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CRACK GROWTH BEHAVIOR OF CRACKED COPPER PIPES (12200) UNDER CYCLIC TORSION LOADS

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ABSTRACT

This work investigate a crack propagation and the direction of crack path due to cyclic torsion effect on the different crack inclination in thin pipes where mixed modes (I/II) have been considered to estimate crack direction, therefore a new rig has been manufactured to simulate the real service conditions of small bore pipes under different loads with ≈30 Hz (oscillation) which is suitable also to implement uniaxial and multi axial cyclic loads, however , cyclic torsion loads had been discussed in this study, so the experiments have been carried out concerning copper pipe (12200) under cyclic torsion load for specified stress ratio (R=-1) , and the results have been justified practically via crack trajectory that compared with previous well known formulas to illustrate the compatibility between these formulas and actual practice in real conditions. Moreover, state of art concept have been achieved by using previous theories regarding short crack and brittle material to be applicable with studied case for long crack in very ductile pipes. Good agreement has been received to demonstrate the validity of proposed rig for this kind of loads and the compatibility between previous theories with actual real service.

Keywords: cyclic torsion, copper pipe (12200), crack

INTRODUCTION

There are different mechanical components like piping system in practical implementation that are subjected to cyclic torsion load which cause a crack propagation in particular direction that leads to final fracture, so a new test rig has been proposed to study a crack growth and the path direction of long pre crack that introduced with two different inclination ($\propto = 60^0$ and $\propto = 90^0$) with respect to pipe axial axis; It is worth mentioning that the dimension of specimens were selected from real service conditions to be applicable and suitable also with specialized charts that had been established for long pipes with short crack to find out stress intensity factors (SIF), noting that a state of art concept has been considered in this work by introducing a long cracks in the specimens and using these charts (which established already for short crack), adding to this that one of the previous laws regarding crack direction that had been established for brittle plate were adopted in this work for ductile pipe.

New rig to test have been manufactured to be suitable under different uniaxial and multi axial cyclic loads, however the efforts have been focused on the cyclic torsion loads where the data monitored for each period as well as special graphs have been drawn to illustrate crack behavior, the motivation of this research is to proof the durability of the rig by estimation the direction of crack path to be compared with previous well known laws concerning this issue and demonstrate the compliance between real service and previous theories.

Reference [1] concluded that the crack extended in plate in the direction which is perpendicular on the maximum tension which was considered as satisfactory form for brittle material under plane loading and transverse shear. Reference[2] studied a mixed mode crack growth, and new empirical model had been proposed to guess crack path direction. Reference [3] investigated the crack growth direction in AISI 304L stainless steel under axial – torsional loads. Reference[4]considered crack growth path for plate specimen with two holes under mixed mode conditions with studying of residual life for the two dimensional structural elements.

Copper pipes (specimens) with the same dimensions in real service have been considered in this study and all mechanical and chemical properties were estimated, noting that there is lack of information regarding cyclic torsion effect on this type of copper pipe that selected to be suitable with the proposed rig with different crack inclination , where mode II and mixed mode I/II have been focused on.

EXPERIMENT PROCEDURE AND DATA MONITORING

The real service condition has been demonstrated in Figure(1) and this condition simulated in the new rig where the important portion exhibited in Figure2, so the reciprocated slider acting on the action shaft to twist the specimen where the oscillation of twisting was equal to around 1830 r.p.m. , noting that the process was governed by control system, It is worth mentioning that the procedure includes several steps and as indicated hereunder:

Firstly cracks have been introduced in pipes in such away the crack was through toward inside portion. Secondly the specimen settled in the rig and the limitation pads adjusted in such away the displacement governed to be checked and measured again during the test by mechanical and digital caliper, subsequently, this displacement

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Ø substituted in the following formulas which indicated in reference [5].

$$\tau = r_o \frac{G\emptyset}{L}$$ ....(1)

τ=shear stress (Mpa)
r_o=outside radius (m)
G=shear modulus (Gpa)
$\emptyset$=angle of twist (rad.)

An incremental in crack lengths recorded at each period to be discussed by figures, where the rig was turned off each period, according to crack propagation to be monitored easily If total crack length (a) reaches to around 8 mm after growth at each side (i.e. 2a≈16 which is equal to around 40% of specimen circumference) the displacement will be changed suddenly and Mode III appeared , so any readings of crack increment have not been considered out this range and the test should be stopped where the fracture will be occur after very few seconds and the number of cycles (N)

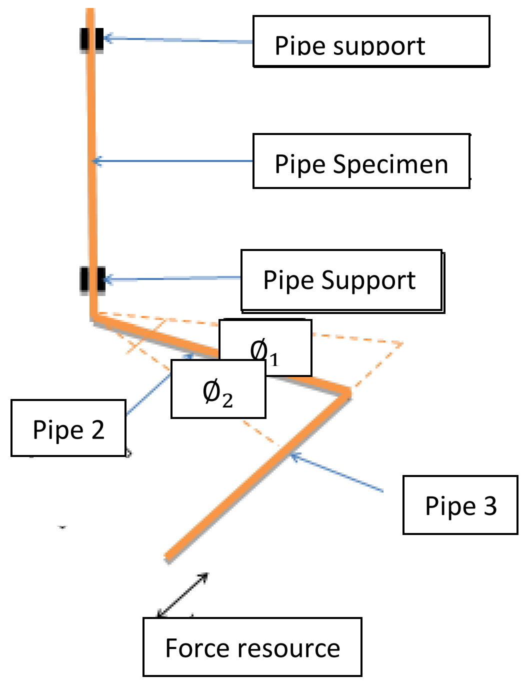

Figure1. Piping system under real service conditions

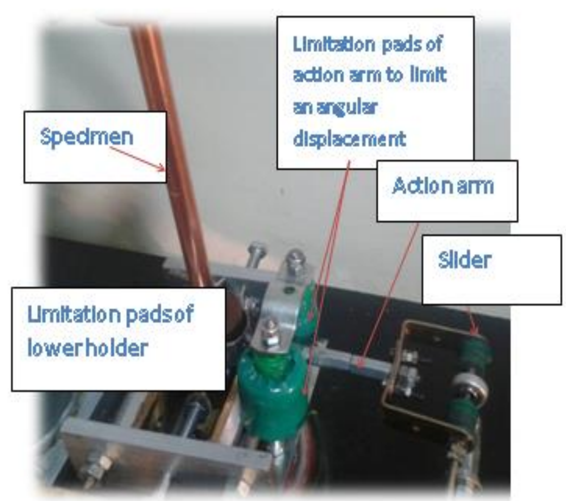

Figure 2. Important portion in the rig that simulate the real service conditions

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Table 1: Mechanical and chemical properties

Mechanical properties				
Yield point stress (Mpa) , $\sigma_{y.p.}$	Ultimate stress (Mpa) , $\sigma_{ult.}$		modulus of rigidity (Gpa) , G	Plane strain toughness , K_{IC}
240	269.5		43.583	90
Chemical properties				
Zn%	Pb%	P%	Fe%	Al%
0.0062	0.0205	0.0376	0.0127	0.0221
S%	Ni%	Bi%	Sb%	Cu%
0.0116	0.0052	0.0147	0.114	≈99

should be recorded to be discussed via figures. For considered specimen, gauge length was equal to (180 mm) , the wall thickness equaled to 0.7 mm and outside diameter equaled to 12.6 mm. The angular displacement $\emptyset_1$ and $\emptyset_2$was equal to (0.0367 rad.), i.e. shear stress (τ) equal to 55.92 Mpa , so according to Von mises criteria the yield shear strength should be determined from tensile yield stress and $\tau_{y.p.} = \sigma_{y.p.}/\sqrt{3}$ whereas Tresca stated that $\tau_{y.p.} = \sigma_{y.p.}/2$ [6], therefore $\tau = 0.4\, \tau_{y.p.}$ and $\tau = 0.466\, \tau_{y.p.}$ according to above criteria respectively, adding to this that initial surface crack length ($2a_i$) was equal to 6.94mm for $\propto=90^0$ and ($2a_o$) was equal to 7.4mm for α=60, So the crack grew after test commencement in the left hand side (LHS) and right hand side (RHS) toward upper crack (UC) and lower crack(LC) with different growth behavior and as shown in Figure(3) and Figure(4). In other word the cracks branched in four different directions. It is evident that cracks were branched from different points at each side regarding $\propto=60^0$, noting that the crack non uniformly grew at both sides and this phenomena had been observed also by [7], so the change of growth is a property of the material microstructure itself and this change maybe observed in the same specimen at both sides and as stated also by reference [8].

ANALYTICAL PART

The experiments have been analyzed to confirm the validity of the rig and its results, moreover, crack trajectory has been investigated by using maximum tangential stress theory that proposed by Erdogan-Sih [1], as well as empirical formula that proposed by Richard. It is worth mentioning that special curves had been established by H.V. Lakshminarayana and M.V.V.Murthy [9] and used in this study by finding out specified constant β to be considered with curves to find out stress intensity factor (SIF) for (mode I) and (mode II) for these different crack inclination thereafter substituted in above mentioned formulas and as indicated hereunder:

$$\beta^2 = \frac{a^2}{8rt}[12(1 - \upsilon^2]^{0.5} \qquad (2)$$

β = specified constant from which the SIF will be found, a= initial crack (m), t= Wall

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thickness (m) , υ = poisons ratio= 0.33 and r=mean radius $(\frac{Outside\ diameter-t}{2})(m)$

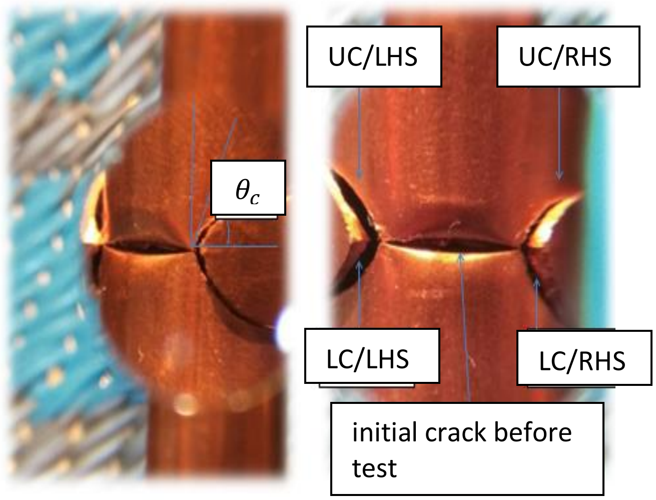

Figure 3. Illustrates a sample of crack path due to torsion cyclic load for the case of ∝=90

Figure 4. Illustrates a sample of crack path due to torsion cyclic load for the case of ∝=60.

Table 2: Required factors for K_I and K_{II}

Factors	For ∝=60	For ∝=90
$\frac{K_I^{(m)}}{\sigma\sqrt{a}}$	1.44	0
$\frac{K_{II}^{(m)}}{\sigma\sqrt{a}}$	-1	- 1.4
$\frac{K_I^{(b)}}{\sigma\sqrt{a}}$	-0.8	0
$\frac{K_{II}^{(b)}}{\sigma\sqrt{a}}$	-0.17	- 0.6

$$K_I^{eff}=K_I^{(m)}+0.5K_I^{(b)}=K_I \qquad (3)$$

$K_I^{(m)}$ = membrane stress intensity factor

$$K_{II}^{eff}=K_{II}^{(m)}+0.5K_{II}^{(b)}=K_{II} \qquad (4)$$

/mode I (Mpa$\sqrt{m}$)
$K_{II}^{(m)}$ =membrane stress intensity factor /mode II (Mpa$\sqrt{m}$)
$K_I^{(b)}$ = bending stress intensity factor / mode I (Mpa$\sqrt{m}$)
$K_{II}^{(b)}$ = bending stress intensity factor / mode II (Mpa$\sqrt{m}$)
K_I^{eff} =effective stress intensity factor / mode I (Mpa$\sqrt{m}$)
K_{II}^{eff} = effective stress intensity factor / mode II (Mpa$\sqrt{m}$)

Maximum tangential stress formula (MTS) for Erdogan-Sih is:

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$$\theta_C = \pm arccos\left(\frac{3K_{II}^2+K_I\sqrt{K_I^2+8K_{II}^2}}{K_I^2+9K_{II}^2}\right) \quad (5)$$

Empirical formula for Richard is:

$$\theta_c = \pm\left[155.5^0\frac{|K_{II}|}{|K_I|+|K_{II}|}\right] - 83.4^0\left[\frac{|K_{II}|}{|K_I|+|K_{II}|}\right]^2 \quad (6)$$

$\theta_c =$ angle of crack growth according to crack line(degree)

It is evident that above mentioned formula depend on Mode I and Mode II and insensitive to Mode III, noting that any reading of crack incremental within mode III existence does not used, and only mode I/II considered to estimate crack direction in this work.

RESULTS AND DISCUSSION

Based on the observed reading of increasing in crack lengths, important graphs have been illustrated to be discussed with each branch where each curve has incremental profile, i.e. the slope of curve increased due to cycles increasing and this is obvious state and branching of crack appeared as a consequence of stress ratio (R=-1) [10] , and in case of R=0 branching will not observed. However , for the case of ∝=60 upper crack (UC) on the right hand side (RHS) represent the most dangerous state and lower crack (LC) on the left hand side (LHS) represent the least dangerous state, noting that the cracks on both sides tend to grow from crack tip which was sharp , whereas UC/LHS and LC/RHS did not grow from crack tip, so it were short, see Figure(5).

Regarding the case of α=90 upper crack (UC) on the left hand side (LHS) represent the most dangerous state and lower crack (LC) on the left hand side (LHS) represent the least dangerous state, see Figure(6), and as mentioned previously that the crack might be grew non uniformly at both sides and this phenomena had been observed by other researchers due to property of the material microstructure itself , adding to this that crack growth direction was different at each branch (but within acceptable regime concerning θ_c).

It is clear that the case of ∝=60 was less dangerous than the case of ∝=90 (in spite of that the length of the first case was more) due to the fact that the effect of cyclic torsion dispersed into two modes (I/II), whereas cyclic torsion modes concentrated upon one mode (II) regarding the case of ∝=90.

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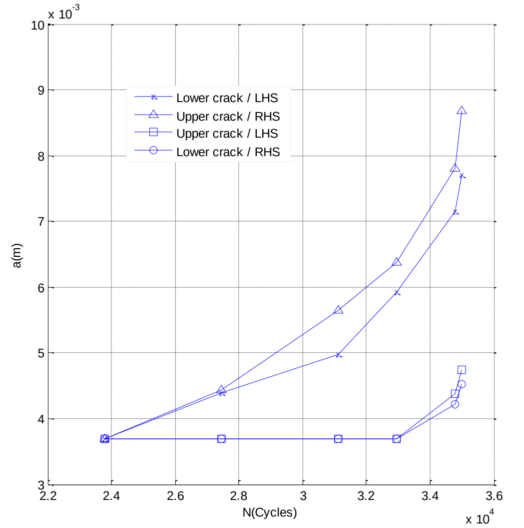

Figure 5.Crack Growth (case of ∝=60)

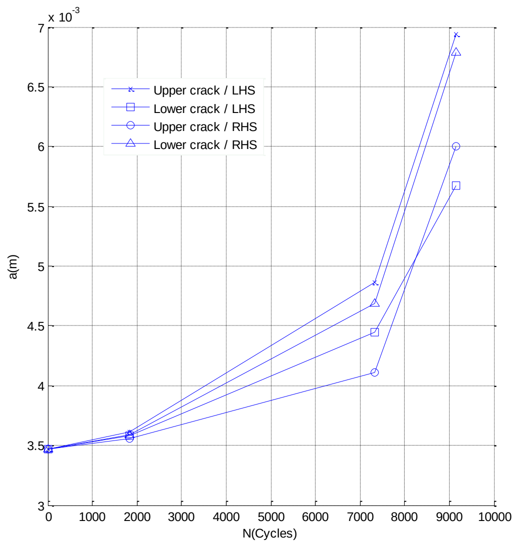

Figure 6.Crack Growth (case of ∝=90)

Table 3: θ_c Experimental and θ_c Analytical (∝= 90)

Branch	θ_c experimental	θ_c analytical	Err. (%)
UC /LHS	60^0	70.52 (Erdogan-Sih)	14.9
		72.1 (Richard)	16.7
LC /LHS	64^0	70.52 (Erdogan-Sih)	9.2
		72.1 (Richard)	11.2
UC /RHS	70^0	70.52 (Erdogan-Sih)	0.73
		72.1 (Richard)	2.9
LC /RHS	65^0	70.52 (Erdogan-Sih)	7.8
		72.1 (Richard)	9.8

Table 4: θ_c Experimental and θ_c Analytical (∝= 60)

Branch	θ_c experimental	θ_c analytical	Err. (%)
LC /LHS	60^0	53.76 (Erdogan-Sih)	11.6
		57.65 (Richard)	4
UC /RHS	60^0	53.76 (Erdogan-Sih)	11.6
		57.65 (Richard)	4

CONCLUSIONS

It is evident from above outcomes that Erdogan-Sih formula gives better results to guess crack growth direction, for the case of ∝=90 noting that good agreement has been received also from Richard formula , on the other hand Richard formula was better concerning the case of ∝=90 with good agreement for both methods regarding both cases. It is worth mentioning that Erdogan-Sih established for brittle plate under mixed mode conditions and in this study very ductile pipe considered with good agreement. Moreover, H. V. Lakshminarayana and M. V. V. Murthy established the special curves for initial small length crack and these curves have been used in this work for initial long length crack ($2a_i$ ≈17% of specimen circumference) with good agreement also.

It is evident also that the case of ∝=60 was less dangerous than the case of ∝=90 . According to above mentioned results the durability of the new test rig confirmed to test this type of pipes under real service conditions, and actual practice is compatible with previous theory.

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