Experimental measure and model validation of COD of cracked pipes under bending

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ABSTRACT. In order to apply the "Leak Before Break" (LBB) Analysis is very important to know the cracks area. Particularly for pipes under bending the area depends from crack position related to the bending plane.
Considering symmetrical cracks respect to the flexural plane cannot be a conservative assumption. In this work has been carried out an experimental investigation in order to evaluate COD distribution for off-axis cracks on pipes under bending. Have been tested pipes with different thickness and different cracks lengths and orientations. COD distribution has been monitored by digital image correlation (DIC). Experimental data have been used to validate an analytical model (HCM Hodograph Cone Method) previously proposed by the authors.

SOMMARIO. La conoscenza dell'area dei difetti in tubazioni pressurizzate è determinante per poter applicare la "LeakBefore Break" (LBB) Analysis. In particolare per tubi soggetti a flessione l'area dipende dalla posizione della cricca rispetto al piano di flessione. Nell'applicazione della LBB considerare la cricca in posizione simmetrica rispetto al piano di flessione non è necessariamente un'assunzione conservativa. Nel presente lavoro è stata condotta un'indagine sperimentale volta a determinare la distribuzione del COD in tubi in flessione per cricche fuori centro rispetto al piano di flessione. Sono stati testati tubi di differente spessore cricche di differenti lunghezze e con differenti angoli di fuori asse. La distribuzione del COD è stata misurata con metodi ottici (digital image correlation) e usati per validare un modello analitico (Metodo del Cono Odografo) precedentemente proposto dagli autori.

KEYWORDS. COD; Off-axis cracks; Pipes; DIC.

INTRODUCTION

The authors in previous works proposed a new methodology, the hodograph cone method, HCM, [1 - 4], to take into account the crack opening displacement (COD) distribution in order to estimate the flaw size for piping under bending.
The target was to apply the leak-before-break (LBB) approach to pipes system with cracks under bending and/or internal pressure. In this work a newest experimental investigation that confirm the previously results is presented.
Has been verified that the proposed method works very well for cracks symmetrically placed with respect to the bending plane since the maximum COD/COA, for given applied moment, is obtained in this configuration and the COD

distribution along the crack length is assumed elliptical according with several reference solutions such as GE-EPRI, [5]. However the proposed method is very useful also if the crack may result to be off-center with respect to the acting load. In this work the authors present a further experimental investigation in order to show that this method is very robust. Particularly experimental tests have been conducted in order to verify the model applicability to the off-centered, off axis cracks.

THE HODOGRAPH CONE METHOD

Here is presented shortly the HCM. Further details can be found in [1-4].
The geometrical locus of the COD distribution in a cylindrical pipe can be considered as an intersection between a cone and a cylinder. The cone represents an hypothetical 3D COD surface and the cylinder exemplifies the middle surface of the pipe. The cone has an elliptical base, with semi-axes equal to the half of the maximum COD, for given bending load, and half of the crack length projected on the COD tangent plane (Fig.1). The vertex is on the opposite side the pipe circumference with respect to the maximum COD (that is the height of the cone is equal to the pipe diameter), Fig. 1.

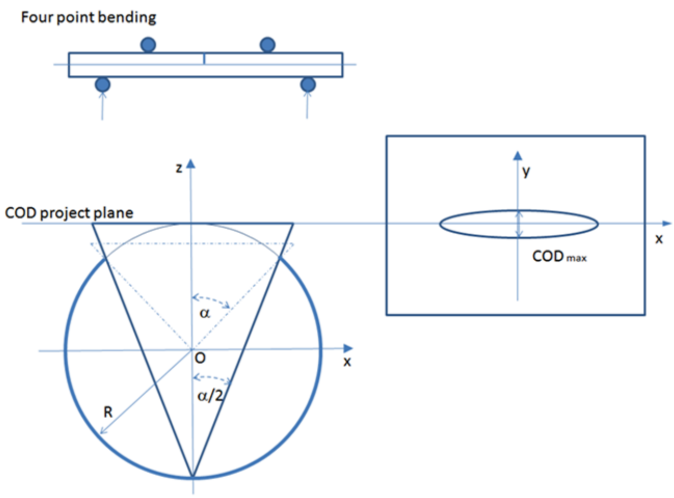


Figure 1: Geometric representation of the hodograph cone for the reference in-axis configuration, [1].

The intersection between the cone and the cylinder, that gives the COD distribution for a circumferential crack length 2αR and a generic off-center angle ϕ , is given by the following equations,

$$\begin{cases} y = \frac{b}{2}\left\{\left[\cos(\beta) + \cos(\phi)\right]^2 - \right. \\ \left. \left[\sin(\beta) - \sin(\phi)\right]^2 \tan^{-2}(\alpha/2)\right\}^{1/2} \\ x = R\sin(\beta) \\ z = R\cos(\beta) \end{cases} \tag{1}$$

where $\beta \in [-\alpha; +\alpha]$
When the crack is off-center, the COD cone vertex rotates along the cylinder circumference in the opposite direction, by an angle equal to that of off-center angle, Fig. 2.
According to this, crack closure stars when the crack goes in the compression region that is predicted to occurs at an angle that depends on the crack length such as,

$$\phi = \frac{1}{2}(\pi - \alpha) \tag{2}$$

Details on the derivation of these equations are given elsewhere, [1].

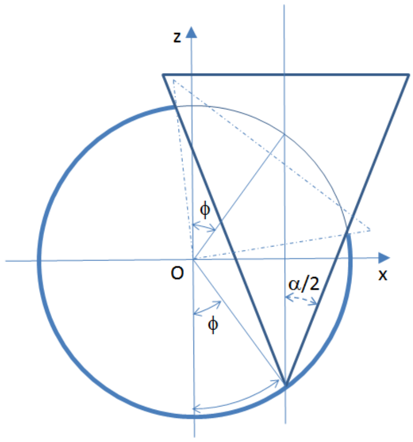


Figure 2: HCM for the generic off-center crack configuration [1].

EXPERIMENTAL MEASURE OF COD PROFILE

Only the initial experimental data, presented in [4], of COD profile for off-center cracks are available in the literature.

Therefore, an experimental investigation with the objective to provide data for the qualification of both the numerical simulation and the HCM, has been planned and carried out.

To this purpose and referring to GE-EPRI [5] code, have been tested two different thickness of pipe with two different cracks length and configuration. The crack length and the pipe thickness are positioned in range indicated by GE-EPRI: The ratio between the mean radius and the pipe thickness is between 5 and 20; the ratio of half crack angle α and π included between 0 and 0.55. On Tab. 1 is reported the tests configuration. Pipes have been tested under four point bending, Fig. 3.

The measure of the COD along the crack has been performed by means of the digital imaging correlation (DIC) system ARAMIS by GOM which ensure an accuracy on strain measurements of 0.01%. In order to allow speckle analysis the pipe surface was previously prepared as illustrated in [4]. The selected pipe was obtained by drawing and this ensure limited ovalization and constant thickness. The crack was machined using circular saw. As a result of this, the tip shape was squared with half-average distance between the crack faces of 0.5 mm. No fatigue pre-cracking was performed to sharp the tip radius since, at this stage, the interest was limited to the COD profile only and not to the material fracture resistance or stress concentration. However, it has been verified by FEM that the tip shape does not influence the profile or measure of the COD along the crack at least in the elastic range.

Configuration	Rm [mm]	t[mm]	α/π	ϕ(°)	Forza [N]
2a50T2	29	2	0.139	0, 30, 60	500
2a90T2	29	2	0.25	0, 30, 60	500
2a50T5	27.5	5	0.139	0, 30, 60	1500
2a90T5	27.5	5	0.25	0, 30, 60	1500

Table 1: Matrix test configuration.

Since the COD profile is a 3D locus in coordinate space, two cameras were used to determine the coordinates of the physical points, which are mapped onto the image pixels, to obtain deformation and strain comparing digital images at different times. An example of the acquired digital image of the near crack region is shown in Fig. 4.

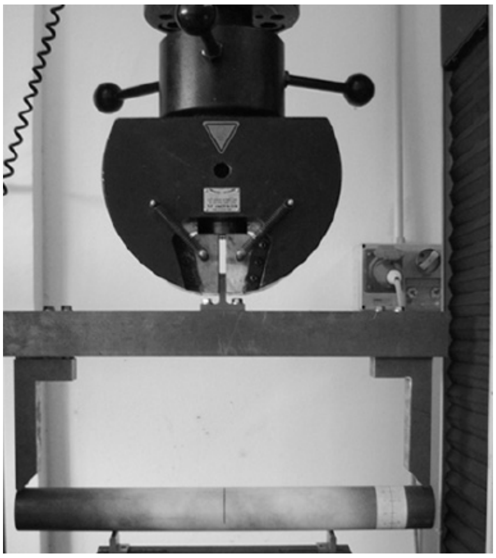
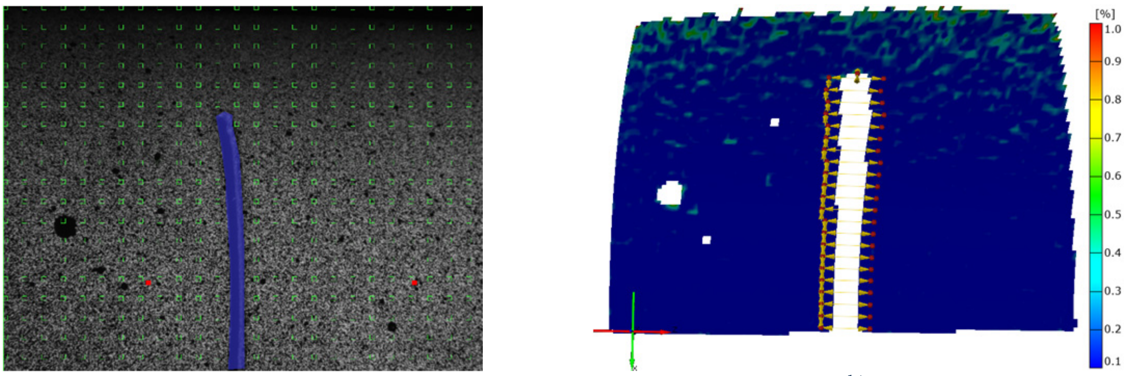


Figure 3: Pipe four point bend loading fixture. Picture shows pipe surface prepared with stochastic pattern for DIC measurement, [4].



a) b)

Figure 4: a) Detail of the pipe prepared for speckle analysis: the green squares are the facet and the lighter zone is crack; b) Computational strain by Aramis whit the virtual clip gauges in evidence (yellow arrows).

Results and discussion

The authors already presented the good agreement between the proposed model and the numerical solutions, [2-4]. Starting from this point and assuming that the maximum COD at the crack center δ_0 it is possible to evaluate the COD distribution using the following relationship, [4]:

$$\delta(\phi)=\frac{\delta_0}{4}\left\{\left[\cos(\beta)+\cos(\phi)\right]^2 - +\left[\sin(\beta)-\sin(\phi)\right]^2\tan^{-2}(\alpha/2)\right\}^{1/2} \qquad (3)$$

with the correction factor

$$\delta_0^* = \delta_0 \cos(\phi/\phi_0) \qquad (4)$$

where ϕ_0 is a factor that depends on the amplitude of the applied bending and crack length and it is equal to the ratio of half crack angle α and the off center angle for which there is half closure of the crack. This correction will be applied only for half crack angle greater than 45°.
The comparison between model and experimental results are reported in the following figures.

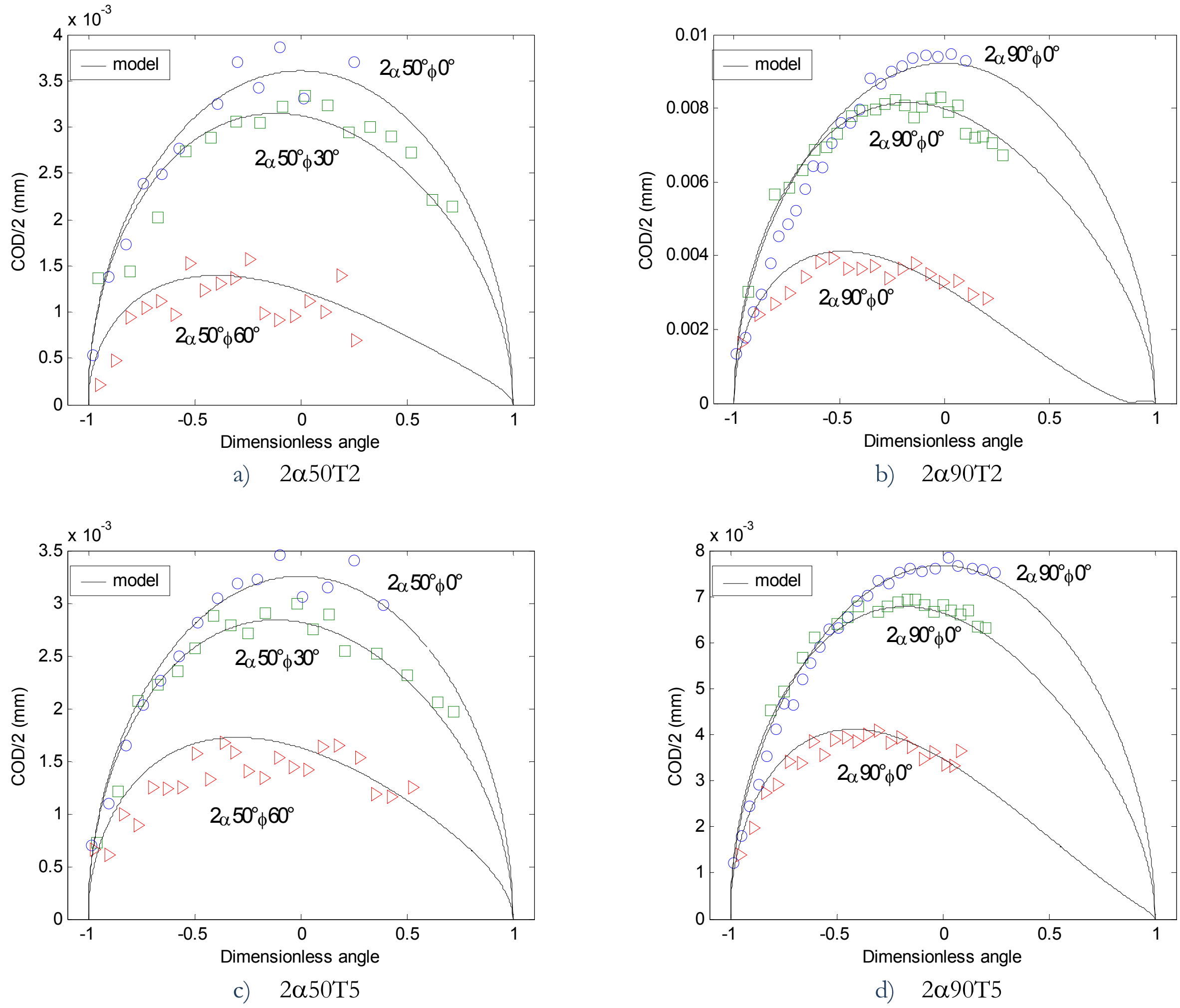


Figure 5: COD profile for all the configurations tested.

From Fig. 5 it is possible to note that all the test performed give a good agreement with the HCM theory also for cracks with off axis angle greater than 30° and half crack angle greater than 30°. This results confirm the conclusion emerged in [4] where has been shown the good agreement between the theory and the finite element calculation.
Finally, in Tab.2 the comparison between maximum COD calculated by GE-EPRI and the experimental values is reported. From the comparison it seems that decreasing the thickness and the crack length the error increases.

Configuration	GE-EPRI [mm]	Exp. measure (mm)	Error (%)
2α50T2	4.9E-3	7.2E-3	32
2α90T2	1.5E-3	1.8E-3	17
2α50T5	5.4E-3	6.5E-3	14
2α90T5	1.4E-3	1.5E-3	7

Table 2: Comparison between maximum COD calculated by GE-EPRI and the measured values

Further tests are at the moment in progress in order to better investigate the range of the off axis angle and also off plane cracks. Different thickness and different loads are under investigations. All the results will be presented as soon as possible.

CONCLUSIONS

In order to verify the proposed HCM model have been performed experimental tests on different pipes under bending. The results are in very good agreement with the proposed model and the numerical simulation previously performed by the authors, [4]. The measures have been done by DIC technique. The results indicate that the HCM is a robust method for evaluate the effective COD/COA for an off-centered configuration.
Also the GE-EPRI numerical solution seems that overestimates the experimental results for the lower crack length and pipe thickness tested.
In order to have an extensive experimental data base and also investigate the possibility to apply the HCM to the cracks with different angles respect to the pipe axis, further experiments are currently in progress.

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