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ON THE USE OF CHARPY TRANSITION TEMPERATURE AS REFERENCE TEMPERATURE FOR THE CHOICE OF A PIPE STEEL

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Abstract: Transition temperature is not intrinsic to material but depends on specimens and mode of loading used for tests. Here, the linear dependance of transition temperature with constraint is show . Constraint is evaluated by the effective T stress which is the value of the stress difference distribution for the effective distance provided by the Volumetric method. Application of this approach is a better choice of the reference transition temperature and its degree of conservatism when comparing with transition temperature of the studied structure.

Key words: Transition temperature, Constraint ,effective T stress, reference temperature

1. INTRODUCTION

The concept of brittle-ductile transition temperature was developed during the Second World War, because of the rupture of liberty ships at sea. The ductile-brittle transition temperature (DBTT), nil ductility temperature (NDT), or nil ductility transition temperature (NDTT) of a metal represents the point at which the fracture energy passes below a pre-determined value.

Design against brittle fracture considers that the material exhibits at service temperature, a sufficient ductility to prevent cleavage initiation and sudden fracture with an important elastic energy release. Concretely, this means that service temperature T_s is higher than transition temperature T_t :

$$T_s \geq T_t \quad (1)$$

Service temperature is conventionally defined by codes or laws according to the country where the structure or the component is built or installed. For examples, in France, a law published in July1974 indicates that service temperature in France is -20°C.

However, despite the introduction during the 1960's of Fracture Mechanics tests to measure fracture resistance of materials, the practice of the Charpy impact test remains. It always gives a simple and inexpensive method to classify materials by their resistance to brittle fracture. The current trend is also to use these tests to measure fracture toughness and ductile tearing strength. The comparison of the two methods requires taking into account two major differences:

- Charpy test uses a notched sample, and fracture mechanics tests use a pre-cracked specimen (but a pre-cracked Charpy specimens may also be used).
- Charpy tests are dynamic tests, although the conventional fracture mechanics tests are static ones.

Different Charpy specimens are used in standard. The most widely used is Charpy V specimens (V notch, notch radius $\square = 0.25$ mm , notch depth $a=2$ mm). Other specimens like Charpy U (U notch, notch radius $\square =1$ mm , notch depth $a=(5$ mm) are also used in standards [1].

Increase of notch acuity of Charpy specimen shift transition temperature to higher value and increase scatter in transition temperature [2] [3].

Several definition of transition temperature are used in Charpy test :

- temperature at a conventional level of Charpy energy (generally 27 joules) and called T_{K27} ,
- temperature corresponding to half also at half the jump between brittle and ductile plateau ($T_{K1/2}$) ,
- temperature corresponding to 50% of fracture cristallinity T_{K50}

A Fracture Mechanics based design ensures that design stress intensity factor is lower than admissible fracture toughness and fracture toughness is greater than $100 \text{ MPa}\sqrt{\text{m}}$ (i.e. the reglementary service temperature defined

is above the reference temperature). This additional criterion introduces the concept of reference temperature RT and is expressed by:

$$T_s \geq RT_i + \Delta T \quad (2)$$

where ΔT is the uncertainty on reference temperature (8°C for ASME API 579 code) [4]. This reference temperature RT_i varies according to codes (RT_{NDT} : Nil ductility transition reference temperature or RT_{T0} : reference temperature for a conventional value of 100 MPa√m):

$$\begin{aligned} RT_{NDT} &= T_{NDT} \\ RT_{T0} &= T_0 + 19.4 \text{ °C} \end{aligned} \quad (3)$$

Generally, in codes the choice of the reference temperature is under the responsibility of the designer. Due to the fact that different fracture tests give different transition temperatures, the choice of the most adequate test to provide a value close to the “structure or component” transition temperature T_{struct} is an open question. Thus, it is necessary to know the degree of conservatism of the designer approach.

It has been seen that transition temperature is sensitive to constraint [5]. Transition temperature decreases when effective T stress decreases. Therefore, the choice of the reference temperature can be made on the basis of a specimen providing a constraint value close to the structure one to minimise conservatism or to increase safety factor. One notes that choosing a specimen providing high constraint like Charpy V test is conservative.

In this paper, a selected pipeline steel API 5L X65 is controlled by 3 different instrumented Charpy impact using three types of specimens (Charpy V, Charpy U and a modified Charpy U). Then transition temperatures are expressed versus effective T stress computed by finite element method. A discussion on effect of loading rate and comparison with T_0 transition temperature is proposed.

2. MATERIAL

The typical chemical composition is given in Table 1, mechanical properties at room temperature are given in Table 2, and microstructure in Figure 2.

Table 1. Typical chemical composition of pipe steel API 5L X65 (wt %).

	C	Si	Mn	P	S	Mo	Ni	Al	Cu	V	Nb
min.	0.05	0.15	1.00	-	-	-	-	0.01	-	-	-
max.	0.14	0.35	1.50	0.020	0.005	0.25	0.25	0.04	0.080	0.080	0.040

Yield stress R_e (MPa)	Ultimate strength R_m (MPa)	Elongation at failure A %	Charpy Energy K_{CV} (J)	Fracture Toughness K_{Jc} (MP√am)	Hardness HV
465.5	558.6	10.94	285.2	280	205



Figure 2. Microstructure of pipeline steel API 5L X65 (x100, nital etching).

Tensile tests at very low temperature exhibits brittle fracture and ductile failure at high temperature. At very low temperature, fracture always occurs at yield stress. This phenomenon was proven by compressive tests where no failure occurs, but yield stress is easily determined. When test temperature reaches transition temperature, failure occurs with plasticity at ultimate stress. Plasticity is a thermal activated process and yield stress decreases exponentially with temperature according to the following relationship:

$$R_e = R_e^{\mu} + AExp(-BT) \quad (4)$$

where R_e^{μ} is a threshold, A and B are constants and T is temperature in Kelvin.

Similarly the ultimate strength decreases to temperature according to:

$$R_m = R_m^{\mu} + CExp(-DT) \quad (5)$$

where R_m is a threshold, C and D are constants. Tensile tests have been performed on standard specimens in a temperature range [120 - 293 K] with a strain rate of about $10^{-3}s^{-1}$. Stress-strain diagrams have been recorded and the (static) yield stress and ultimate strength determined. Values of yield stress R_e , and ultimate strength R_m are reported on Figure 3. Data are fitted with equation (4) and (5). Values of R_e , R_m and constants A, B, C, D are reported in Table 3. Yield stress value at 0K is independent of loading rate and equal to 2320 MPa. This value is generally considered as equal to cleavage stress.

Table 3. Values of constants of equation (3) and (4) for API 5L X65 pipeline steel for static loading.

R_e (MPa)	A (MPa)	B (T^{-1})	R_m (MPa)	C (MPa)	D (T^{-1})
434	1910	-0.01405	507	843	-0.0094

3.THE USE OF INSTRUMENTED CHARPY IMPACT TEST TO DETERMINED DYNAMIC YIELD STRESS AND TRNSITION TEMPERATURE

The test campaign was conducted with an instrumented Charpy pendulum with initial energy of 300 Joules and an impact rate of 5.5 m / s. The friction of the hammer were determined by vacuous load tests before each test campaign. The corresponding loss energy is 1.2 J.

The acquisition of the results takes the form of voltage-time data $V_F = f(t)$. The treatment algorithm presented in Figure 16, allows to draw a dynamic behaviour law of the material in force-displacement $F_N = f(\delta)$

With: $F_V = f(t)$ is the voltage versus time recorded during the test; $F_N = C F_V$ is a calibration force / voltage, $v(t)$ is the instantaneous hammer velocity, $\delta(t)$ is the displacement of the hammer, $F_N = f(\delta)$ is the function force-displacement m is the hammer mass, v_0 the initial velocity of impact, t_0 time at the beginning of deformation and t later time.

These curves show more or less light oscillations, consequently of the impact exciting system vibration characterized by loss of contact (hammer-specimen and/or anvil-specimen) so the peaks of inertia [6].

For ductile failure, the load increases up to reach the point (F_{GY}) denoting the beginning of plastic flow of the ligament and the end of the strip loading at point (F_{max}) the load reaches its peak load. Crack initiation occurs between load at general yielding and maximum load at critical load (F_c), figure3.1. For brittle fracture, after several oscillations, failure occurs at maximum load (F_{max}), figure3.2.

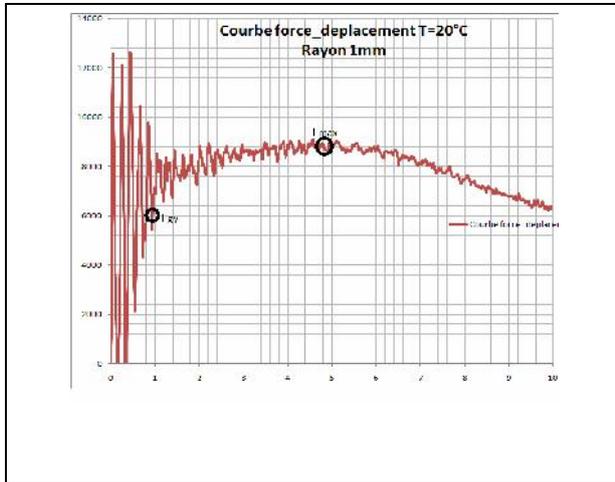


Figure 3.1 Instrumented Charpy impact test load-displacement curve for ductile failure, notch type U₁.

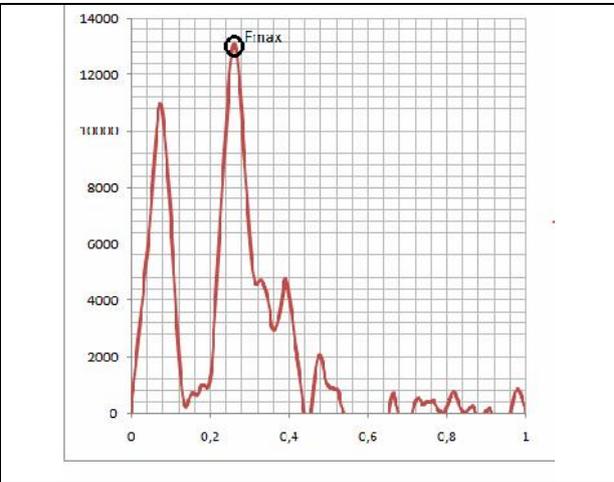


Figure 3.2 Instrumented Charpy impact test load-displacement curve for brittle fracture, notch type U₁.

According to Chaoudi et Puzzolante [7] the critical load is given by the following relationship :

$$F_c = (F_{max} - F_{gy}) / 2 \quad (6)$$

Dynamic yield stress (strain rate $10^2 s^{-1}$) is determined by the method of instrumented Charpy impact test. The load versus time diagram is recorded and the load at general yielding P_{GY} is evaluated (see Figure 3.1). Dynamic yield stress is then obtained using the Green and Hundy solution [8]:

$$R_{e,d} = \frac{4 \cdot W \cdot F_{gy}}{B \cdot L \cdot (W - a)^2} \quad (7)$$

where W is specimen's width, B thickness, a is notch depth, and L is the constraint factor with a value of $L=1.31$ for Charpy V specimen [4].

Data for Charpy V specimen are reported in figure 4 and have been fitted using equation (4). Values of coefficients $Re_{e,d}$, A_d and B_d are reported also in this figure.

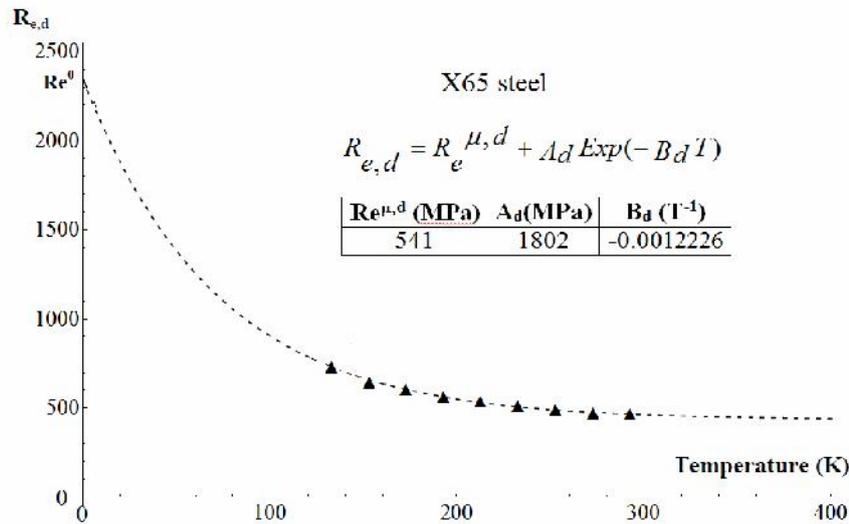


Figure 4 : Evolution of dynamic yield stress with temperature for X65 steel.

Dynamic yield stress can be also evaluated using U Charpy specimen but values of constraint factor are different. Assuming that yield stress is independent of notch geometry, one can find corresponding values of constraint factor.

Table 4 : Values of constraint factor for specimens with notch type U_1 , U_{05} et V.

specimen	U_1	U_{05}	V
L	1.13	1.25	1.38

Values of the dynamic yield stress will be used for a loading rate correction of transition temperature later.

4. TRANSITION TEMPERATURE

Plotting fracture energy K_{CV} (J) temperature and fitting data according to equation (1), one gets a S shape curve (figure 1a, 1b):

$$K_{CV} = A_{CV} + B_{CV} \cdot \tanh\left[\frac{T - D_{CV}}{C_{CV}}\right] \quad (8)$$

where A_{CV} , B_{CV} , C_{CV} , and D_{CV} are constants. A_{CV} represents Charpy energy at transition temperature D_{CV} , B_{CV} is the energy jump between brittle and ductile plateaus and $2C_{CV}$ is the temperature range of the Charpy energy transition. Transition temperature has been determined at conventional level of 27 joules and called T_{K27} and also at half the jump between brittle and ductile plateau ($T_{K50} = D_{CV}$). Charpy impact tests have been performed on API 5L X65 pipe steel with V, U_1 and U_{05} Charpy specimens at temperature range $[-196^\circ\text{C}$ up to 20°C]. Charpy energy and fracture aspects reveal the two failure modes below and above the transition temperature. For U_1 and U_{05} Charpy U notch, one notes a bimodal fracture mode and not for Charpy V. In the temperature range $[187 - 195 \text{ K}]$ for U_{05} and $[150 - 190 \text{ K}]$ for U_1 , the two failure modes coexist. Values of the four constants A_{CV} , B_{CV} , C_{CV} and D_{CV} are reported in Table 5. Transition temperature T_{K27} et $T_{K1/2}$ for each specimen type are reported in table 6. Due to this bimodality, transition temperature $T_{K1/2}$ at half jump between ductile and brittle plateau has been considered and corresponds to D_{CV} values.

Table 5 : Values of constants A_{CV} , B_{CV} , C_{CV} et D_{CV} for curves related to specimen types U_1 , U_{05} et V.

	A_{cv} [J]	B_{cv} [J]	C_{cv} [K]	D_{cv} [K]
U 1	50.70	59.01	22.88	149.47
U 0,5	61.67	59.67	8.22	187.48
V	141.3	135.6	4.43	179.2

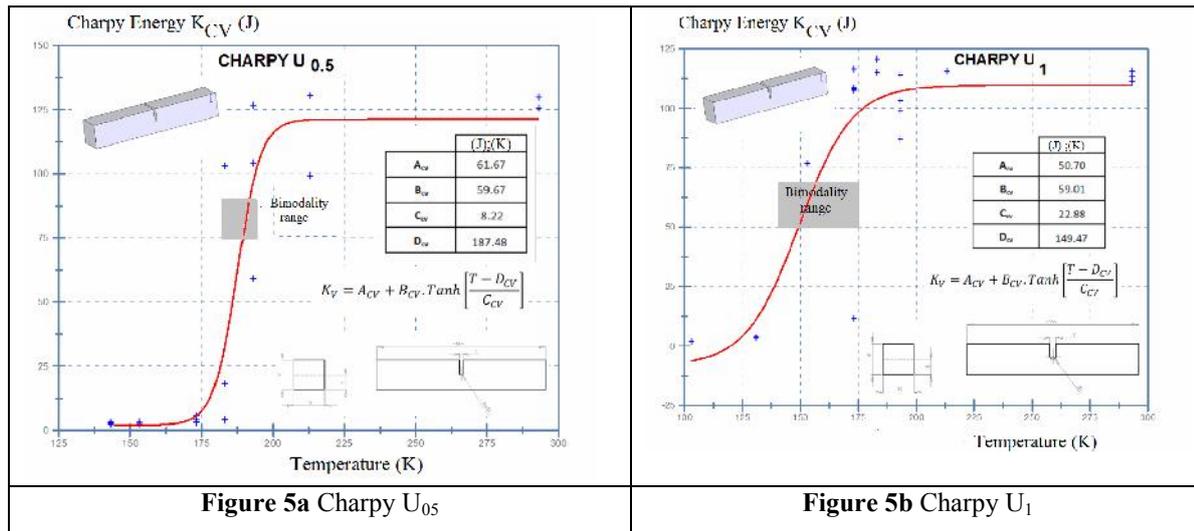


Figure 5 Charpy energy versus temperature curve for API 5L X65 pipe steel ; values of parameters of Equation (4).

The fact that bimodality temperature range increases with decreasing notch radius has been note previously (3).

Table 6 : Transition temperature T_{K27} et $T_{K1/2}$ for specimen types U₁ , U₀₅ et V.

Specimen	U ₁	U ₀₅	V
T_{K27} (K)	141	185	178
$T_{K1/2}$ (K)	150	187	179

5. EFFECTIVE T STRESS FOR A NOTCH TIP STRESS DISTRIBUTION

Material strength like all mechanical properties, is sensitive to geometric parameters such as size, specimen geometry, thickness loading mode, etc. Influence of these parameters is related to plastic constraint. This is the consequence of the Poisson effect limitation due to material elasticity nearby the localized plastic zone. Then a greater load is needed to get the same level of deformation.

Several parameters have been proposed to describe this phenomenon: constraint factor L [10], stress triaxiality β [11], Q parameter [12] and stress difference [13] ($\sigma_{xx} - \sigma_{yy} = \sigma_{yy} (v_{ap}-1)$) where v_{ap} is the apparent Poisson's ratio indicating how lateral contraction is hampered. This stress difference is now widely used to translate plastic constraint

In the case of a singular stress distribution at crack tip, this stress difference is identical to T stress [13]. Several methods have been proposed in the literature to determine T stress for a cracked specimen (Chao et al. [15], Ayatollahi et al. [16] and Wang [17]). Here, the difference in stress method (SDM) proposed by Yang and Chatel [18] is used and evaluated from the stress distribution calculated by Finite Elements method.

Physically T is the stress acting parallel to the crack line in direction xx to the extension of crack with amplitude proportional to gross stress. The term non-singular T may be positive (tensile) or negative (compression). A positive T stress leads to an increase in constraint, a negative T constraint to a loss. In the crack tip singular distribution,

For a tensile smooth specimen, the strain difference is rater used and the parameter has the same dimension than T.

$$u = E(\epsilon_{xx} - \epsilon_{yy}) \quad (9)$$

In case of a distribution reflecting a stress concentrations stress difference ($\sigma_{xx} - \sigma_{yy}$) is not constant along ligament and increases slowly after a given distance. This stress difference ($\sigma_{xx} - \sigma_{yy}$) is called T_{\square} . It is therefore evaluated for a conventional distance X_{ef} given by the volumetric method [13] and related to the size of the fracture process zone.

The volumetric method is a local failure criterion used for fracture emanating from notch. It is assumed in this method, that fracture process requires a physical volume. This volume is assumed to be quasi-cylindrical and centered at notch tip. The radius of the cylinder is called the "effective distance". By calculating averaging opening stress in this volume, one gets the effective stress. This local failure criterion is therefore based on two parameters, namely, the effective distance X_{ef} and stress the effective σ_{ef} . The distance corresponding to the minimum of relative stress gradient is conventionally regarded as the relevant effective distance. The value of the relative stress gradient is given as follows:

$$\chi(r) = \frac{1}{\sigma_{yy}(r)} \frac{\partial \sigma_{yy}(r)}{\partial r} \quad (10)$$

χ is the stress gradient and σ_{yy} the maximum principal or opening stress respectively. The effective stress is defined as the average of the opening stress weighted within the area of the fracture process:

$$\sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_d} \sigma_{yy}(r) \Phi(r) dr \quad (11)$$

where σ_{ef} , X_{ef} Φ are effective stress, effective distance and weight function, respectively.

The Unit and Peterson weight functions are the simplest weight functions. The Unit weight function deals with the mean stress and Peterson weight function gives the stress value at a specific distance.

Figure 6 represents stress distribution of in the case of Charpy specimens U_1 . The maximum stress is related to a stress concentration factor $k_t = 1.95$

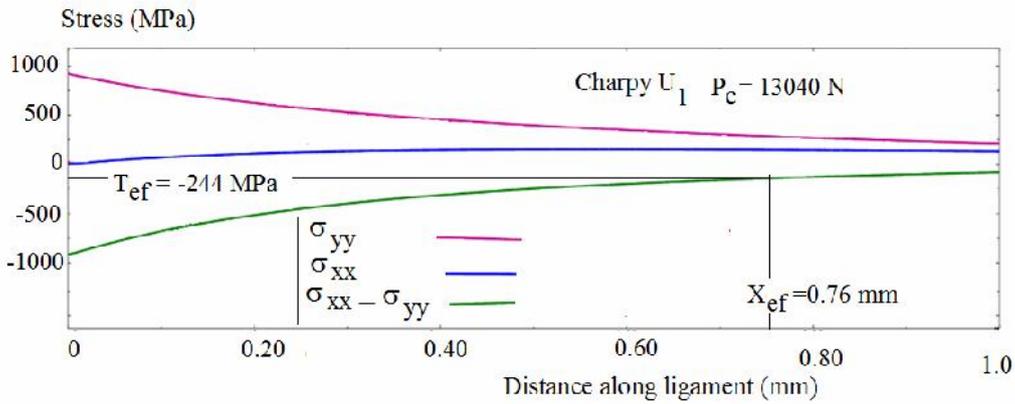


Figure 6: stress distribution at notch of in the case of Charpy specimens U_1 . Determination of T_{ef} on stress difference distribution.

Values of T_{ef} has been determined for different ligament ratio (a/W) and for the 3 notch geometries. Results are reported in Table 7

Table 7: Values of T_{ef} for different ligament ratio (a/W) 3 notch geometries.

a/W	U_1		U_{05}		V	
	T_{ef} [MPa]	X_{ef} [mm]	T_{ef} [MPa]	X_{ef} [mm]	T_{ef} [MPa]	X_{ef} [mm]
0,2	-	-	-	-	-230.8	0.49
0,3	-318,9	0,74	-242,3	0,56	-221.4	0.51
0,4	-285,2	0,75	-236,8	0,58	-202.5	0.53
0,5	-244,2	0,76	-228,1	0,6	-194.7	0.57
0,6	-228,6	0,77	-225,1	0,62	-189.5	0.6
0,7	-221,9	0,78	-223,8	0,65	-186.3	0.64

One notes that T_{ef} increases when (a/W) ratio increases. Values associated with each notch geometry are reported in table 8.

Table 8 : T_{ef} Values associated with each notch geometry.

	U_1	U_{05}	V
a/W	0.5	0.5	0.2
T_{ef} [MPa]	-244,2	-228,1	-230.8

One notes that T_{ef} values are relatively close. Increase of constraint by increase (a/W) ratio is counterbalanced by increase of notch acuity when comparing U_{05} and V notch.

6. DISCUSSION

The use of Charpy V T_{K27} or $T_{K1/2}$ transition temperature as reference temperature needs to introduce a correction due to the fact that this test is made at a loading rate of about 10 s^{-1} and consequently higher than the

loading rate corresponding to a static loading ($10^{-3}s^{-1}$). An empirical relationship between transition T_t and yield stress Re proposed by Rolfe and Barsom [14] is used.

$$T_t = 0.17 Re - 125 (K, MPa) \quad (12)$$

Knowing transition temperature for Charpy Test $T_{t,d}$ (174K), it is easy to know the equivalent static transition temperature $T_{t,s}$ by reporting dynamic yield stress (661MPa) at this temperature into modify equation (1).

$$\Delta T_t = 0.17(Re_d(T_{t,d}) - Re_s(T_{t,s})) \quad (13)$$

This equation is solved knowing relationship between static yield stress and temperature by dichotomy method.

$$R_e = R_e^u + A \exp(-BT) \quad (14)$$

R_e^u is a threshold constants A and B are given in Table 3. For API X65, the shift in transition temperature is 10°C. This corrected transition temperature is reported in figure 8.

The fracture bimodality induces some difficulty to fit data and defined the transition temperature. For this reason, transition temperature $T_{1/2}$ defined at half the energy jump between brittle and ductile plateaus is used.

The stress difference method (SDM) is used to determine T or T_{\square} .

$$T, T_p = \sigma_{xx}(\theta = 0) - \sigma_{yy}(\theta = 0) \quad (15)$$

It appears on figure 6 that this difference is not constant but presents a plateau or a small increase at some distance of crack or notch tip. Therefore, the chosen value T_{ef} is defined by a conventional manner. In this paper two ways have been used :

- method proposed by Maleski et al [15],
- method using the effective distance obtained from Volumetric method.

In method proposed by Maleski et al, effective T stress T_{ef} is obtained by linear extrapolation to origin of T distribution. This value corresponds to the effective distance on this distribution. One notes that these values are very closed for V notch but far for U notch.

Table 9: Comparison of Methods to determine T_{ef}

Method	Maleski et al [15],	From effective distance
T_{ef} for U_1 specimen	- 410 MPa	-244,2 MPa
T_{ef} for V specimen	-230.8 MPa	-220 MPa

The method based on Volumetric method has been chosen in this paper because of difficulty to choose the appropriate linear extrapolation.

Transition temperature have been determined for specimens with U_1 , U_{05} and V notch in the present study together with effective T stress T_{ef} . From a previous study [5], data from tensile tests and fracture toughness on CT specimen are also reported in Table 11.

Table 10 : Transition temperature and Effective T stress for different specimens made in X65.

Notch	T_{ef} (MPa)	T_t (K)
U_1	-244,2	150
U_{05}	-228,1	187
V	-230,8	179
CT	-330	156
Tensile	-510	123

Transition temperature for Charpy specimens (U_1, U_{05} and V) are corrected to take into account the strain rate effect and reported in figure 7.

Data are fitted according linear interpolation and relationship between transition temperature and effective T stress is given by :

$$T_t = 0.14T_{ef} + 197 \quad (16)$$

This equation represents the material master curve $T_t = f(T_{ef})$ which is the key to determine the appropriate reference transition temperature by comparison with structure transition temperature

Values of T_{ef} are close for Charpy V, U_1 and U_{05} like values of transition temperature relative to the same specimen notch geometry. They are higher than CT specimen which exhibits a lower plastic constraint than 3PB specimen. CT specimens loaded both by bending and tension have a transition temperature intermediate with those of tensile and Charpy specimens.

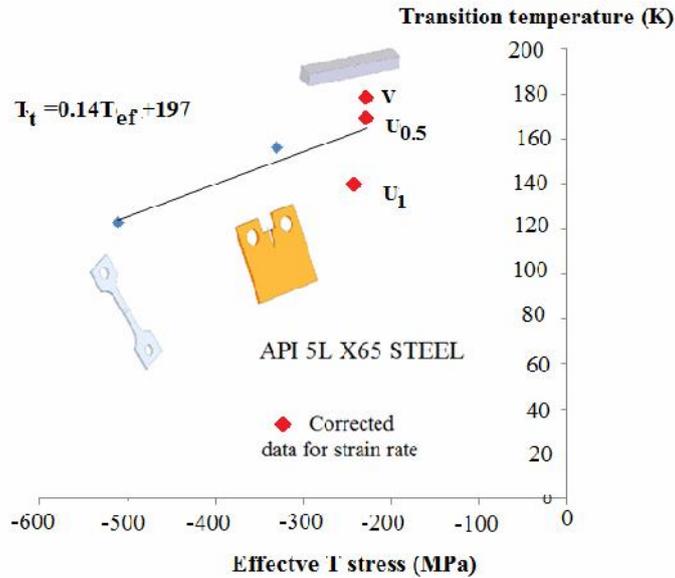


Figure 7 : material master curve $T_t = f(T_{ef})$ for pipe steel API 5LX65.

Transition temperature relative to the investigated component is obtained using two material master curves : transition temperature master curve $T_t = f(T_{ef})$ and material master curve $K_c = f(T_{ef})$ where K_c is fracture toughness.

The effective T stress for a component $T_{ef, comp}$ is obtained through a procedure described in [13]. The material master curve at transition temperature has been drawn using the fracture toughness at transition temperature of CT specimen (156K, 100 MPa√m) and Charpy V (156 K, 92 MPa√m).

Transition temperature of component has then been determined for a pipe steel made in API 5L X65 with 355mm diameter and 19 mm thickness . This pipe exhibits a surface notch with a notch angle $\alpha = 0^\circ$, a notch radius $\rho = 0.25$ mm and a notch depth (a) to thickness (t) ratio equal to $a/t = 0.5$. Loading curve $K_{ap} = f(T)$ has been computed by finite element assuming elastic behaviour, the steel is considered as brittle at transition temperature. This loading curve $K_{ap} = f(T)$ intercept the material master curve at point (T_{ef}^*, K_c) figure 8.

The obtained value of T_{ef}^* is -495MPa. In [16], the determination of the material master curve is more precise because 4 specimen types has been used (SENT, CT, TR and DCB) , each specimen with different a/W ratio. In this procedure, we have used available data in order to have a cheaper and faster procedure. To take into account this uncertainty, it is better to estimated the constraint range -450 MPa and -550 MPa.

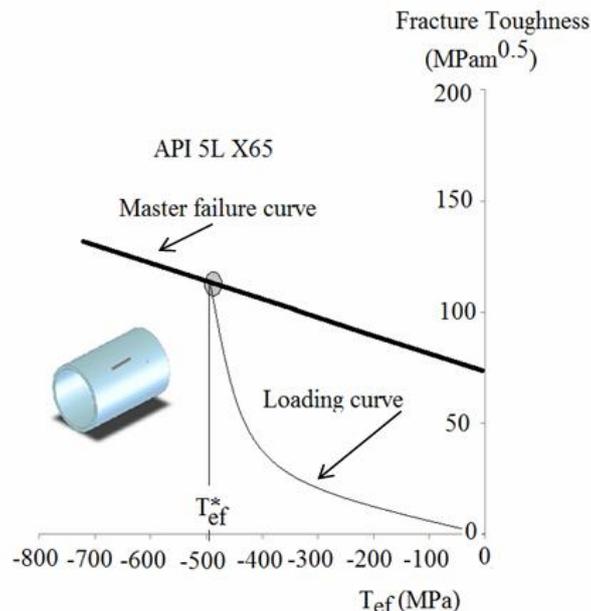


Figure 8 : Material Failure curve for API 5L X65 steel and loading curve $K_{ap} = f(T)$ for a pipe exhibiting a surface notch

The conservative range induces by the choice of the reference transition temperature T_0 is determined from the transition temperature of the component. $T_{t, comp}$ is obtained by reporting T_{ef}^* value on transition temperature master curve $T_t = f(T_{ef})$ and equal to $T_{t, comp} = 150$ K. The critical exposure temperature + margin of 8°C [4] is equal to 185 K. Conservative range ΔT^* according to T_0 choice a given in table 11.

Table 11 : Conservative range ΔT^* according to T_0

Transition temperature	$T_{t, comp}$	T_0	$T_{K1/2}$
ΔT^* (K)	35 ± 10	29	6

Due to uncertainties on material master curve $K_c = f(T_{ef})$, a error of $\pm 10^\circ\text{C}$ on component transition temperature has been estimated. One notes that the transition temperature T_0 is close to component one For both CT specimen and pipe, values of plastic constrain are very close. However the choice of Charpy V transition temperature as reference temperature is justified. A sufficient conservative range of 11°C is obtain and offers the possibility to enlarge material choice.

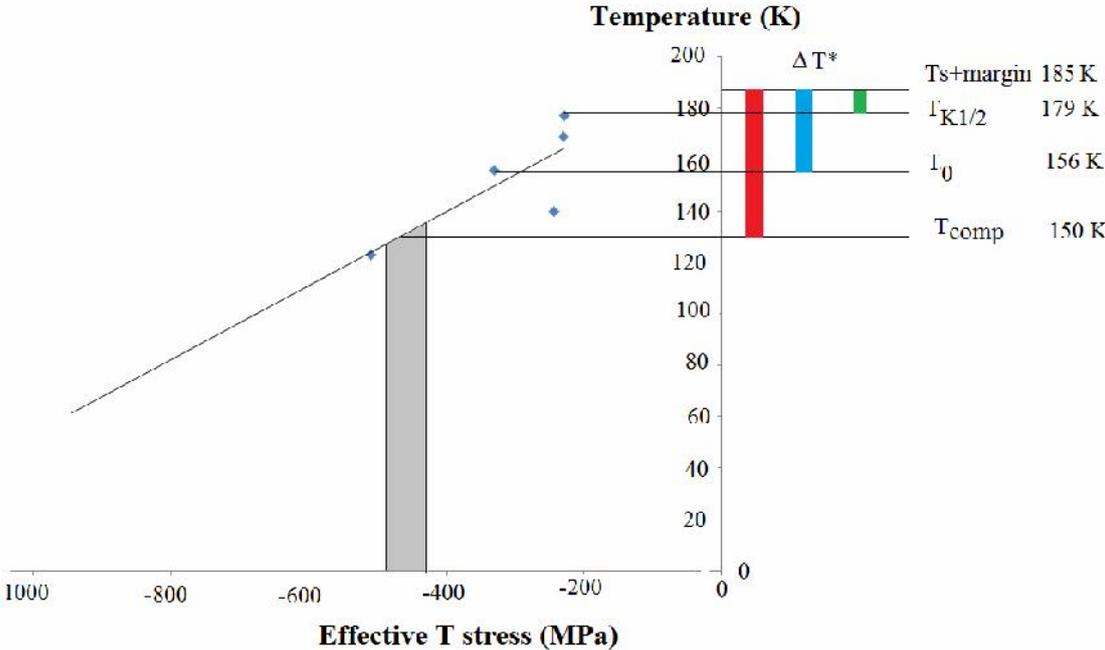


Figure 9 : Estimation of conservative range ΔT^* according to T_0 from material failure curve.

7. SUMMARY

The choice of the referece temperature is, according to codes like API 579-1 ASME FFS-1 is open and is under responsibility of designer.

In this paper, we propose a method to estimate the degree of conservatism induces by a choice of a reference transition temperature. This method is based on the relationship between transition temperature and constraint and a transition temperature associated with component.

This one is obtain by intersection of material master curve $K_c = f(T_{ef})$ and loading curve $K_{ap} = f(T)$.

Reducing the conservatism range, offer the possibility to enlarge material choice according to availability in large quantities, price and time for delivering.

However , this procedure is time consuming and costly because it need to determine several transition temperature with different specimens and finite element computing.

At least, selection based on Charpy V transition temperature $T_{K1/2}$ offer the most conservative approach. This is due that plastic constrain induced by bending is lower than in tension or mixture of bending and tension like for CT specimen.

REFERENCE

- [1] AFNOR standard: NF EN ISO 14556 (2001). *Acier. Essai de flexion par choc sur éprouvette Charpy à entaille en V. Méthode d'essai instrumentée*, Association Française de Normalisation, Saint Denis La Plaine.
- [2] Toth. L. "Rissbildungen und Ausbreitungsarbeit hinsichtlich der kerb-geometrie von kerbschlag biegeversuchen". Publications of the Technical University for Heavy Industry. Series C, Machinery, Vol 34, pp31-47, (1978).
- [3] G. Pluvinage et F. Montariol. "Contribution à l'étude des transitions de résilience dans le cas d'un acier doux" *Rev. Met.*, LXV, No 4, pp. 297-308, Avril, (1968).
- [4] API 579-1 ASME FFS-1 June 5 (2007)
- [5] Capelle, J. Furtado, Z. Azari. S. Jallais And G. Pluvinage, "Design based on ductile-brittle transition temperature for API 5l X65 steel used for dense CO₂ transport", to appear to appear in *Engineering Fracture Mechanics*
- [6] G. Fearnheoug et C. Hoy, "Mechanism of deformation and fracture in the Charpy test as revealed by dynamic recording of impact loads", *J. of the Iron and Steel Institut*, 1964, pp. 912-920.
- [7] R. Chaouadi, J.L. Puzzolante, "Loading rate effect on ductile crack resistance of steels using precracked Charpy Specimens", *International Journal of Pressure Vessels and Piping* 85 (2008) 752–761
- [8] Green, A. P., and Hundy, B. B. (1956). Initial plastic yielding in notch bend tests, *Journal of Mechanics and Physics of Solids*, **4**, 128-144.
- [9] ASTM E1921-11a, (2003). *Standard Test Method for Determination of Reference Temperature, T₀ for Ferritic Steels in the Transition Range*, American Society for Testing and Materials, Philadelphia.
- [10] M. Mouwakeh, G. Pluvinage, S. Masri . « Failure of water pipes Containing Surface Cracks Using Limit Analysis Notions". *Res. J. of Aleppo Univ. Engineering Science Series* No.63, (2011).
- [11] Henry, B. S., Luxmore, A. R. (1997). The stress triaxiality constraint and the Q-value as a ductile fracture parameter, *Engineering Fracture Mechanics*, **57**, pp. 375-390.
- [12] Ruggieri, C., Gao, X., and Dodds, R. H., (2000). Transferability of elastic-plastic fracture toughness using the Weibull stress approach: significance of parameter calibration; *Engineering Fracture Mechanics*, **67**, 101-117.
- [13] Hadj Meliani, M., Matvienko, Y. G., Pluvinage, G. (2011). Two-parameter fracture criterion ($K_{\square} T_{ef,c}$) based on notch fracture mechanics, *International Journal of Fracture*, **167**, 173-182.
- [14] S.T Rolfe and J.M Barsom, *Fracture and Fatigue control in structures*. Prentice-Hal (1977)
- [15] M.J. Maleski, M.S. Kirugulige and H.V. Tippur. A Method for Measuring Mode I Crack Tip Constraint Under Static and Dynamic Loading Conditions. *Society for Experimental Mechanics*. Vol. 44, No. 5, October 2004.
- [16] M. Hadj Meliani, Z. Azari, G. Pluvinage, J. Capelle Gouge assessment for pipes and associated transferability problem, *Engineering Failure Analysis*, Volume 17, Issue 5, July 2010, Pages 1117-1126