The Effect of Cyclic Bending Loads on Crack Growth in Pipes for Inclined and Transverse Cracks with or Without Internal Pulsing Pressure

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ABSTRACT

In the present research a new test rig has been proposed to be suitable for different cyclic loads such as cyclic bending, cyclic torsion, proportional and non proportional loads. In this work the efforts were concentrated on the cyclic bending loads concerning cracked pipes with or without internal pulsing pressure to study crack propagation in small bore pipes (up to 1") for transverse or inclined cracks. The rig simulates the real service conditions under different stresses by means the least dangerous case will be suggested, so the experiments were considered for copper pipe, and the results have been tabulated and drawn to demonstrate the crack growth behavior as well as to justify the outcomes practically, consequently the durability of this new rig has been confirmed with new concluded facts.

Key words: cyclic bending load, copper pipe, crack growth

تأثير احمال الحني الدورية على نمو الشق في الانابيب التي فيها شقوق مائلة او العرضية بوجود او عدم وجود الضغط النبضي الداخلي

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الخلاصة

هذه الدراسة تقترح جهاز مستحدث بحيث يكون ملائم لتسليط انواع حمل عديدة مثل احمال الحني الدورية واحمال اللي الدورية والاحمال التناسبية والغير تناسبية الدورية ، لكن في هذه الدراسة تم التركيز على احمال الحني الدورية لعينات من الانابيب فيها شق بدائي بوجود او عدم وجود ضغط نبضي داخلي لدراسة نمو الشق في الانابيب ذات القياسات الصغيرة (الى قياس(1) بوصة) للشقوق العرضية اوالشقوق المائلة والتي تحاكي واقع الحال لانواع مختلفة من الاجهادات بحيث يتم اقتراح الحالة الأكثر أمانا. لذا تمت التجربة على أنابيب النحاس ومن ثم جدولة ورسم النتائج الخاصة بنمو الشق لتوضيح تصرف هذا الشق وتبريرهذه النتائج بصورة عملية لاثبات متانة هذا الجهاز المستحدث والحصول على حقائق واستنتاجات جديدة .

1. INTRODUCTION:

There are many mechanical components that are subjected to cyclic loads that lead to damage such as crack that may propagate till final rupture. Pipes are one of the such components that are used in several industrial units like oil field, plumbing, air conditioning and refrigeration…..etc., and for this reason a new test rig has been designed and manufactured to investigate a crack growth for different stress ratio (R). This new rig is suitable to test the pipe under proportional cyclic loads , non proportional cyclic loads, bending cyclic loads and torsion cyclic loads with a little bit changes in some simple parts according to each case but in this study the efforts have been concentrated on the cyclic bending loads, a little consideration will show that the pipes that are used in real service conditions might be defected already due to shipment or sharp tool marks that cause transverse or inclined crack which may not be observed, so the dangerous state of pipe behavior will be estimated under different loads before rupture , in other words , diagnosis of the metal state seriousness as soon as possible , taking into account that the crack growth direction (θ_c) might be examined for each state, adding to this that the test rig designed to simulate the real service of pipes and the used specimens have the same dimensions in actual practice to monitor the behavior of crack growth in pipes, so the main goal of this research is to verify the results of this new rig to be reliable as a useful device .

Pavlou D.G. 2000 focused on the direction of mixed mode crack propagation for inclined crack in plate (which was included already in the specimen before test commencement), so the main conclusion demonstrates the clockwise direction of crack initiation angle as well as mode that had been considered only for crack growth prediction. **Robertson S.W. and et al, 2006** investigated crack growth properties of the super elastic alloys and a sample which cut from Nitinol tube with different orientation as a compact tension specimen (new test samples) that is used under cyclic uniaxial load as well as different orientation had been discussed. **Boljanovic Slobodanka and Maksimovic Stevan, 2014** sstudied mixed mode crack propagation in plate specimen with two holes regarding crack path and life estimation, so good agreement was observed between experiments and finite elements work.

1Generally there is no standard rig for cyclic load experiments, therefore, researchers build a rig that meets their requirements, noting that the results of two different test rigs are hard to compare, **Pauw J.De, et al, 2011.** In this study an increasing of crack length due to cyclic loads has been observed against number of cycles and the transverse crack and its inclination effect has been considered also for copper pipes as a type of multiaxial cyclic stress case due to force analyzing that caused mixed mode case, and the state of art concept had been studied for another specimen that gathers an applied remote stresses and internal pulsing pressure as an overload state. Cyclic load test rig is based on two main issues, the first is the configuration of a test specimen and the second is an increasing the functionalities, **Pauw J.De, et al, 2011**. So in this study the specimen configuration has been illustrated accordingly.

Carful tests for several material were studied via previous works regarding crack growth data that ranged within the regime (from about 10^{-4} to 10^{-2} mm/cycles), **Ragab, A. and Bayoumi, S., 1998**. Other opinions were ranged between (10^{-6} and 10^{-3} mm/cycles), **Vethe, S. 2012,** and these results for the specimens under cyclic tension loads, so it is obvious that the results near 10^{-4} refers to the slow crack growth as well as a very good toughness of the material and any crack growth data within same range represent a bonus of the rig outcomes.

A little consideration will show that the crack growth were non uniform at both sides and the phenomena had been observed by **Rozumek Dariusz and et al**. **2008**. As well as the change of growth is a property of the material microstructure itself and this change might be observed in the same specimen at both sides as stated also by **Hos Y. and Vormwald M. 2015**.

2. EXPERIMENT WORK:

The new manufactured rig consists of rig base (0.6x60x105)cm , electrical motor (1.5 HP) and the power transmitted via pulleys and belts to the crank shaft that transmitted this power to the specimen via action shaft where the oscillation of the specimen was equal to around 1800 rpm, so the process was governed by control system . Pumping system equipped also to introduce an internal pulsing pressure with 1800 rpm as in **Fig.1**. It is worth mentioning that the procedure includes several steps and as indicated here under:

1. The crack had been introduced in pipes and the crack was partly through toward an inside portion, as in **Fig.2**. In other word the crack already was existent and after test commencement the crack grew due to cyclic load.

2. The specimen settled in the rig and the limitation pads arranged in such away the displacement was equal to (3.25 mm) that checked and measured again during the test by mechanical and digital caliper.

3. After several minutes of a test commencement the crack grew toward inside a pipe (i.e. through the thickness), thereafter a crack initiation was observed on the specimen surface such that the crack lengths have been recorded as the following tables, to be investigated and clarified by drawing (a) against (N). It is worth mentioning also that the rig was turned off each period according to crack growth rate to be possible an observation of crack lengths increment.

4. The displacement substituted in the following formulas, **Hearn , E. J. , 1981.** to find out the load and the direct stress .

$$(load)w = \frac{3EIx}{l^3} \tag{1}$$

$$(direct\ stress)\sigma = \frac{My}{I} = \frac{(wl)y}{I} \tag{2}$$

5. In case of internal pulsing pressure the air media entered via specimen upper hold and the pump turned on that synchronized with turning on the electrical motor, so the pressure was equal to (1 Mpa) which represents small value comparing with applied remote stress to demonstrate the clear difference of crack growth behavior due to internal pressure, so the hoop stress was estimated to be equaled to (8 Mpa) by using the following formula, **Hearn, E. J., 1981.**

$$\sigma_h = \frac{PD}{2t} \tag{3}$$

Noting that the dimension of all specimens were 180 mm (gauge length), 12.6mm (outside diameter) and 0.7mm (wall thickness), so all specimens were classified as thin pipe, and the copper pipe was tested in laboratory to find out mechanical and chemical properties that indicated in **Table 1.**

For displacement (x) = 3.25 mm the applied remote stress was equal to(219.77 Mpa), i.e. around 91% of $\sigma_{y.p.}$ to accelerate the test as much as possible in such away the crack monitored carefully.

Three cases of specimens have been considered, the first was pre cracked specimen (i.e. the crack introduced before test commencement) with transverse crack length (2a) equal to 6.48 mm, the second was similar to the first specimen with hoop stress equal to 8 Mpa, and the third was pre cracked specimen where the crack (2a) was inclined by 30^0 to get clear reading regarding(θ_c) and crack length was equal to 6.48 mm also, so these three different specimens were considered to demonstrate the less dangerous state.

2.1. Specimen (1)

After (around 32.5) minutes of the test commencement, the crack completely grew through the thickness and after around 0.5 minutes the crack initiation has been observed on the specimen surface such that the crack lengths have been recorded as indicated in **Table 2**.

2.2. Specimen (2)

After (around 27.5) minutes of the test commencement , the crack completely grew through the thickness and after around 0.5 minutes the crack initiation has been observed on the specimen surface such that the crack lengths have been recorded as indicated in **Table 3**.

2.3. Specimen (3)

After (around 18.5) minutes of the test commencement, the crack completely grew through the thickness and after around 0.5 minutes the crack initiation has been observed on the specimen surface such that the crack lengths have been recorded as indicated in **Table 4**.

The experiments were analyzed to verify the durability of the new test rig to illustrate new facts about a damage models and as indicated here under:

1. Regarding the above mentioned crack growth data for specimen (1) under cyclic bending loads that affect the element by the same way of the cyclic tension loads the outcomes was equaled to around 10^{-4} (i.e. within the same acceptable regime), adding to this that the crack path was approximately perpendicular to the applied remote tensile stress in this case, **Qian , J. and Fatemi A. , 1996,** as seen in **Fig.3**.
2. Regarding the specimen (2), hoop stress equal to 8 Mpa that was implemented to accelerate crack growth as overload case that was considered besides to the external cyclic bending load which was equal to 219.77 Mpa, noting that the existence of the internal pulsing pressure must be more dangerous because the overload increment even though the hoop stress tend to close the crack for a particular period.

3. Regarding specimen (3) the crack initiated in the clockwise direction and at angle was equal to 58^0 due to mixed mode existent, however, the direction of crack growth for this specimen under cyclic load and monotonic load is approximately the same**, Pavlou D.G. 2000**, and according to special curves that proposed by **H.V. Lakshminarayana and M.V.V. Murthy, 1976**, and regarding to the specified constant β the following formulas had been considered to find out stress intensity factor (SIF) of (mode I) and (mode II) from the special curves which is suitable with studied case .

$$\beta^2 = \frac{a^2}{8rt}[12(1-\vartheta^2]^{0.5} \quad (4)$$

$$\frac{K_I^{(m)}}{\sigma\sqrt{a}}=1.2 \quad (5)$$

$$\frac{K_{II}^{(m)}}{\sigma\sqrt{a}}=0.35 \quad (6)$$

$$\frac{K_I^{(b)}}{\sigma\sqrt{a}}= -\ 0.12 \quad (7)$$

$$\frac{K_{II}^{(b)}}{\sigma\sqrt{a}}=1.25 \quad (8)$$

$$K_I^{eff}=K_I^{(m)}+0.5K_I^{(b)}=K_I \quad (9)$$

$$K_{II}^{eff}=K_{II}^{(m)}+0.5K_{II}^{(b)}=K_{II} \quad (10)$$

Via two main formulas the direction of crack growth regarding the line of crack that were defined with positive value in counter clockwise direction and the reverse is also true,so θ_C were estimated either by the following formula that used by, **Blazic, M. et al, 2014**.

$$\theta_C = 2tan^{-1}\left(\frac{K_I}{4K_{II}} - \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2+8}\right) \text{ for } K_{II} > 0 \quad (11)$$

Or by using this hereunder formula that used by**, Vethe, S. June 2012**.

$$\theta_C = -arccos\left(\frac{2K_{II}^2+K_I\sqrt{K_I^2+8K_{II}^2}}{K_I^2+9K_{II}^2}\right) \quad (12)$$

Where the durability of this new rig has been verified again via the result of specimen with inclined crack .

4. RESULTS AND DISCUSSION:

Based on the received data that monitored from experiments for different scenarios that are indicated in **Table 5**, several important figures have been established to be discussed accordingly.

Regarding **Fig.4** the differences between two cracks at left hand side (LHS) and right hand side (RHS) was less with respect to specimen (2) for overall curves, in the other hand the difference was more regarding specimen (1), so the internal pulsing pressure made a convergence between LHS and RHS curves due to the fact that the hoop stress try to close the crack from 30 minutes to 48 minutes and this action led to crack growth deceleration up to a point for this period and the cracks at both sides of specimens has enough time to grow closely, while the more divergence had been observed for the case of transvers crack without internal pulsing pressure among these three specimens where the change of growth is a property of the material microstructure itself and this change might be observed in the same specimen at both sides as demonstrated by **HosY. and Vormwald M. 2015,** so it is normal phenomena, a little consideration will show that the first reading of initial crack increment (which is very short compared with other reading) was not clear and classified as threshold stage and this is common problem.

Regarding **Fig.5** the cracks at LHS and RHS, the initiation of crack propagation observed clearly and earlier for specimen (3) compared with other specimens due to shear existence beside direct stress which resulted from crack inclination. In the same context the crack initiated for the case of transverse crack with internal pulsing pressure earlier than the case of the transverse crack without internal pulsing pressure, but the crack lengths increment due to cyclic load was more in the case of the pressure existence compared with other specimens despite the crack deceleration for particular period (from 30 to 48 minutes) thereafter the crack grew dramatically. In the other hand the increment of crack lengths in the case of inclined crack was less among these three specimens where the effect of opening mode decreased where this mode represent the most effective mode for crack growth comparing with other well-known modes (shearing mode and tearing mode).

The direction of the crack angle that grew in the specimen (1) and (2) to be approximately perpendicular to the applied tensile load due to bending, and the direction of crack initiation of specimen (3) was estimated according to eq.11 and eq.12 to be verified. A little consideration will show that θ_C will be observed due to crack inclination thereafter the crack grew in the direction to be approximately perpendicular to the applied bending load and this is normal phenomena that is observed in previous similar cases. This I shown in **Table6.**

5. CONCLUSIONS

1. In spite of implementation 91% of $\sigma_{y.p.}$ concerning specimen (1), the crack grew slowly to be equal to about 10^{-4} mm/cycles due to the fact of the high toughness for this type of copper pipe.

2. Despite crack initiation of specimen (3) earlier than other specimens, this case of inclined crack represents the least dangerous state, and the case of transverse crack with internal pulsing pressure represents the most dangerous state among other specimens.
3. Concerning the case of inclined crack, it will be more sensible to use the equation (12) to guess the crack direction because the error between experimental and analytical part was around 0. 97 %.
4. The durability of the new test rig has been confirmed according to above mentioned outcomes to illustrate the compatibly between previous opinions and actual practice.

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NOMENCLATURE :

a=crack length (mm)

β = specified constant from which the stress intensity factor will be found according to each mode

σ =direct stress (Mpa)

σ_h =hoop stress (Mpa)

D=Inside diameter(m)

E=young modulus (Gpa)

I=moment of inertia (m^4)

$K_I^{(m)}$ = membrane stress intensity factor for mode I (Mpa$\sqrt{m}$)

$K_{II}^{(m)}$ = membrane stress intensity factor for mode II (Mpa$\sqrt{m}$)

$K_I^{(b)}$ = bending stress intensity factor for mode I (Mpa$\sqrt{m}$)

$K_{II}^{(b)}$ = bending stress intensity factor for mode II (Mpa$\sqrt{m}$)

$K_I^{eff} = K_I$ = effective stress intensity factor for mode I (Mpa$\sqrt{m}$)

$K_{II}^{eff} = K_{II}$ = effective stress intensity factor for mode II (Mpa$\sqrt{m}$)

l=gauge length(m)

M=bending moment (N.m)

N=number of cycles (r.p.m.)

P=Internal pulsing pressure (Mpa)

r=mean radius ($\frac{Outside\ diameter-t}{2}$)$(m)$

R= stress ratio ($\frac{\sigma_{min}}{\sigma_{max}}$)

SIF= stress intensity factor (Mpa$\sqrt{m}$)

t=Wall thickness (m)

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

w=required load to cause a displacement (N)

ϑ = poisons ratio =0.33

x=linear displacement (m)

y=$\frac{\text{Outside diameter}}{2}$ (m)

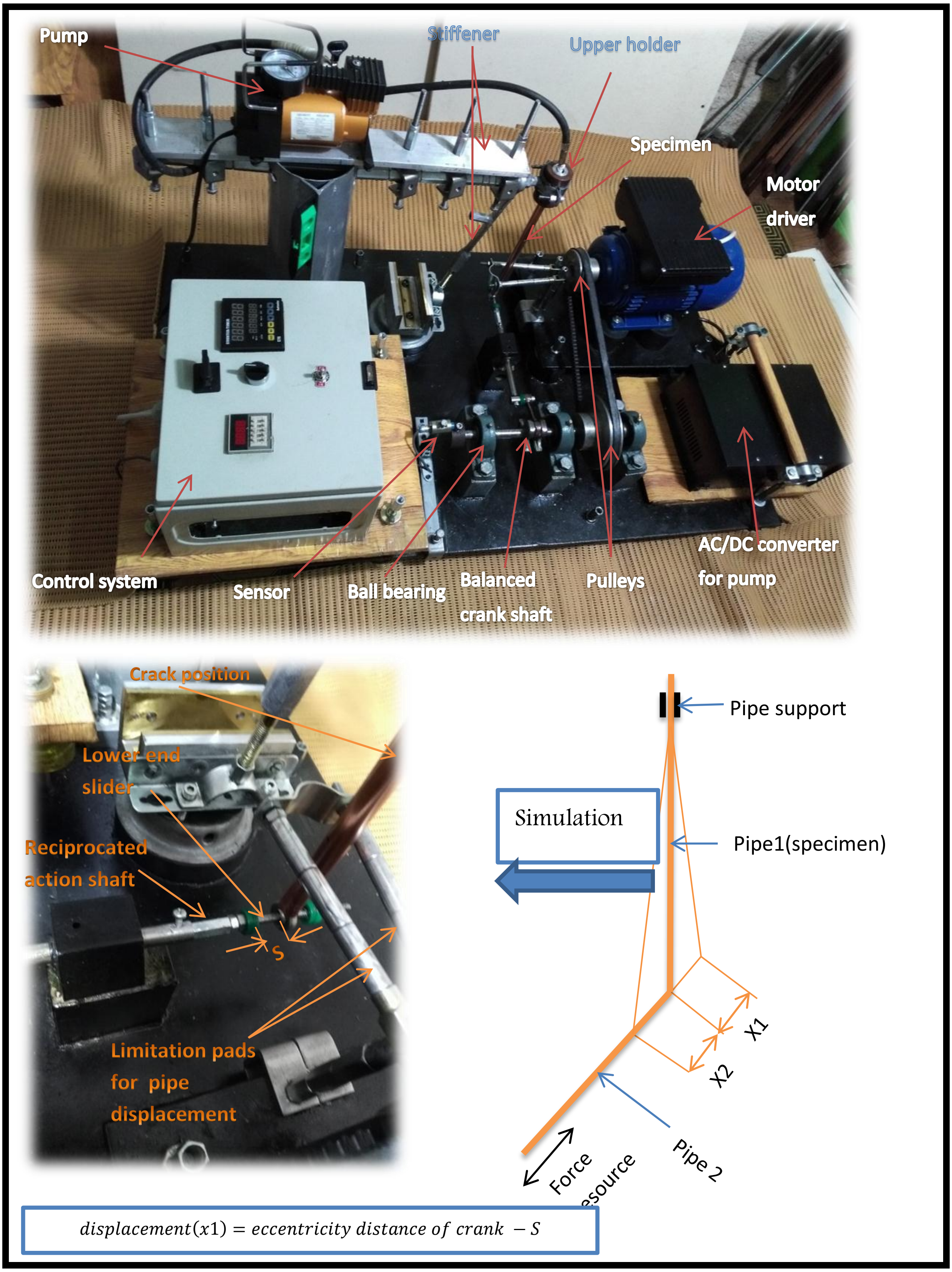


Figure 1. New test rig with its simulation form.

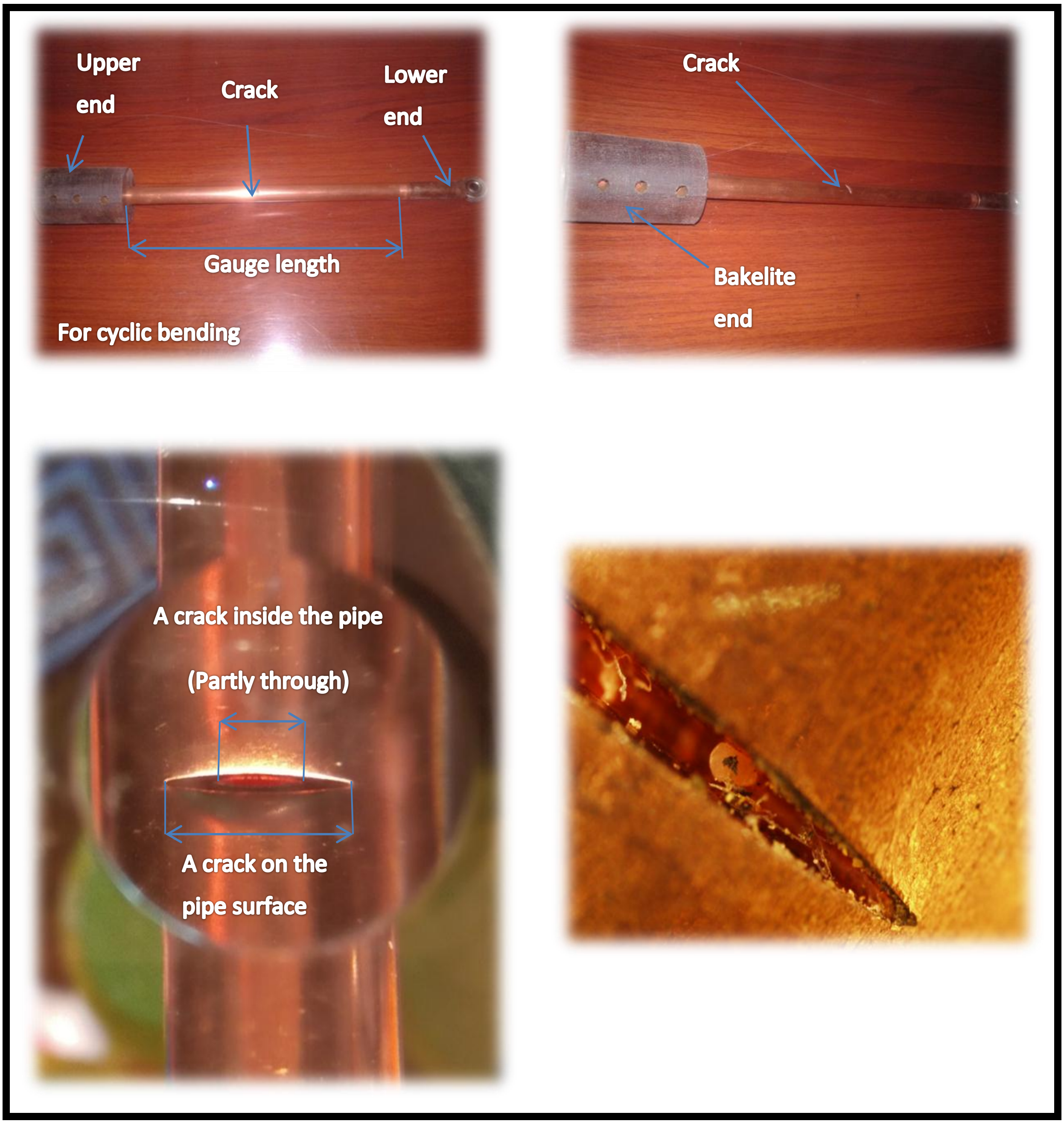


Figure 2. Specimen shape.

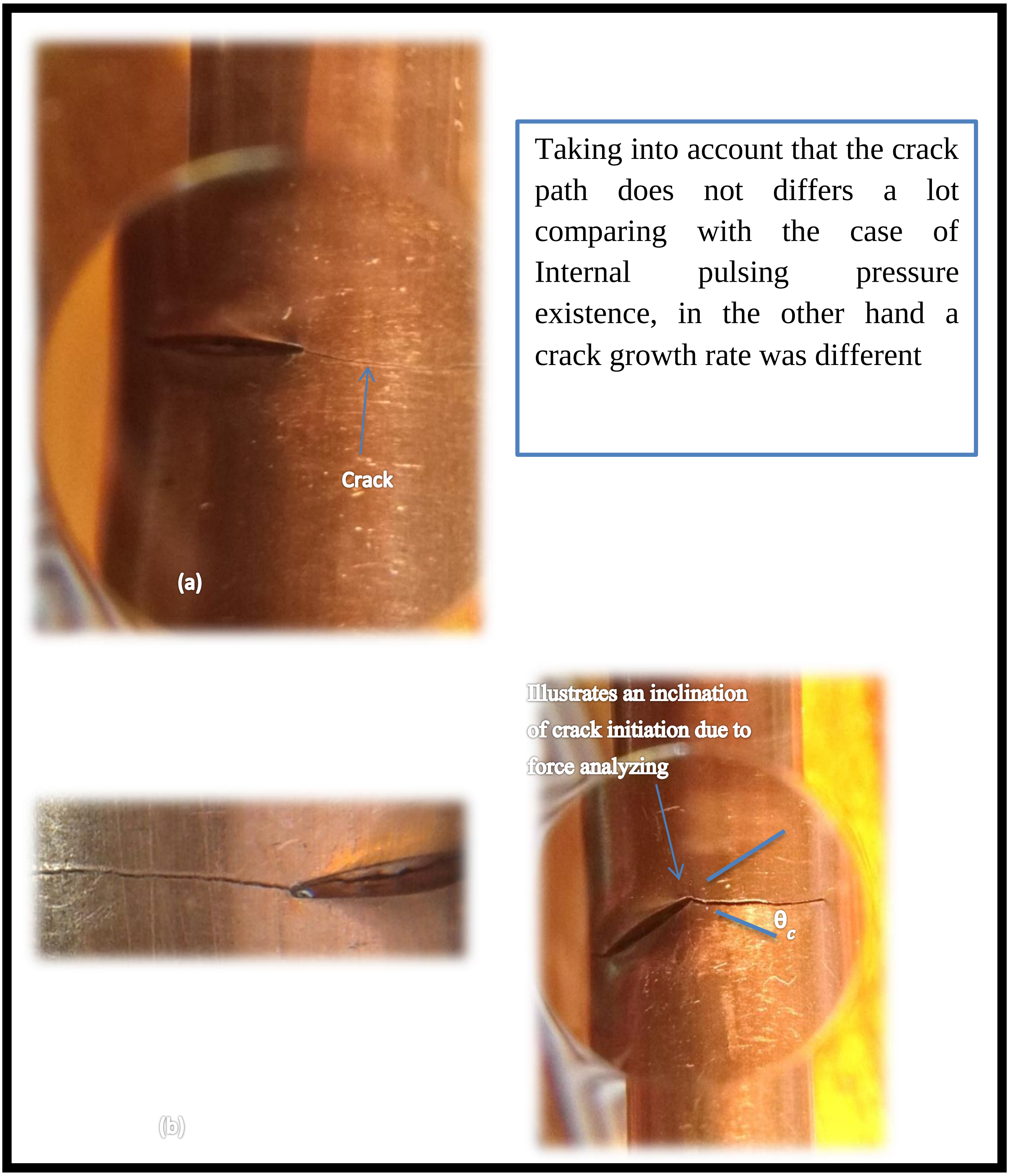
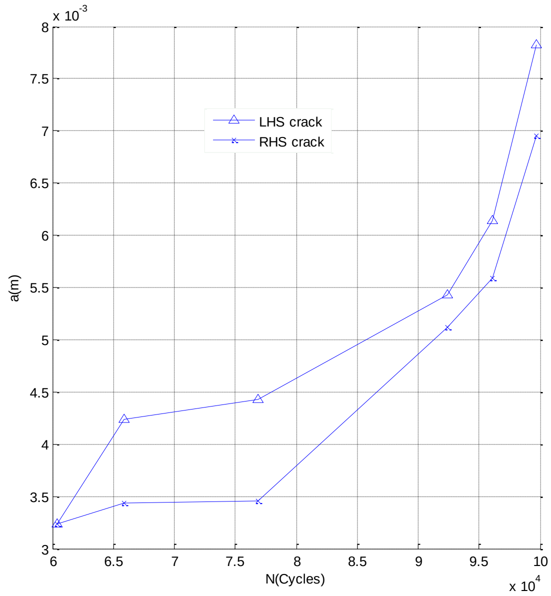
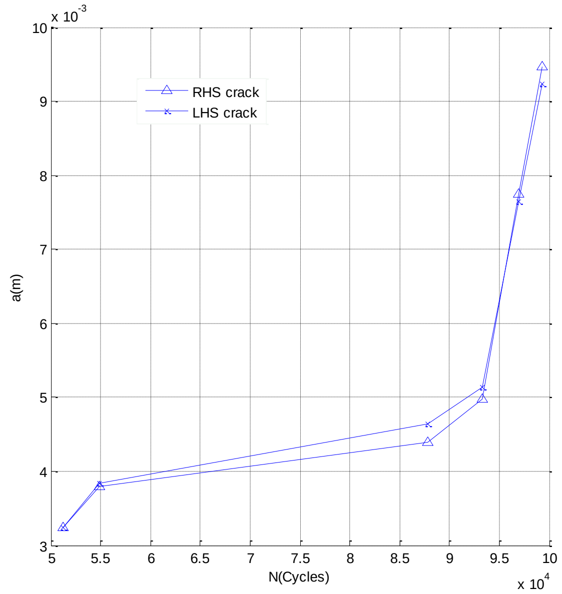


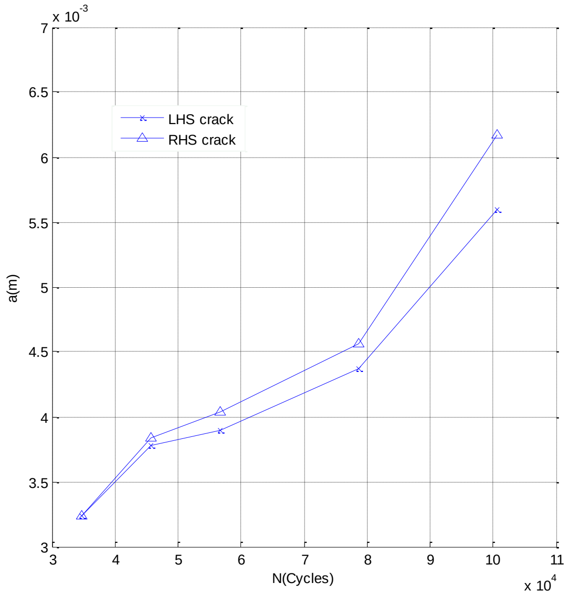
Figure3. Illustration of crack growth



Specimen (1)

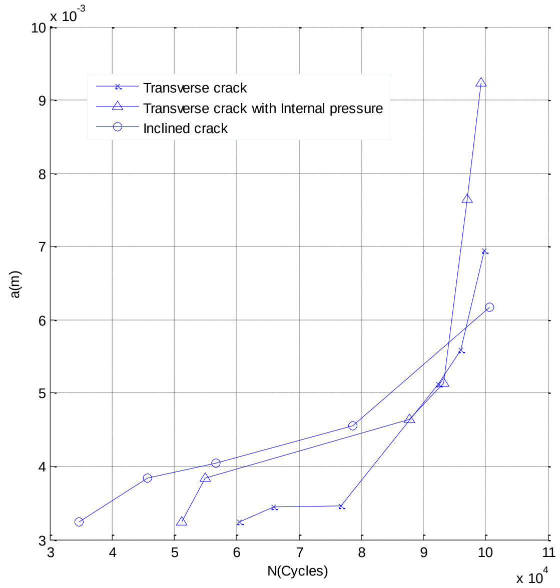


Specimen (2)

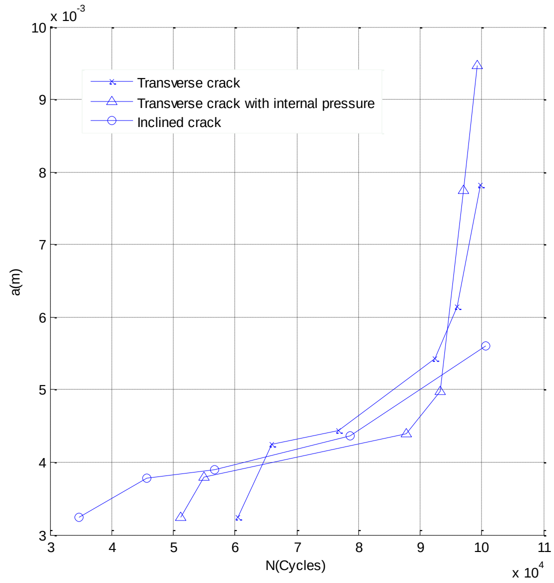


Specimen (3)

Figure4. Illustration of LHS crack and RHS crack growth in specimen (1), specimen (2) and specimen (3)



LHS crack for three specimens



RHS crack for three specimens

Figure5. Illustration of comparison between LHS crack growth and RHS crack growth in three specimens

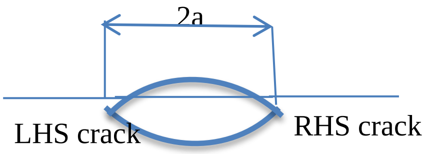
Table1. Mechanical and chemical properties

Mechanical properties			
Yield point stress (Mpa) , $\sigma_{y.p.}$	Ultimate stress (Mpa) , $\sigma_{ult.}$	Young modulus (Gpa) , E	Plane strain toughness , K_{IC}
240	269.5	115.93	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

Table2. Specimen (1)

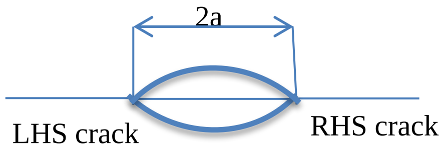
G.L.=180 mm
Disp.=3.25 mm
2a=6.48 mm
N=1830 r.p.m.



LHS Crack length (m) x10^{-3}	$\frac{da}{dN}$ (LHS)	RHS Crack length (m) x10^{-3}	$\frac{da}{dN}$(RHS)	The required time for crack growth
1	-	0.2	-	After 3 minutes(i.e. from 33 minutes to 36 minutes)
1.19	$\frac{1.19-1}{(6*1830)}$	0.22	$\frac{0.22-0.2}{(6*1830)}$	After 6 minutes (i.e. from 36 minutes to 42 minutes)
2.19	$\frac{2.19-1.19}{(8.5*1830)}$	1.88	$\frac{1.88-0.22}{(8.5*1830)}$	After 8.5 minutes (i.e. from 42 minutes to 50.5 minutes)
2.9	$\frac{2.9-2.19}{(2*1830)}$	2.35	$\frac{2.35-1.88}{(2*1830)}$	After 2 minutes (i.e. from 50.5 minutes to 52.5 minutes)
4.58	$\frac{4.58-2.9}{(2*1830)}$	3.71	$\frac{3.71-2.35}{(2*1830)}$	After 2 minutes (i.e. from 52.5 minutes to 54.5 minutes)
-	Av.=1.83 *10^{-4}	-	Av.=1.52*10^{-4}	-

Table3. Specimen (2)

G.L.=180 mm
Disp.=3.25 mm
2a=6.48 mm
N=1830 r.p.m.



(With Internal pulsing Pressure)

LHS Crack length (m) $x10^{-3}$	$\frac{da}{dN}$ (LHS)	RHS Crack length (m) $x10^{-3}$	$\frac{da}{dN}$(RHS)	The required time for crack growth
0.55	-	0.6	-	After 2 minutes(i.e. from 28 minutes to 30 minutes)
1.16	$\frac{1.16-0.55}{(18*1830)}$	1.4	$\frac{1.4-0.6}{(18*1830)}$	After 18 minutes (i.e. from 30 minutes to 48 minutes)
1.74	$\frac{1.74-1.16}{(3*1830)}$	1.9	$\frac{1.9-1.4}{(3*1830)}$	After 3minutes (i.e. from 48 minutes to 51 minutes)
4.5	$\frac{4.5-1.74}{(2*1830)}$	4.41	$\frac{4.41-1.9}{(2*1830)}$	After 2 minutes (i.e. from 51 minutes to 53 minutes)
6.23	$\frac{6.23-4.5}{(1.25*1830)}$	5.99	$\frac{5.99-4.41}{(1.25*1830)}$	After 1.25 minutes (i.e. from 53minutes to 54.25 minutes)
-	Av. = $4.08*10^{-4}$	-	Av.= $3.72*10^{-4}$	-

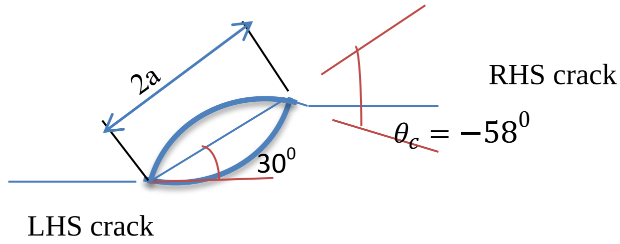
Table4. Specimen (3)

G.L.=180 mm

Disp.=3.25 mm

2a=6.48 mm

N=1830 r.p.m



LHS Crack length (m) x10^{-3}	$\frac{da}{dN}$ (LHS)	RHS Crack length (m) x10^{-3}	$\frac{da}{dN}$(RHS)	The required time for crack growth
0.54	-	0.6	-	After 6 minutes(i.e. from 19 minutes to 25 minutes)
0.66	$\frac{0.66-0.54}{(6*1830)}$	0.8	$\frac{0.8-0.6}{(6*1830)}$	After 6 minutes (i.e. from 25 minutes to 31 minutes)
1.13	$\frac{1.13-0.66}{(12*1830)}$	1.32	$\frac{1.32-0.8}{(12*1830)}$	After 12 minutes (i.e. from 31 minutes to 43 minutes)
2.36	$\frac{2.36-1.13}{(12*1830)}$	2.93	$\frac{2.93-1.32}{(12*1830)}$	After 12 minutes (i.e. from 43 minutes to 55 minutes)
-	Av. =2.94*10^{-5}	-	Av. =3.83*10^{-5}	-

Table5. Proposed scenarios

No.	Remote applied load	Crack inclination	Internal pulsing pressure effect
(1)	cyclic bending load	transvers crack(0^0)	without Internal pulsing pressure
(2)	cyclic bending load	transvers crack(0^0)	with Internal pulsing pressure
(3)	cyclic bending load	inclined crack(30^0)	without Internal pulsing pressure

Table6. Comparison between θ_C experimental and θ_C analytical

Equations	θ_C experimental	θ_C analytical	Error %
Eq. (11)	-58	-50.61^0	14.6
Eq. (12)	-58	-57.44^0	0. 97