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ATLAS+ Round Robin Studies

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ABSTRACT

The Horizon 2020 ATLAS+ project "Advanced Structural Integrity Assessment Tools for Safe Long-Term Operation" (ATLAS+) commenced in 2017 and finished in November 2021. Representatives from around 20 European organisations were involved with the project and there were strong links to researchers in the USA and Japan. ATLAS+ aimed to quantify inherent safety margins introduced by the conservative approaches used during design and dictated by codes and standards employed throughout the life of the plant. The outcomes from ATLAS+ provide information for which to develop more advanced, best estimate assessment methodologies to assess the integrity of piping and associated components.

One of the work packages (WP4) of ATLAS+ was devoted to determining the probability of failure in nuclear piping components. A series of round-robin studies were undertaken using various Leak-before-Break (LbB) assessment tools. These LbB tools comprised of deterministic models that varied between the different participants. This paper summarises the main findings of the deterministic round-robin studies, particularly with regard to an overview of the LbB tools, and the evaluation of "limit state" for surface defects.

INTRODUCTION

The various stages in the development of a LbB argument may be explained with the aid of the diagram shown in Figure 1. An initial part-through crack is represented by a point on the diagram. The crack may grow, for example by fatigue until it reaches some critical depth at which the remaining ligament ahead of the crack may break through the wall. The crack then continues growing in surface length until there is sufficient opening to cause a detectable leak or until the crack becomes unstable. A LbB argument is aimed at demonstrating that leakage of fluid through a crack in the wall of a pressure vessel can be detected prior to the crack attaining conditions of instability at which rapid crack extension occurs. In safety critical applications, there must also be ample margin between the detectable limit and the critical crack length.

A series of ATLAS+ round-robin studies have been undertaken to investigate the differences between the ATLAS+ LbB assessment tools, in particular, the evaluation of "limit state" (i.e. ligament instability) of surface crack-like defects. The ATLAS+ LbB assessment tools (Table 1) were based on either plastic instability or remaining ligament thickness, utilizing the various following methods:

- Fracture methodologies including elastic-plastic fracture mechanics (EPFM) methods, mainly based on the R6 method [EDF Energy 2019],
- Stress intensity factor (SIF) solutions,

- Limit load (LL) solutions,
- Failure assessment diagram (FAD).

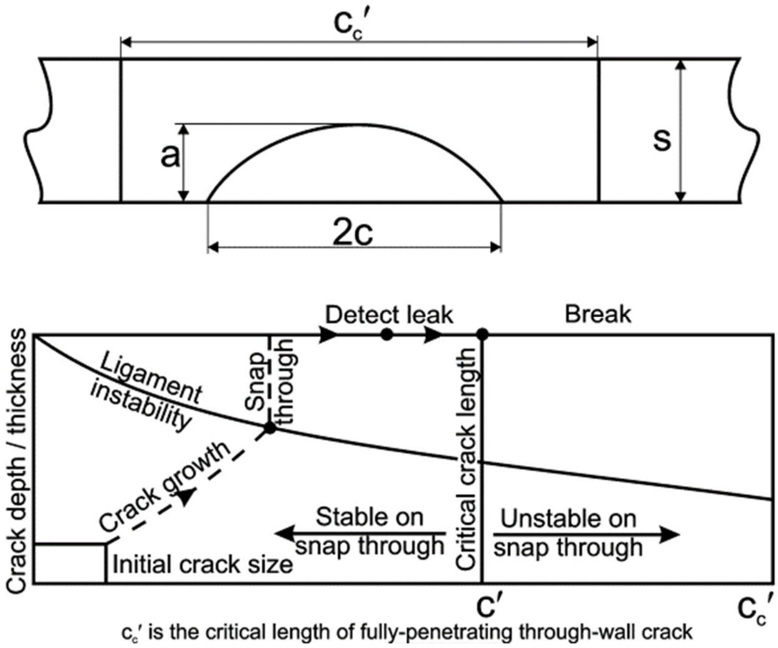

Figure 1. LbB Diagram of the various Crack Growth Stages (from R6 [EDF Energy 2019])

Overview of LbB Tools

A comparison of fracture methodology, SIF solution, Limit Load (LL) solution and failure assessment method used within the LbB assessment tools is summarized in Table 1. It is noted that the majority of the LbB assessment tools utilize the R6 Failure Assessment Diagram (FAD) procedure (i.e. 6 out of 9), and the Chapuliot SIF solutions (i.e. 4 of 9). The major difference between the LbB assessments tools are: eight LL solutions and four FAD options (i.e. none, BS7910, R6 option 1 or 2). The round-robin study results, presented in this paper, have been determined by the following organizations (with the LbB assessment tools employed in brackets):

- KIWA (NURBIT),
- JACOBS (LbB probabilistic tool),
- MHI (PREFACE),
- VTT (VTTBESIM),
- BZN (In-house tool),
- FRA-G (In-house tool),
- OCI (SIAM-OCI),
- TECNATOM (WinPRAISE),
- MPA (Xpipe).

The LbB assessment tools are:

- NURBIT: NUclear RBI analysis Tool (Version 6.0) developed by KIWA in 2020.
- PREFACE: Mitsubishi Heavy Industries (MHI) Probabilistic Fracture Mechanics (PFM) tool developed in 2016-2017.
- VTTBESIM: VTT in-house tool developed during the ATLAS+ project.
- SIAM-OCI: Structural Integrity Assessment Modular – Oakridge Consulting International part of the general computational platform for NPP primary circuit components.
- WinPRAISE: WinPRAISE 07 probabilistic treatment of: fatigue crack initiation, PWSCC, FAC, etc. developed by TECNATOM
- Xpipe: Fracture assessment software developed by MPA University of Stuttgart, additions developed during the ATLAS+ project.

Table 1: LbB Tools used in Round-Robin Studies

Participant (Tool)	FAD	SIF	LL
R6 Methodology			
KIWA (NURBIT)	R6 Option 2	Chapuliot et. al. (1998)	Delfin, P. (1998)
JACOBS (In-house)	R6 Option 1	Chapuliot et. al. (2007)	Lei, et. al. (2004)
MHI (PREFACE)	R6 Option 2	JSME S NA1 (2016)	EPRI NP-192 (1976)
BZN (In-house)	R6/SINTAP [FITNET]	R6 solutions	R6 solutions
MPA (Xpipe)	R6 Option 1	Chapuliot et. al. (1998)	SAQ/FoU Report 96/05
Other Methodologies			
FRA-G (In-house)	EPFM	Chapuliot et. al. (2015)	R6 solutions
VTT (VTTBESIM)	BS7910:2013	SSM-R-2018-18	BS7910:2013
OCI (SIAM-OCI)	ASME XI	Rahman et. al. (1998)	None
TECNATOM (WinPRAISE)	EPFM	API-579	ASME XI Appendix C

The round-robin LbB assessment tools compute both the probability of leakage and failure for the remaining service life of a piping. For an initiated through-wall crack at break-through, the following four mutually exclusive cases exist:

1) The failure time exceeds the total service life of the component. Hence, there is no contribution to the failure probability (i.e. no break, no leak).
2) The failure time is less than the total service life, but the mass leak rate at failure exceeds the detection limit. Hence, there is no contribution to the failure probability (i.e. LbB).
3) The failure time is less than the total service life, the mass leak rate at failure is less than the detection limit, but is detected by NDT. Hence, no contribution to the failure probability (i.e. NDT before break).
4) The failure time is less than the total service life, the mass leak rate at failure is less than the detection limit, and the crack is not detected by NDT. This event will contribute to the failure probability (i.eLbB).

Limit State for Snap-through of Surface Defects

“Limit State” for surface defects, particularly in the context of LbB, defines the defect depth at which a surface-breaking defect growing through the wall thickness breaks through to the wall back surface by ductile mechanisms and becomes a through-wall crack. The precise way of evaluating stable “break-through” conditions by fracture mechanics methodology is by way of undertaking an instability analysis but this is a somewhat complex analysis.

Because of the complexity of ligament instability analysis, the determination snap-through of the surface crack to through-wall crack has been based on a “Limit State” hypothesis. Any fracture analyses of the surface defect ligament is dependent on the SIF and/or plastic LL solutions, and it is noted that most such solutions have a validity limit of crack depth of 80% or 90% of the wall thickness. It is for this reason and for simplicity that some LbB practitioners evaluate the limit state based on one of these wall thickness percentages. Other practitioners may base the limit state solely on tearing initiation, which is really non-conservative and some methodologies may not use a fracture mechanics approach but be based solely on plastic collapse considerations. The various limit state approaches used by the participants were:

- Crack depth (a) is equal to or greater than a percentage of wall thickness (t):
  - JACOBS and TECNATOM used 80 % of t,
  - KIWA used 90 % of t,
  - VTT used 95 % of t.
- R6 FAD (i.e. failure assessment curve or Lr^{max} cut-off line) was used by KIWA, Jacobs, MPA, MHI and VTT.
- Plastic Collapse based on “engineering model” was used by OCI, FRAMATOME-G and TECNATOM.

ROUND ROBIN EXERCISE

The round robin exercise focussed on austenitic stainless steel piping (250 mm diameter & 25 mm thick), and the crack growth mechanism was assumed to be by stress corrosion cracking (SCC) for simplicity (SCC is much easier to compute than fatigue crack growth). The dimensions of the cylinder and initial circumferential surface breaking crack length (10 mm) and depth (1 mm) are shown in Figure 2. The axial membrane stress was taken as 150 MPa, the primary global bending stress as 30 MPa and the secondary global bending stress as 50 MPa. 60 years of operation was assumed.

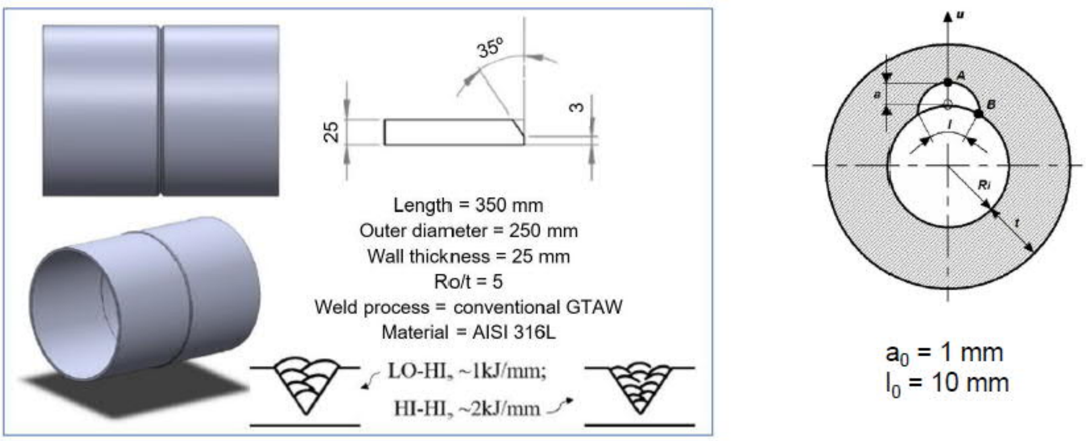

Figure 2. Weld and Pipe Geometry for PBC-6 Case

The ATLAS+ baseline material data for austenitic stainless steel at 288°C was used:

- Yield Strength = 228 MPa (Figure 3 only)
- Tensile Strength = 501 MPa (Figures 3 & 4)
- Young's Modulus = 179,273 MPa (Figures 3 & 4)
- Fracture toughness = 146 MPa√m (Figure 4 only)

One of the aspects considered in analysing the round-robin results was the influence of fracture toughness on limit state (Figure 3) and this indicated reasonable agreement, with some deviation.

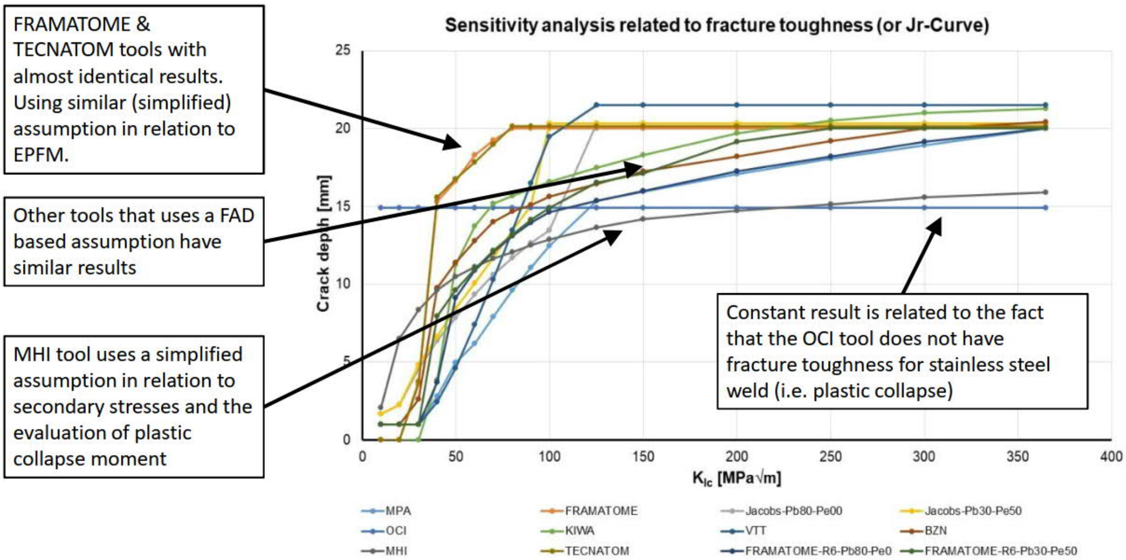

Figure 3. Influence of Fracture Toughness on Surface Defect Limit State.

As noted in Figure 3, the constant value associated with the OCI result is related to the fact that the limit state evaluation was based solely on plastic collapse. Framatome and Tecnatom LbB tools have almost identical results because they used a similar (simplified) assumption in relation to elastic-plastic fracture mechanics (EPFM). Framatome also performed additional analysis using the R6 Option 1 failure assessment diagram (R6 Option 1).

The MHI results have a different behaviour because the limit load solution is based on yield strength (i.e. the other results are based on flow stress defined as the mean value of the yield strength and ultimate tensile strength), the secondary membrane stress (P_e) is not considered in the SIF calculation, and the plastic collapse moment analysis is based on the bending stress being the dominant condition (whereas the. round-robin is associated with a large membrane stress). The fracture toughness results (Table 2) can be grouped together into three seperate types of methods used:

1) VTT, MPA, FRAMATOME (Additional) & Jacobs based on R6 Option 1;
2) MHI, KIWA & BZN based on R6 Option 2;
3) OCI, FRAMATOME & TECNATOM based solely on plastic collapse.

Table 2: Influence of Fracture Toughness on Limit State

	Crack Depth against Fracture Toughness			
	50 MPa√m	**100 MPa√m**	**150 MPa√m**	**Failure Assessment Diagram**
VTT	4.5 mm	19.4 mm	21.5 mm	BS7910:2013 (similar to R6)
MPA	4.9 mm	12.4 mm	15.9 mm	R6 Option 1
FFRAMATOME	9.1 mm	14.9 mm	17.1 mm	R6 Option 1 (Additional)
Jacobs	8.4 mm	20.3 mm	20.3 mm	R6 Option 1
MHI	10.4 mm	12.8 mm	14.1 mm	R6 Option 2
KIWA	11.2 mm	16.5 mm	18.3 mm	R6 Option 2
BZN	11.4 mm	15.6 mm	17.2 mm	R6/SINTAP [FITNET]
OCI	14.8 mm	14.8 mm	14.8 mm	None
FRAMATOME	16.6 mm	20.0 mm	20.0 mm	None
TECNATOM	16.7 mm	20.1 mm	20.1 mm	None

On the face of it, it may be somewhat surprising that the R6 based methods show significant scatter. However, as noted above, the different participants had different ways of defining "limit state". For example, in Jacobs case, "limit state" was defined either when failure was predicted by way of the FAD or when crack depth attained a value of 80% of the wall thickness, whichever occurred first.

The deterministic round-robin study also investigated the influence of yield stress (Figure 4 and Table 3) on limit state evaluation for the surface crack. Again, the results have indicated a large difference between the various assessment tools employed. As previously noted, some limit load formulations assume that the global bending stress is the dominating load parameter (whereas this is not the case in practice for the round robin case being considered). Net-section collapse solutions are based on either the yield stress or the flow stress The yield strength results can be grouped together into four groups:

1) OCI & MHI (Plastic collapse);
2) TECNATOM using ASME XI Appendix C;
3) BZN, FRAMATOME, KIWA & VTT using R6 limit load solutions;
4) MPA (SAQ/FoU Report 96/05) & Jacobs (Lei. et. al. (2004)).

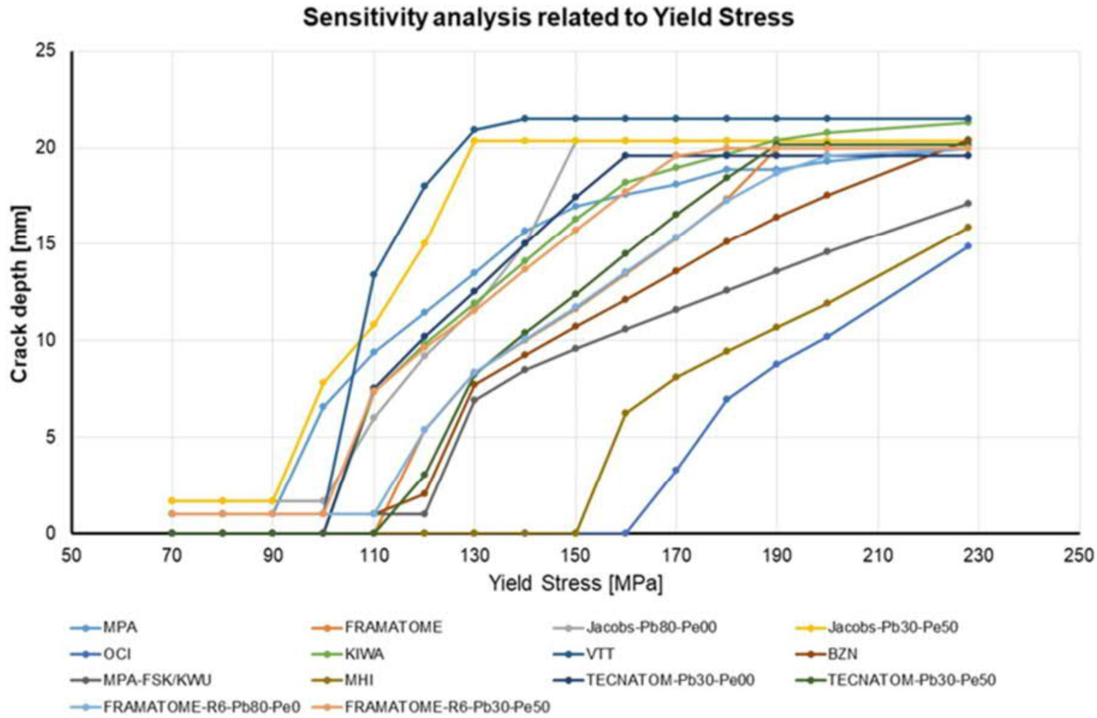

Figure 4. Influence of Yield Stress on Surface Defect Limit State.

Table 3: Influence of Yield Strength on Limit State

	Crack Depth against Yield Strength			
	100 MPa	**150 MPa**	**200 MPa**	**Limit Load Solution**
OCI	0 mm	0 mm	10.2 mm	None
MHI	0 mm	0 mm	11.9 mm	EPRI NP-192 (1976)
TECNATOM	0 mm	12.3 mm	20.1 mm	ASME XI Appendix C
KIWA	0 mm	16.3 mm	20.8 mm	Delfin. P. (1998)
BZN	1 mm	10.7 mm	17.5 mm	R6 solutions
FRAMATOME	1 mm	15.7 mm	20.0 mm	R6 solutions
VTT	1 mm	21.5 mm	21.5 mm	BS7910:2013 (similar to R6)
MPA	6.6 mm	17.0 mm	19.3 mm	SAQ/FoU Report 96/06
Jacobs	7.8 mm	20.3 mm	20.3 mm	Lei. et. al. (2004)

CONCLUSIONS

The results of the ATLAS+ round-robin have been presented and discussed in this paper in terms of the evaluation of "limit state" of surface cracks for the geometry, material and loading conditions specified. The results obtained by the various participants have indicated significant differences. However, the reasons for these differences are generally understood and are mainly a consequence of the various structural integrity methodologies, stress intensity factor and limit load solutions, and final "break-through" assumptions employed by the different participants.

The fact that there are such large variations in the results points to the fact that a world-wide unified approach to fracture mechanics methodology would be beneficial, although the significant difficulties in being able to achieve this is fully appreciated.

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NOMENCLATURE

a	Crack depth
ATLAS+	Advanced Structural Integrity Assessment Tools for Safe Long Term Operation
EPFM	Elastic-Plastic Fracture Mechanics
FAD	Failure Assessment Diagram
ID	Inside Diameter
LbB	Leak-before-Break
LL	Limit Load
SCC	Stress Corrosion Cracking
SIF	Stress Intensity Factor
t	Wall thickness
OD	Outside Diameter
NDT	Non-Destructive Testing
P_e	secondary membrane stress

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