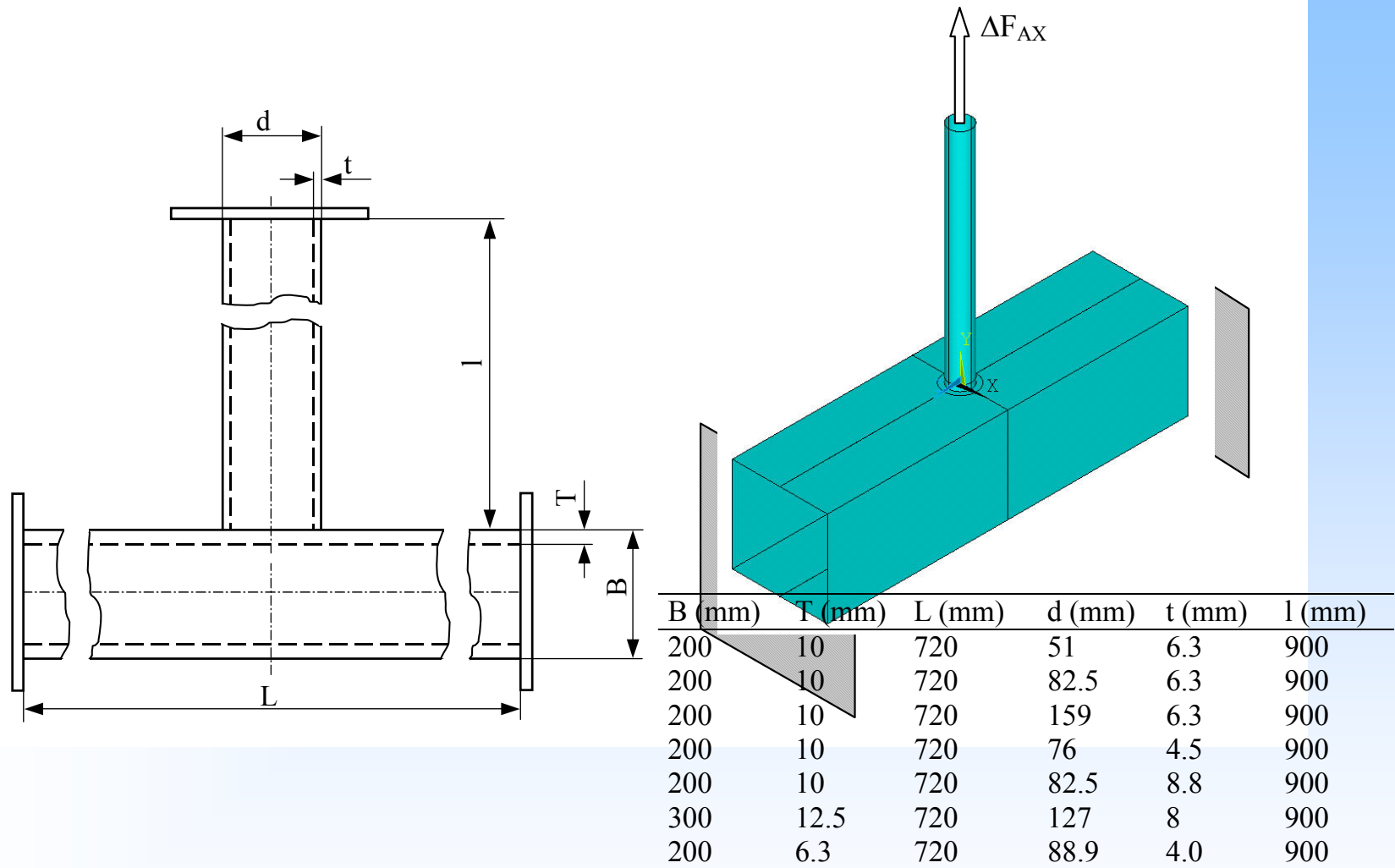
# Circular Hollow Section T-joints



[34] Chiew SP, Lie ST, Lee CK, Huang ZW. *J Struct Eng* 2004.



# CHS-to-SHS T-joints



[35] Gandhi P, Berge S. *J Struct Eng* 1998.



# Summary of the considered fatigue test data

Ref.	Joint geometry	Thicknesses $t; T^\circ$ (mm)	Material	Yield Stress (MPa)	Load Ratio	Load type
[15, 29]	Tube-to-Tube Cruciform	12.5; 12.5	Fe 510	355	0.1	Bending
[31, 32]	CHS K-joint *	8,12.5; 12.5,20	S 355 J2H	355	0.1	Axial/Bending
[33]	SHS T-joint **	10,12,16; 16	Structural Steels	366, 370	0	Axial/Bending
[34]	CHS T-joint	25.4; 27.8	Structural Steel	302	0	Axial/Bending
[35]	CHS-to-SHS T- joint	4,4.5,6.3,8,8.8; 6.3,10,12.5	Structural Steel	355	-0.36	Axial

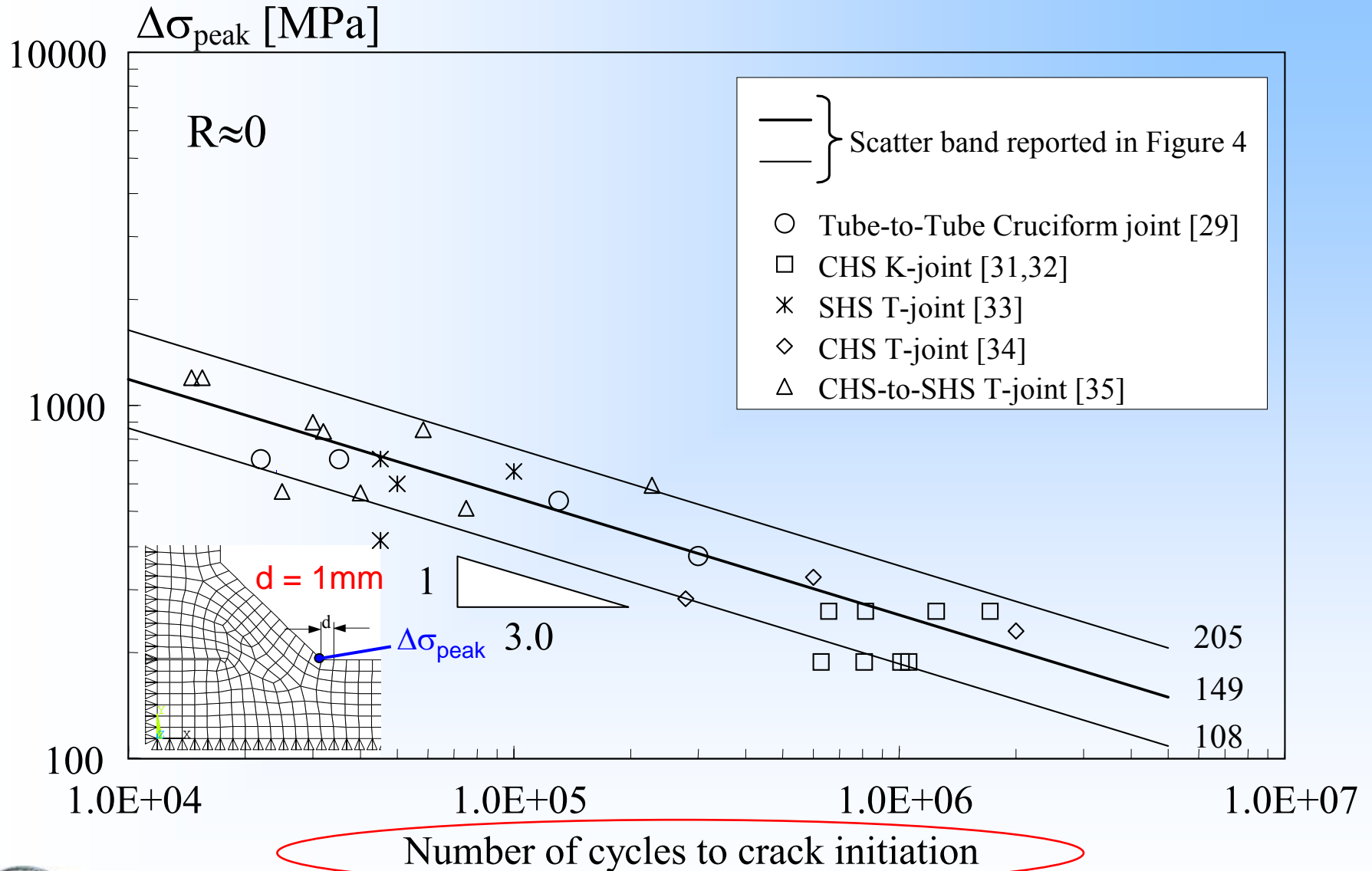
\*: CHS, Circular Hollow Section

\*\* : SHS, Square Hollow Section

$^\circ$ : t = thickness of the brace element; T = thickness of the chord element



# Comparison between design curve and experimental results



# Conclusions

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- The fatigue strength of a **tubular joint adopted in a roller coaster structure** has been analysed
- A significant fraction of the total fatigue life is spent in crack propagation outside the (small) zone governed by the N-SIF
- The Peak Stress Method (PSM) allows us to estimate the mode I Notch-Stress Intensity Factor parameter from a simple FE analyses:

$$\frac{K_1^N}{\sigma_{\text{peak}}} = \text{const.}$$

- The peak stress  $\sigma_{\text{peak}}$  is relatively simple to numerically evaluate than  $K_1^N$ . **According to the Peak Stress method, The design stress is the fictitious elastic peak stress evaluated at the weld toe by means of a finite element analysis performed with a given pattern of elements**
- A fatigue design curve in terms of  $\Delta\sigma_{\text{peak}}$  for fatigue strength assessment of as-welded fillet-welded joints in steel has been previously defined. Then The design curve have been utilised to estimate the fatigue strength of as-welded fillet-welded tubular joints subject to Mode I loading.
- The N-SIF approach or the Peak Stress Method should be adopted to estimate fatigue life up to crack initiation.
- It is believed that the Peak Stress Method is convenient in practical applications because it combines both the simplicity of a point-like method and the robustness of the NSIF local approach.

