Ductile instability analysis of HSLA coiled tubing

J. Wainsteina*, J. Perez Ipiñab

aUniversidad Nacional de la Patagonia San Juan Bosco-CONICET – Ruta Prov n°3 km 4, Comodoro Rivadavia, 9000, Argentina
bLPM-GMF Universidad Nacional del Comahue, CONICET, Bs As 1400, Neuquén, 8300, Argentina

Abstract

Coiled tubing are thin walled steel tubes of 25 to 89 mm diameter and thousands meters long used in the oil industry for production and maintenance services. J Integral evaluation, based on elastoplastic fracture mechanics, has a central role in critical crack length evaluation for fracture instability of coiled tubing. The instability analysis requires the critical load determination at which the crack will grow in an unstable manner. Due to coiled tubing diameter and thickness, standard specimens could not be constructed. J-R curves were experimentally determined from four point bending tests of 1 m long coiled tubing specimens. Instability was evaluated through tearing modulus T, using J-T curves, where the instability point is found on the intersection of both curves, T_{material} and T_{applied}. Two calculus schemes were employed for a through wall thickness cracked tube: J EPRI and the Reference Stress Method (RSM) of Ainsworth. For every coiled tubing specimen J_{critic}, applied tearing modulus and critical crack extension were determined. Critical load was also determined.

© 2012 Published by Elsevier Ltd. Selection and/or peer-review under responsibility of SAM/CONAMET 2011, Rosario, Argentina. Open access under CC BY-NC-ND license.

Keywords: Coiled Tubing, Ductile instability, J Integral, Fracture Mechanics

* Corresponding author. E-mail address: jwainste@gmail.com

1. Introduction

Coiled Tubings are thin walled steel tubes of 25 to 89 mm in diameter and several thousand meters long. They are used in oil and energy industries to provide a number of production tasks and maintenance services. They suffer plastic deformation during unwinding of the reel, passing through a goose neck arch guide and an injection unit. Plastic Strain levels are about 2-3%, making the tubing fails by low cycle fatigue
in around 100 wrap-unwrap cycles. The fracture behavior of a component is necessary to know in order to assess the integrity of structures containing crack like defects. For pipe materials with high toughness, elastic-plastic fracture mechanics (EPFM) provides realistic estimates of the fracture performance of cracked pressurized pipes. Coiled tubing made of high strength low alloy (HSLA) steel behaves in a ductile manner at working temperatures in and out the well. Hence, fracture could occur by ductile tearing or plastic collapse, making necessary the use of an elastic plastic analysis. $J$-integral based on EPFM has become a useful analytical technique for dealing with ductile materials. Simple solutions of $J$ for various cases are available through a $J$ estimation handbook, such as the one developed by the Electric Power Research Institute (EPRI). In this method, elastic-plastic $J$ integral solutions for various cases are calculated as the sum of linear elastic solution for an effective crack length and a fully plastic solution based on the non-linear Ramberg-Osgood (R-O) power hardening law, Saxena et al., 2007. This equation assumes that the relationship between stress and strain for the material follows a simple potential curve. On the other side, when the material stress-strain behavior deviates from this model, the Reference Stress Method (RSM) developed by Ainsworth, Anderson TL, 1995, can be used. It reflects more closely the flow behavior of many real materials U. Zerbst et.al., 2000. The equations given by both methods; EPRI and RSM are very close in the linear elastic range and some discrepancies between the two approaches are observed when the plastic term is significant, Saxena et al., 2007. The aim of this paper is to present a ductile instability analysis in coiled tubing. For this purpose, $J$ integral evaluation of experimental results based on elasto-plastic fracture mechanics was assessed at two stages. The first stage corresponded to initiation of stable crack growth and the second stage corresponded to the development of instability. This analysis required also the determination of the critical load at which the crack grows in an unstable manner.

2. Experimental Procedure

$J$-$R$ curves of coiled tubing were determined using 1m long coiled tubing specimens. Due to coiled tubing diameter and thickness, no standard specimens could be used, ASTM E1820-08, 2008.

2.1. Test arrangements

Four point bending tests were carried out in a 400 kN Wolpert Universal Testing Machine at room temperature adapting Chattopadhyay methodology, Chattopadhyay et.al, 2000, to coiled tubing specimen dimensions. The specimens were fatigue precracked (2-10mm at each side) before performing the fracture tests. This ensured a sharp crack tip. The geometric details of the tested specimens are given in Table I. These data were originally reported in Wainstein et al., 2011.

Table 1. Details of test specimen

| Tube | Spec. | Out. diameter [mm] | Wall thickness [mm] | Span [mm] | Initial Arc length [mm] | Angle [$\theta$,] |
|------|-------|--------------------|---------------------|----------|------------------------|-----------------|
|      |       |                    |                     |          |                        |                 |
| 1    | CTA-1 | 38.1               | 3.20                |          | 36.5                   | 52.10           |
| CTA-2| 38.2  | 3.25               |                      |          | 58.7                   | 86.70           |
| CTA-3| 38.3  | 3.25               |                      | 275      | 55.7                   | 83.30           |
| CTA-4| 38.2  | 3.25               |                      | 700      | 59.8                   | 93.50           |
| 2    | CTA-5 | 38.2               | 3.25                |          | 54.3                   | 82.60           |
| CTA-6| 38.3  | 3.30               |                      |          | 67.2                   | 100.7           |
The data gathered for instability analysis included load vs. load line displacement, crack arc extension (2C) vs. load line displacement and J-R curves determined from this data. Fracture instability was evaluated by the tearing modulus $T$, using $J-T$ graphics, where the instability point was determined by the intersection of both curves, $T_{\text{material}}$ and $J_{\text{applied}}$, $T_{\text{applied}}$. The $J$-EPRI scheme and RSM equations were used for circumferential through wall thickness tube Chattopadhyay et.al, 2000, Figure 1.

**3. Analysis Procedure**

As was already mentioned, coiled tubing suffers plastic deformation during the service process. Plastic strain levels are approximately 2-3%, making coiled tubing work in elastic plastic regime. Such deformation levels, together with internal pressure and its own weight, makes coiled tubing fail in around 100 wrap and unwrap cycles. Therefore, coiled tubing bears cycles of bending (unwrap and wrap and passing through the goose neck), internal pressure and its own weight (tensile). The most dominant factors controlling the deformation behavior of coiled tubing are the bending-straightening (tensile) cycles associated with the spool and gooseneck, Figure 1 b). Hence, equations for combined tension and bending, Anderson T.L, 1995, were utilized for EPRI and RSM methods. Following, the equations used for both methods are described.

**3.1. EPRI Method**

\[ J_{\text{tot}} = J_{el} + J_{pl} \]  \hspace{1cm} (1)

\[ J_{el\,(aef)} = \frac{K_{(aef)}^2}{E} \]  \hspace{1cm} (2)

\[ a_{\text{eff}} = a + \frac{1}{1+(P/P_0)^2} \frac{1}{n} \frac{n-1}{\beta \pi} \left( \frac{k}{\sigma_0} \right)^2 \]

where

\[ J_{pl} = \alpha \varepsilon_o \sigma_0 R(\theta - \pi) \theta \frac{1}{\pi} h_i \left( \frac{P}{P^*} \right)^{n+1} \]  \hspace{1cm} (3)
where \( P_0^* = 0.5 \left\{ -\frac{\lambda \rho R_0^2}{M_0} \left[ \left( \frac{\lambda \rho R_0^2}{M_0} \right)^2 + 4 P_0^2 \right] \right\} \), 
\[ \lambda = \frac{M}{PR} \]
\[ M_0 = 4 \sigma_0 R^2 \left[ \cos \frac{\theta}{2} - 0.5 \sin \theta \right] \]

where \( K \) is the stress intensity factor defined as a function of effective crack length; \( \theta \) is crack half angle; \( M_0 \): plastic collapse moment; \( P_0 \): plastic collapse load; \( \beta \approx 2 \) for plane stress. The stress intensity factor solution given by Zahoor and \( h1 \) solutions given by Anderson T.L., 1995, are used in the EPRI method.

3.2. Reference Stress Method

Ainsworth proposed the following equation, Anderson T.L., 1995

\[ J_p = \frac{\mu K^2}{E} \left( \frac{E \varepsilon_{ref}}{\sigma_{ref}} - 1 \right) \]

with \( \sigma_{ref} = L, \sigma_y = \frac{F}{F_y} \sigma_y \) (4)

where \( K \) is the stress intensity factor. In this method the stress intensity factor is calculated as a function of crack length without plastic corrections and taking into account the bending/straightening load scheme.

Then, the tearing modulus is determined as:

\[ T = \frac{E}{\sigma_0} \frac{dJ}{d\Delta a} \]

and \( T_{\text{applied}} \) is

\[ T_{\text{app}} = \frac{E}{\sigma_0} \frac{dJ_{\text{app}}}{d\Delta a} \]

for the material is:

\[ T_{\text{mat}} = \frac{E}{\sigma_0} \frac{dJ_{\text{mat}}}{d\Delta a} \]

with \( \frac{dJ_{\text{mat}}}{d\Delta a} = C_1 C_2 (\Delta a)^{\gamma-1} \)

4. Results and discussion

Figure 2a) shows true stress vs. true plastic strain curve for coiled tubing material. The material behavior was fitted with a potential law following ASTM E646-07.

Fig 2.a) True stress-true plastic strain curve  b) J-R curves coiled tubing specimens, Tube 1 and Tube 2

Figure 2b) shows J-R curves for coiled tubing specimens. As it can be seen on Figure 2b) J-R curves of coiled tubing, vary with the \( 2C_0/W \) ratio. Initial arc crack lengths varied from 36 mm to 70 mm hence \( 2C_0/W \)
varied from 0.30 to 0.61. The differences on the $J-R$ curve slopes could be related to the in-plane constraint dependence, the bigger $2C_0/W$, the lower the curve is.

Once $J-R$ curves were obtained, instability analysis was performed. It was determined for coiled tubing with a circumferential through wall crack, loaded in bending plus tension as was explained in the Analysis Procedure section.

As was aforementioned, two methods were applied to carry out the instability analysis, the EPRI method and the Reference stress method (RSM)

To apply the EPRI method, the stress intensity factor solution must be employed to compute the elastic component of $J$, $J_{el}$ and a separate solution for $h_1$ is necessary in order to compute the plastic term, $J_{pl}$. Both are listed in the EPRI Handbook and Anderson T.L., 1995. $J_{el}$ was determined without difficulties using stress intensity factor and the applied load scheme to coiled tubing i.e. tensile and bending. However, $J_{pl}$ was not as simple to determine as $J_{el}$. First of all, the EPRI method requires that the material stress-strain curve follows a potential law. As it can be seen on Figure 2a) the true stress-true plastic strain curve of coiled tubing material, HSLA steel presented a regression coefficient of 0.7

On the other hand, tables 12.45 to 12.56 to determine the $h_1$ coefficients, Anderson T.L., 1995, are displayed for different load modes. They are shown as a function of radius/thickness ($R/t$) ratio and $m=1/n$, where $n$ is the hardness coefficient from Figure 2a). Coiled tubing in service support tensile plus bending loads. The table that corresponds to both solicitations starts at $R/t=10$. In our case $R/t=5$, hence, only bending table was employed. Taking into account this “simplification” crack instability diagrams were constructed after having determining $T_{applied}$ and $T_{material}$.

To reflect more closely general materials behavior, Ainsworth defined the Reference Stress Method (RSM). The equation given by the RSM agrees very well with EPRI on the linear elastic range but there are some discrepancies between the two approaches when the plastic term is significant, Anderson T.L. 1995. RSM relates $J$ to the elastic stress intensity factor and it allows a more general expression that only needs the stress strain curve of the material to determine $\sigma_{ref}$ and $\varepsilon_{ref}$ Zerbst U. et. al, 2000. Hence, from EPRI and RSM scheme $J_{critic}$ values were calculated for every coiled tubing specimen, some examples can be seen in Figure 3 and 4.

The differences between EPRI and RSM can be rationalized because of the simplification used in EPRI method due to the lack of $h_1$ coefficient for both tensile and bending with $R/t=5$ and $m=20$. 

![Graphs](image-url)
Table 2 shows the $J_{IQ}$ values determined from $J$-$R$ curves and with the $J_{critic}$ obtained from ductile instability analysis using the EPRI and RSM scheme. Initiation of the stable crack growth value, $J_{IC}$, was written as $J_{IQ}$ because the plane strain condition could not be reached due to the coiled tubing thickness. Therefore, $J_{IQ}$ cannot be considered as a material property; it is only valid for present conditions.

Fig. 4a) shows the material tearing modulus as well as the applied tearing obtained from both the EPRI scheme and the RSM method. The RSM method has the advantage over EPRI method of being formulated from the stress intensity factor $K$, for which the superposition principle could be used. For in-service coiled tubing this allows to take into account all the load conditions without restriction on $R/t$ ratio or hardening exponent. Three kinds of loads were considered: first the tensile load due to two factors: straightening and its own weight; second the unbending and bending loads due to the unwrapped from spool, bending through the goose neck and unbending for straightening when it pass through the injection unit, and finally the longitudinal stress produced by the internal pressure. For this purpose, SAN ANTONIO INTERNATIONAL Company provided the values of internal pressure normally used in coiled tubing operations and the average of the tensile load registered by the injection unit. Taking into account all these loads, $J_{critic}$ and the applied tearing modulus were determined for every coiled tubing specimen. In addition, the critical crack extensions were obtained, Table 2.

| Specimens | 2C$_{o}$ [mm] | $J_{IQ}$ [kJ/m$^2$] | $J_{critic}$(RSM) [kJ/m$^2$] | $J_{critic}$(EPRI) [kJ/m$^2$] | $\Delta$2C$_{critic}$ [mm] |
|-----------|------------|-----------------|-----------------|-----------------|-----------------|
| Tube 1    |            |                 |                 |                 |                 |
| CTA-1     | 36.5       | 130             | 348             | 282             | 1.27            |
| CTA-2     | 57.8       | 109             | 311             | 226             | 1.35            |
| CTA-3     | 55.7       | 101             | 337             | 254             | 1.98            |
| Tube 2    |            |                 |                 |                 |                 |
| CTA-4     | 59.8       | 125             | 233             | 161             | 1.00            |
| CTA-5     | 54.3       | 118             | 211             | 128             | 1.60            |
| CTA-6     | 67.2       | 120             | 136             | 60$^*$          | 1.05            |

From Table 2, it could be seen that critical crack extension varies from 1 to 2 mm.
The small value of J\textsubscript{critic} for the specimen CT6 could be attributed, as it was already mentioned, to the simplifications made in order to use the EPRI method.

A sensibility analysis was carried out varying once at a time the following variables: internal pressure from 0 to 25 MPa and the tensile force from 0 to 120000N, which are the force and the range of internal pressure used in services conditions, figure 5.

It could be seen from figures 5a) and b) that Fi variation affects the RSM T-J curve moving the J\textsubscript{critic} to smaller values. This is not the case for the Pi variation that produces a similar curve as the initial RSM curve.

Plastic collapse loads were determined from the

\[ P_0 = 2\sigma_y R[t\pi - \theta - 2\sin^{-1}0.5\sin\theta] \]

given by Saxena et al., 2007. In every case for the variation of Fi, the determined critical load is smaller than the obtained plastic collapse load, indicating that the ductile tearing instability is the probable failure mechanism of coiled tubing under the actual services conditions.

Table 3. Sensibility analysis

| Specimens | J\textsubscript{crit}(RSM) [kJ/m\textsuperscript{2}] | Var Fi | P\textsubscript{plastic collapse} [kN] |
|-----------|-------------------------------------------------|--------|-------------------------------|
|           | J\textsubscript{crit} | F\textsubscript{crit} |                               |
| Tube 1    | CTA-1 | 348 | 265 | 95 | 130 |
|           | CTA-2 | 311 | 227 | 100 | 133 |
|           | CTA-3 | 337 | 209 | 75 | 152 |
| Tube 2    | CTA-4 | 233 | 183 | 95 | 145 |
|           | CTA-5 | 211 | 160 | 90 | 149 |
|           | CTA-6 | 136 | 109 | 85 | 156 |
5. Conclusions

Elastic plastic fracture mechanics based $J$-integral combined with $J$-$T$ analysis gives a description of high strength low alloy steel coiled tubing behavior. 

$J$-EPRI scheme and RSM equations were used for coiled tubing ductile instability analysis. Due to radio/thickness ratio and high strain hardening exponent of these tubes, various simplifications had to be made in order to use EPRI calculus scheme for coiled tubing.

Ainsworth Reference Stress Method (RSM) was also applied, in which the only requirement is to know the stress-strain curve of the material. $J_{\text{critic}}$ values were determined from $T_{\text{material}}$ vs $T_{\text{applied}}$, $J_{\text{critic}}$ values. These values are higher than the $J_{\text{IQ}}$ values, resulting in an important arc crack growth before it reaches a critica value. Stable crack growths at instability were determined to be between 1 and 2mm.

A sensibility analysis was performed. It could be seen that $F_i$ variation has more influence on the RSM curve than $P_i$ variation.

The critical loads determined for the $F_i$ variation from 0 to 120000N in the sensibility analysis were in all the cases less than plastic collapse loads, indicating the ductile tearing as the probable failure mechanisms of coiled tubing.

Acknowledgements

The authors wish to acknowledge CONICET, San Antonio Internacional, Universidad Nacional del Comahue (UNComa) and Universidad Nacional de la Patagonia San Juan Bosco (UNPSB) for the helpful support.

References

Anderson T.L. ,1995, Fracture Mechanics Fundamentals and applications. CRC Press, 2ndChapter 9, p 459.
ASTM E646-07 Standard Test Method for Tensile Strain-Hardening Exponents (n-Values) of Metallic Sheet Materials ASTM International.
ASTM E1820-08. Standart Test Method for Measuremente of Fracture Toughness ASTM International.
Chattopadhyay, J., Dutta,B.K., Kushwaha,H.S., 2000, Experimental and analytical study of three point bend specimen and through wall circumferentially cracked straight pipe, Int. Journal of Pressure Vessels and Piping 77 p 455.
Saxena,S., Ramachandra Murthy,D.S., 2007, On the accuracy of ductile fracture assessment of through-wall cracked pipes. Engineering structures 29, p 789.
Wainstein, J., Perez Ipiña, J., 2011, Fracture toughness of HSLA coiled tubing used in oil wells operations, Journal of Pressure Vessels Technology, ASME 2011, DOI: 10.1115/1.4004569.
Zerbst,U., Ainsworth,R.A., Schwalbe, K.H., 2000, Basic principles of analytical flaw assessment methods Int. Journal of Pressure Vessels and Piping 77 p 855.