Proceedings of the 9th International Pipeline Conference
IPC2012
September 24-28, 2012, Calgary, Alberta, Canada

DRAFT - IPC2012-90593

COMPARISON OF PIPELINE GIRTH WELD DEFECT ACCEPTANCE AT THE ONSET OF YIELDING ACCORDING TO CSA Z662 AND EPRG GUIDELINES

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ABSTRACT

Within a stress-based design context, different codified engineering critical assessment procedures are available for defect assessment. This paper aims at comparing the recently updated EPRG Tier 2 guidelines with the Canadian CSA Z662 Annex K procedure. Therefore, the requirements for both procedure are discussed and the maximum allowable defect dimensions are graphically compared. It is observed that the use of the EPRG guidelines is significantly more restricted in terms of steel grades and pipe geometry. However, within the limits of the EPRG's applicability, the CSA procedure requires significantly more material testing, while resulting in (extremely) low defect acceptance.

INTRODUCTION

Defects are unavoidable in pipeline girth welds. In order to assess the severity of girth weld defects, defect acceptance criteria have been established throughout the years.

In general defect assessment codes contain multiple levels of complexity, where a higher complexity results in higher defect acceptance. A first assessment level is typically based on workmanship criteria. These criteria require limited input parameters (e.g. only defect location) and tend to allow defects no longer than 25 mm [1, 2]. The defect height is in this case of minor importance; sizing of the height is not required. Although this method takes advantage from its simplicity, it potentially leads to overly conservative assessments. Accordingly, a second level approach consisting of an engineering critical assessment (ECA) is often advisable. This assessment method aims at allowing larger defects based on more detailed material characterization and considering the exact pipe dimensions. Within an ECA detailed defect sizing is also required, next to the defect length the defect height becomes a primary variable. Consequently, this approach clearly implies extra costs, originating from e.g. the material testing and non destructive evaluation. It is believed that this cost can be compensated for by the lower weld repair rate if larger defects become acceptable [3].

Focusing on stress based design conditions, where the applied load is expressed in terms of applied stress, several codified ECA procedures are identified. However, clear differences are noted between the procedures. Some require extensive material characterization or long calculations, whereas others rely on simple calculations and only limited material characterization. This paper aims at comparing the defect acceptance criteria described by the Canadian CSA Z662 procedure with the European EPRG guidelines at the onset of yielding (remote strain equal to 0.5%) [1, 4]. To date, it is unclear which method yields the most stringent requirements or if such methods are potentially unconservative.

First, both defect acceptance criteria are described in detail in the second paragraph. The third paragraph outlines the procedure used for comparing the maximum allowable defect dimensions. In the fourth paragraph some remarkable observations regarding the defect acceptance are outlined. Next, a comparison is made in the fifth paragraph leading to the conclusions, listed in the final paragraph.

OVERVIEW ASSESSMENT PROCEDURES

The focus of this article is on stress-based design conditions. Accordingly, the applied load is limited to the onset of plastic deformation; a remote tensile strain level of 0.5% is assumed. This paragraph provides a detailed description of the considered procedures, outlining the requirements and noticeable differences. A detailed overview of both procedures is provided in Table 1.

Table 1 – Overview specifications CSA Annex K and EPRG Tier 2 guidelines

	CSA Z662 Annex K	EPRG Tier 2
Pipe properties		
Pipe grade	unlimited	Up to API-5L X80
Y/T-ratio	unlimited	≤ 0.90
Pipe dimensions		
Diameter *D*	unlimited	*D* ≥ 30” (762 mm)
Wall thickness *t*	unlimited	7.5 ≤ *t* ≤ 25.4 mm
Failure assessment		
Plastic collapse	Yes	Yes
Fracture	Yes	No
Validation		
Full Scale Bend test	48	18
CWP test	-	485
Toughness		
CTOD testing	Yes	No
CVN testing	≥ 40J	≥ 30/40J
Weld metal		
All weld metal test	No	Yes
Cross weld test	Yes	No
Mismatch level	YS cross weld ≥ SMYS	YS all weld metal ≥ SMYS+100 MPa
Max flaw dimensions		
Height	0.50*t* for gas 0.25*t* for liquid	min(5; 0.50*t*)
Length	0.10 π D	7*t* per 300 mm
Correction factor		
Loading mode	Load x 1.5 in tensile loading	No

CSA Z662 : 2011 : Annex K

The Canadian oil and gas pipeline standard, CSA Z662, provides guidance in assessing weld defects. An overview of the workmanship criteria is given in clause 7; defect acceptance merely depends on defect type and location. In addition, an engineering critical assessment procedure is presented in Annex K. As more material characterization and calculations are required for this ECA, larger defect tolerance is expected. Therefore, the ECA procedure is considered for the comparison presented in this paper.

Focusing on the ECA procedure, the CSA procedure assumes that girth weld defects can imply failure either through brittle fracture or plastic collapse, an often reviewed approach in standards, e.g. API 1104 Appendix A [2]. Regarding the probability of brittle fracture, a graphical procedure is provided in Annex K, essentially relying on the use of the CTOD design curve [5]. This requires at least three high constraint CTOD fracture toughness tests (SENB) for every notch location, preferably taken near the 12 o’clock position. In addition, a minimum Charpy V-notch impact toughness of 40J shall be assured.

To assess the likelihood of plastic collapse, a limit load solution is provided:

$$\frac{\sigma_a}{\sigma_f} = \frac{\cos(\eta\beta\pi) - \dfrac{\eta \sin(2\beta\pi)}{2}}{1 + \left(\dfrac{4}{\pi} + 1\right)\dfrac{\eta\beta}{0.025}} \qquad \eta\beta \leq 0.025$$

$$\frac{\sigma_a}{\sigma_f} = \frac{\cos(\eta\beta\pi) - \dfrac{\eta \sin(2\beta\pi)}{2}}{\dfrac{4}{\pi}} \qquad \eta\beta > 0.025 \tag{1}$$

With:

σ_a	Applied tensile bending stress [MPa]
σ_f	Flow stress [MPa]
h	Defect height [mm]
t	Wall thickness [mm]
D	Radius of the pipe [mm]
l	Defect length [mm]
η	h/t = Relative defect height [-]
β	$l/\pi D$ = Relative defect length [-]

This limit load solution assumes a global bending load. In case of tension loading, the load is to be multiplied by 1.5, either on the level of the applied stresses or the applied strains. No theoretical or experimental evidence is provided for this statement, notwithstanding tensile loading indeed represents more severe conditions.

As already noted, this paper focuses on a global tensile load corresponding with a remote strain level of 0.5%. However, the applied load level should be multiplied by 1.5. Applying this multiplication factor to the yield stress, which in this case corresponds with the applied load, would result in unrealistically high stress levels. Accordingly, the applied strain is multiplied by 1.5. To obtain the corresponding remote stress level needed for the limit load equation, the stress-strain behavior is to be known. Annex C of the CSA Z662 recommends the use of the Ramberg-Osgood relationship. The constitutive behavior is described by:

$$\varepsilon = \frac{\sigma}{E} + \varepsilon_{py}\left(\frac{\sigma}{\sigma_0}\right)^n \tag{2}$$

With:

ε	Strain [-]
σ	Stress [MPa]
σ_0	Yield strength [MPa]
n	Strain hardening exponent [-]
ε_{py}	$= 0.005 - \frac{\sigma_0}{E}$
E	Young's Modulus [MPa]

In the above equation, the strain hardening exponent, n, can be related to the yield-to-tensile (Y/T) ratio of the material.

$$n = 3 + \frac{2.5\,Y/T}{1.03 - Y/T} \quad (3)$$

To determine the Y/T-ratio of the considered materials, the CSA procedure provides a relation between the flow and yield strength. This flow strength is defined as the average between yield and tensile strength. The described relation is graphically displayed in Figure 1. It is clear that the estimated Y/T-ratio is relatively high for grade X80 pipes; for yield strength levels over 550 MPa the predicted Y/T-ratio equals 0.943 [6].

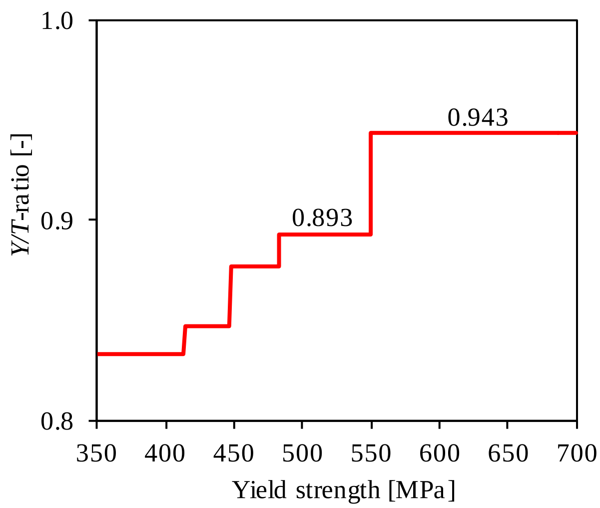

Figure 1 – Estimation of Y/T-ratio in CSA Z662

Furthermore, it should be noted that the maximum flaw dimensions highly depend on the fluid in the transportation pipelines. For gas transporting pipelines defect heights up to half wall thickness can be accepted, whereas only quarter of the wall thickness is allowed for oil transporting pipelines. This difference is attributed to the susceptibility of oil transportation pipelines to fatigue.

Finally, it is observed that the CSA assessment procedure is not restricted in terms of pipe grades or pipe geometries. However, to the authors' knowledge this procedure has only been validated for vintage pipelines with diameters ranging from 508 mm (20") to 1067 mm (42") [7, 8].

EPRG Tier 2 Guidelines

The European Pipeline Research Group (EPRG) established pipeline defect acceptance criteria. These criteria comprise different levels of complexity, whereby an increased complexity aims at allowing larger defect sizes. The first level, the so-called Tier 1 approach, is a set of workmanship criteria. These criteria are primarily based on the API 1104 and BS 4515 workmanship criteria.

Next to the workmanship criteria, the recently updated Tier 2 comprises an ECA approach, which is the subject of this paper [4]. Within this approach, plastic collapse is assumed at a remote strain level of 0.5%. To assure this limit state, the Charpy V-notch toughness is to be determined. A minimum toughness level of 30J and an average of 40J are required. No additional fracture toughness testing, e.g. CTOD testing, is required.

The above requirements mainly originate from experimental work (curved wide plate testing) performed at Ghent University. The resulting set of guidelines is shown in Table 2.

Table 2 – EPRG Tier 2 Guidelines [4]

Defect height h [mm]	$h \leq 3$	$3 < h \leq 4$	$4 < h \leq 5$
Defect length l [mm]	$l \leq 7t$	$l \leq 5t$	$l \leq 3t$

Note that these guidelines are easy in use and allow an unambiguous interpretation. Furthermore, these equations are assumed to yield conservative predictions. This firstly originates from the experimental nature of these equations; they are primarily based on curved wide plate testing. Secondly, a nice correspondence between curved wide plate test results and full scale tests is presented by the authors in an accompanying paper [9].

The major shortcoming of the Tier 2 approach is its limited area of applicability. This approach may only be applied with confidence for Y/T-ratios, pipe grades and pipe geometries within the test matrix used for the determination of the empirical equations. Accordingly, this approach is only used for pipes up to grade API-5L X80 and Y/T-ratios at maximum equal to 0.90.

Regarding the mismatch definition, it should be noted that the EPRG guidelines clearly aim at obtaining yield strength overmatched welds, accounting for the variability of the base material properties. It is widely acknowledged that defects located in such welds are shielded from the applied load. In contrast, the CSA Z662 guidelines only require the yield strength of the weld metal to meet the minimum requirements. Again considering the variability of the base metal properties, it is understood that this could result in effectively yield strength undermatched welds.

METHOD FOR COMPARISON

In accordance to the aforementioned procedures, the allowable defect length has been determined given a defect height, material properties and pipe dimensions. The considered defect lengths range from 0 to 200 mm, corresponding to frequently observed pipeline girth weld defects [10-12].

The selection of a representative test matrix is of primary importance to draw trustworthy conclusions from the comparison. A variety of pipe diameters and wall thicknesses has been selected. Next, the material's yield strength has been varied, representing steel grades up to API-5L X80 [13]. Another parameter influencing the defect allowance in case of the CSA procedure, namely the material's fracture toughness, has also been varied. This toughness is expressed in terms of critical Crack Tip Opening Displacement ($CTOD_c$). Near to brittle materials ($CTOD_c = 0.05$ mm) as well as ductile materials ($CTOD_c = 0.30$ mm) have been considered. An overview of the test matrix is given in Table 3, all possible combinations have been assessed. Note that the Charpy V-notch toughness has not been considered as a variable material parameter. It is assumed that in all cases the minimum requirements, as stated by the EPRG guidelines, are met.

The comparison between both procedures is performed in a graphical way; the maximum defect length is plotted against the maximum defect height. An example case is shown in Figure 2, the material and geometrical properties considered for this example case are indicated in bold in Table 3. Defects resulting in an assessment point below the curve (towards the origin) are accepted; these will not result in failure of the pipe. In contrast, assessment points outside the curve would result in pipe failure prior to a remote strain level of 0.5%. Note that the workmanship (WMS) criteria are also depicted in Figure 2. No restriction has been placed on the defect height in this case as workmanship criteria generally do not require sizing of the defect height. For this example case, it is obvious that the allowable defect dimensions in case of the EPRG procedure are in general significantly higher than for the CSA procedure. For extremely short ($l < 20$ mm) and extremely long ($l > 7t$) defects, the CSA procedure allows larger defect heights.

Table 3 – Test matrix for comparison of defect acceptance

CTOD$_c$ **[mm]**	***D*** **[mm (inch)]**		***t*** **[mm]**	***YS*** **[MPa (ksi)]**	
0.05	762	(30)	10	358	(52)
0.10	**1016**	**(40)**	**15**	**448**	**(65)**
0.20	1270	(50)	20	483	(70)
0.30	1524	(60)	25	552	(80)

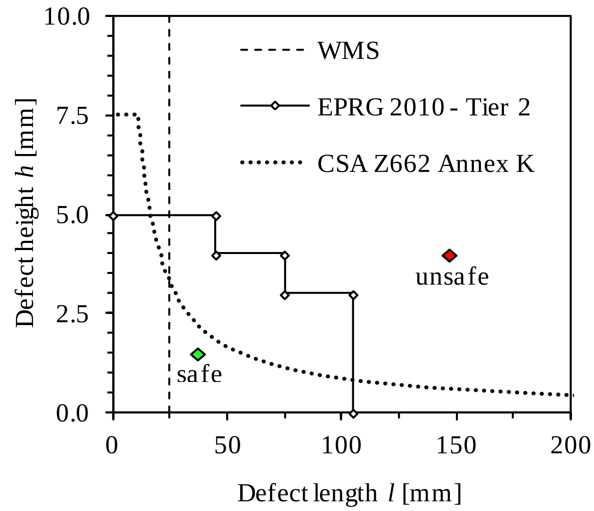

Figure 2 – Flaw acceptance in accordance with EPRG guidelines and CSA Z662 Annex K procedure (D = 762mm; t = 15mm; YS = 448 MPa; $CTOD_c$ = 0.20 mm)

INFLUENCING PARAMETERS

This paragraph focuses on observations regarding the defect allowance resulting from both procedures.

<u>CSA Z662 : 2011 : Annex K</u>

First, attention is given to the loading mode; the defect allowance for a tensile loaded pipe is compared to a pipe subjected to a global bending. Shown in Figure 3 is the prominent decrease in maximum defect dimensions when tensile load conditions are assessed. By applying a correction factor of 1.5 on the applied stresses, the allowable defect length decreases by as much as 50% for a given defect height.

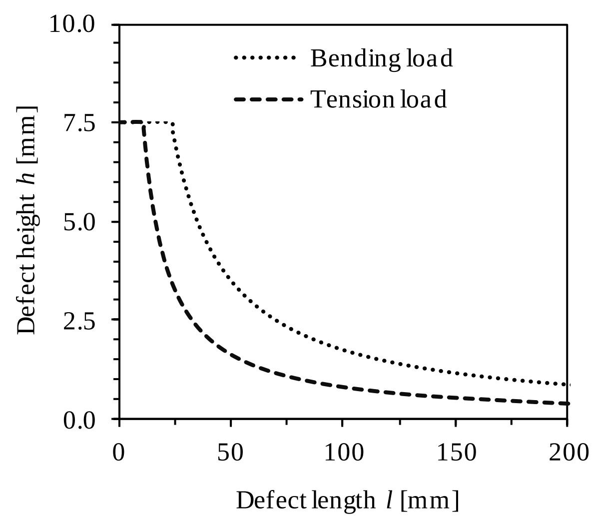

Figure 3 – Influence of loading mode on defect allowance (D = 762mm; t = 15mm; YS = 448 MPa; $CTOD_c$ = 0.20 mm)

Focusing on situations of pure tension loading, a second observation regards the strong limitation put on the defect acceptance by the plastic collapse failure mode. When the maximum allowable defect size is determined for both failure modes considered in the CSA Z662 procedure, the likelihood of brittle fracture is extremely limited. Only for very low toughness levels, brittle fracture becomes a controlling factor. Indeed, illustrated in Figure 4 are the maximum defect dimensions for different fracture toughness levels. Only for the lowest considered toughness level, $CTOD_c$ = 0.05 mm, fracture is predicted, however, only for short (l < 50 mm) defects.

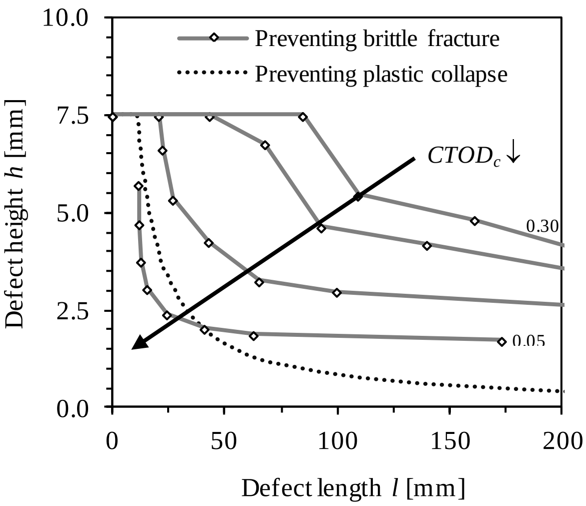

Figure 4 - Influence of fracture toughness on defect allowance (*D* = 762mm; *t* = 15mm; *YS* = 448 MPa)

Third, the strong coupling between pipe grade and *Y/T*-ratio causes a significant decrease of the defect allowance with increasing yield strength levels. This influence is illustrated in Figure 5a. When the effect of the yield strength is not coupled to the *Y/T*-ratio, the influence of the yield strength is far less pronounced. This is shown in Figure 5b. In contrast, the effect of a varying *Y/T*-ratio for a given yield strength level is significantly more pronounced, as indicated in Figure 5c. This effect is caused by the evident influence of the flow stress level on the plastic collapse limit, as is seen from *eq.1*.

EPRG Tier 2 Guidelines

Regarding the Tier 2 guidelines of the EPRG, an apparent independence of the flaw tolerance with respect to the pipe diameter is noted. In Figure 6, influence of both a varying wall thickness and pipe diameter is illustrated. Notwithstanding the maximum defect dimensions are independent of the pipe's diameter, it should be noted that the EPRG guidelines prescribe the defect tolerance within an arc length of 300 mm. Consequently, although longer defects are not accepted in higher diameter pipes, the number of allowable defects increases with pipe diameter.

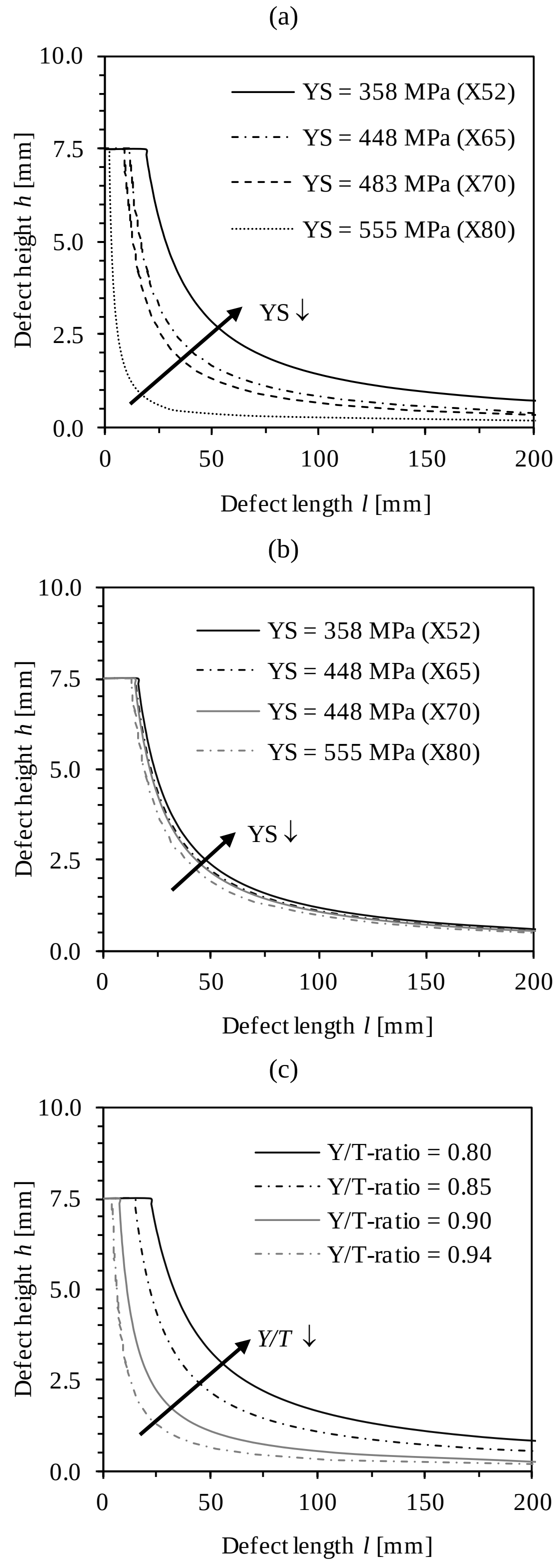

Figure 5 – Influence of yield strength on defect acceptance in accordance to CSA Z662 Annex K (a), with fixed *Y/T*-ratio but varying YS level only (b) and with fixed YS level and varying *Y/T*-ratio (c) (*D* = 762mm; *t* = 15mm; $CTOD_c$ = 0.20mm)

In contrast to the diameter of the pipe, the wall thickness does significantly influence the dimension of the maximum allowable defects; a higher wall thickness implies the allowance of longer defects.

Furthermore, it should be noted that the guidelines in Table 2 imply that defect tolerance is independent of steel grade and consequently also independent of the *Y/T*-ratio.

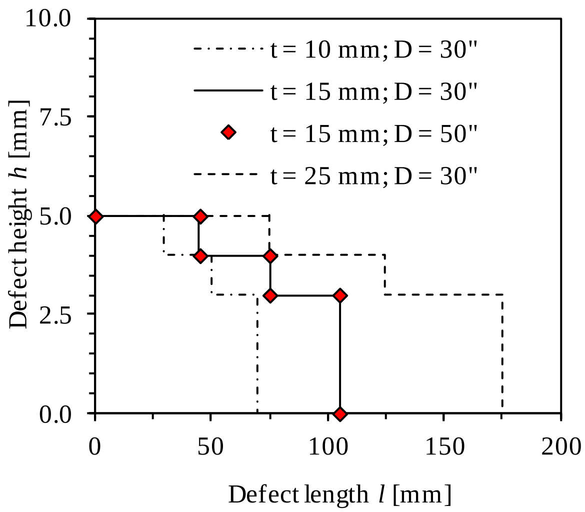

Figure 6 – Influence of pipe wall thickness and diameter on defect allowance according to EPRG Tier 2 guidelines

DISCUSSION

Considering the influences reported above, it can be seen that the highest defect acceptance is obtained for the CSA procedure when a high toughness low grade pipe is considered. In addition, the lowest defect acceptance is observed for the EPRG guidelines for low wall thickness pipes. For example, a comparison of the defect acceptance for a grade X52 pipe with a 10 mm wall thickness is shown in Figure 7. It is observed that, regardless the loading mode, the CSA procedure allows significantly longer defects; defect lengths up to 200 mm are accepted. Apart from these long defects, the EPRG guidelines predict at least comparable defect dimensions as the CSA Z662 procedure. This is an understatement if tension load is considered; in this case the CSA procedure becomes extremely restrictive.

A next example considers a high diameter high wall thickness pipe, with a yield strength corresponding to a grade API-5L X80 material, a *Y/T*-ratio not exceeding 0.90 and a critical CTOD of 0.20 mm. The EPRG guidelines yield a significantly higher defect acceptance than the CSA Z662 procedure, shown in Figure 8. It should be noted that the defect tolerance in case of tensile loading according to CSA Z662 Annex K is extremely low and becomes even significantly more stringent than the workmanship criteria.

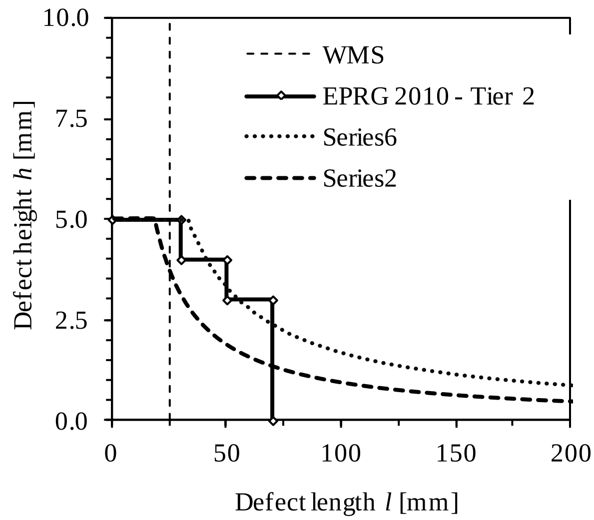

Figure 7 - Defect acceptance for low strength, low wall thickness pipeline with high fracture toughness for tensile and bending loading (D = 762mm; t = 10mm; YS = 358 MPa; $CTOD_c$ = 0.20 mm)

Next to the above two extreme cases, all possible combinations from the test matrix have been analyzed. It is consistently observed that the defect tolerance of the EPRG guidelines is (far) less restrictive than the CSA Z662 Annex K tolerance. Exception is made for defect lengths beyond 7*t*; the CSA Z662 procedure still allows defects whereas no defects are accepted by the EPRG guidelines.

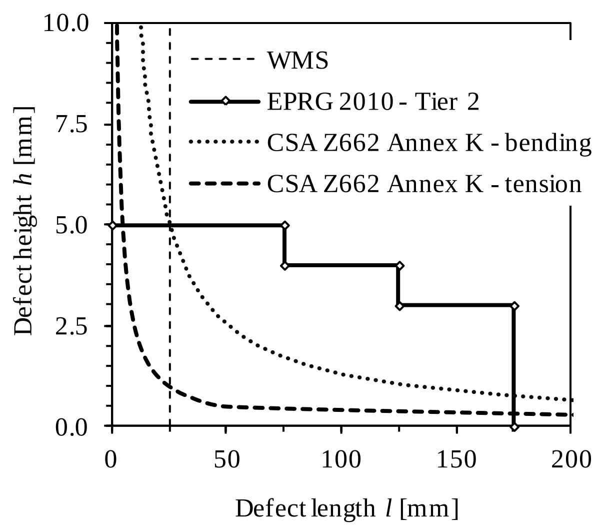

Figure 8 – Defect acceptance for high strength, high wall thickness pipeline with high fracture toughness in case of tensile and bending loading (D = 762mm; t = 25mm; YS = 555 MPa; $CTOD_c$ = 0.20 mm)

CONCLUSIONS

A comparison is made between the defect allowance in the ECA procedures described by the EPRG Tier 2 guidelines and the CSA Z662 Annex K procedure. It is concluded:

- The CSA Z662 procedure requires a significant number of fracture toughness (SENB) tests. In contrast to the EPRG guidelines, which only require Charpy V-notch toughness testing.
- For girth weld defect assessment in tension loaded pipelines at the onset of yielding, the CSA Z662 Annex K ECA method is significantly more restrictive than the EPRG Tier 2 guidelines.
- The more restrictive predictions of the CSA Z662 Annex K procedure are primarily attributed to a correction factor of 1.5 that is to be applied in case of tensile loading.
- A strong coupling between the yield strength and the *Y/T*-ratio is believed to be the second factor lowering the defect allowance in the CSA Z662 Annex approach.
- Yield strength overmatch is in welds assessed through the EPRG guidelines. Taken into account the variability of the base material properties, yield strength undermatch can still be accepted by the CSA procedure.
- The application of the ERPG guidelines is significantly more restricted in terms of assessable steel grades and pipe dimensions. However, this approach has been experimentally validated for a significant number of situations within the limitations. This contrasts the CSA procedure, which has only been validated for a narrow range of conditions but allows application to a close to unlimited set of conditions.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the IWT (Agency for innovation by science and technology – grant n° SB-091512 and SB-093512) and the FWO (Research Foundation Flanders – grants n° 1.1.880.09.N.00 and 1.1.880.11.N.01).

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