EXPERIMENTAL INVESTIGATION ON REPAIRING OF STEEL PIPES USING COMPOSITE MATERIALS: PART II

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الملخص

يقدم هذا البحث دراسة عملية حول إصلاح الأنابيب المعدنية بإستخدام المواد المركبة المصنوعة من الألياف الزجاجية و مادة البولمر اللاصقة. تمت محاكاة الأنابيب المعطوبة بأنابيب مصنوعة من الحديد المكربن بطول 900 مم و قطر داخلي 83 مم و سمك 12.5 مم. ثقبت الأنابيب في منتصفها بأقطار 10 و 15 و20 مليمتر لتحاكي الأعطاب التي يمكن أن تصاب بها في الواقع. كما تم لف شريط من الألياف الزجاجية، عدة لفات حول الثقب، بعد نقعه في المادة البوليستر اللاصقة. بعد إتمام عملية اللف ربط مكان الإصلاح بالقامطة الحديدية ربطا جيدا ثم تركت لتجف لمدة 48 ساعة. تم ضغط الأنابيب بضغط داخلي بعد جفافها بواسطة جهاز الضغط الهيدروليكي الذي يتكون من مضخة هيدروليكية (ذات سعة 600 بار) وأنابيب توصيل ومجسات انفعال وعداد لقراءة الضغط.

لقد بينت التجارب أن القامطة الحديدية المبتكرة في هذا البحث، حيث تجرب لأول مرة، تعمل بكفاءة عالية حيث وصل أعلى ضغط الي قيمة 200 بار، ويعتبر هذا الضغط عاليا جدا مقارنة مع الضغوط في خطوط الأنابيب المستخدمة في الصناعات النفطية. كما أتضح أن مخططات الإجهاد والانفعال العملية اتخذت علاقة غير خطية مقارنة مع المخططات النظرية. ولقد بينت الإختبارات المجهرية وجود تشققات مجهرية وجيوب هوائية دقيقة وكذلك انفصال بين الطبقات نتيجة تأثير الضغط المسلط. من أهم نتائج هذا البحث هو أن عملية الإصلاح بإستخدام المواد المركبة يمكن استخدامها في إصلاح الأنابيب الحديدية المعطوبة نتيجة الصداء وغيرها من العوامل الأخرى بكفاءة عالية. يعزز هذه الكفاء إستخدام القامطة الحديدية التي منعت مشكلة التسرب نتيجة التشققات و إنفصال الطبقات منعا تاما.

ABSTRACT

This Paper presents an experimental study of composite materials for the rehabilitation of steel pipes. Three specimens, of 83 mm internal diameter, 12.5 wall thickness and 900 mm length, were cut from new carbon steel pipes with ASTM specification (SA-106). In each specimen a hole was drilled at its mid length to simulate the corrosion defect. The diameters of the holes were chosen as 10, 15, and 20 mm. The composite repair materials were fiber glass woven roving (type E) and polyester resin. Bolted steel clamps were used to clamp the composite repairs around the pipes at the defect holes to minimize the delamination effect and stop the leakage of water during the tests of the pipes. A special rig was designed to carry out pressurized tests on the repaired pipes. It was concluded that the maximum pressure obtained was 200 bar for the pipe with 10 mm defect hole. The microscopic examination showed that matrix cracking and delamination were the dominant failure mode in the most of failed pipes.

KEYWORDS: Composite; Steel pipe; Delamination; Matrix cracking; Clamp, Quasi-isotropic; Laminate; Blister pressure; Rehabilitation; Failure mode; Stress and strain.

INTRODUCTION

The most common cause for repair of metal tubular systems is external corrosion-caused loss of wall thickness. To prevent an area of corrosion damage from causing a pipeline to rupture, the area containing the corrosion damage must be reinforced. Other pipeline defects that commonly require repair include internal corrosion, original construction flaws, service induced cracking, and mechanical damage. These damages can cause substantial damage to the system that leads to shutdown of the plant, loss of the production and increase of maintenance costs.

There are three options can be chosen to solve the problem either replacement, down rating or rehabilitation. The choice depends on the severity of the problem and the economy of the option. The replacement and down rating are expensive options [1]. The rehabilitation can be done by hot or cold repairs.

Industrial pipeline repair by direct deposition of hot weld metal, or weld deposition repair, is a proven technology that can be applied directly to the area of wall loss (e.g., external repair of external wall loss) or to the side opposite the wall loss (e.g., external repair of internal wall loss). There are no apparent technical limitations to applying this repair method to the inside of an out-of-service pipeline. Deposited weld metal repairs are also used to repair circumferentially defects (e.g., intergranular stress corrosion cracks adjacent to girth welds) in the nuclear power industry. Remote welding has been developed primarily by needs in the nuclear power industry, though working devices have been built for other applications [2]. However, Application of this repair method to in-service pipeline which carried flammable liquid, such as oil, would require to shutdown the plant, isolate and dismantle the damaged pipes for welding.

The cold work is the most usual method can be used to repair damaged pipes, since it does not require plant shutdown, special machines, electric supply or very skilled people. Furthermore, it is safe to apply in damaged pipe systems in sensitive plants, such as refineries, gas plants, and petrochemical plants. One of attractive cold work is to use composite technology by over-wrapping repair or bonded repair in which several layers of impregnated fiber fabric are warped over the defected area (see Figure 1). The fiber-reinforced composite repairs are becoming widely used as an alternative to the installation of welded, full-encirclement sleeves for repair of pipelines. These repairs typically consist of glass fibers in a polymer matrix material bonded to the pipe using an adhesive. Adhesive filler is applied to the defect prior to installation to allow load transfer to the composite material [3].

The primary advantage of these repair products over welded, full-encirclement sleeves is that the need for welding is precluded. Composite material, used for repairing, consists of fiber and resin. Fiber may be glass, carbon or Kevlar and the resin may be polyester, epoxy or vinyl ester [5]. The material chosen for the repair system depends on the several reasons, for example glass fiber is preferred for economic reasons and the polyester resin is found to provide an attractive combination on site process ability and metal-composite bond toughness.

Figure 1: Repairing process of a damaged gas pipeline by wrapping of impregnated fiber fabric over the defected area [4]

The use of composite systems as a repair methodology in the pipeline industry has grown in recent years. Most of these works have been focused on experimental and theoretical analysis. For example, Mableson et al [6] presented experimental and theoretical studies for repairing metal pipes using composite materials. They demonstrated that it is possible to employ composite based systems for the external repair of metallic tubular pipes. Their theoretical model appeared to describe the blister propagation problem well. Frost and Lee [7] summarized to date a set of guidelines covering qualification, design installation and inspection for repair of tanks and pressure vessels using composite over warps technique. The main goal for their study was to provide the operators by a framework to allow them to select the composite repair option with confidence.

Bruce et al [8] presented a report for the status of existing pipeline repair technology that can be applied to the inside of a gas transmission pipeline. The report includes results from a comprehensive computerized literature search, together with information obtained from discussions with companies that are currently developing or evaluating novel pipeline repair methods. They identified two broad categories of inside repair technologies: deposited weld metal repairs and fiber-reinforced composite repairs. Both are used to some extent for other applications and could be further developed for internal, local, structural repair of gas transmission pipelines. Baek et al [9] investigated the fracture behavior of repaired pipe using full scale burst test and to select the appropriate repair method of in-service gas pipelines including full encirclement sleeve, epoxy sleeve, and composite repair. They concluded that these repair methods can be used to repair flaws having a depth ratio of 80% of a wall thickness with safety factor of 2.5 and maximum working pressure of 7.8 MPa. Recently, Al Shrif et al [10] developed a theoretical model to predict elastic constants, stress strain curves and failure pressure values for steel pipes repaired by composite materials. They found that the proposed model described the formation and blister propagation well.

In this paper, a novel technique for repairing metallic pipes using composite material and bolted clamp will be presented including experimental procedure to evaluate the failure modes, stress-strain curves and microscope analysis.

EXPERIMENTAL PROCEDURE

Specimens Preparation

Three specimens of 83 mm internal diameter, 12.5 mm wall thickness and length 900 mm length, were cut from new carbon steel pipes with ASTM specification (SA-106) as shown in Figure (2). In each specimen a hole was drilled at its mid length to simulate the corrosion defect. The diameters of the holes were chosen as 10, 15, and 20 mm. The specimens were flanged at their ends and provided with hydraulic fillings. The outer surfaces of the specimens were machined to remove the rusty skin. The warped material was fiber glass tape (type E), and the polymer was polyester resin. Bolted steel clamps, as shown in Figure (3), were designed and manufactured to clamp the repaired area in order to minimize the delamination effects and stop the water leakage.

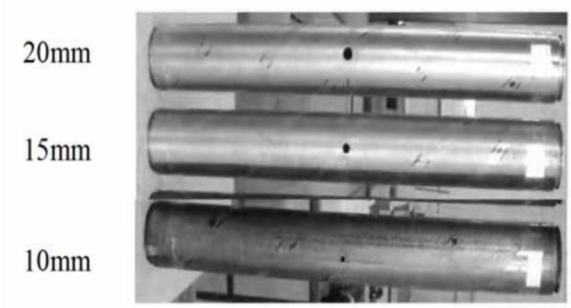

Figure 2: Specimens of pipes with defected holes of 10, 15 and 20mm

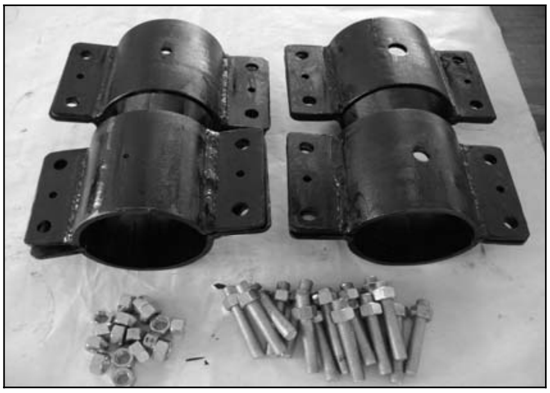

Figure 3: Bolted steel clamps

Repairing Method

The scenario of repair is started by wrapping the specimens with several layers of fiber glass tape impregnated with a polyester resin to obtain the required thickness, as shown in the Figure (4). After that an electric strain gauge is bonded, in radial direction of the pipe, on the top surface of the repaired area. Immediately after this step, the repaired pipe is clamped by the bolted clamp, as shown in Figure (5), in order to minimize the delamination between the outer metal surface of the pipe and the inner surface of composite layer during the test stage. Finally the repaired pipe is lifted to dry at room temperature for 48 hours prior to the test.

Figure 4: The beginning of the over wrapping the pipe with layers of fiber glass

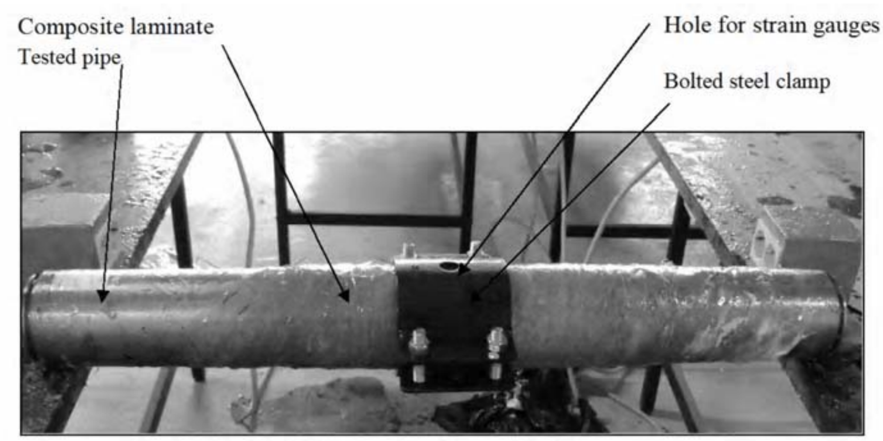

Figure 5: A repaired pipe with bolted steel clamp

Testing method

Prior to the tests, the repaired pipe was hold on a stand and supported by two long U-bolts at its ends. The two ends of pipe are provided by two flanges which were firmly fitted to the ends by using four tie-rods. One flange contains a threaded hole for valve connection, and the other contains two threaded holes for the hydraulic connections. A hydraulic water pump with capacity of 600 bars is used to pressurize the repaired pipe. Figure (6) shows the assembly of the test rig with a repaired pipe.

The test was started by filling the pipe by fresh water and switching-on the pump, and then the pressure was increased by small increments until failure occurred. At each pressure increment, pressure and strain readings were recorded from the pressure gauge and the strain meter respectively.

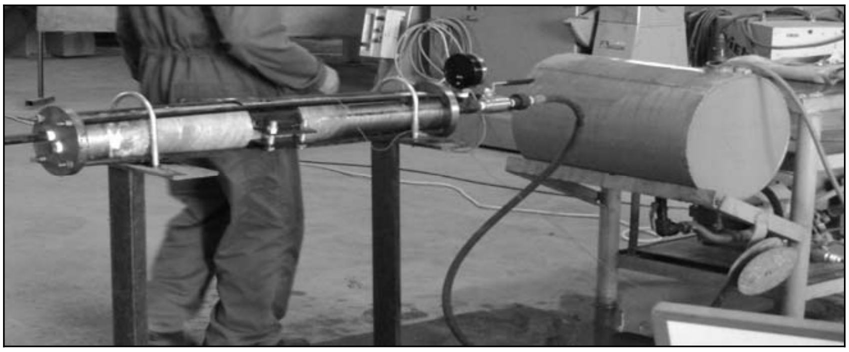

Figure 6: Assembly of the test rig

Optical Microscopic Examination

Optical microscopic examination was carried out to examine the microstructure of failure layer of the composite repair. A number of 8 mm x 8mm samples were carefully cut from the composite repair of a failed pipe. Each sample was mounted on an epoxy resin in form of a small mould. All samples were labeled for identification. The molded samples were ground to flatten the surface and remove rough edges using a grinding machine with silicon carbide paper. When the surface of the sample became flat, it was polished using an oil based cloth until all scratches disappeared. After that, the samples were examined by optical microscope to observe any micro-cracks or delamination.

MODELLING PROCEDURE

The theoretical calculations of stress and strain for composite repair were carried out by the model which was developed by Al Shrift et al [10] as a part I of the present study. The model was based on the standard laminate theory, as explained for instant by Hull [11], and fracture mechanics [6]. It was assumed that the composite repair can be regarded as a quasi-isotropic laminate, i.e. property variations with direction in the plane of laminate are ignored. Moreover, the model treated the repaired area as a circular plate with built-in ends. By introducing the material properties of composite repair and applying the laminate theory and elementary bending theory of plates and shells [12], the elastic constants and the local stresses and strains in radial and tangential directions can be calculated at each increment of applied pressure. These calculations were implemented in a Visual Basic Program.

RESULTS AND DISCUSSION

Figures (7, 8 and 9) show the experimental and theoretical radial stress versus radial strain curves for pipes with defect holes of 20mm, 15mm, and 10mm. It can be observed that all the curves exhibited the same manner. The experimental curves are linear in the early stages and then exhibited non-linear behaviour up to failure, while the theoretical curves are linear up to failure. The non-linearity of the experimental curves is probably related to the matrix cracking in composite layers. The non-linearity due to matrix cracks is well documented in the literature [13-15]. The immediate effect of micro cracks is to cause degradation of the stiffness due to redistribution of stresses and variation of strain in cracked laminate [16]. The matrix cracks can induce delamination which leads to fibre breakage or provides pathways for the entry of pressurized liquid between the layers and may lead to laminate failure. Good correlations between the two curves can be observed at the early stages of loading. However, discrepancies between the theoretical and experimental curves can be seen at high strain to failure. This is probably due to further damage in the composite layer.

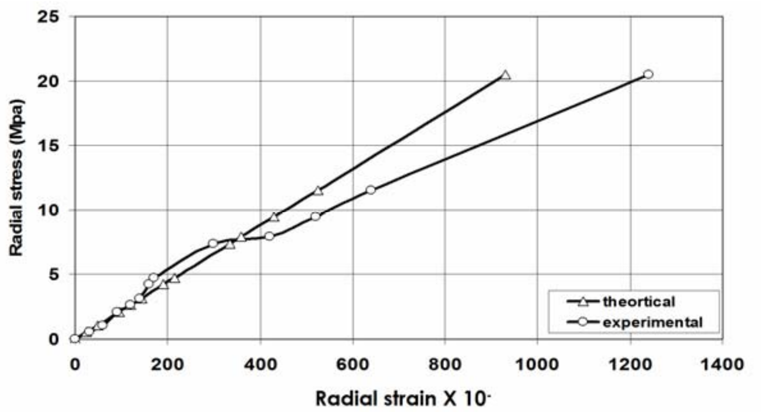

Figure 7: Radial stress versus radial strain for a pipe with 20 mm defect hole

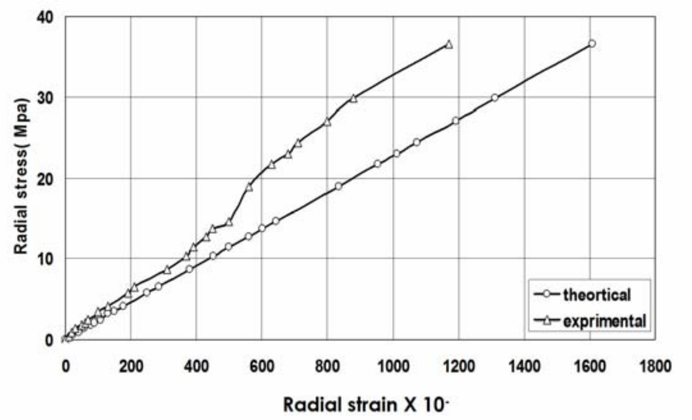

Figure 8: Radial stress versus radial strain for a pipe with 15 mm defect hole

Figures (11 and 12) show failure modes of the failed pipes. It can be seen that the pipes with 20mm and 15mm holes exhibited similar mode of failure called circumferential delamination [6]. This mode of failure occurs when delamination in the region of a hole spreads around the full circumference of the pipe as shown in the Figure (13). It can be seen that over the region of the delamination, the substrate pipe is unloaded and the pressure load on composite repair results in a gap formed between the repair and steel that leads to water leakage from both ends of the pipe.

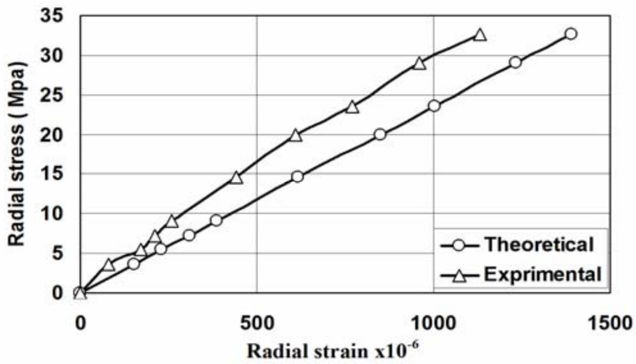

Figure 9: Radial stress versus radial strain for a pipe with 10 mm defect hole

Figure (10) shows a comparison between the present study and Mableson' s study [6] for defect hole diameter versus the failure pressure for the failed pipes. Clearly, it can be seen, in both studies, that the failure pressure decreases rapidly with increasing hole diameter. The failure pressure of clamped pipes increases by about 4 times than that of unclamped pipes. This indicated that the clamp works efficiently for defect holes.

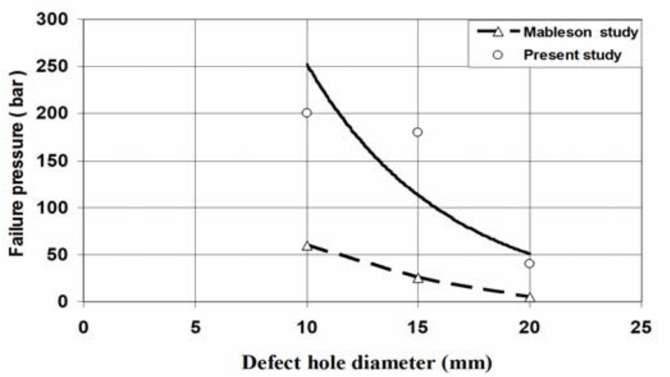

Figure 10: A comparison between the present study and Mableson's study [6] for defect hole diameter versus the failure pressure for the failed pipes

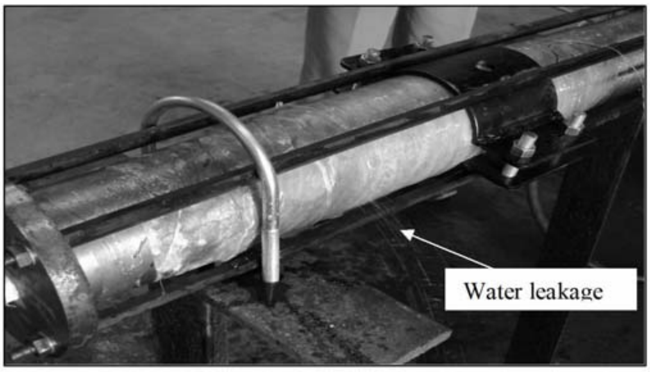

Figure 11: The circumferential delamination failure mode with defect hole of 20mm.

Figure12: The circumferential delamination failure mode with defect hole of 15mm.

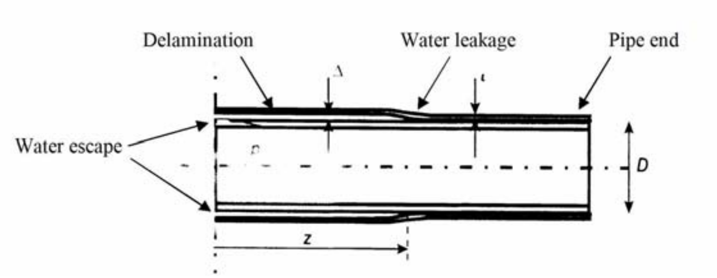

Figure13: A schematic diagram of the circumferential delamination mode [6]

Figure (14) shows the pipe failed at its flanges rather than the repaired region due to the extremely high pressure, about 200 bars. This demonstrated that the bolted clamp worked efficiently without any leakage of water.

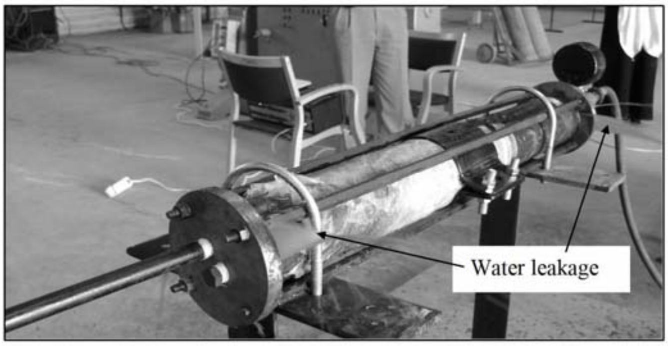

Figure 14: A pipe failed from its end flanges

Microscopic Examinations

Figure (15a and b) shows optical micrographs of polished sample from the failed pipe. The small circles represent the fibre aligned unidirectionally at an angle of (+ θ) to the pipe axis and ovoid fibre were at an angle of (- θ) with pipe axis. The tiny black lines are matrix cracks. It can be seen that the crack appeared and travelled through the (+ θ) ply. This type of cracks was more frequently observed in all failed pipes. Usually, these cracks grew in length and increased in number with an increase in creaking noise as the pressure intensified, finally spread over the repaired region. The formation of these cracks is probably related to the effect of radial and longitudinal stresses and to matrix strain to failure which is lower than that of fibre. These cause debonding at the fibre/matrix interface and resin cracking.

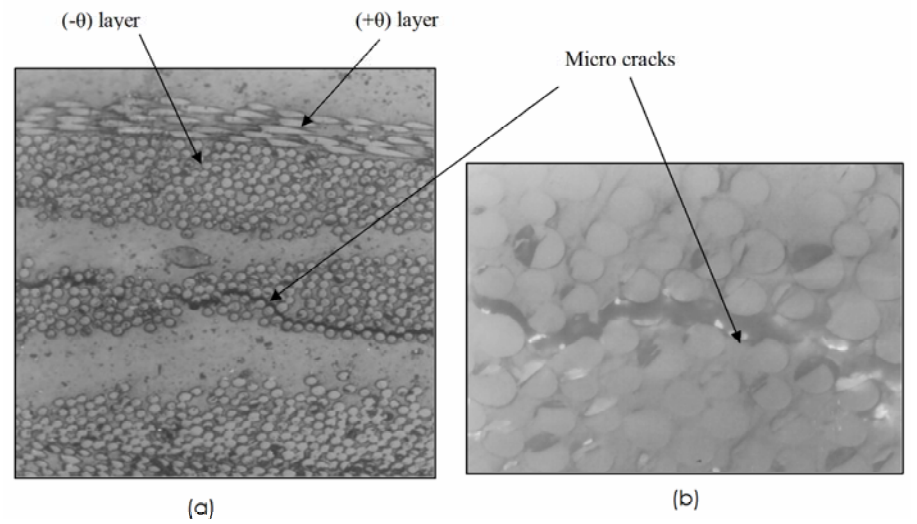

Figure 15: Optical micrograph of polished sample from the composite layer repaired pipe. (a) Magnification X 20 and (b) magnification X 50

Figure (16) shows a delamination which occurred between two plies as a result of interlaminar microcracks. The delamination may lead to the ply separation. The occurrence of delamination may cause continuous crack paths which increase the probability of weepage occurring by increasing the length of cracks crossing by other cracks [17].

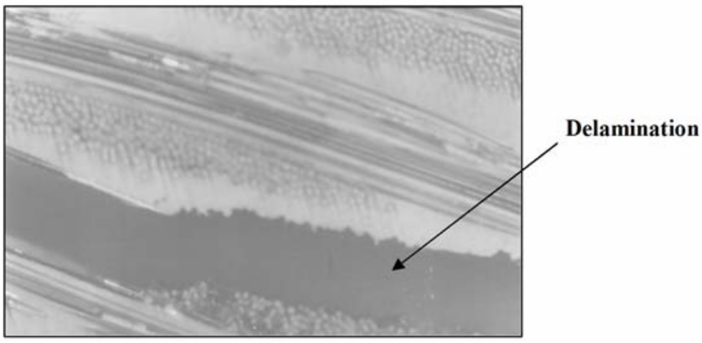

Figure 16: A delamination between the layers (magnification X20)

Figure (17) illustrates a microcrack induced by a micro-void (black spots) in the interface region between two plies. It can be observed that the microcracks initiated and propagated from one void to the other. One possible explanation for these cracks is that the voids which were entrapped during the repairing process caused a stress concentration in the laminate like a plate with an open hole.

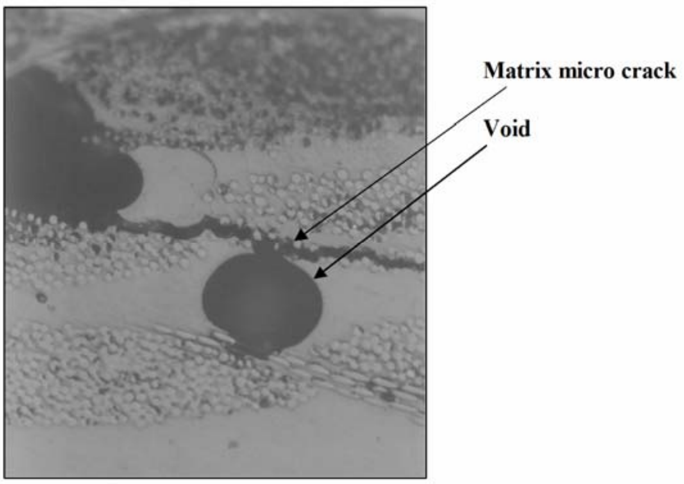

Figure 17: A micro crack propagates in a laminate from one void to another

CONCLUSIONS

- The work reported showed that it is possible to employ composite material for the external repair of metal pipes.
- A reasonable agreement between the experimental and theoretical results of the radial stress-strain curves was achieved and observed at the early stages of loading. However, discrepancy was observed at high strain to failure, which could be related to other relevant damage such as delamination and matrix macro-cracks.
- Delamination and weepage failure modes were observed in most of the failed pipes
- Microscopic damages such as matrix cracks, delaminations and voids were observed in microscopic examination.

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REFERENCES:

[1] Mableson, A. R., Dunn, K. R., Dodds, N., and Gibson, A. G., “ A New Composite –Based Repair Technique for Metallic Tubular.”, Eighth International Conference on Fibre Reinforced Composites, 13-15 September, 2000, PP 438-446, University of Newcastle upon Tyne, UK.

[2] Bowdoin, L. A., “Direct Deposit Welding Advance Make It a Viable Repair”, Journal of Technique. Pipeline & Gas Industry, Nov., 2000, pp. 67-72.

[3] Eckhold, G.C., “Design of Composite Work Repairs”, Specification Produced for Shell Exploration and Production, AEA T5771, AEA Technology, March, 2000.

[4] Mohitpour, M., Mcmanus, M., and Trefanenko, B., “Trend in Pipeline Integrity Inspection and Rehabilitation Techniques”. Proceedings, 4th International Pipeline Conference, IPC2002-27035, Calgary, Canada, 2002.

[5] AEA Technology Consulting, “Temporary/permanent pipe repair – Guidelines”, Offshore Technology Report 2001/038, Oxford, UK. 2001.

[6] Mableson, A. R., Dunn, K. R., Dodds, N., and Gibson, A. G., “Refurbishment of Steel Tubular Pipes using Composite Materials”. Plastics, Rubber and Composite, Vol.29, No.10, 2000, pp. 558-565.

[7] Forst, S. and Lee, R., “Composite Over-warps for Piping System and Pressure vessel System Repair”, The 4th MERL International Conference, 3-4 November, Institute of Electric Engineering, pp 99-111, 2003, London, UK.

[8] Bruce, B., Gordon, R., Sullivan, M. and Neary, C. “Internal Repair of Pipelines Technology Status Assessment Report”, DOE Award No.: DE-FC26-02NT41633, Edison Welding Institute, Columbus, USA. November 27, 2002.

[9] Baek, J, Kim, W. and Kim, Y., “Comparative Study for various Repair Methods of In-service pipeline using full Scale burst Test”, 23th World Gas Conference, Amsterdam 2006.

[10] Al Shrif, Z., Saied, O. R., Muftah, T. A. and Elarbi, M. B. “Repair of steel Pipes for Oil and Gas Industry Using Composite materials: part I”. 10th Mediterranean Petroleum Conference and Exhibition, February, 26-28, International Energy Foundation, Tripoli, Libya, 2008, pp. 29-39.

[11] Hull, D., “An introduction to composite materials”, Cambridge University Press, 1981, UK.

[12] Timoshenko, S.P. and Krieger, S.W., “Theory of Plates and Shells”, Second Edition, 28th printing, 1989, McGraw-Hill Book Company.

[13] Petit, P.H. and Waddoups, M.E, “Method of Predicting the Non-linear Behaviour of Laminated Composite”, Journal of Composite Materials, Vo. 3, 1969, pp. 2-19.

[14] Nahas, M.N, “Analysis of Non linear Stress-Strain Response of Laminated Fibre Reinforced Composite”, Fibre Science and Technology, Vol. 20, 1984, pp. 297-313.

[15] Saied, R.O., and Shuaeib, F.M., “Modelling of the Nonlinearity of Stress-Strain Curves for Composite Laminates”, Journal of Engineering Research, Issue 7, March 2007, pp. 1-14.

[16] Talreja, R., “Transverse Cracking and Stiffness Reduction in Composite Laminates”, Journal of Composite Materials, Vol. 19, 1985, pp. 355-375.

[17] Jones, M. L.C. and Hull, D., “Microscopy of Failure Mechanisms in Filament Wound Pipes.” Journal of Materials Science, Vol. 14, 1979, p. 165.