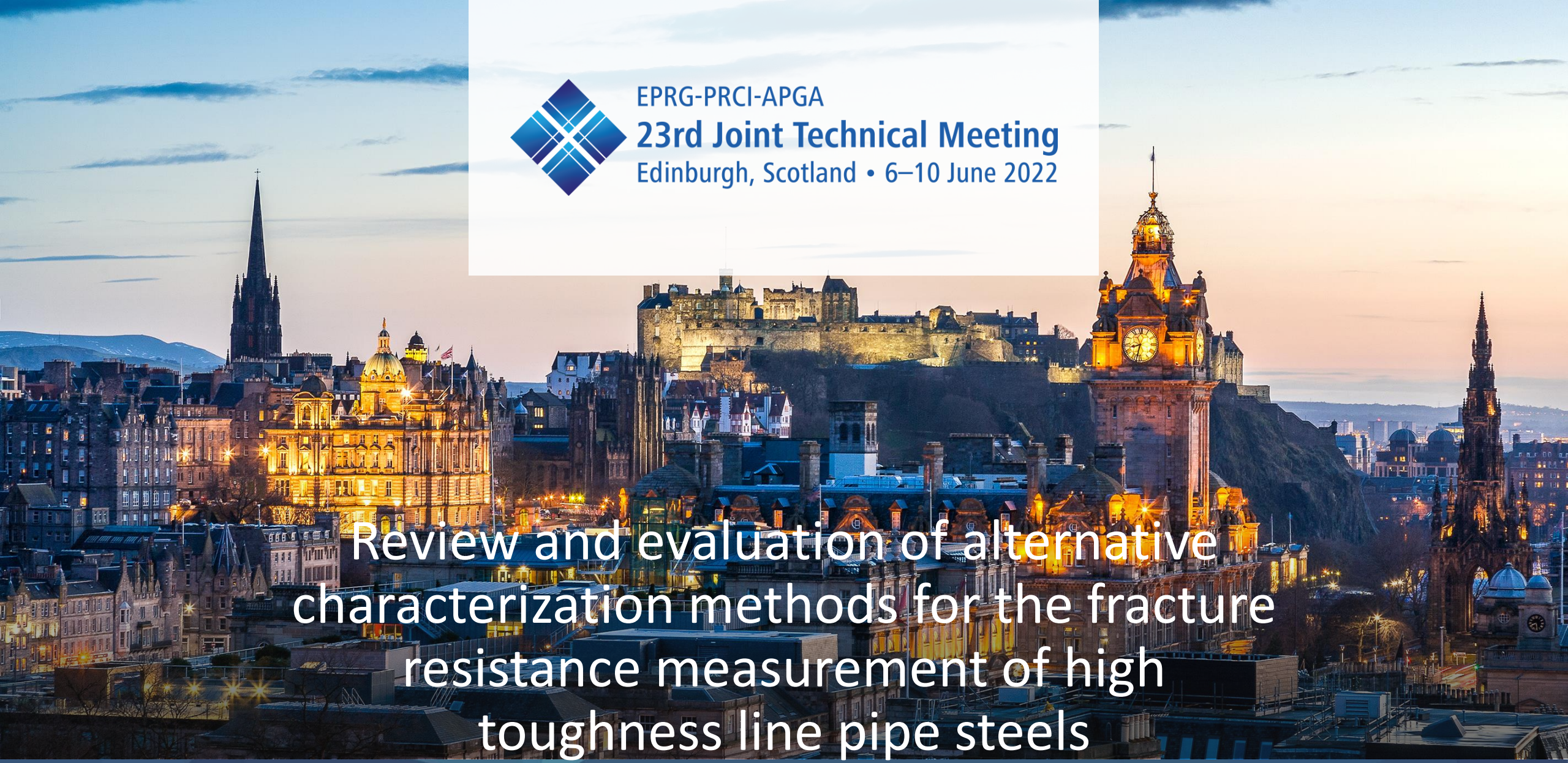
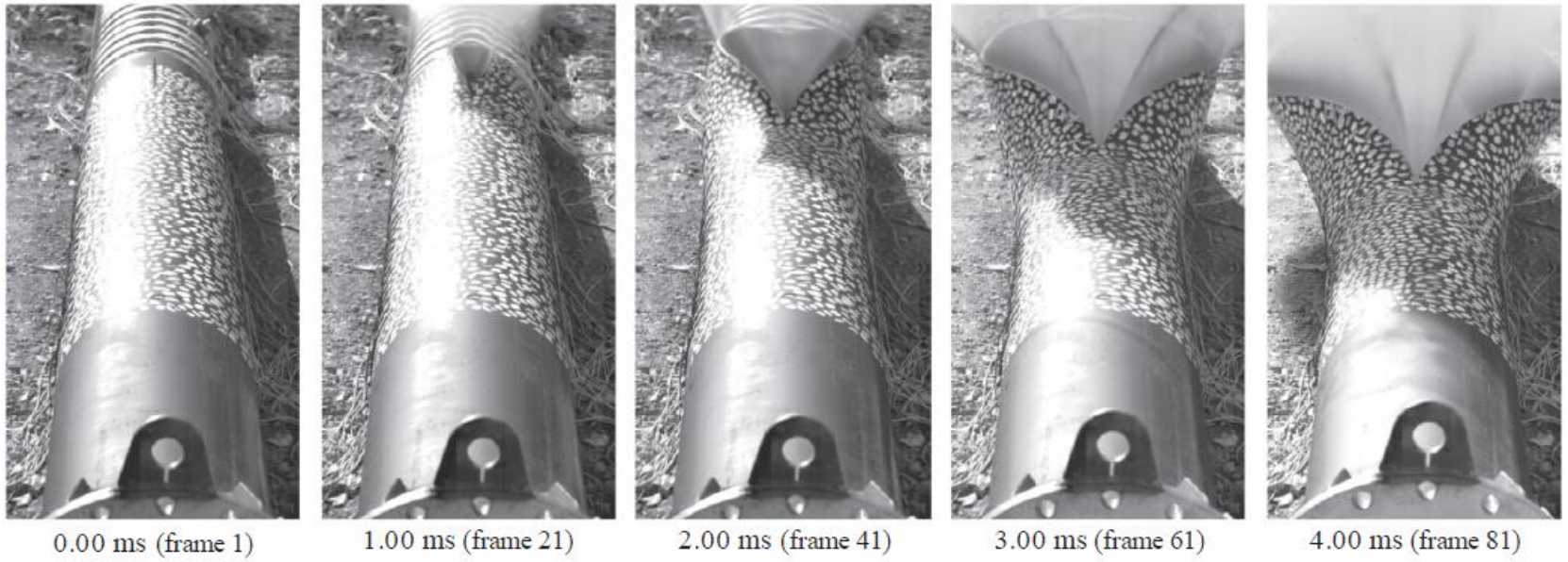


Review and evaluation of alternative characterization methods for the fracture resistance measurement of high toughness line pipe steels

7 June 2022

Running ductile fracture

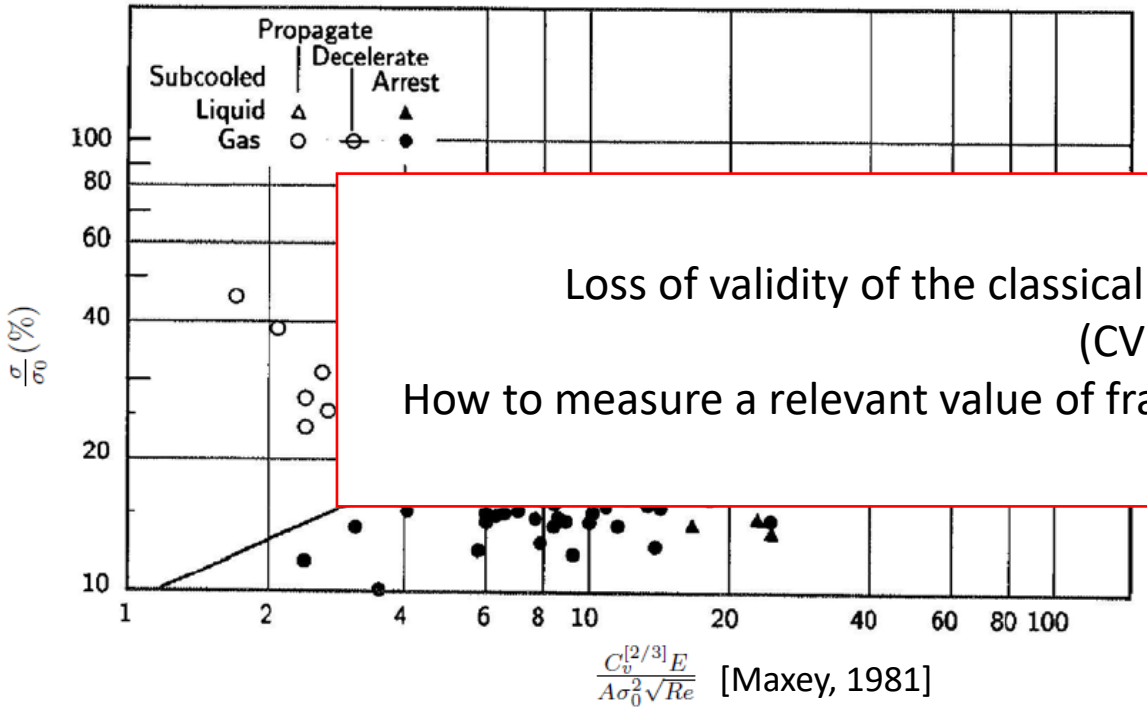


[Shibanuma, 2018]

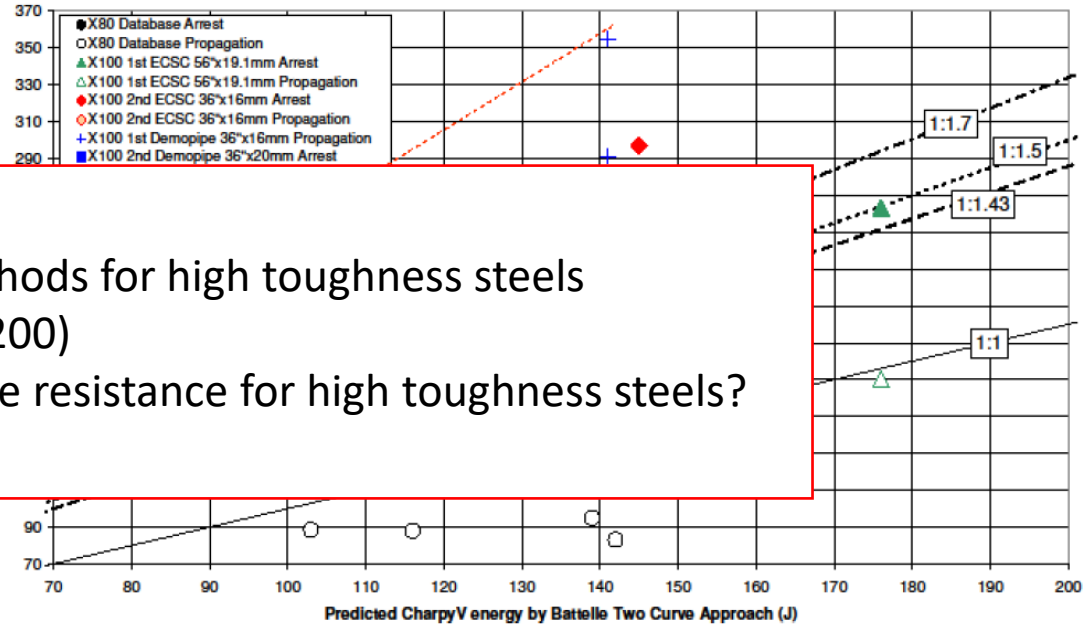
[Mannucci, 2002]

Dynamic failure mechanisms of pipe lines driven by the internal pressure and the fracture resistance of the material

Running ductile fracture



[Maxey, 1981]



Loss of validity of the classical methods for high toughness steels
(CVN > 200)
How to measure a relevant value of fracture resistance for high toughness steels?

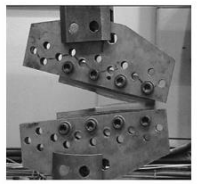
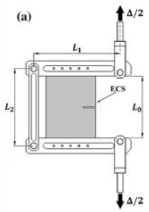
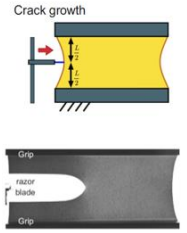
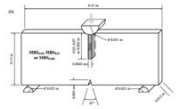
- In the classical methods (as the BTCM), the crack velocity could be estimated based on the CVN-Energy

Two projects between EPRG and Fraunhofer EMI

Measuring the fracture resistance of high toughness steels

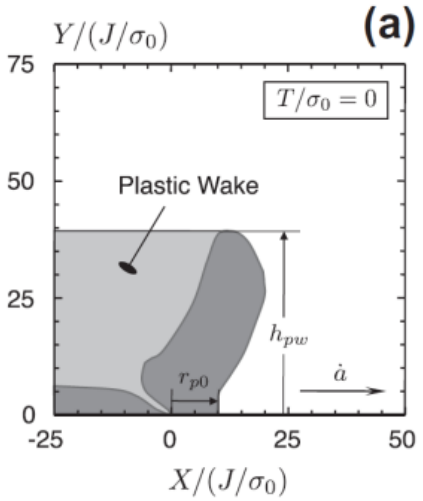
Project 216

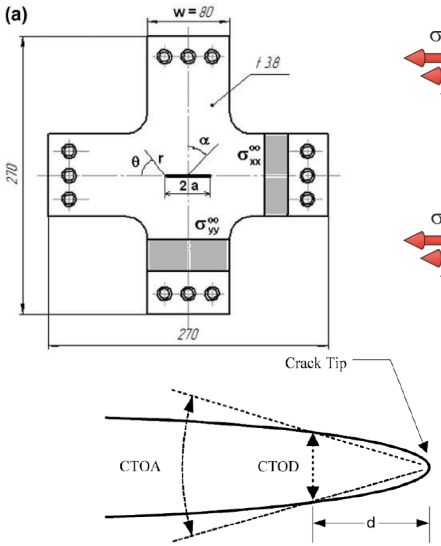
Literature review to identify alternative methods for the measurement of the fracture resistance

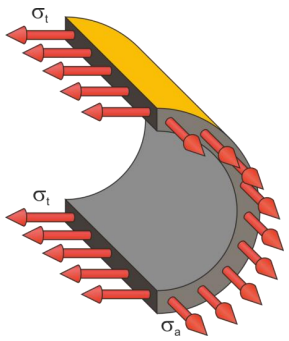
MDCB / MCT	IPS	CCS	WLDCB	USETT	BS-DWTT
					
Modified Double Cantilever Beam / Modified Compact Tension	In-Plane Stretching	Center Crack Specimen	Wedge Loaded Double Cantilever Beam	Unstable Single Edge Tensile Test	Back-Slot Drop Weight Tear Test

Project 216a

Quantitative evaluation of the pre-selected test methods







Loss of validity of the BTCM

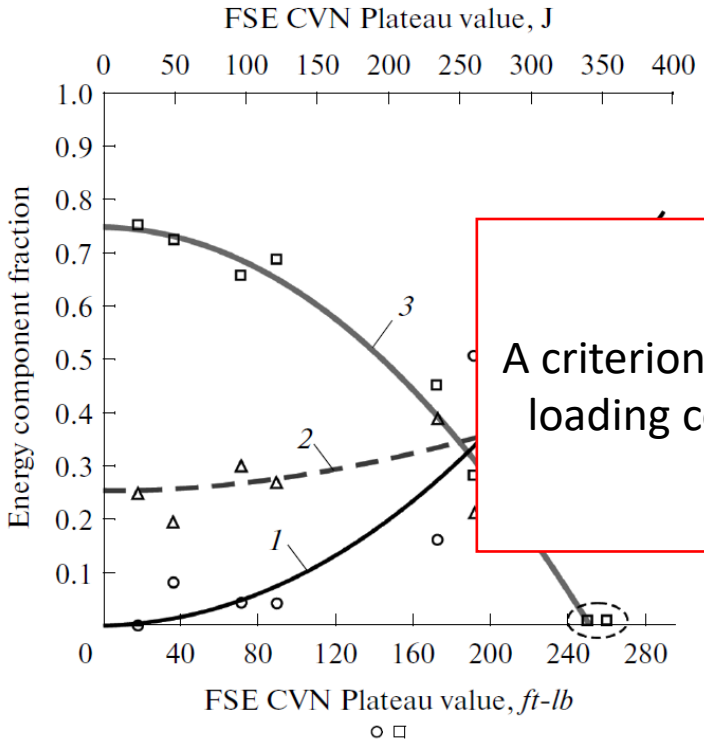
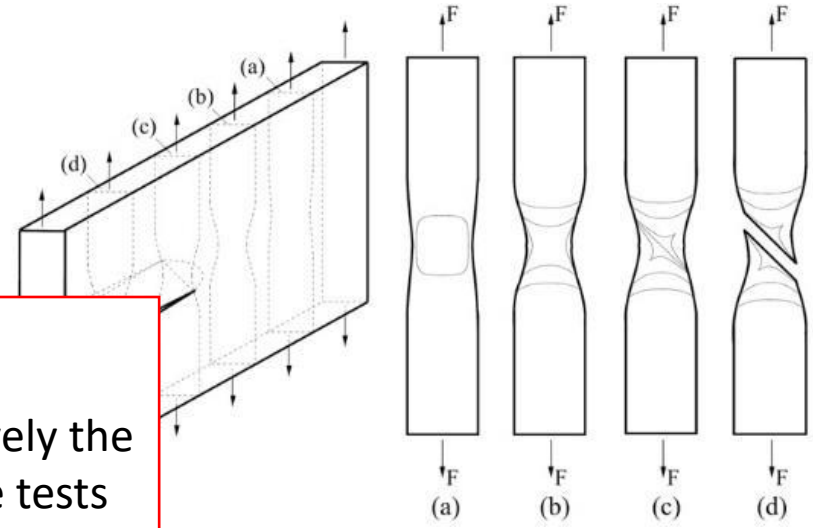


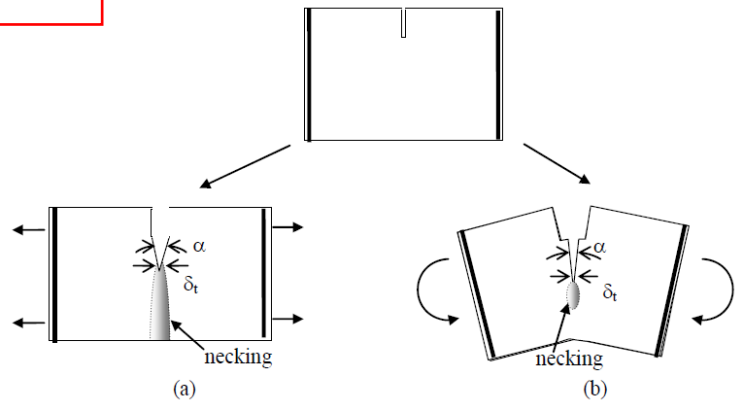
Fig. 10. Shift in CVN dissipation for the initiation, plastic deformation, and propagation components as total energy increases: *1*—Trend D; *2*—Trend I; *3*—Trend P; □—propagate; ○—deformation; △—initiation.

[Leis, 2015]

A criterion is required to compare quantitatively the loading conditions of full-scale and lab-scale tests

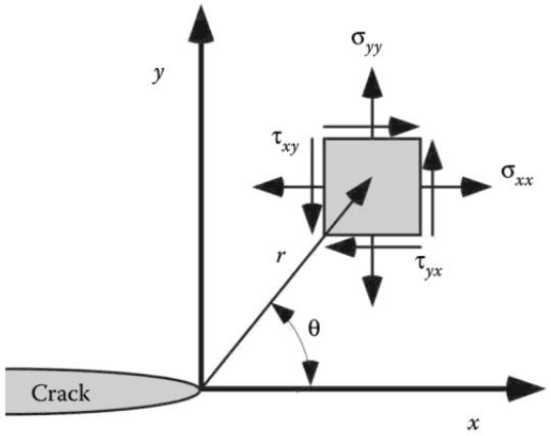


[Nielsen, 2012]



[Schindler, 2010]

Loading of the crack tip



$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 - \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] + T + O\left(r^{\frac{1}{2}}\right)$$

$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\left[1 + \sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] + O\left(r^{\frac{1}{2}}\right)$$

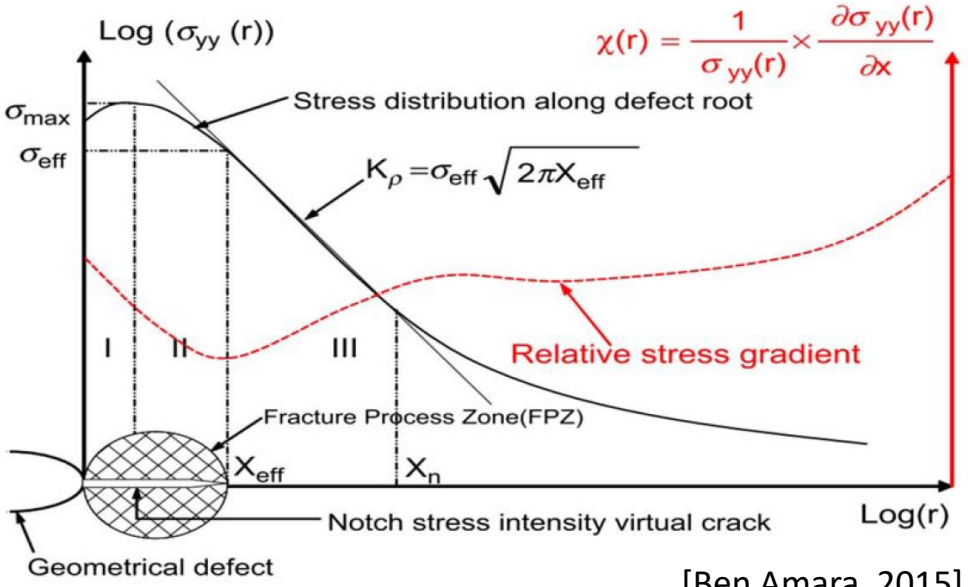
$$\sigma_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right) + O\left(r^{\frac{1}{2}}\right)$$

For purely elastic materials

$$T = \sigma_{xx} - \sigma_{yy}\big|_{r\to 0,\theta=0}$$

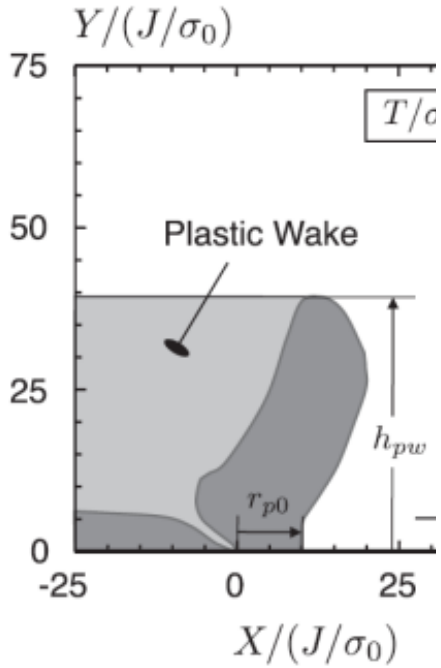
For elastic-plastic materials

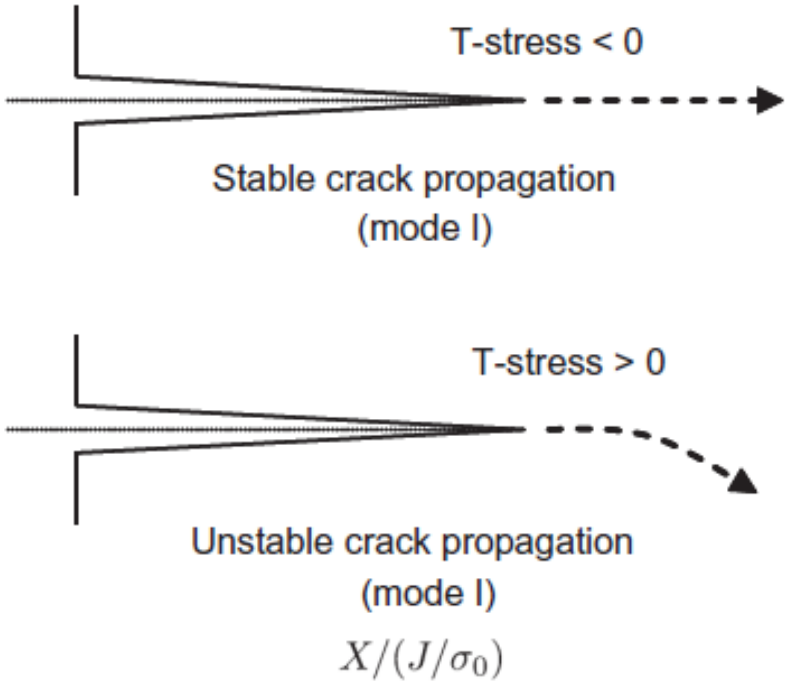
$$T_{ef} = \sigma_{xx} - \sigma_{yy}\big|_{r=X_{ref},\theta=0}$$



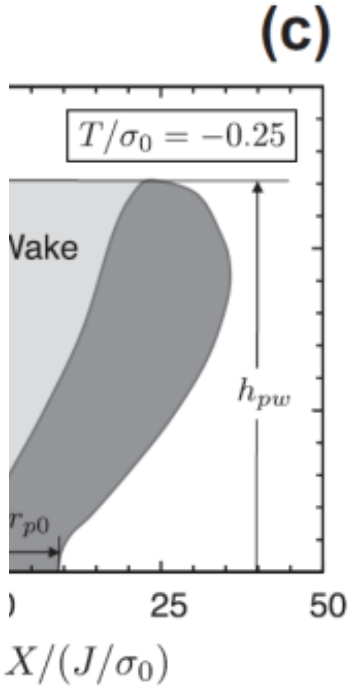
[Ben Amara, 2015]

Physical meaning of the T-stress



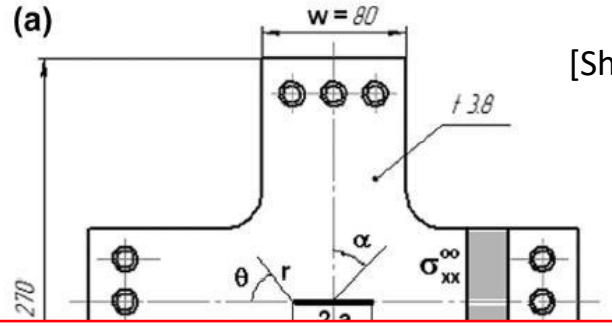


[Moustabchir, 2012]



[Sobotka, 2011]

Estimation of the T-stress value during RDF



[Shlyannikov, 2014]

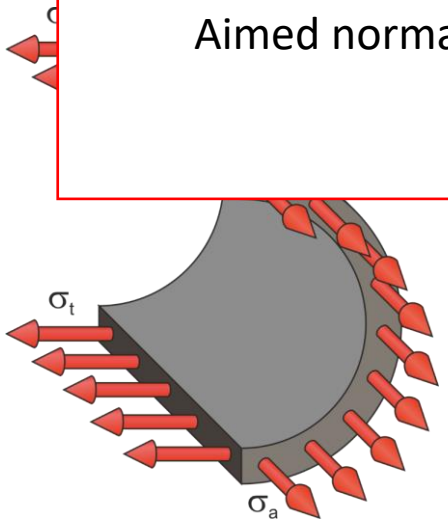
$$\eta = \frac{\sigma_a}{\sigma_h} = \frac{1}{2}$$

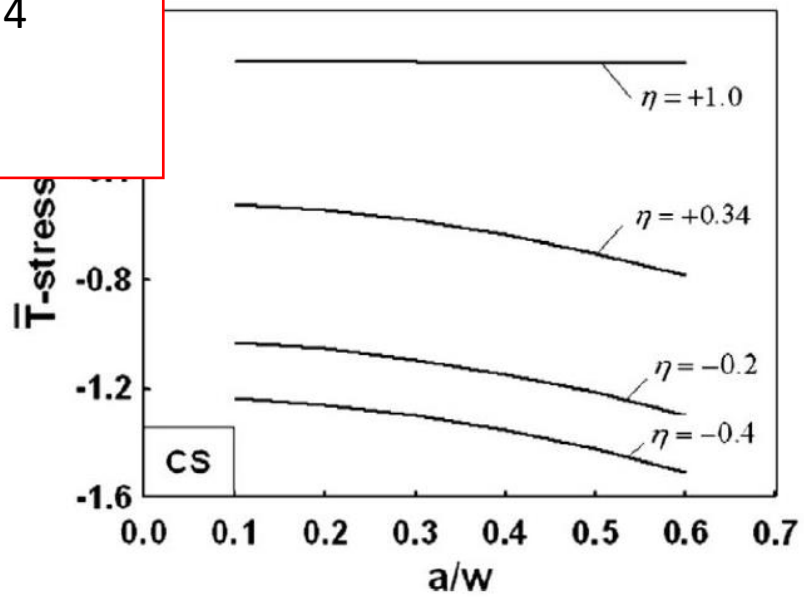
Remote biaxial stress state of the

Aimed normalized T-stress in the range of -0.4

$$\sigma_t = \sigma_h = \frac{Pr}{t}$$

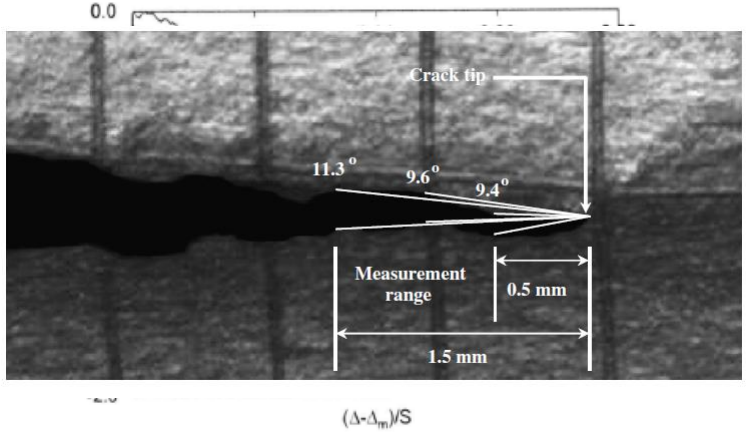
$$\sigma_a = \frac{Pr}{2t}$$





Measurement of the fracture resistance: CTOA

Crack Tip Opening Angle



[Mahmoudi, 2008]

Advantages and drawbacks

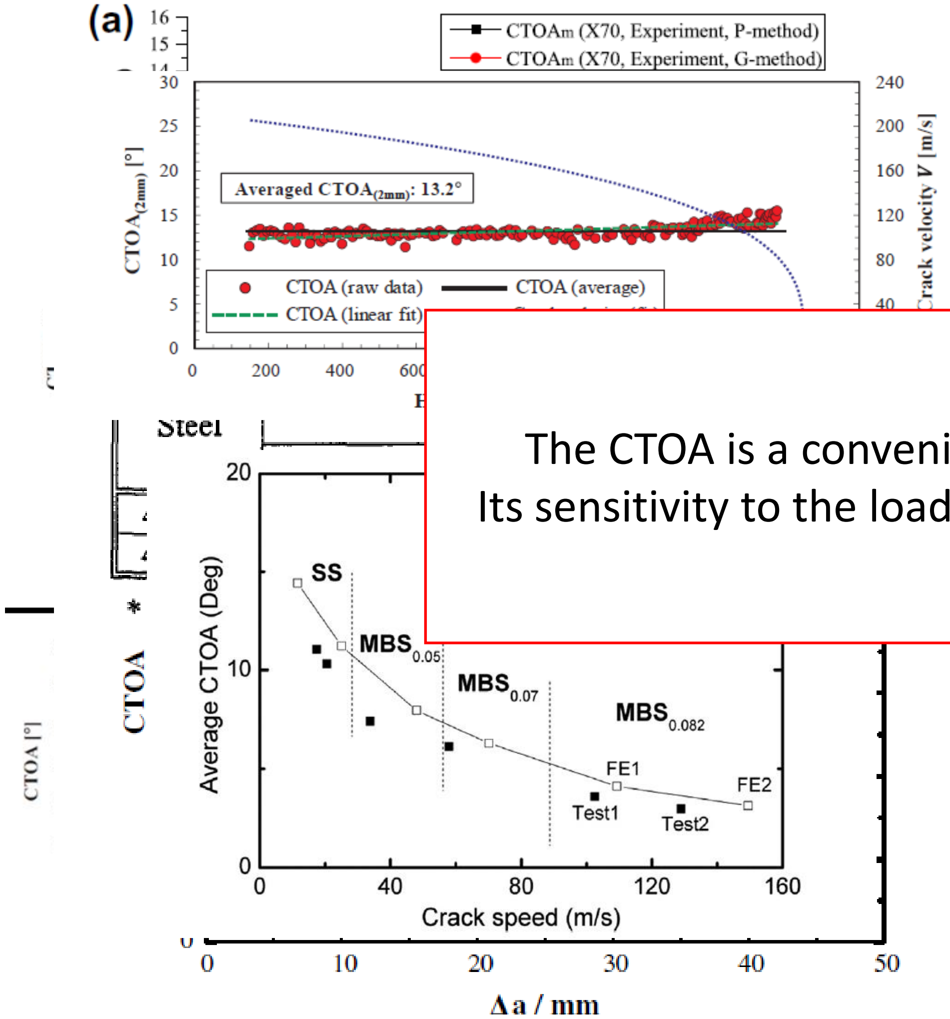
Advantages

- Recommended and standardized by ISO 22889 and ASTM E2472
- Local measurement
- Existing standard (ASTM E3039) for its determination without optical measurement for the DWTT which might be extended to other methods
- Numerical methods exist to use it as a criterion for simulation

Drawbacks

- Potential variability in the measured angle and potential difficulty at high rate.

Measurement of the fracture resistance: CTOA



The CTOA is a convenient quantity to measure the fracture resistance.
Its sensitivity to the loading conditions still needs to be quantified properly

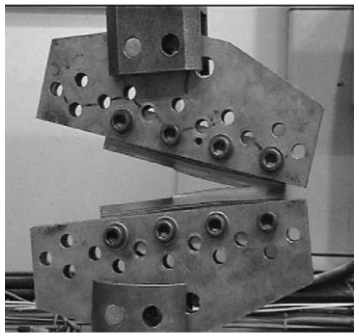
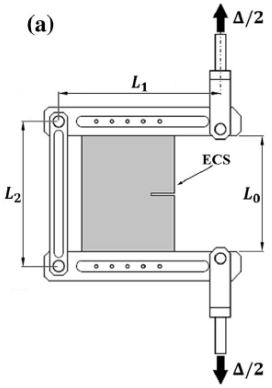
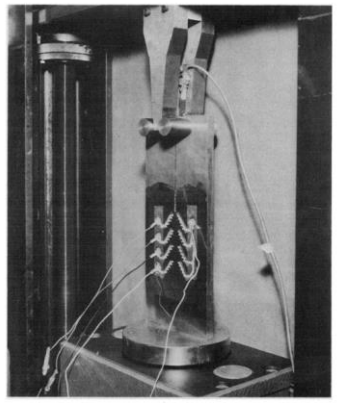
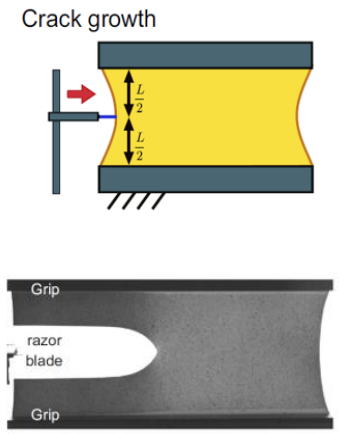
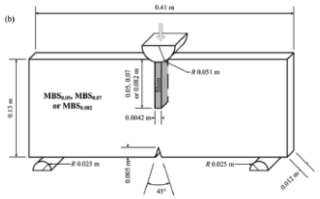
Parameters potentially influencing the CTOA

- Crack length
  - Edge effects have an influence on the CTOA
- ...pecimens should be
  - ...influence is not clear: Quantitative comparison of the loading conditions is required
- Loading rate / crack speed
  - Influence is not clear: further investigations are required

List of non-subjective criteria for the reference methods

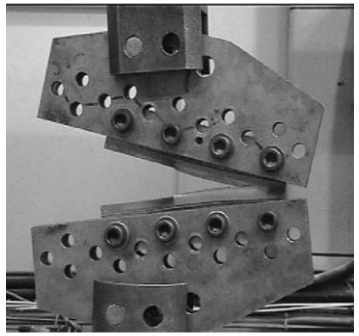
- Crack propagation at a remote stress below the yield stress of the material
  - No generalized plastic deformation of the ligament before the onset of crack propagation
- Normalized T-stress at the crack tip
  - Value in the range of ~ -0.4
- Full pipe line material thickness
- Unstable or high-rate crack propagation
- Force measurement is possible
- CTOA measurement is possible

Reference test methods

MDCB / MCT	IPS	CCS	WLDCB	USETT	BS-DWTT
					
Modified Double Cantilever Beam / Modified Compact Tension	In-Plane Stretching	Center Crack Specimen	Wedge Loaded Double Cantilever Beam	Unstable Single Edge Tensile Test	Back-Slot Drop Weight Tear Test
[Shterenlikht, 2004]	[Nielsen, 2017]	[Simonsen, 2004]	[Hahn, 1974]	[Corre, 2020]	[Yu, 2015]

MDCB/MCT: Modified Double Cantilever Beam / Compact tension

Remote stress	T-stress	Full thickness	Unstable/ High-rate crack propagation	Force measurement	CTOA measurement
✓	✓	✓	✓	✓	✓

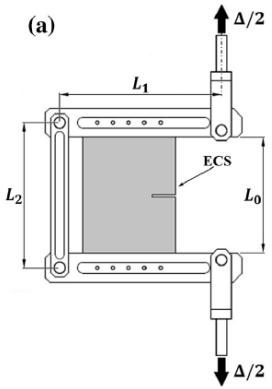


[Shterenlikht, 2004]

- T-Stress: No complete study available in the literature. Negative values obtained by Ben Amara. Sensitivity analysis on the specimen geometry and loading conditions required.
- Full thickness: No tests conducted so far but theoretically possible using welded loading blocks.

IPS: In-Plane Streching

Remote stress	T-stress	Full thickness	Unstable/ High-rate crack propagation	Force measurement	CTOA measurement
✓	✓	✓	✓	✓	✓



[Nielsen, 2017]

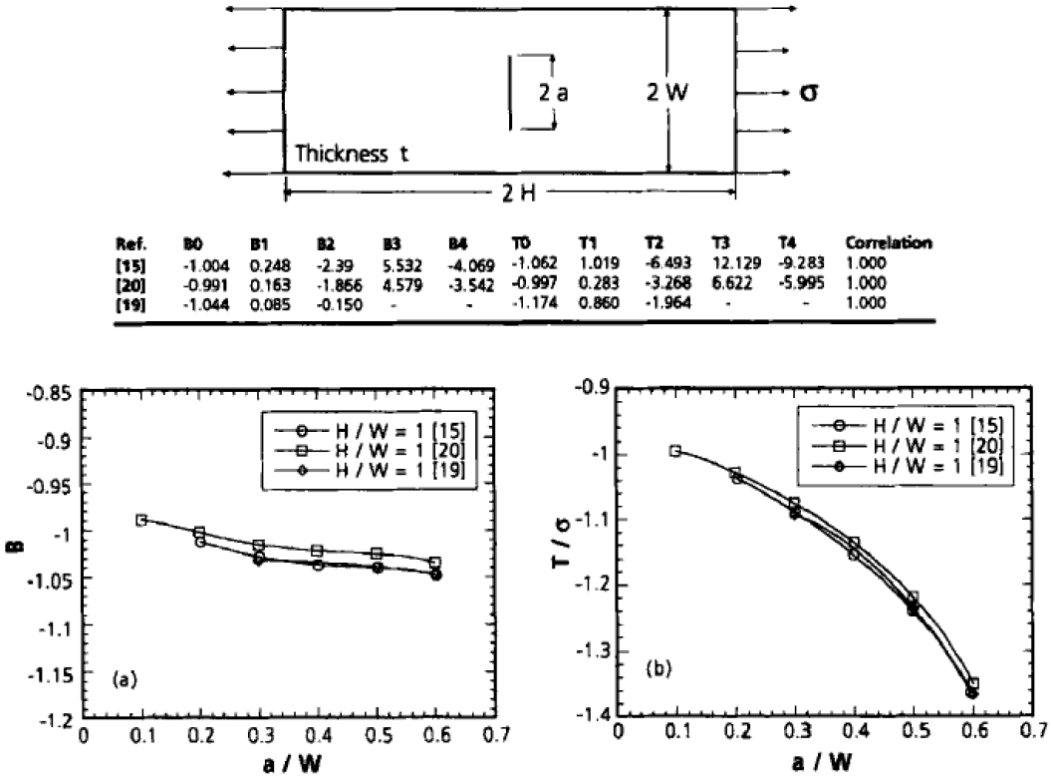
- T-Stress: No study available in the literature. Sensitivity analysis on the specimen geometry and loading conditions required.
- Unstable/High-rate crack propagation: No proof of tests at high velocities have been realized. Due to the similar dimensions of the specimens with the MDCB, high-rate tests should be possible.

CCS: Center Crack Specimen

Remote stress	T-stress	Full	Unstable/ High-	Force	CTOA measurement
✓	✗				✓

[Simonsen, 2004]

- Remote stre… …rge plastic deformatior…
- T-Stress: Val…
- Unstable/Hi… …ecimen dimensions.

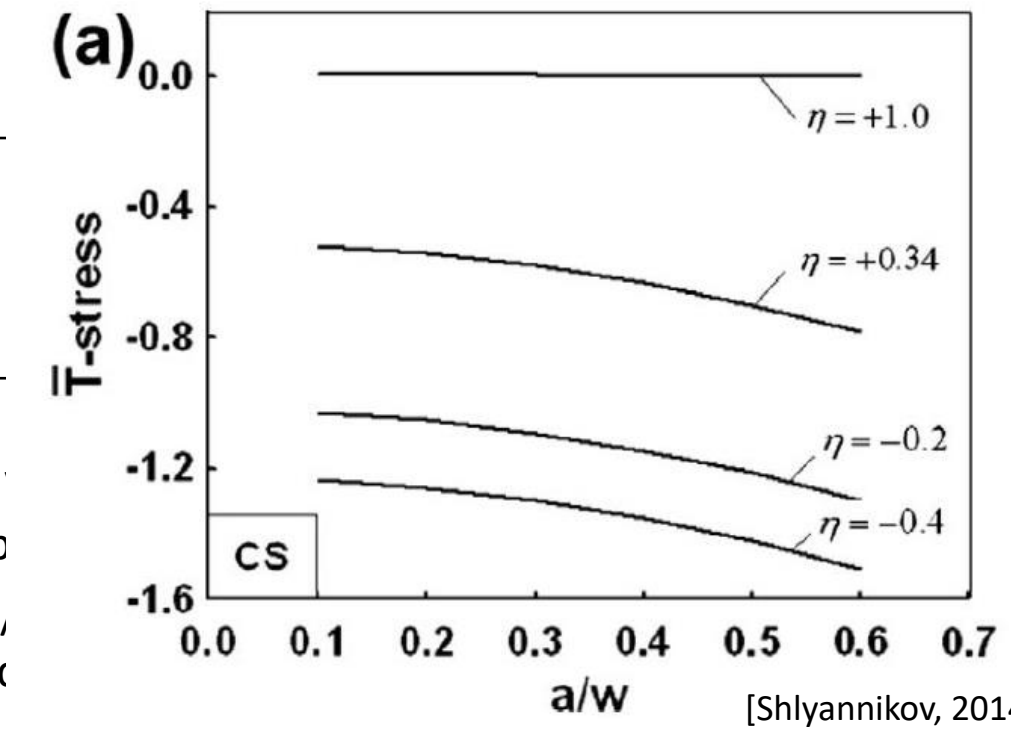


Ref.	B0	B1	B2	B3	B4	T0	T1	T2	T3	T4	Correlation
[15]	-1.004	0.248	-2.39	5.532	-4.069	-1.062	1.019	-6.493	12.129	-9.283	1.000
[20]	-0.991	0.163	-1.866	4.579	-3.542	-0.997	0.283	-3.268	6.622	-5.995	1.000
[19]	-1.044	0.085	-0.150	-	-	-1.174	0.860	-1.964	-	-	1.000

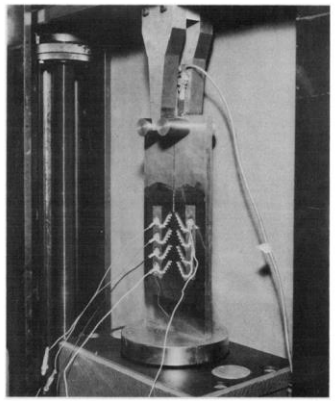
[Sherry, 1995]

WLDCB: Wedge Loaded Double Cantilever Beam

Remote stress	T-stress	Full	Unstable/ High-	Force	ent	CTOA measurement
✓						✓



[Shlyannikov, 2014]

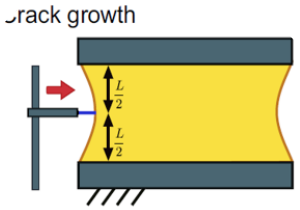


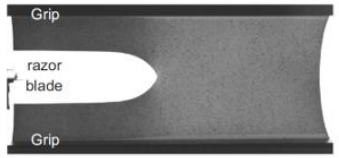
[Hahn, 1974]

- T-Stress: to the compressive force app
- Unstable, tion likely not possible
- Force measurement: The opening force applied on the DCB can only be determined indirectly.

USETT: Unstable Single Edge Tensile Test

Remote stress	T-stress	Full thickness	Unstable/ High-rate crack propagation	Force measurement	CTOA measurement
✗	✓	✓	✓	✓	✓





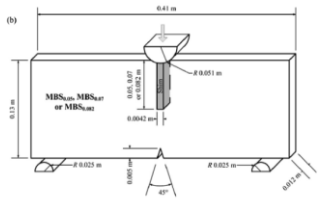
[Corre, 2020]

- Remote stress: Values of remote stress expected to be higher than the yield stress.
- Unstable/High-rate crack propagation: Unstable crack propagation likely not possible due to the large plastic domain of the linepipe steels. High rate crack propagation should be possible.

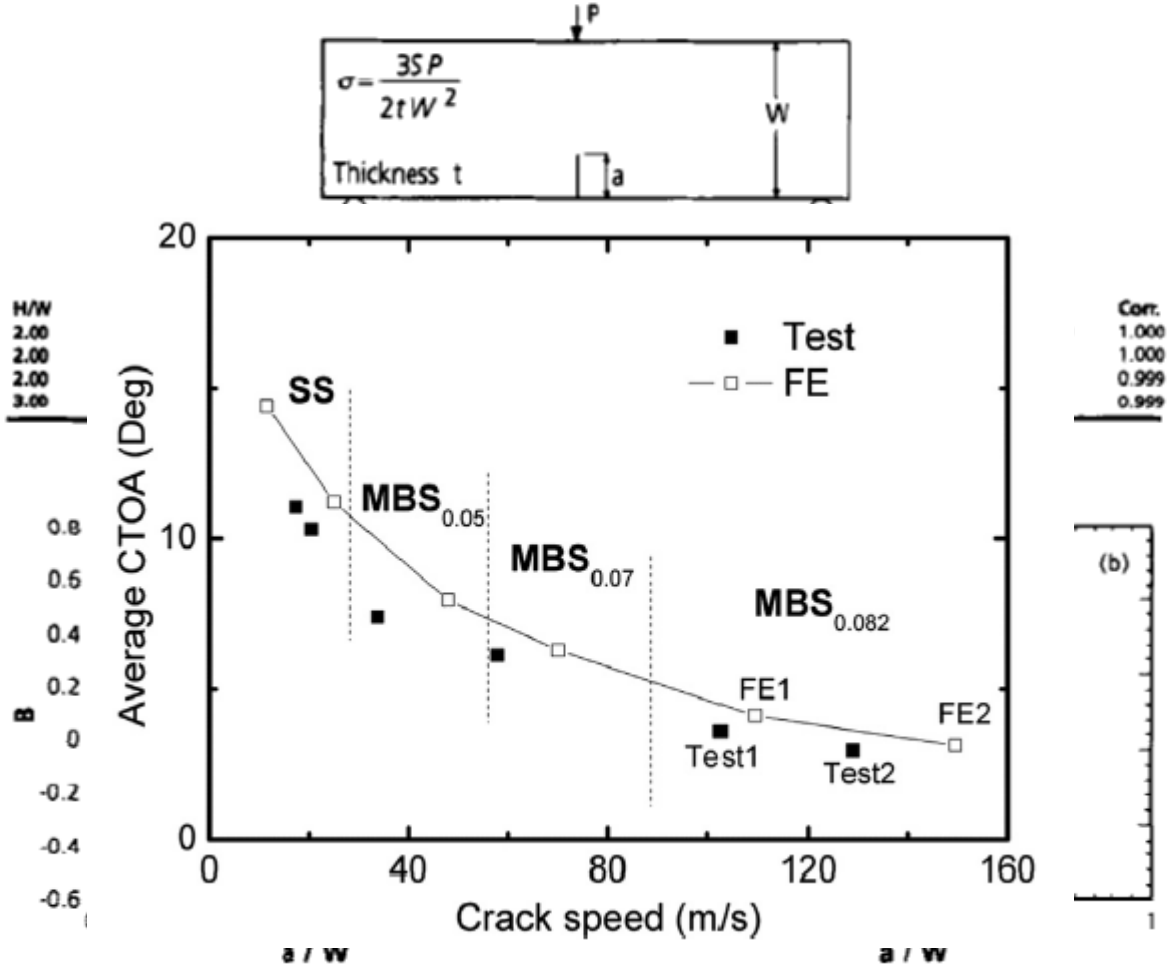
DWTT/BS-DWTT: Drop Weight Tear Test/Back-Slot Drop Weight Teat

Remote stress		TOA measurement
✓		✓

- T-S needs to be

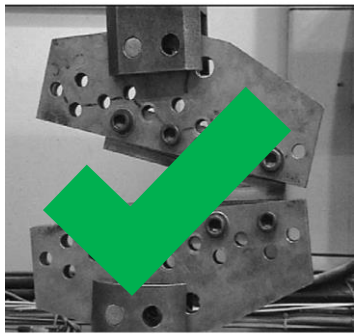
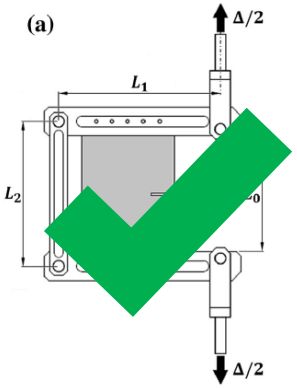
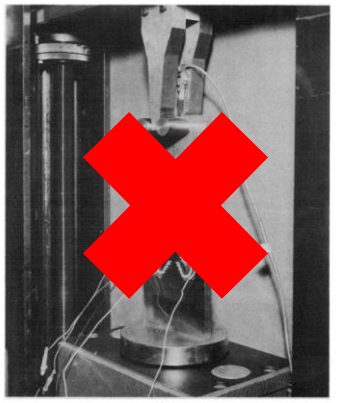
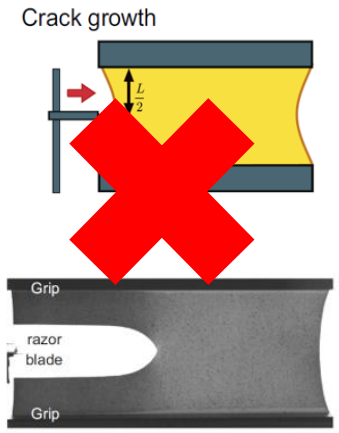
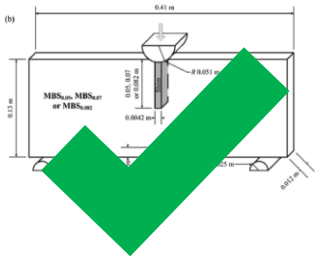


[Yu, 2015]



[Shen, 2015]

Evaluation of the reference test methods

MDCB / MCT	IPS	CCS	WLDCB	USETT	BS-DWTT
					
Modified Double Cantilever Beam / Modified Compact Tension	In-Plane Stretching	Center Crack Specimen	Wedge Loaded Double Cantilever Beam	Unstable Single Edge Tensile Test	Back-Slot Drop Weight Tear Test
[Shterenlikht, 2004]	[Nielsen, 2017]	[Simonsen, 2004]	[Hahn, 1974]	[Corre, 2020]	[Yu, 2015]

Suggested strategy for the future investigations

A two step strategy is suggested :

- Ensure the transferability of the measured values of CTOA between different specimen geometries and thus between lab and full-scale using the T-stress as criterion.
  - For example: 3 tests : 2 different tests designed with equivalent values of T-stress and one designed to exhibit a different T-stress.
  - It should be possible to quantify, using DIC, the real stress or strain state close to the crack tip in the plastically deformed specimen.

- Evaluate the sensitivity of the CTOA to the loading rate and set basis for an industrial process based on a T-stress optimized BS-DWTT.

Conclusion and perspectives

- The loss of validity of the BTCM for high toughness steels is due to the measurement of an inappropriate value of the fracture resistance in the CVN test

- Necessity to quantify precisely the biaxial stress state at the crack tip
  - The “T-stress” has been proposed as a criterion to compare the stress states at the crack tip induced by different reference methods

- The CTOA has been identified as an convenient quantity to measure the fracture resistance
  - The sensitivity of the CTOA to the loading conditions has been evaluated and needs to be further investigated

Conclusion and perspectives

- The 6 reference test methods have been evaluated using non-subjective criteria
  - The MDCB/MCT, IPS and BS-DWTT/DWTT have been selected for further investigations

- A strategy has been proposed to enable determining the most appropriate method to measure a relevant value of fracture resistance for high toughness steels

- Investigations should be conducted to determine how the measured CTOA should be used in the design of the pipelines

Thank you for your attention.