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DESIGN AND TEST ANALYSIS OF A MULTI STAGE CANTILEVER BEAM TYPE SUSTAINED LOAD STRESS CORROSION TESTING RIG

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Abstract: The design and test evaluation of a multi stage cantilever beam type sustained load testing rig was undertaken in this research. The aim was to make available to local researchers a cost effective, technically efficient, and easily operated testing facility for stress corrosion cracking studies. The design criteria and materials selection were based on design theory and operational principles, local availability of raw materials and components, material properties, materials and fabrication costs, ease of utilization and maintenance, specimen and testing specifications, and basis for data generation. The testing procedure involved the use of circumferential notch specimens subjected to sustained loads noting the time to failure; with 10 % load shedding used for successive loading of specimens to failure. Macroscopic crack evolution of aluminium samples tested with 5 wt% NaCl solution as specific environment showed promise of the rig for reliable SCC studies. The rig was also observed to be safe for use and the precautions prescribed adequate to guarantee accurate data generation and maintenance of the rig. The cost for the design of the test rig was about 50,000 Naira ($250.00) which is cheaper in comparison to conventional SCC testing equipment operating on similar principles which are designed abroad.
Keywords: Stress corrosion cracking; sustained load fracture; circumferential notch specimens; fracture mechanics; cantilever beam

INTRODUCTION

Stress corrosion cracking (SCC) is a prominent failure mechanism in engineering materials which results from a combined action of stress and specific corrosive environment. This form of failure is the most catastrophic form of corrosion; and occurs as a result of interaction of three factors: an active or residual tensile stress, susceptible material and a specific environment (corrosive media) [1]. It is often characterised by cracking of metals under active or residual tensile (usually below the yield strength of the material) stresses in specific environments from pre-existing defects or defects initiated in the material while in service. Crack initiation in materials can also result from localised corrosions (intergranular, crevice, dealloying) which create sites for stress concentration and amplification within the material [2]. Other variables that decide the extent or nature of SCC failure are the stress state (plane stress or plane strain), loading mode (tension or torsion), chemical composition, microstructure, grain sizes, grain boundaries, solution species, temperature, pressure, pH and electrochemical potential [3][4].Stress corrosion cracking can go undetected in many service applications and can result in loss of lives, reduce production efficiency and increase production cost [5] .The SCC of service components or parts of mechanical systems has been a source of concern in major industries like petrochemical, oil and gas, food processing, spacecraft, nuclear, pulp production, and other production industries [6]. Therefore design against SCC is very paramount in many engineering applications to enhance material functionality and service life.

The design against SCC requires a basis of assessing susceptibility of a material to this failure mechanism. Over the years, several test methods have been developed for evaluation of SCC behaviour of engineering materials [5]. SCC studies in metallic materials have been based on adoption of fracture mechanics principles and often evaluation is based on specimen geometry and loading conditions. In this regards, testing conditions are categorised as; Test on smooth samples under static loading, Test on pre-cracked sample under static loading and Tests on pre-cracked or smooth samples under dynamic loading

[7]. However, most SCC evaluations are based on the static loading technique under the assumption that most materials undergo SCC failure under constant loading conditions.

Several standards have been proposed for SCC investigation in different materials with specified specimen configurations and testing conditions. These are namely ASTM G58 – 85[8], ASTM E1681-03 [9] and ASTM G139 – 05 [10]. The aforementioned standards are based on the principle of constant loading of pre-cracked or smooth specimens. There exist other standards such as ISO 7539-7 [11] and ISO 7539-9 [12] which are based on the assumption that material's maybe subjected to unpredicted dynamic loading and propose slow strain rate testing(ISO 7539-7, ISO 7539-9). However, the existing testing methods for SCC evaluation facilities, specimen configuration and testing procedure which are difficult to attain in many African research environments. This has necessitated studies on developing a more pragmatic approach for SCC studies from an African perspective.

The use of circumferential notch tensile testing technique has been well reported as a less sophisticated and cost effective means for fracture studies of materials [13] [14]. The adaptation of this technique to SCC studies has been proposed with the use of pre-cracked specimens under sustained loading conditions by several researchers [15]. Alaneme [6] applied this technique in the design of a low cost rig for SCC studies of metallic materials with satisfactory data generated for SCC analysis. The test rig developed however, had some limitations which include: having only a single loading arm which increased the overall testing time for materials. This impaired simultaneous study of SCC susceptibility using varied loading conditions on different samples which can hasten the process of data accumulation as the basis of SCC studies naturally demands long periods for specimen fracture to occur.

This research work seeks to address the highlighted problem by designing a low-cost multi loading stage SCC test rig. The testing facility (a multiple loaded test rig) is designed based on the use of cantilever load beam and circumferential notch specimens. The design, testing procedure, interpretation of SCC tendencies from data generated from the use of the test rig and performance evaluations are discussed in this paper.

MATERIALS AND METHOD

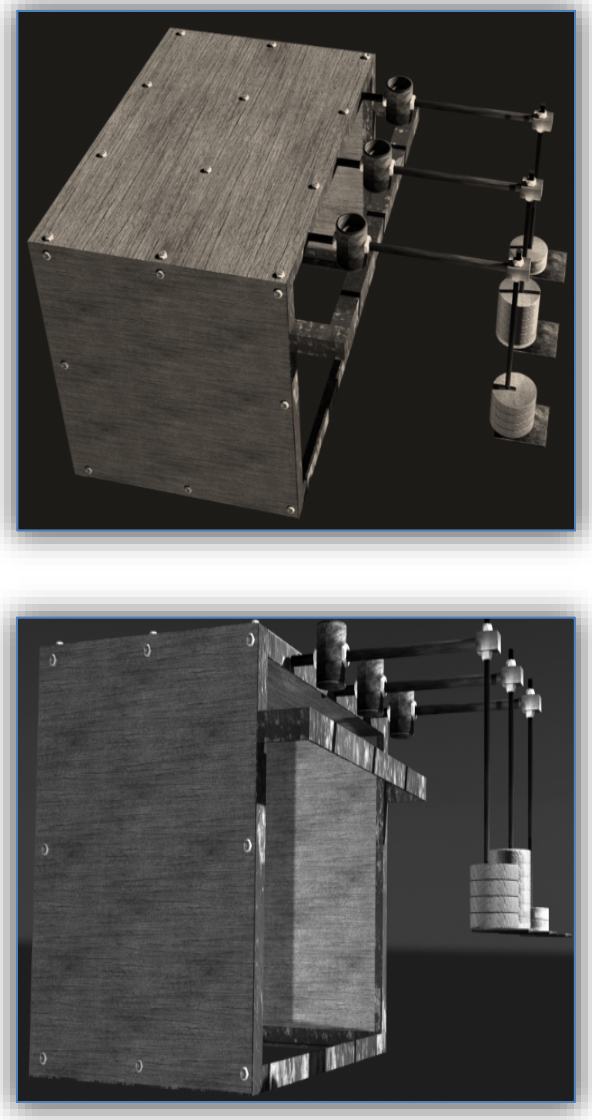
Design Theory

The design theories and testing procedures are in accordance with the cantilever load beam principles and CNT testing techniques, respectively. The design principle is based on cantilever beam loading principle, an approach described in details by Alaneme (2011). It entails the use of circumferential notch samples held in a fixed position at one end and subjected to applied load at the other end of the specimen. The applied load creates stress amplification at the notch, a triaxial stress state is also created at the notch tip which suppresses tendency toward plastic yielding and instigates the process of crack nucleation. The crack nucleation and propagation is accentuated by the specific corrosion environment which the specimen is exposed to at the notch region Figure 1. For each loading condition and specific environment (environment in which the material is susceptible to SCC), the time to failure for each sample is noted and the corresponding stress intensity factor determined.

Design Consideration and Material Selection

The design criteria was based on several considerations including cost, local availability of potential materials required for fabrication, material properties, rigidity and service life of the rig, ease of adjustment and utilization of the rig, non-reliance on electrical power supply and basis of data generation and evaluation. The design incorporates the main parts of the test rig which include: the test frame (which gives rigidity and balance to the apparatus); loading frame consisting of loading beam and load hanger (which serves as anchor between the applied load and the specimen); timer (which records the time taken for a specimen to fail); corrosion cell (a thermoplastic container holding a specific solution); and dead weights (used to apply known weights to the specimen). The material selection for the test frame, loading arm, loading hanger and corrosion cell were in line with the specifications utilised by Alaneme [6].

The test frame is designed to sustain the applied load to prevent failure of the rig in service; hence high strength low alloy steels which possess high strength and toughness were employed for the design. The loading frame is required to sustain applied loads for long periods without undergoing plastic deformation or change in dimensional integrity. Therefore, high strength low alloy steels were utilised for the design of the loading beam and load hanger to prevent yielding of these component parts in service. The dimensions of the loading frame were also carefully selected so that its weight does not affect the total weight acting on the specimen which would affect the results generated from the test. A portable hour-minute-second timer was selected to record time to failure for accuracy and precision. The corrosion cell was carefully selected to be lightweight, corrosion resistant and non-reacting to reagents; a thermoplastic material was selected for this purpose. A pictorial representation of the test rig is shown in Figure 1.



(a)

(b)

Figure 1: showing (a): 3D top view of the test rig and (b) 3D side view of the test rig

Specimen Specification

The test specimen is a circumferentially notched cylindrical bar machined following standard CNT specimen configuration. The specimen had a total length of 200mm with gauge length of 160mm, gauge diameter of 8 mm, notch depth of 2.5mm and notch angle of 60°. The specimen configuration and dimensions are presented in Figure 2.

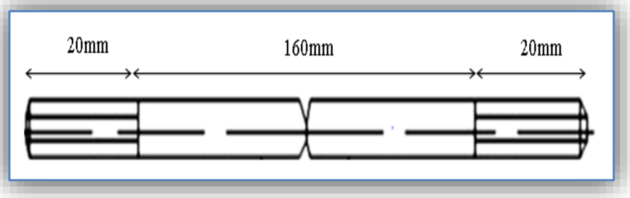


Figure 2: Specimen specification for circumferentially notched cylindrical bar samples

Testing Procedure

The circumferential notch cylindrical bar test specimen is fastened to the grip fixture on the test frame and passed through a thermoplastic container (with drilled holes at the center) which served as the cell for the specific corrosion medium. The drilled ends of the container are sealed after the insertion of the test specimen to prevent dripping of the corrosion solution during testing. It is ensured that the container is situated at the notch region of the sample to help accentuate the process of crack nucleation. The other end of the specimen is screwed to the loading arm which is connected to the load hanger of the testing rig. Pre- determined dead weights are placed on the load hanger and the timer is switched on. The loading conditions are such that the start load is sufficient to induce fracture of the test material within a short time interval. Load shedding of 10% is applied as successive loads to the test specimen and time to failure for each test case recorded. This is done until a threshold load is attained below which it becomes unrealistic to expect fracture of sample after an infinite time interval under a specific environment where the material is ordinarily susceptible to SCC failure. Typical stress intensity factor – time to failure data generated from the sustained load SCC testing is schematically illustrated in Figure 3.

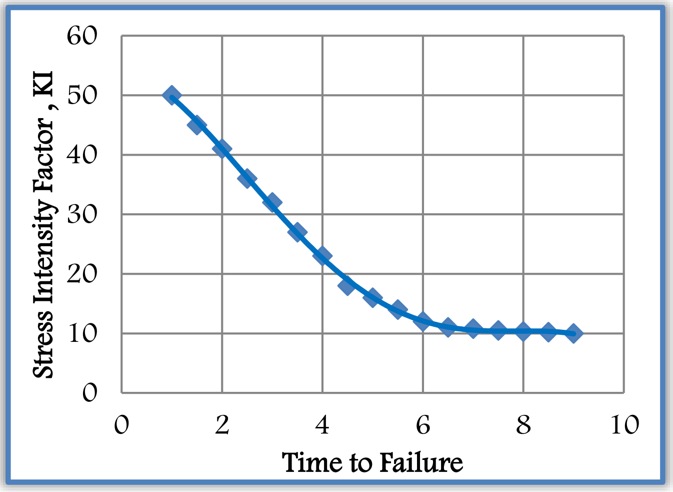


Figure 3: A schematic plot of stress intensity against time to failure (ttf)

PERFORMANCE EVALUATION

Visual Examination of SCC Progression to Failure

Stress corrosion cracking (SCC) data generation using the sustained load cantilever beam principle can take several months depending on the test conditions, specific environment and the susceptible material under study. Thus the use of multiple loading stages helps to speed up the overall time required for data generation since multiple samples can be anchored with varied dead weights and tested simultaneously. The stress corrosion cracking behaviour of an aluminium test specimen was investigated in 5wt% NaCl solution (a medium in which aluminium shows susceptibility to SCC) using the designed multi stage test rig.

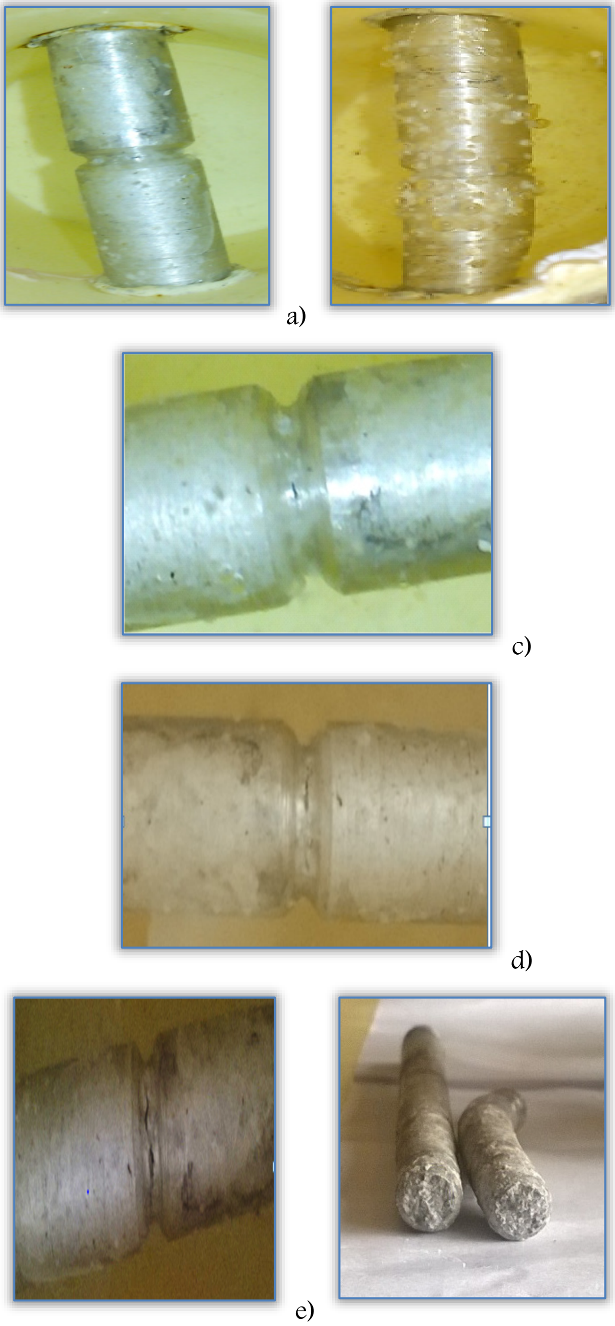


Figure 4: Representative photomicrographs showing the nature of macroscopic crack evolution to final fracture in the test specimen (a) after 4 days of testing, (b) for 9 days of testing, (c) 15 days of testing, (d) 25 days of testing, (e) 35 days of testing, (f) fracture on 40th day of testing

The pace of macroscopic crack manifestation and growth was specifically monitored by visual examination throughout the test period for each specimen. Representative photomicrographs showing the nature of crack evolution in the test specimen with time are presented in Figure 4.

From Figure 4(a) it is observed that surface discoloration due to formation of corrosion products became evident on the fourth day of sustained load testing. On the ninth day of testing, conspicuous sign of bubbles formation which is a macroscopic indicator of crack initiation on the surface of the specimen was noticeable (Figure 4b). The crack became visible after fifteen days (15) days of sustained loading as observed in Figure 4c. The progression of crack growth increased with increase in the test period to 25 days (Figure 4d). The crack advance before fracture was very prominent after thirty five (35) days of sustained load bearing (Figure 4e) and fracture occurred after 40 days of testing (Figure 4f).

Working Efficiency, Safety and Cost Analysis

SCC testing with the rig requires some basic precautions to be taken to ensure reliable results are generated and to safeguard the user and rig from potential harm due to exposure to corrosive medium. In the first place care is exercised by ensuring that the test specimens are securely fastened to the grip fixture of the main frame of the rig to safeguard against removal of specimen when subjected to loading during operation.

Table 1: Bill for Engineering Management and Evaluation

S/N	Material	Specification	Quantity	Unit Cost (N)	Amount (N)
1	Angle iron	2mm	2.5 lengths	2280	5700
2	Cutting disc		2	650	1300
3	Grinding disc		2	650	1300
4	Electrode		Half packet	700	700
5	Bolt	6mm	40	30	1200
6	Bolt	8mm	6	50	300
7	Nut	6mm	48	30	1440
8	Nut	8mm	4	50	200
9	Red oxide		Half bottle	550	550
10	Saw blade		3	250	750
11	Plywood		1 sheet	3350	3350
12	Drill bit	6mm	3	400	1200
13	Adhesive	Aradite			200
14	NaCl	Anapuna	4	60	240
15	Machining	All			13840
16	Transportation/ logistics				3860
17	Labour Cost				10000
18	Total				49530

The thermoplastic container used as corrosion cell is properly sealed to ensure that the specific environment used as test solution does not drain out from the container and result in the gradual corrosion of the test frame and entire rig with time. The load hanger is also securely fastened to the loading arm of the load frame so that it does not pull out from the loading arm when dead weights are anchored on it. In this regards, it is equally ensured that protective barricades are placed around the load hanger to ensure that if the dead weights accidentally slips off the hanger it does not drop and injure the operator. The operation principles of the test rig are very easily comprehended and does not require complicated basis for data recording. The parts of the machine can be easily dismembered for repairs in the case a part of the rig malfunctions or is damaged. Replacement of any part of the rig and acquisition of fabrication materials required for repair purposes can easily be obtained as all parts used in the design are relatively cheap and can be sourced locally.

The materials and components used for the design of the multi loading stage SCC test rig are presented in Table 1. The materials and equipment used were locally sourced and overall cost of design is approximately 50,000 Naira ($250). The test rig is cheaper in comparison to conventional SCC testing equipment operating on similar principles which are designed abroad.

CONCLUSION

The design and test evaluation of a multi stage cantilever beam type sustained load testing rig was undertaken in this research. The rig was observed to be effective and safe for use. The precautions prescribed for its use were found to be adequate to guarantee accurate data generation and maintenance of the rig. Macroscopic crack evolution observed for aluminium samples tested with 5 wt% NaCl solution as specific environment showed the potential of the rig for reliable SCC studies. The cost for the design of the test rig was about 50,000 Naira ($250.00) which is cheaper in comparison to conventional SCC testing equipment operating on similar principles designed abroad.

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