EXPERIMENTAL REFERENCE DATABASE OF MECHANICAL DAMAGE DEFECTS FOR DEVELOPING AND VALIDATING DEFECT ASSESSMENT MODELS

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PRCI Projects on Mechanical Damage Assessment - MD-4

- **Two projects are presented here:**
- **MD-4-1:** ***Full-Scale Experimental Validation of Mechanical Damage Assessment Models*****– Dent &Gouge defects: GDF SUEZ R&I Division**
- **MD-4-4:** ***Improved Model for Predicting the Time/Cycle Dependent Behavior of Dent+Gouge Damage*****: Battelle Columbus**

- **Other projects too, not developed here:**
- **MD-4-2:** ***Full-Scale Demonstration of the Interaction of Dents with Localized Corrosion and Welds:*** **BMT Fleet**
- **MD-4-3:** ***Improved Model for Predicting the Burst Pressure of Dent + Gouge Damage:*** **Kiefner & AFAA**
- **MD-4-5 to MD-4-10: Strain in dents, Defects for inspection, etc.**

MD-4-1: Full Scale Experimental Database for MD – Dent+Gouge

- **Objective: Provide *detailed* Experimental Database on *realistic* Mechanical Damage "dent + gouge" defects**

- ***Detailed* Experimental Database means:**
  - **Material characterisation is very complete**
  - **Replicate tests are performed to characterise the damage, burst test it, and fatigue test it**
  - **A very detailed set of instrumentation was defined in interaction with the modelling teams for both burst and fatigue tests**
  - **Detailed post-failure investigations are performed on both burst tested and fatigue tested samples**

- ***Realistic* Mechanical Damage means:**
  - **Dent and gouge created simultaneously by excavator tooth impact**
  - **Pipe is pressurised, representative of in-service damage**

MD-4-1: Full Scale Experimental Database for MD – Dent+Gouge

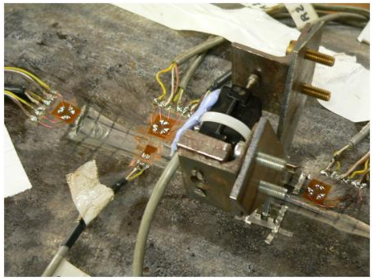
- Instrumented Defect Creation under pressure / Detailed Characterization

Dynamic, sharp tooth

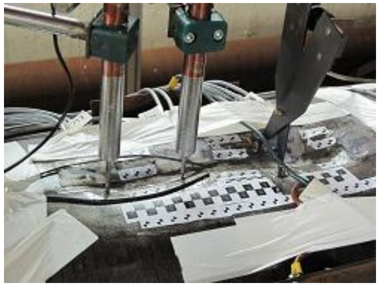
Deep gouge (single)

Slower, worn tooth

- Instrumented Burst test (monotonic load)

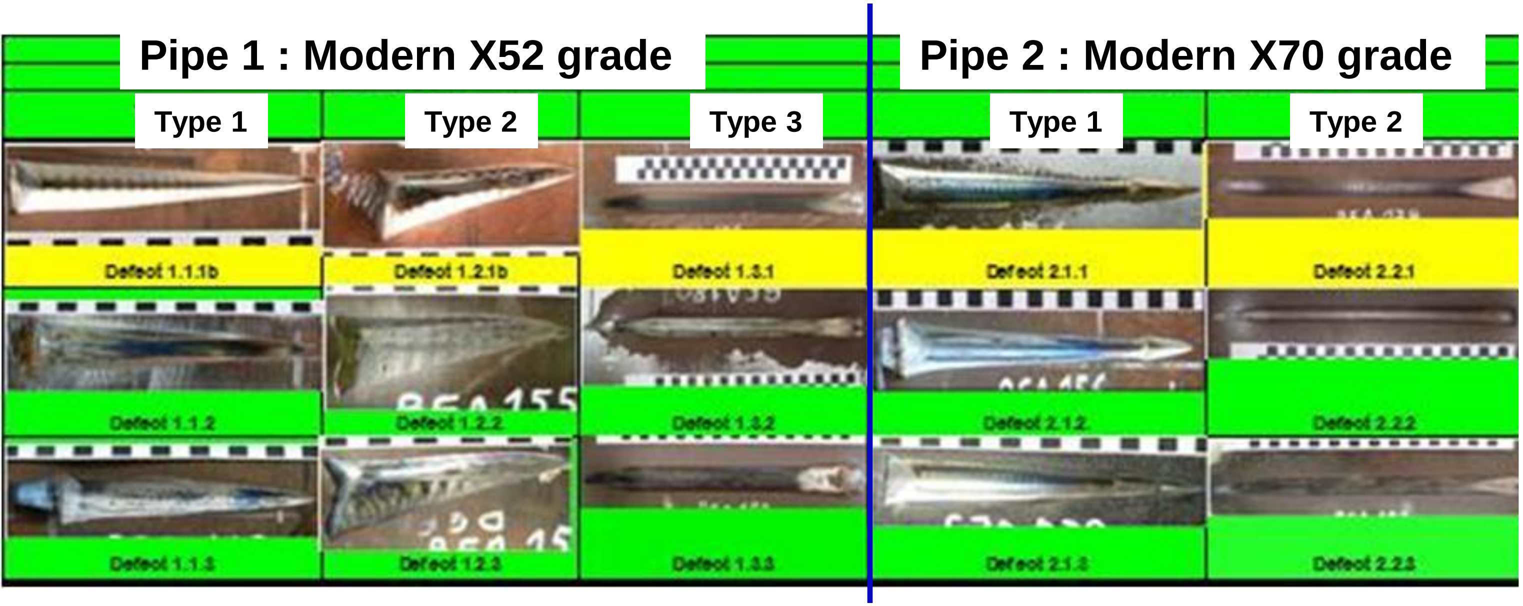


- Instrumented Fatigue test (cyclic load)



MD4-1: Dent+Gouge on Modern Pipe

- **Project overview – Test matrix for modern pipes (1/2)**



Full defect characterisation

Burst test

Fatigue test

DOT # 339 + MD-4-6 : Dent + Gouge on Vintage pipe

- **Project overview – Test matrix for vintage pipes (2/2)**

DOT # 339		MD 4-6		
Pipe 4 (older steel)		**Pipe 3** (older steel)		
Type 1	Type 2	Type 1	Type 2	
Defect 4.1.1	*Defect 4.2.1*	*Defect 3.1.1*	*Defect 3.2.1*	***Full defect characterization***
Defect 4.1.2	*Defect 4.2.2*	*Defect 3.1.2*	*Defect 3.2.2*	***Burst test***
Defect 4.1.3	*Defect 4.2.3*	*Defect 3.1.3*	*Defect 3.2.3*	***Fatigue test***

- **Pipes just selected, work will start before year's end**

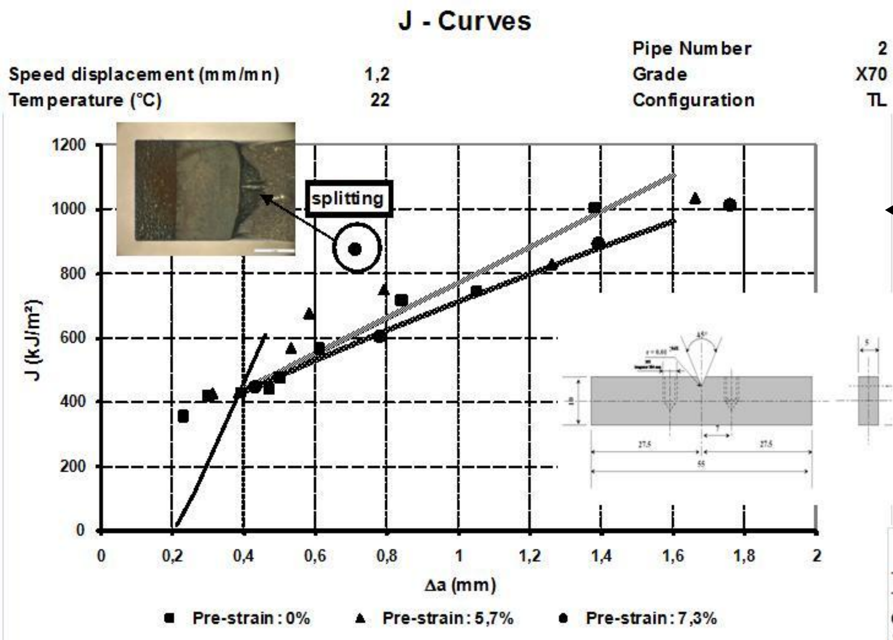
MD-4-1: Material Characterisation
Modern X52 and X70 grades

- **Chemical composition :** low carbon < 0.05%, clean (%S < 0.005, P%<0.010)
- **Tensile properties :** Isotropic - YS longi/YS transverse > 95%, UTS longi/UTS transv >98%, almost X65 for specified X52 and almost X80 for specified X70
- **Toughness :** Very high : Charpy > 150J/cm² or 137 ft.lb at 20°C, high Energy J-Curves
- **Pre-strain effect on toughness** : No significant effect for strain range [0%, 8%]
- **Cyclic behaviour** : slight softening with cyclic load

Conclusion: Excellent Modern Steels

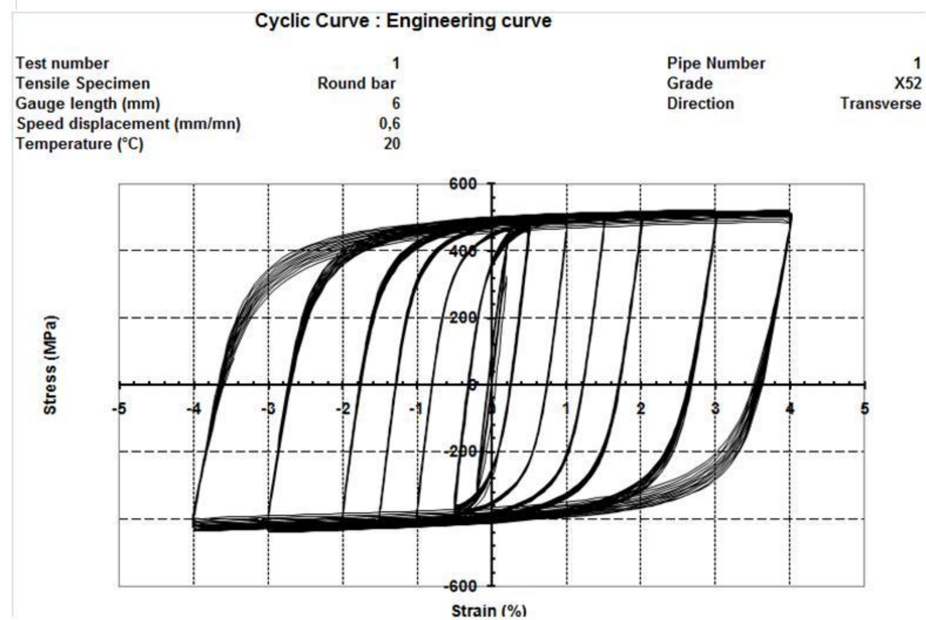
Isotropic, High Strength, High Toughness, Very ductile

Material Characterisation examples



Pre-strain effect on J-Curve – Pipe 2

Cyclic Behaviour – Pipe 1



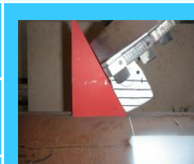
Defect Creation - Data gathered

- **Data on agression :**
  - **Tooth Geometry, tooth trajectory incidence angle**
  - **Time histories of Forces, Energy, Displacements**
  - **Internal strain gauges (optional) vs. time**

- **Defect characterization :**
  - **Defect Size (length, dent depth, gouge depth) by laser mapping**
  - **Magnetic Particle Inspection results (crack detection at gouge surface)**

- **Only for defect X.Y.1 dedicated to destructive characterization:**
  - **Residual stress determination**
  - **Destructive metallurgical investigation :**
    - **Microstructure under defect**
    - **Micro-cracks: presence and size distributions**
    - **Rough experimental estimate of plastic strain**

Defect Creation - Global Results

Defect	Tooth	Aggression	Energy (J)	Pressure (bar)	Dent depth (%)	Gouge depth (%)	Gouge length (mm)
1.1.1b	 Cal44	D	3424	85	1.1	26.5	135
1.1.2			4713	85	1.6	6.3	150
1.1.3			-	85	1.3	11.3	135
1.2.1b	 Esco	D	5816	85	2.6	43.0	110
1.2.2			7676	85	2.6	34.2	115
1.2.3			6145	85	2.5	46.8	105
1.3.1	 C481	SD	34930	30	5.3	27.8	331
1.3.2			28312	30	5.9	29.1	375
1.3.3			23973	30	6.1	20.2	321
2.1.1	 Cal44m	D	7331	85	1.5	22.2	175
2.1.2			5912	85	1.6	18.9	200
2.1.3			4907	85	1.5	20.0	165
2.2.1	 C481	SD	33974	20	4.7	20.0	331
2.2.2			26726	20	5.2	16.7	353
2.2.3			28412	20	5.3	21.1	319

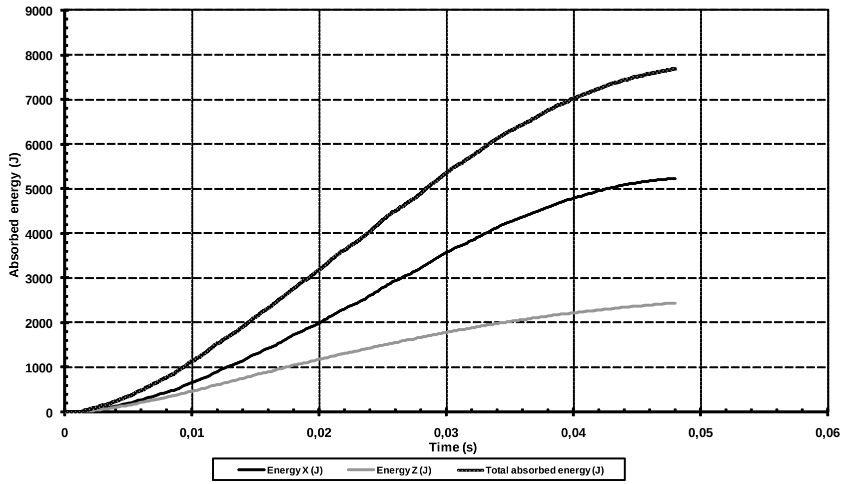
Defect Creation Examples of Detailed Results

DEFECT 1.2.2

X energy, Z energy and total absorbed energy versus time

Actual load factor : 0,73
Internal pressure (bar) : 85
Total absorbed Energy (J) : 7676
Tooth type : ESCO

Diameter (mm) : 609,6
Thickness (mm) : 7.9
Grade : X52
Pipe number : 1



Energies absorbed vs time – 1.2.2

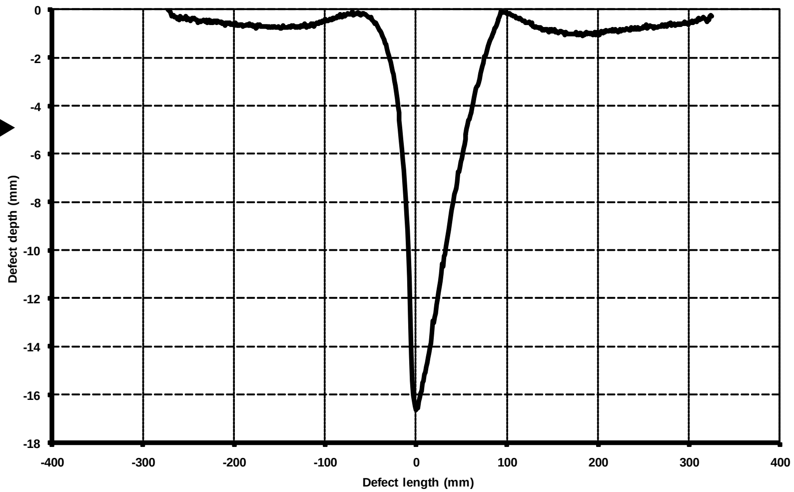
DEFECT 1.2.2

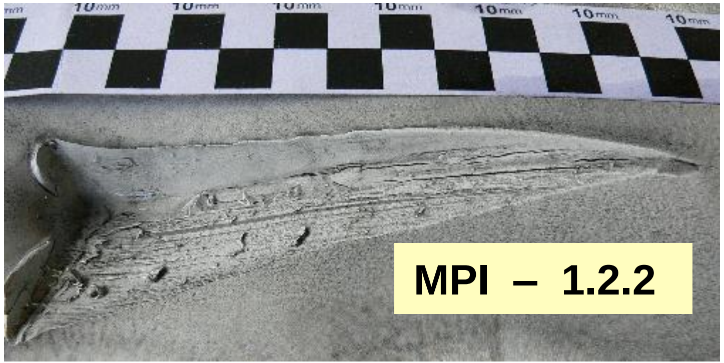
2D longitudinal profile passing by the deepest point of defect (pressure = 0 bar)

Actual load factor : 0.73
Internal pressure during defect creation (bar) : 85
Tooth Type : ESCO

Pipe N° : 1
Diameter (mm) : 609,6
Thickness (mm) : 7.9
Grade : X52

Longitudinal Profile passing by the deepest point – 1.2.2





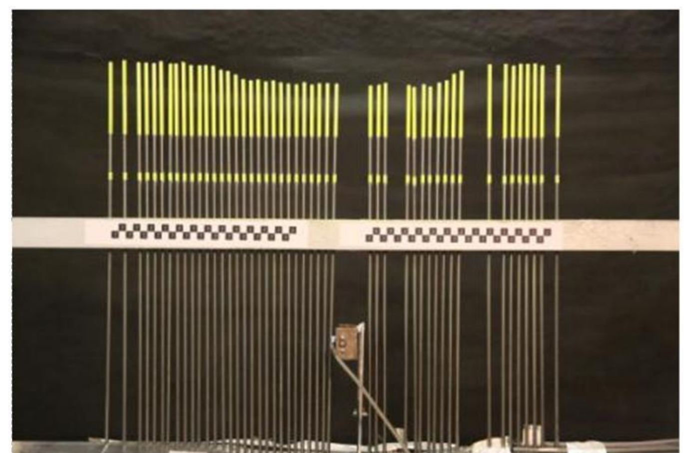
MPI – 1.2.2

Burst test – Instrumentation

- **Strains:**
  - **3 or 4 strain gauge rosettes at different locations along gouge edges**
  - **1 circumferential strain gauge at the gouge bottom**
  - **Longitudinal and circumferential internal strain gauges under the defect (optional)**
  - **Reference Strain gauges on pipe wall away from defect.**

- **Displacements:**
  - **Opening Clip gauge over the gouge**
  - **Dent dynamic profiler with multiple rods to record evolution of longitudinal defect profile during pressure increase (optional)**
  - **Camera (optional)**

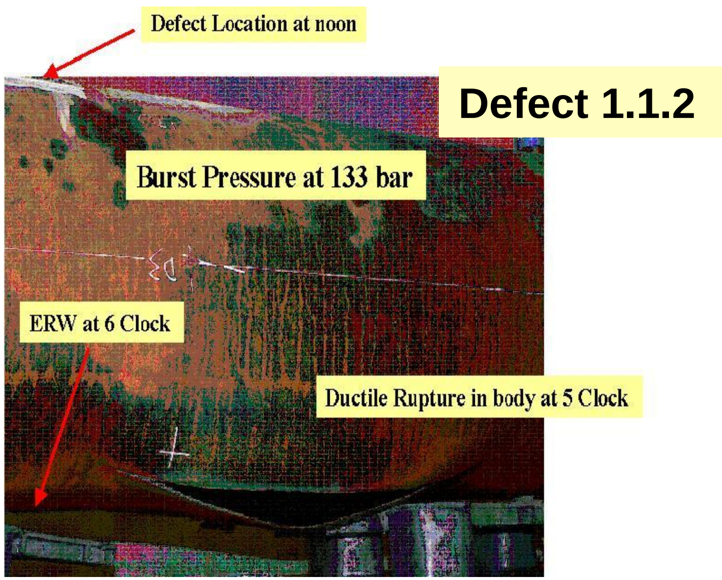
Defect 2.1.2 – Opening clip gauge

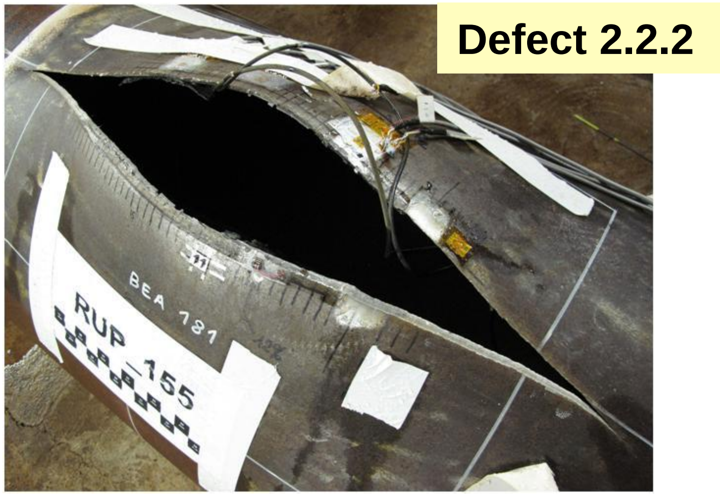


1 **Defect 2.2.2 – Dent dynamic profiler**

Burst tests – Summary of Results

Defect	Failure Pressure (bar)	Theoretical failure pressure of pipe body (Barlow formula)	Comments
1.1.2	133.3	132.7 – 146.0 **(UTS=512 MPa-563.2MPa)**	Failure outside of defect in pipe body (not in seamweld ERW)
1.2.2	110.3	132.7-146.0	Ductile Failure in defect
1.3.2	130.9	132.7-146.0	Ductile Failure in defect
2.1.2	185.1	185.4 – 204.0 **(UTS=628 MPa-691 MPa)**	Ductile Failure in defect
2.2.2	193.5	185.4 - 204.0	Ductile Failure in defect



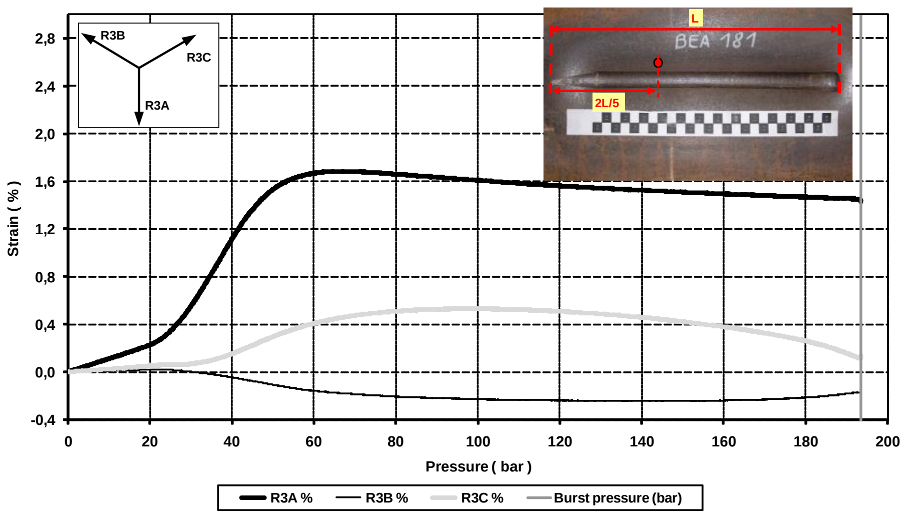


Burst tests: Examples of Detailed Results

Internal Pressure during defect creation (bar):	20	Pipe	2
Burst Pressure (bar):	193,5	Diameter (mm)	609,6
		Thickness (mm)	9
		Grade	X70

Defect 2.2.2

Evolution of strain gauges from rosette R3 versus pressure

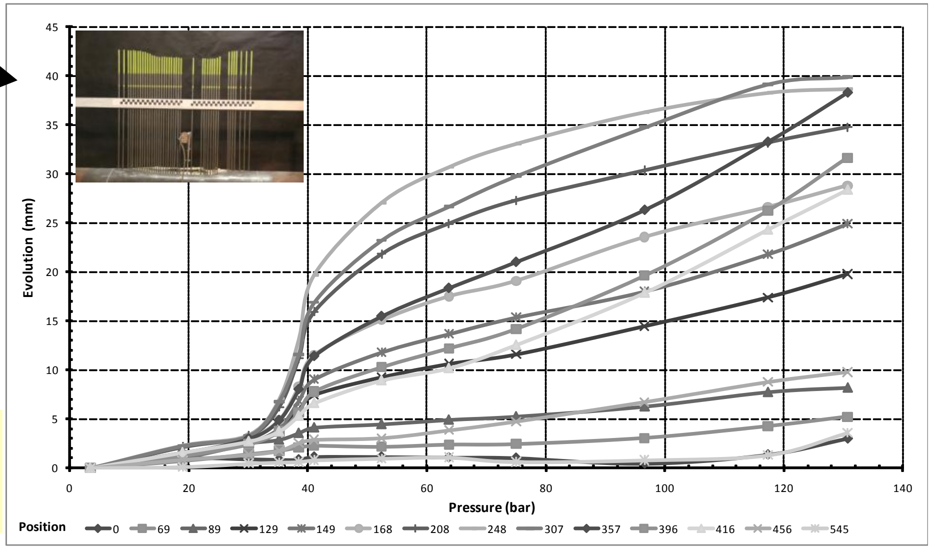


Strains from rosette vs pressure – 2.2.2, + principal strains & principal directions angles vs. pressure

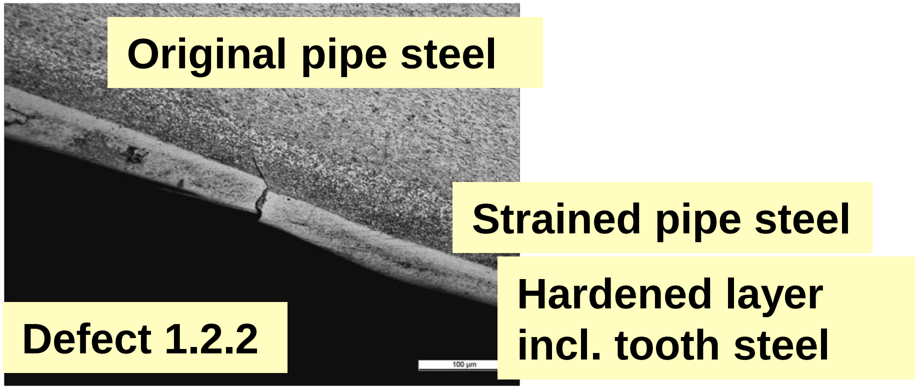
Internal Pressure during defect creation (bar):	30	Pipe	1
Burst Pressure (bar):	130,9	Diameter (mm)	609,6
		Thickness (mm)	7,9
		Grade	X52

Defect 1.3.2

Defect profile evolution versus pressure



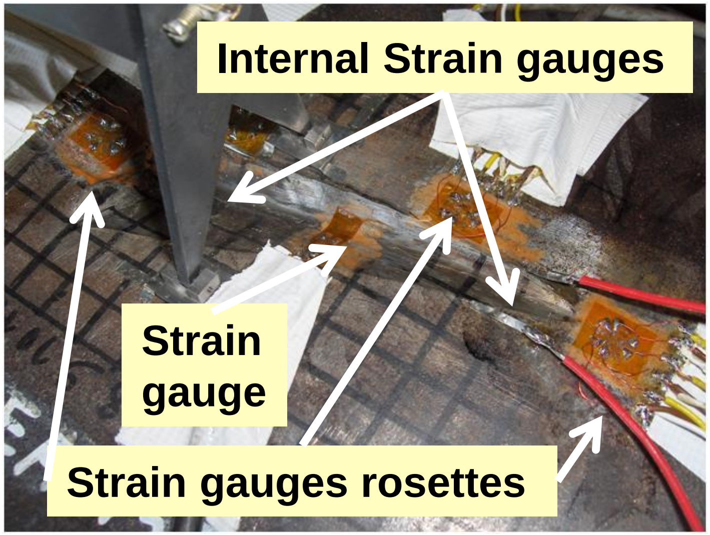
Profile evolution vs pressure – 1.3.2 Clear Bulging Effect for Deep Dents

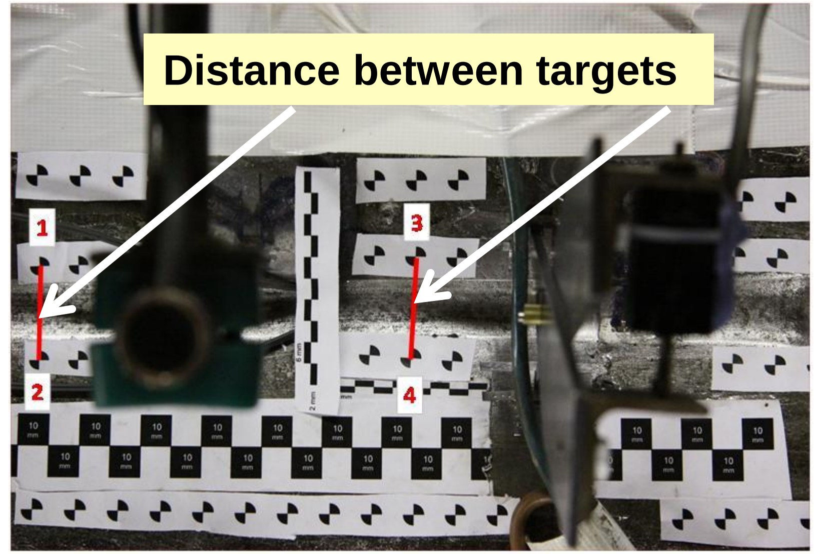


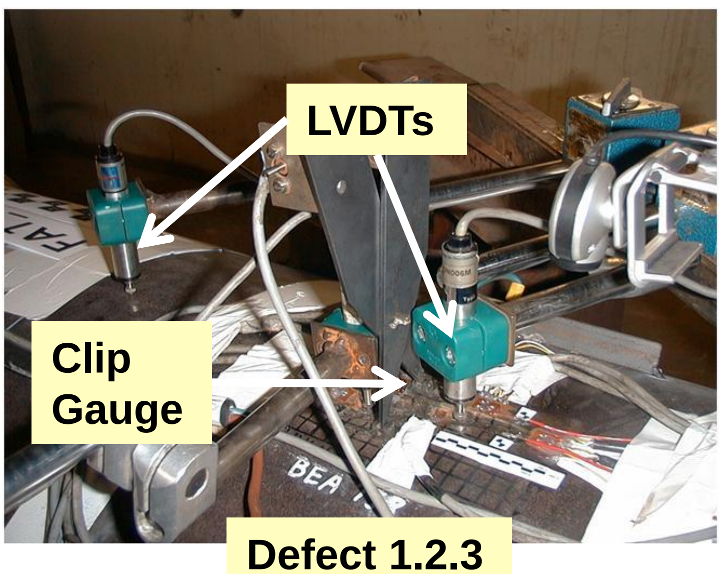
Fatigue tests - Instrumentation

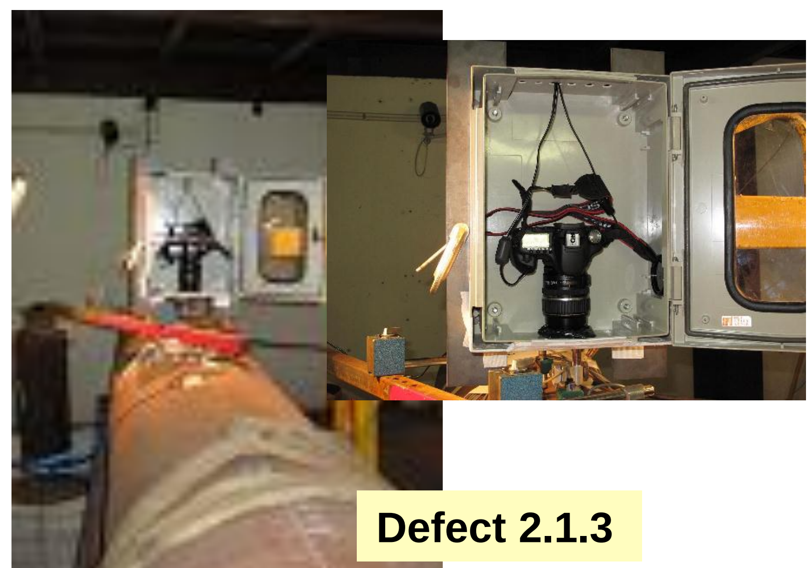
- **Strains :**
  - 3 or 4 rosettes at different locations along gouge edges
  - 1 circumferential strain gauge at the gouge bottom
  - Longitudinal and circumferential internal strain gauges under the defect (optional);
  - Reference Strain gauges on pipe wall away from defect
- **Displacements :**
  - Opening Clip gauge over the gouge
  - Targets on each side of gouge with camera (optional)
  - 1 LVDT in defect
  - 1 LVDT on pipe body for reference
- **Detection of crack-initiation, crack propagation and leak :**
  - Potential Drop
  - Targets on each side of gouge with camera (optional)

Fatigue tests - Instrumentation



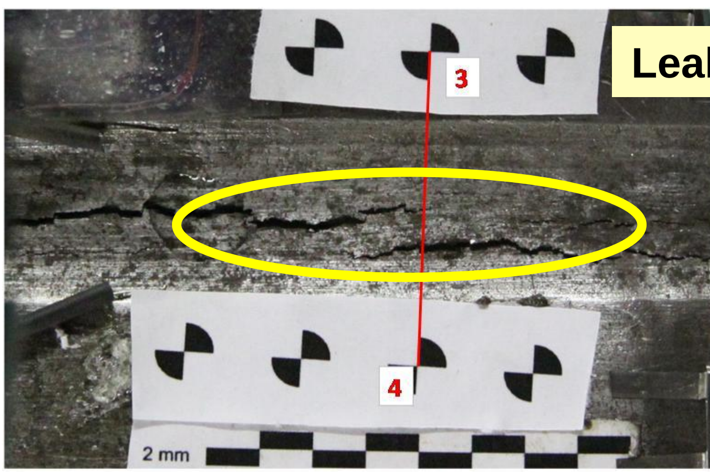






Fatigue tests – Summary of Results

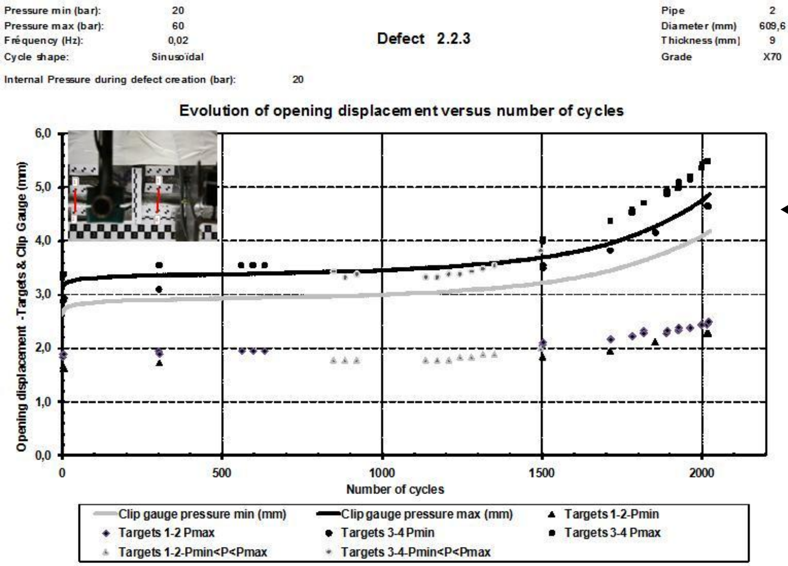
Defect	Pmin - Pmax (bar)	Number of cycles to failure	Comments
1.1.3	45 bar – 85 bar	10869	Several interruptions of fatigue test
1.2.3	45 bar – 85 bar **(0.38 – 0.73 YS)**	5200	
1.3.3	53 bar – 93 bar **(0.46 – 0.80 YS)**	20494	Cycling loading **above** the pressure range of bulging
2.1.3	88 bar – 128 bar **(0.55 – 0.80 YS)**	17700	Pressure max at 0.80 of current YS
2.2.3	20 bar – 60 bar **(0.12 – 0.37 YS)**	2007	Cycling loading **in** the pressure range of bulging



Leak – 2.2.3

Crack-initiation – 2.2.3

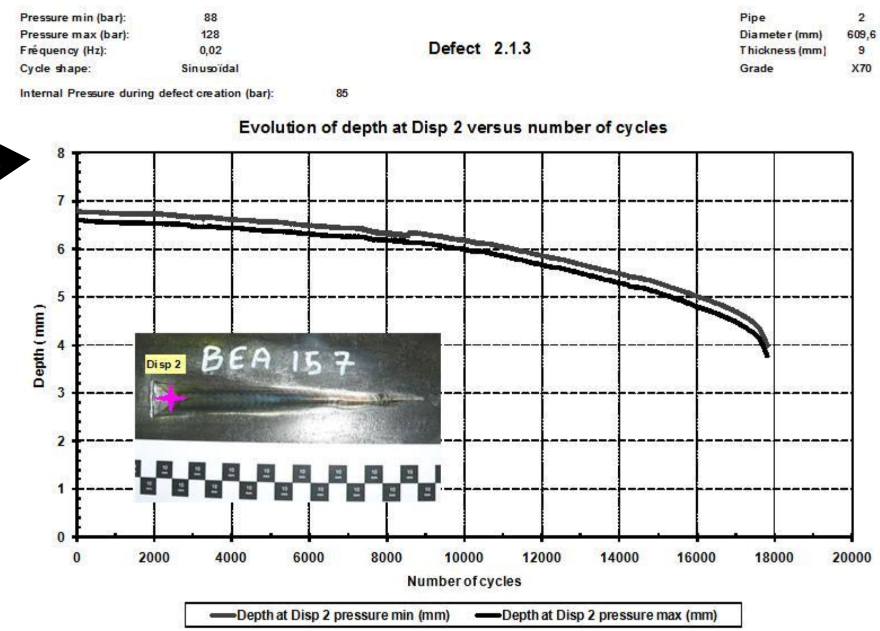
Fatigue tests – Examples of Detailed Results



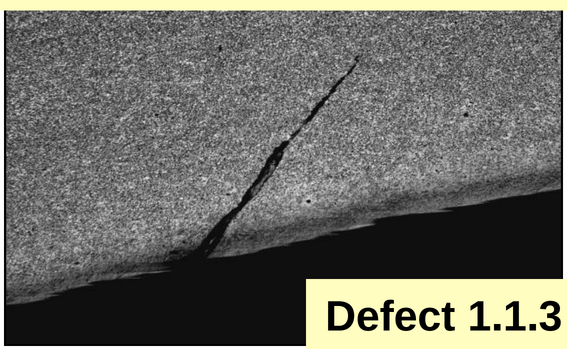
Distances between targets and clip gauge opening vs number of cycles – 2.2.3

Gouge Opening vs Nb of cycles

Defect depth vs number of cycles – 2.1.3



Post Failure Investigation



Defect 1.1.3

Dent Rerounding vs Nb of cycles

Fatigue modelling - 1st Approach

- **Four key parameters control predicted life:**
  - **Local stress range sensed by the crack tip**
  - **Threshold for growth**
  - **Initial and final crack sizes**

$$N = \int_{a_i}^{a_f} f(\Delta K)\, da$$

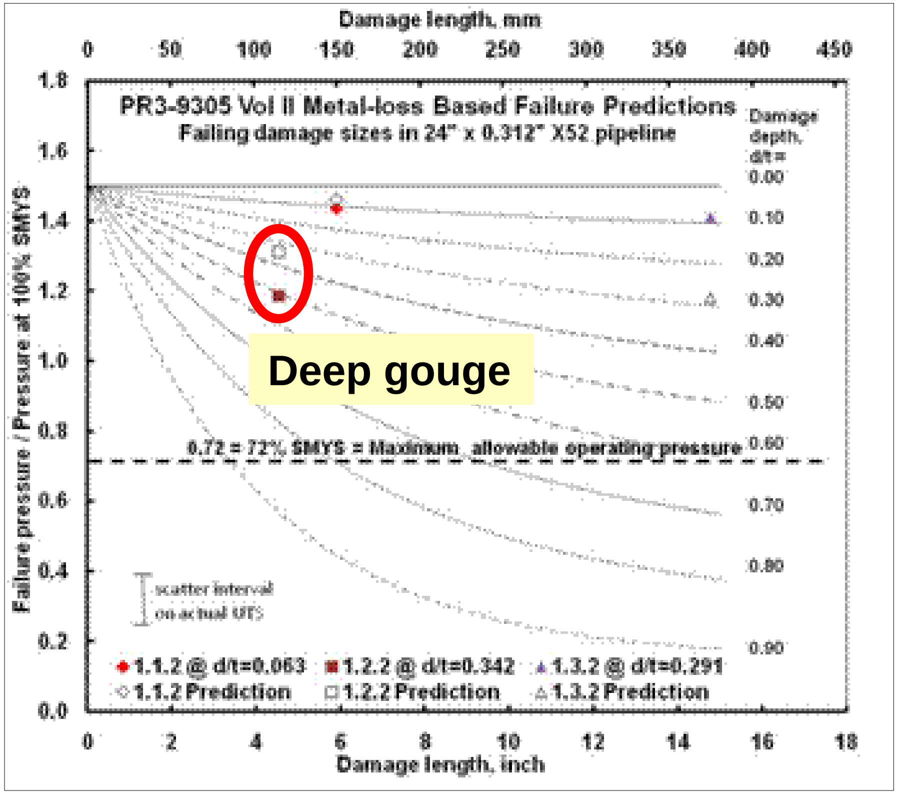
- **Initial crack size is of paramount importance, - relatively uncharacterized as yet for Mechanical Damage**

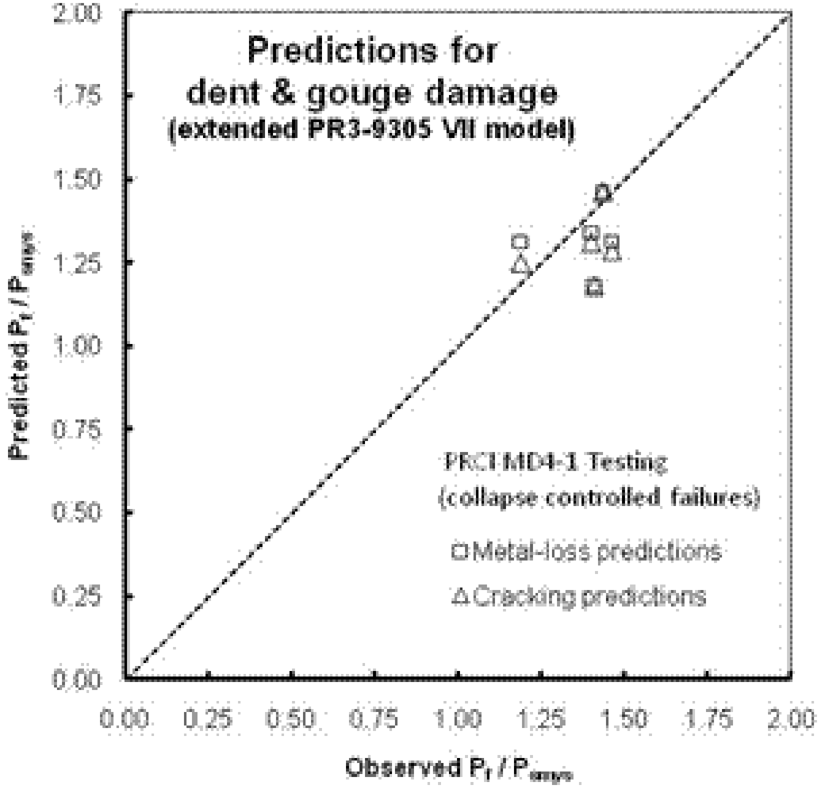
- **Before performing Nonlinear Analysis, influence of D, D/t and properties on Final Crack Size can be assessed by using existing information as a 1st approach – trending based on PRCI project PR3-9305**

Fatigue modelling - 1st Approach

- **Burst test prediction for Pipe 1 - X52 using PR3-9305:**
  - **Failure pressure normalised by pressure at 100% SMYS vs. Defect length**
  - **Damage depth / wall thickness as a parameter**

- **Good predictions for Final Crack Depth, nonlinear analysis needed before general application – here all failed by Plastic Collapse**





Fatigue modelling - 1st Approach

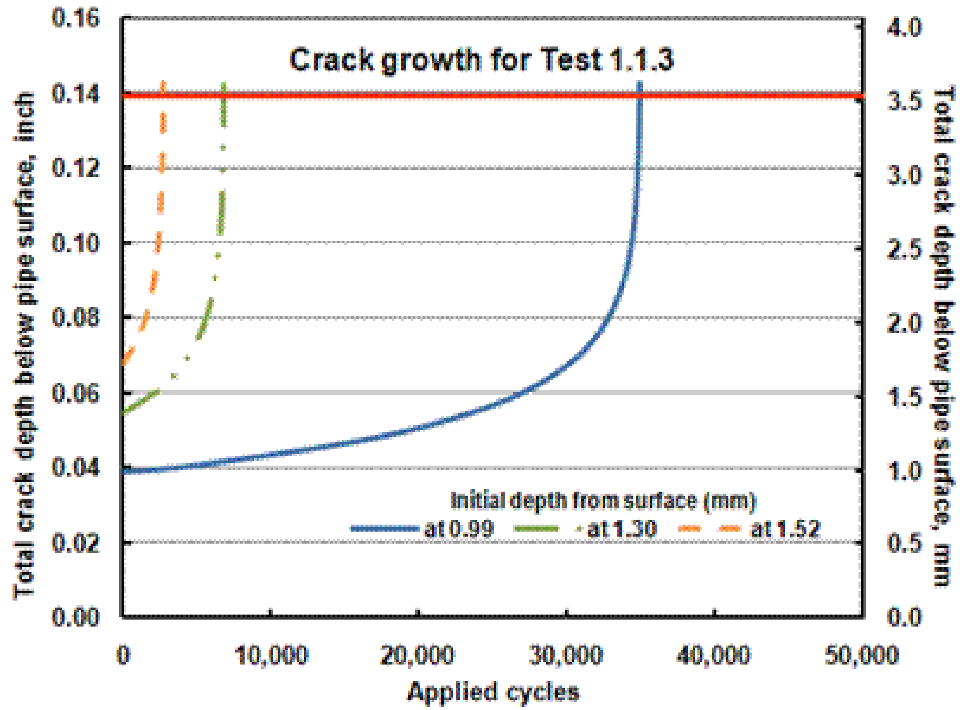
- **Predicted Fatigue life:**
  - **Total Defect depth = µcrack + gouge has to be accounted for**
  - **Cracking upon rerounding is a key factor – depends on material toughness and crack driving force**
  - **Initial crack sizes in MD-4-1 range from 6% to 36% of wall thickness**
- **Sensitivity study showed Initial crack size its the leading parameter**
- **Nonlinear rerounding & material behaviour analysis will refine model**

Example predictions D 1.1.3:

50% increase of defect depth

13 times decrease in cycles nb

Characterising defect depth in real life is critical



Conclusions - Experiments

- **New realistic and very detailed – modelling driven – experimental database on Mechanical Damage Dent & Gouge defects:**
  - **Significant experimental advances were achieved: internal strain gauges, tracking of rerounding during burst (detailed) and fatigue tests (local), defect opening history tracked, etc.**
  - **Two extreme defect families investigated more deeply – shallow dent and moderate gouge / deep dent and moderate gouge**
  - **Highly dynamic impact with sharp tooth generates a very hard superficial layer with µcracks 0.1 to 0.2 mm deep, not the case for slower aggressions with worn tooth**
  - **First stage on Modern tough steels – burst failure by plastic collapse, moderate damage – no significant decrease in burst pressure**
  - **For deeper dents, influence of the pressure cycling range w/r to the bulging pressure was established – cycling just above defect creation pressure minimises fatigue life**

Conclusions - Modelling

- **First approach to modelling fatigue life explored:**
  - **Burst strength evaluation based on existing technology is promising**
  - **Fatigue strength evaluation & sensitivity study showed importance of knowing initial defect depth**
  - **Non linear effects of rerounding effects, of nonlinear material not explicitly accounted for**

Conclusions – Further work

- **Experimental work :**
- **Will go on with tests on vintage pipes**
- **Non-destructive evaluation of residual stresses by neutron diffraction will be finalised – a strong contribution to be accounted for in models**

- **Modelling work:**
- **Non-linear analysis will be performed to fill the gaps:**
- **Influence of rerounding, changes in material properties, etc.**

- **Outcome for industry: better founded & more accurate models for mechanical strength of Dent and Gouge defects**

We're Done!

- **Thank you for your attention**

- **Any questions?**