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Effect of Miniature Cracks on the Fracture Strength and Strain of Tensile Armour Wires

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Abstract**—**Tensile armour wires provide a flexible pipe's resistance to longitudinal stresses. Flexible pipe manufacturers need to know the effect of defects such as scratches and cracks, with dimensions less than 0.2mm which is the limit of the current non-destructive detection technology, on the fracture stress and fracture strain of the wire for quality assurance purposes. Recent research involving the determination of the fracture strength of cracked wires employed laboratory testing and classical fracture mechanics approach using non-standardised fracture mechanics specimens because standard test specimens could not be manufactured from the wires owing to their sizes. In this work, the effect of miniature cracks on the fracture properties of tensile armour wires was investigated using laboratory and finite element tensile testing simulations with the phenomenological shear fracture model. The investigation revealed that the presence of cracks shallower than 0.2mm is worse on the fracture strain of the wire.

Keywords**—**Cracks, Finite Element Simulations, Fracture Mechanics, Shear Fracture Model, Tensile Armour Wire

I. INTRODUCTION

TENSILE armour wires provide a flexible pipe's resistance to longitudinal stresses which arise during installation and in service, and are thus vital to the structural integrity of flexible pipes. Flexible pipes are used for risers and flowlines, among other applications in the offshore oil and gas industry and their tensile armour wires are subjected to high strain particularly during installation. Manufacturers desire an understanding of the effect of defects such as scratches and cracks with dimensions less than the 0.2mm defect detection capability of the inline defect detection system used on the fracture properties of the wires for design and quality assurance purposes.

The need to employ fracture mechanics based analysis to estimate the safe load carrying capacity of cracked wires has been emphasized by [1] and [2] because the current practice used by engineers to estimate the safe load carrying capacity of a cracked wire by multiplying the ultimate strength obtained from a tension test by the original nominal area of the wire may overestimate the strength of the wire due to crack tip plasticity [1].

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Research reported in the published literature such as that conducted by [1] on cracked bridge cable wires, and by [2] and [3] on cracked concrete pre-stressing wire employed laboratory testing and used the classical fracture mechanics for the determination of the fracture mechanism and fracture strength of cracked wires. These researchers employed linear elastic fracture mechanics (LEFM) and the net section theory/plastic collapse fracture mechanics, and used non-standardised fracture mechanics specimens as the wires are not large/thick enough for standard fracture mechanics test specimens to be manufactured from them.

Micromechanism-based fracture mechanics models serve as alternatives to classical fracture mechanics when standard fracture mechanics specimens cannot be obtained and when a safe use of the fracture mechanics concepts cannot be ensured [4].

Phenomenological models are one of the micromechanism-based fracture mechanics models that predict ductile fracture based on the assumption that ductile fracture occurs when a weighted measure of the accumulated plastic strain, such as the equivalent plastic strain reaches a critical value [5].

The work in this paper was undertaken to provide an understanding of the effect of miniature cracks with depths less than or equal to 0.2mm on the tensile properties of the tensile armour wires, and to provide technical data which could be used to make decisions on the crack acceptance criteria in the tensile armour wire standards for the quality control and quality assurance of the wires by the tensile armour wire and flexible pipe manufacturers. The work involves laboratory and Finite element (FE) simulation of the tensile testing of crack-free and notched pre-cracked wire specimens. FE simulation was subsequently used as the virtual experiment to investigate the effect of miniature cracks on the fracture stress and fracture strain of the wires as the miniature cracks are difficult to make experimentally.

II. EXPERIMENTAL

Details of the laboratory and numerical experimental methodologies are presented in this section.

A. Laboratory tensile testing

Laboratory tensile tests were conducted on 50mm gauge length crack-free and notched pre-cracked (with 2mm deep, 60 degree V-notch and 1mm crack) wire specimens shown in Figs 1(a) and (b) respectively. The pre-cracking was done by subjecting the notched specimen to cyclic axial loading. The laboratory tensile testing was conducted with an Instron IX4505 universal testing machine fitted with an Instron 2518 series load cell with a maximum static capacity of ±100kN. The displacement was measured using an Instron 2630-112 clip-on strain gauge extensometer with a 50 mm gauge length. The laboratory tensile testing was conducted on two wire sizes with 12mm x 5mm and 12mm x 7mm cross-sectional dimensions.

(a) Crack-free wire specimen

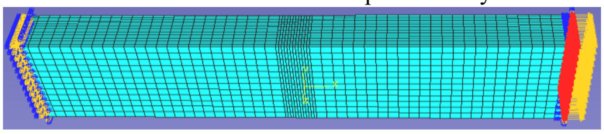
(b) Notched and pre- cracked wire specimen

Fig. 1 Crack-free, and notched pre- cracked laboratory wire specimens

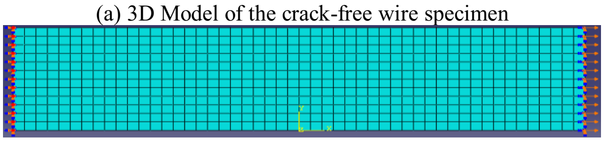
B. FE Tensile Testing Simulation

Both two and three dimensional FE simulations of the tensile testing of the crack-free wire specimens were conducted to establish that both 2D and 3D simulations were able to predict the tensile and fracture properties of the wire in terms of the stress-strain response of the wire and the cup and cone fracture exhibited by the fractured experimental test specimens. The local mesh at the middle of the three dimensional model needed to be refined with 1mmx25mmx0.25mm as shown in Fig 2(a) to obtain the cup and cone fracture, while no mesh refinement was needed for the two dimensional model which was modeled with the global 1mmx1mmx1mm elements as shown in Fig 2(b).

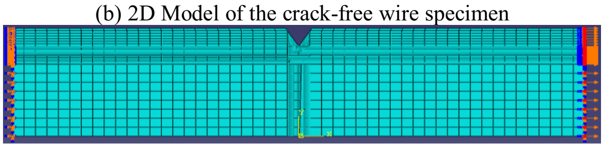
Only two dimensional simulation of the tensile testing of the notched pre-cracked specimen was conducted due to the large computer resources required for the computation involving the large number of elements associated with the 0.02mmx0.02mm fine elements required around the crack tip for accurate computation as shown in Fig 2(c). The crack was modeled as a seam (used in Abaqus to model cracks and faces that are originally closed but open during analyses) and is not visible in the meshed model shown in Fig 2(c) and is therefore shown in the wireframe image of the model in Fig 2(d). The models were meshed with C3D8R elements (8-node hexahedral linear brick reduced integration elements with hourglass control) and the tensile testing simulations were conducted by fixing the left hand ends of the models and subjecting the right hand ends, which are free to move only in the direction of the tensile load to a longitudinal displacement as shown in Figs 2(a), (b) and (c). The shear failure criterion used for the FE simulations is a phenomenological model for predicting the onset of damage and failure due to shear band formation and localisation, crack initiation and ductile crack propagation within the shear bands [6]. The shear damage and fracture modelling parameters used are fracture strain of 0.3451, Shear stress ratio of 12.5, Strain rate of 0.000125 s^{-1} and a material parameter Ks of 0.3, which have been established by [7] as the appropriate parameter combination for predicting the fracture behavior of the tensile armour wires. Both 2D and 3D simulations were validated and the 2D simulation was subsequently used as the virtual experiment to investigate the effect of crack depth from 0.05mm to 0.2mm on the fracture stress and strain of the wire as the miniature cracks are difficult to manufacture experimentally.



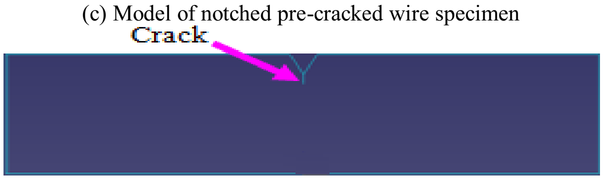
(a) 3D Model of the crack-free wire specimen



(b) 2D Model of the crack-free wire specimen



(c) Model of notched pre-cracked wire specimen



(d) Model of notched pre-cracked wire specimen in wire frame

Fig. 2 FE models of crack-free and notched pre-cracked wire specimens

III. RESULTS

For confidentiality, all the force-displacement and the stress-strain curves in this paper are normalised. The normalised experimental and FE predicted force-displacement curves for the crack-free and the notched pre-cracked wire specimens are shown in Fig 3. The experimental and FE predicted fracture shapes for the crack-free wire are shown in Fig 4. The elastic Mises stress, the plastic Mises stress and the equivalent plastic strain distributions around the crack tip are shown in Figs 5 (a), (b) and (c) respectively. The experimental and FE predicted fracture shapes for the notched pre-cracked wire specimens are shown in Figs 6(a) and (b) respectively.

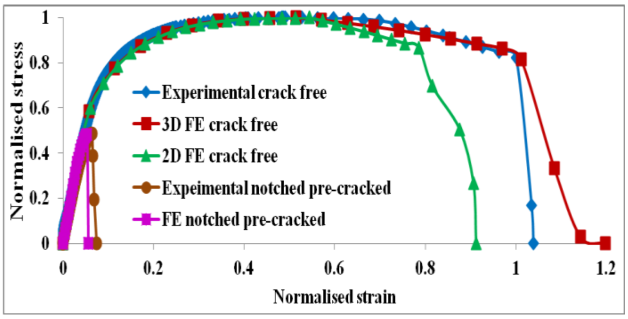
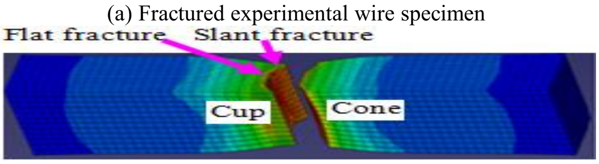
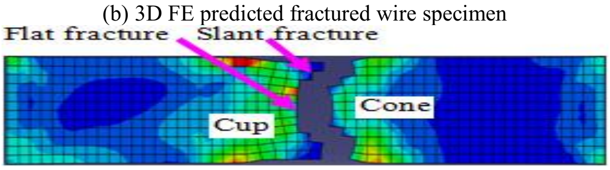


Fig. 3 Experimental and FE force-displacement curves for crack-free and notched pre-cracked wire specimens

(a) Fractured experimental wire specimen

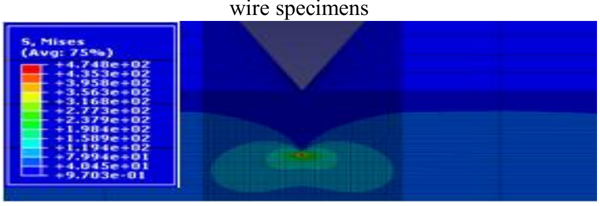


(b) 3D FE predicted fractured wire specimen

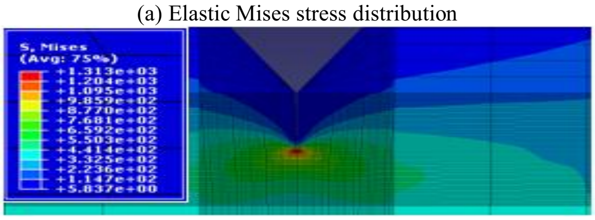


(c) 2D FE predicted fractured wire specimen

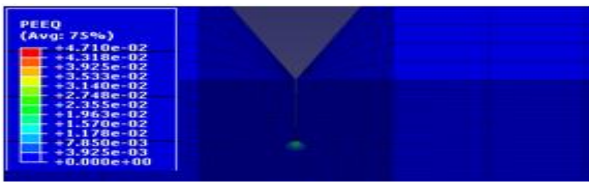
Fig. 4 Experimental and FE predicted fracture shapes for crack-free wire specimens



(a) Elastic Mises stress distribution

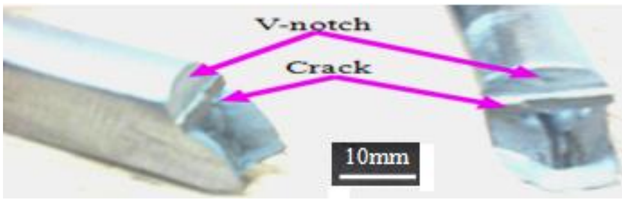


(b) Plastic Mises stress distribution

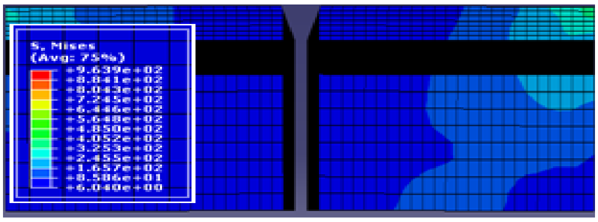


(c) Equivalent plastic strain distribution

Fig. 5 Mises stress and equivalent plastic strain distribution around crack tip



(a) Fractured experimental wire specimen



(b) 2D FE predicted fractured wire specimen

Fig. 6 Experimental and FE predicted fracture shapes for notched pre-cracked wire specimens

The assembled fractured experimental specimen pieces of the crack-free and the notched pre-cracked wire specimens showing the reduction in thickness and width of the necked region are shown in Figs 7(a) and (b) respectively. The necked 2D and 3D wire specimen models showing the lateral (along width) contraction alone, and the lateral and transverse contractions of the necked region of the specimen are shown in Figs 7(c) and (d) respectively.

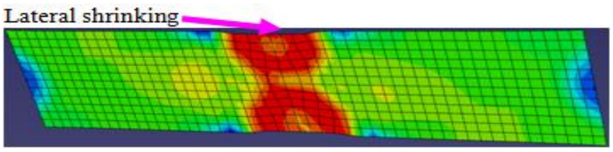
The typical variations of the normalised stress-strain responses of the 12mmx5mm wire with crack depths are shown in Fig 8. A Similar variation in stress-strain responses with crack depths were obtained for the 12mmx7mm wire. The typical variations of the fracture stress and the fracture strain with crack depths for the 12mmx5mm wire are as shown in Figs 9 and 10. Similar variations of the fracture stress and the fracture strain with crack depths were obtained for the 12mmx7mm wire.

IV. DISCUSSION

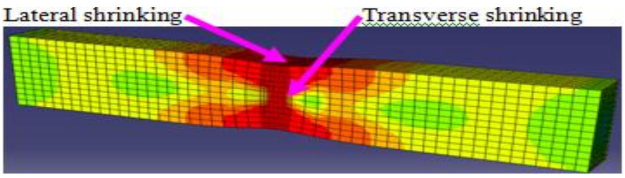
The good agreement between the experimental and FE force-displacement curves obtained for the tensile testing of the crack-free and the notched pre-cracked wire specimens as shown in Fig 3 confirms the accuracy of the FE simulations. Also the prediction of the “cup and cone” fracture exhibited by the experimental fracture specimens shown in Fig 4(a) by the two and three dimensional simulations of the tensile testing of the crack-free wire as shown in Figs 4(b) and and (c), further confirms the accuracy of the FE simulations and establishes that the shear phenomenological fracture behaviour of both crack-free and cracked tensile armour wires. While the crack is not visible in the deformed images shown in Fig 5, the equivalent plastic strain distribution shows that plasticity is limited to areas around the crack tip.

(a) Assembled fractured crack-free wire specimen pieces

(b) Assembled fractured notched pre-cracked wire specimen pieces



(c) Lateral contraction alone in 2D simulation



(d) Lateral and transverse contractions in 3D simulation

Fig. 7 Necking of experimental specimens and FE models

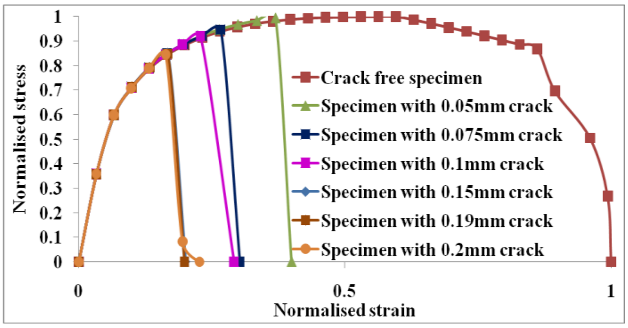


Fig. 8 Variation of stress-strain response of 12mmx5mm wire with crack depths

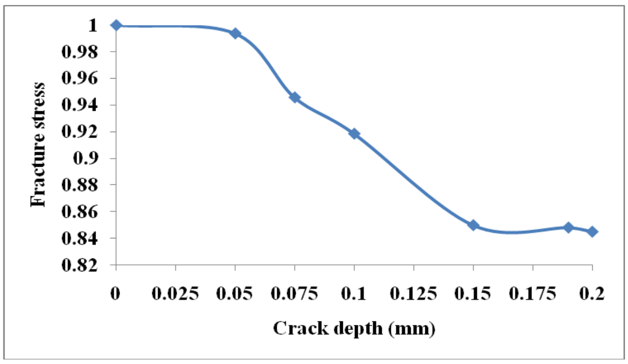


Fig. 9 Variation of fracture stress with crack depth for 12mmx5mm wire

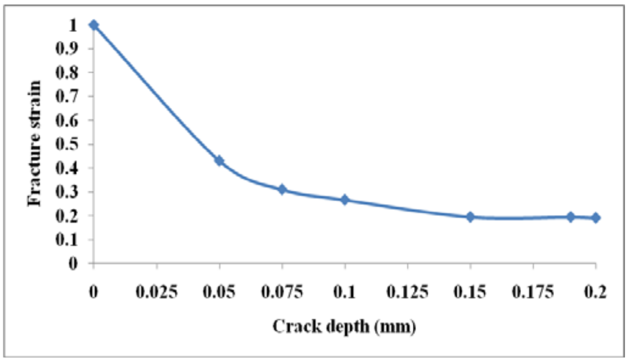


Fig. 10 Variation of fracture strain with crack depth for 12mmx5mm wire

As shown in Fig 3, both the 2D and 3D simulations predicted the same stress-strain response for the crack free wire up to the ultimate stress, beyond which, the 2D simulation predicted a frature strain much lower than the values obtained experimentally and from the 3D simulation. This result agrees with what is reported by [8] who concluded that 2D simulation provides an “unrealistic tensile response”. However, as shown in Fig 3, the 2D simulation predicted the same stress-strain response for the notched pre-cracked specimens which exhibit no significant necking as shown in Fig 7(b).

The lower fracture strain predicted by the 2D simulation could be attributed to the fact that the extension of the specimen after the onset of necking (from the ultimate stress point) is limited to the extension resulting from the lateral contraction alone as shown in Fig 7(c). Thus the lower fracture strain predicted by the 2D simulation is as a result of the inability of the 2D simulation to capture the longitudinal axial elongation accompanying the transverse contraction during necking which occurs in the experimental and 3D FE simulation as shown in Figs 7(a) and 7(d). This explains why the 2D simulation was able to predict the same fracture strain as the experimental notched pre-cracked wire specimen which fractured without any significant necking as shown in Fig 7(b).

The presence of 0.05mm to 0.2mm deep cracks reduces both the fracture stress and the fracture strain of the 12mmx5mm wire as shown in Fig 8 with the fracture stress reduced by 0.62% to 15.48% and the fracture strain reduced by 57.49% to 81.71%. A similar effect of cracks was observed for the 12mmx7mm wire with the fracture stress and the fracture strain reduced by 2.38% to 16.12% and 59.35% to 84.97% respectively due to the presence of 0.05mm to 0.2mm deep cracks. For the 12mmx5mm wire, the presence of 0.19mm deep crack (which cannot be detected by typical inline defect detectors presently used in industry) reduces the fracture stress by 15.17% and the fracture strain by 81.32% compared with the 15.48% and 81.71% reductions in the fracture stress and the fracture strain respectively by the 0.2mm deep crack. Similarly, for the 12mmx7mm wire, the presence of 0.19mm deep crack reduces the fracture stress by 15.97% and the fracture strain by 84.87% compared with the 16.12% and 84.97% reductions in the fracture stress and the fracture strain respectively by the 0.2mm deep crack.

This result indicates that the presence of cracks has more detrimental effect on the fracture strain of the wire than on the fracture stress. The reduction in the fracture strain and invariably the ductility of the wire could be attributed to the high local stress and strain concentrations at the crack tip as shown in Fig 5, which are associated with the magnification of the local strain rate around the notches and the production of high local strain hardening at the crack tip, all of which promote cracking and increase the tendency for a brittle fracture as stated by [9]. The reduction in the fracture stress of the wire could be attributed to the reduction in the gross cross-sectional area of the wire and consequently the reduction in the global strength of the wire. It could also be attributed to the fact that crack propagation in the cracked wire starts at a stress level far lower than the tensile strength of the material because the high local strain hardening associated with the stress concentration at the notch root promotes cracking as stated by [9].

Figs 9 and 10 which show the graphical relationships between the crack depth and fracture stress, and between the crack depth and fracture strain which could be used as design charts for estimating the fracture stress and fracture strain of the cracked tensile armour wires. The design charts could also be used to determine the maximum crack size that can be accepted for a target strength or ductility and could be used as the basis for specifying the acceptable crack size in the standards for quality control and thus be useful in the quality assurance of tensile armour wires.

V. CONCLUSION

In this paper, it is demonstrated that the phenomenological shear fracture model is able to predict the fracture behavior of both crack-free and notched pre-cracked tensile amour wire in terms of the stress-strain response and the fracture shapes of the wire and serves as a suitable alternative to using non-standardised classical fracture mechanics specimens used by previous authors. For the 12mmx5mm wire, the presence of 0.19mm deep crack which cannot be detected by the inline defect detector presently used by the wire manufacturers reduces the predicted fracture stress and the predicted fracture strain by 15.17% and 81.32% respectively. Similarly, for the 12mmx7mm wire, the presence of 0.19mm deep crack reduces the predicted fracture stress and the predicted fracture strain by 15.97% and 84.87% respectively.

This study also presents in graphical form the relationship between the crack depth and predicted fracture stress, and the relationship between crack depth and predicted fracture strain of the tensile armour wires which could be used as design charts for estimating the fracture stress and fracture strain of cracked tensile armour wires. The design charts could also be used to determine the maximum crack size that can be accepted for a target strength or ductility, and could be used as the basis for specifying the acceptable crack size in the tensile armour wire standards for quality control (if such crack sizes can be detected using equipment commercially available today), and thus be useful in the quality assurance of tensile armour wires.

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