BEHAVIOUR OF REPAIRED COMPOSITE STEEL PIPELINE USING EPOXY GROUT AS INFILL MATERIAL

LIM KAR SING

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Universiti Teknologi Malaysia

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DEDICATION

This thesis is especially dedicated to:

My beloved parent,
Mr. Lim Chin Hock and Mdm. Tam Kam Ming;

My dear siblings,
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ABSTRACT

The use of Fibre Reinforced Polymer (FRP) composites together with infill grout has been proven effective for repairing damaged steel pipelines. The common understanding of the role of grout is to fill the damaged section and to transfer loads from damaged pipeline to composite wrap. The properties of grouts are important parameters used in numerical simulation or theoretical prediction on the behaviour of a repair system. However, relatively limited information on the behaviour and role of grout in composite repair system has restricted efforts to explore the contribution of grouts as a secondary load bearing component. Therefore, this study aimed to investigate the performance and behaviour of epoxy grouts in terms of load transfer mechanism and load bearing capacity of pipeline composite repair system through detailed material characterization, hydrostatic burst test and finite element analysis (FEA). Selected mechanical and thermal tests were carried out on ten different grouts, steel pipe coupon and FRP composite wrap. Four hydrostatic burst tests were conducted on non-defect steel pipe, defective steel pipe and two composite repaired steel pipes. FEA was then utilized to enrich the information of grout in terms of load transfer mechanism and load bearing capacity. The finite element (FE) models were developed to simulate all hydrostatic burst tests for sensitivity analysis purposes. Results revealed that Grout A with highest silica sand filler content exhibits the highest modulus under all loading conditions. In terms of strength, Grout A shows the best performance under compressive load but the lowest resistance under tensile, flexural and lap shear load. Modified grout with no filler content, Grout A (1:0), shows contradictory properties and behaviour. In studying the effect of different grouts on overall performance of composite repaired steel pipe, Grout A and Grout A (1:0) were used to repair two steel pipe segments. Both grouts have increased the burst pressure of the steel pipe by about 23% and 26%, respectively. All FE models were found to be capable of predicting the behaviour and burst pressure of experimental test with margin of error less than 8%. The grout has experienced relatively high tensile stress when compared with the compressive stress. The highest tensile stress of grout was found at hoop direction while the highest compressive stress was recorded at radial direction. In addition, sensitivity analysis revealed that repair using Grout B resulted in 8% decrease of burst pressure, while grout with high tensile modulus and strength increased the burst pressure by 11%. Thus, based on the experimental test and numerical analysis, it is proven that the role of grout is not limited to transferring load and filling the defect, as it also provides additional reinforcement. It was also confirmed that different properties of grout affect the overall performance of repair. For a low tensile strength grout, an increase of modulus shows little difference of burst pressure, while for high tensile strength grout, a similar increase in modulus has led to a considerable increment in burst pressure. The finding in this study is significant as it provides comprehensive understanding of the role and contribution of grout in composite repaired steel pipeline. This can serve as an initial step towards optimizing the current design, such as minimizing the usage of composite layers and subsequently design repair without composite layers.

ABSTRAK

Penggunaan komposit polimer diperkuat gentian (*FRP*) bersama isian *grout* telah terbukti efektif untuk membaiki talian paip keluli yang mengalami kerosakan. Pemahanan umum tentang peranan *grout* adalah untuk mengisi bahagian kecacatan dan memindahkan beban dari paip ke pembalut komposit. Sifat-sifat *grout* merupakan parameter penting yang digunakan dalam simulasi berangka atau ramalan teori bagi kelakuan sesuatu sistem pembaikian. Walau bagaimanapun, maklumat yang terhad mengenai kelakuan dan peranan *grout* di dalam sistem pembaikian komposit telah membataskan usaha untuk meneroka sumbangan *grout* sebagai komponen galas beban sekunder. Oleh itu, kajian ini bertujuan untuk mengkaji prestasi dan kelakuan *grout* epoksi dari segi mekanisma pemindahan beban dan keupayaan galas beban bagi sistem pembaikian komposit melalui pencirian bahan yang terperinci, ujian letus hidrostatik dan analisis unsur terhingga (*FEA*). Ujian sifat-sifat mekanikal dan termal yang terpilih telah dijalankan terhadap sepuluh jenis *grout*, kupon paip keluli dan pembalut komposit *FRP*. Empat ujian letus hidrostatik telah dijalankan terhadap paip yang tiada kecacatan, paip cacat dan dua paip yang dibaiki dengan komposit. Seterusnya, *FEA* telah digunakan untuk memperkaya maklumat *grout* dari segi mekanisma pemindahan beban dan keupayaan galas beban. Model-model *FE* telah dibangunkan untuk mensimulasi semua ujian letus bagi tujuan analisis sensitiviti. Keputusan ujian menunjukkan bahawa *Grout A* yang mempunyai kandungan pengisi pasir silika tertinggi mempamerkan modulus tertinggi di bawah semua keadaan pembebanan. Dari segi kekuatan, *Grout A* menunjukan prestasi terbaik di bawah beban mampatan dan ketahanan terendah di bawah beban tegangan, beban lenturan dan beban ricihan. *Grout* diubah suai yang tidak mengandungi pengisi, *Grout A (1:0)*, menunjukan sifat dan kelakuan yang bertentangan. Untuk mengkaji kesan daripada penggunaan *grout* yang berbeza, *Grout A* dan *Grout A (1:0)* telah digunakkan untuk membaiki dua segmen paip. Kedua-dua *grout* telah meningkatkan tekanan letus paip sebanyak 23% dan 26%. Semua model *FE* didapati mampu untuk meramal kelakuan dan tekanan letus ujikaji eksperimen dengan jidar selisih kurang daripada 8%. *Grout* didapati mengalami tegasan tegangan yang amat tinggi berbanding dengan tegasan mampatan. Tegasan tegangan *grout* yang tertinggi adalah pada arah gegelang manakala tegasan mampatan yang tertinggi direkodkan pada arah jejarian. Sebagai tambahan, analisis sensitiviti mendedahkan bahawa pembaikian menggunakan *Grout B* menyebabkan pengurangan tekanan letus sebanyak 8%, manakala *grout* yang mempunyai modulus dan kekuatan tegangan yang tinggi dapat meningkatkan tekanan letus sebanyak 11%. Oleh itu, ujian eksperimen dan simulasi berangka telah membuktikan bahawa peranan *grout* bukan hanya terhad kepada pemindahan beban dan pengisian kecacatan, malah juga memberi pengukuhan tambahan. Sebagai tambahan, ini telah disahkan bahawa perbezaan sifat-sifat *grout* mempengaruhi prestasi keseluruhan pembaikian. Bagi *grout* yang mempunyai kekuatan tegangan yang rendah, peningkatan modulus hanya menyebabkan sedikit perbezaan tekanan letus, manakala bagi *grout* yang mempunyai kekuatan tegangan yang tinggi, peningkatan modulus yang sama telah mengakibatkan peningkatan tekanan letus yang agak banyak. Penemuan dalam kajian ini adalah penting kerana telah memberikan pemahaman yang komprehensif tentang peranan dan sumbangan *grout* di dalam paip yang dibaiki dengan komposit. Tambahan pula, ini boleh digunakan sebagai langkah awal untuk mengoptimumkan rekabentuk sedia ada, seperti meminimumkan penggunaan lapisan komposit dan kemudiannya merekabentuk pembaikian tanpa lapisan komposit.

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LIST OF ABBREVIATIONS

CFRP	-	carbon fibre reinforced polymer
CLC	-	Combined Loading Compression
CNC	-	Computer Numerical Controlled
DGEBA	-	Diglycidyl ether of bisphenol-A
DSC	-	Differential Scanning Calorimetry
Eq.	-	equation
FE	-	finite element
FEA	-	finite element analysis
FESEM	-	Field Emission Scanning Electron Microscope
FRP	-	fibre reinforced polymer
LVDT	-	Low Voltage Displacement Transducer
MAOP	-	maximum allowable operating pressure
NTSB	-	Natural Transport Safety Board
PGU	-	Peninsular Gas Utilisation
PR	-	Poisson’s Ratio
SMYS	-	specific minimum yield strength
SSGP	-	Sabah-Sarawak Gas Pipeline
UV	-	ultraviolet

LIST OF SYMBOLS

D	-	pipe diameter
E	-	Young's Modulus
E_c	-	tensile modulus of composite laminate (circumferential direction)
Eng_{strain}	-	engineering strain
Eng_{stress}	-	engineering stress
E_s	-	tensile modulus of pipe
E_{tan}	-	Tangent Modulus
G	-	Shear Modulus
L	-	total axial length for repair/minimum composite repair length
L_{defect}	-	defect length
L_{over}	-	extended length of defect region for composite wrap
L_{taper}	-	taper length
P	-	internal design pressure
P_{bare}	-	burst pressure of bare pipe
P_{burst}	-	designed burst pressure for testing facilities
p_f	-	repaired pipe test pressure
P_{live}	-	pipe internal pressure during repair
Ps	-	maximum allowable operating pressure
P_{yield}	-	internal pressure of the pipe substrate at yield
S	-	yield strength in pipe substrate
s_a	-	yield strength of pipe
t	-	thickness of pipe
Tg	-	Glass Transition Temperature

t_{min}	-	minimum repair thickness
$True_{strain}$	-	true strain
$True_{stress}$	-	true stress
t_s	-	minimum remaining wall thickness
ε	-	total maximum strain
ε_c	-	design allowable strain of composite
$\varepsilon_{elastic}$	-	elastic strain
$\varepsilon_{plastic}$	-	extra strain/plastic strain
σ	-	stress
σ_h	-	hoop stress
ν	-	Poisson’s ratio

CHAPTER 1

INTRODUCTION

1.0 Overview

In the oil and gas industry, pipelines are regarded as the most economic and safe way to transport products from one point to another (Kishawy and Gabbar, 2010; Noor *et al.,* 2012; Li *et al.,* 2013, Yusof *et al.,* 2014). Throughout their service years, these pipelines are subjected to damage and deterioration caused by several factors. These include material and construction defects, natural forces, third party damage and corrosion (Peabody, 2011; CONCAWE, 2013; Tahir *et al.,* 2015). A corroded pipeline will reduce its strength and eventually its service life. The deterioration of steel pipelines is a common and serious problem experienced by the oil and gas industry as this may reduce steel pipeline life span and structural integrity. It could also lead to failures such as leaking and explosion which involve considerable cost and inconvenience to the industry and to the public.

As reported by the United States Department of Transport, the average annual cost related to corrosion is estimated at $7 billion for the monitoring, replacement and maintenance of gas and liquid transmission pipelines. About 80% of the cost is related to the maintenance and operation of corrosion related problems (United States Department of Transport, 2007). A rupture pipeline caused by external corrosion on May 2015 had an estimated of 500-barrel (bbl) of crude oil enter the Pacific Ocean. Even though this incident doesn't caused any fatalities or injuries, the total cost of property damage and clean-up was about $143 million (United States

Department of Transport, 2016a). In 2014, an explosion of an underground pipeline in Kaohsiung, Taiwan killed at least 27 people and injured 286 due to a leaked pipeline (Hsu and Liu, 2014). According to Saeed *et al.* (2014), more than 60% of the world's oil and gas transmission pipelines are more than 40 years old. Meanwhile, more than 35% of local onshore pipeline in Malaysia are more than 30 years old (Petronas Gas Berhad, 2014). Most of these pipelines are in urgent need of rehabilitation in order to re-establish their desired operating capacity. Therefore, corrosion and metal loss cause pipeline failures and their repair techniques is of interest to researchers all around the world (Shamsuddoha *et al.,* 2013a; Alexander, 2014; Chan *et al.,* 2015; Shamsuddoha *et al.*, 2016).

1.1 Background of the Problem

Currently, a wide range of rehabilitation techniques and repair methods are available for onshore and offshore pipelines. For years, the most common repair solution for a corroded steel pipeline was to remove the pipe entirely or removing only a localized section and then replacing it with a new one. Alternatively, repair can be done by installing a full-encirclement steel sleeve or a steel clamp. These conventional repair techniques incorporate external steel sleeves that are either welded or bolted to the outside surface of the pipe. The shortcomings of these techniques are bulky, costly and time consuming, especially for underground pipelines (Kou and Yang, 2011; Shamsuddoha *et al.,* 2012). In addition, these methods are generally suitable for straight pipe sections and have limited applications for joints or bends. Thus, researchers have been searching for repair techniques that are relatively lightweight, cheaper, easily applicable, and can be an effective repair solution.

In recent years, it is observed that there is a rapid growth in the development and application of Fibre-Reinforced Polymer (FRP) composites where the method has been proven effective for repairing steel structures such as risers and pipelines (Duell *et al., 2008;* Leong *et al.*, 2011; Alexander, 2014; Chan *et al.,* 2015).

Although the products made by different companies and research institutes around the world have widely different performance, a composite material repair system mainly includes three parts: (i) a high strength FRP composite wrap; (ii) a high performance adhesive; and (iii) a high compressive infill material. FRP composites have been chosen to repair steel pipelines due to their lightweight, high strength and stiffness, excellent fatigue properties and good corrosion resistance. Despite many advantages offered by composite repair systems, several issues regarding the behaviour and performance of the composite repair systems are not fully understood. These issues include the complexity of surface preparation, delamination and de-bonding between steel pipe and composite, performance and contribution of the infill material, load transfer mechanisms, effect of defect geometries, and conservativeness in existing design codes (Duell *et al.,* 2008; Ma *et al.,* 2011; Shamsuddoha *et al.*, 2013b; United States Department of Transport, 2013; Saeed *et al.*, 2014). These gaps in the current body of knowledge demand further investigation in order to have better understanding on the behaviour of composite repaired steel pipeline, and subsequently improve the efficiency of composite repair systems.

1.2 Research Problem

Grout or putty is usually used as infill material in composite repair systems. The common understanding on the role of grout/putty is to fill the damaged sections (i.e. corrosion) and to provide a smooth bed for the composite wrap instead of serving as a secondary layer of protection and sharing the load. In addition, putty also serves as a medium for load transfer from the corroded pipe to the composite wrap. This is important to provide a continuous support to minimise the outward distortion of the corroded section. Therefore, the effectiveness of these repair systems largely depends on the performance of the grout (Farrag, 2013; Shamsuddoha *et al.*, 2013b).

The properties of grout are significant parameters for the numerical simulation or theoretical prediction of the behaviour of a repair system to be optimised in terms of repair design. It is therefore essential to characterize the mechanical and thermal properties of epoxy grouts to determine their efficiency as infill materials in composite repair system (Shamsuddoha *et al.,* 2013b). However, detailed investigations on the properties, role and contribution of putty are very limited in the literature (both experiment test and numerical simulation) for a composite repaired pipe due to its assigned limited function in composite repair system. Hence, this limits the effort to optimise the design of composite repair system. All previous works mainly focused on the performance of the wrapper instead of putty. In most of the past literatures, detail information of infill material in a composite repaired pipe is hardly available, such as in the works done by Duell *et al.* (2008), Alexander *et al.* (2014), and Chan *et al.* (2015). On the other hand, Shamsuddoha *et al.* (2013b) and Shamsuddoha *et al.* (2016) carried out detailed characterization on infill material but no repair work was carried out, thus complete evaluation of these infill materials in composite repair system is not feasible. Owing to this, the overall behaviour of composite repaired pipe is not fully understood yet.

Composite repair system with a legitimate design code in strengthening damaged pipeline is relatively new in the oil and gas industry, and there is still room for improvement in designing the composite repair system. In addition, the future trend in repairing damaged pipeline is to optimize the composite repair system by proper selection of infill material, reducing the usage of composite wrapping layers and less conservative design philosophy. The neglect of infill is also reflected in the closed-form solution in existing codes and standards of current industry practices. The design of composite repair system can be found in ASME PCC-2- Part 4, Nonmetallic and Bonded Repairs (2011) and ISO/TS 24817, Composite Repairs for Pipework (2006). The repair design for both ASME and ISO codes does not account for the presence of infill material, only the minimum remaining wall thickness (of the pipe) and additional strength of composite wrap are considered. Hypothetically, as the putty acts as part of the repair system, it should somehow affect the overall performance of the repair. However, the evaluation on the effect of infill towards overall repair performance is hardly available in previous studies.

In the above mentioned studies and codes, there is lack of detailed information on the performance and contribution of an important component in composite repair system, the infill materials. This could be the reason where comprehensive understanding of the behaviour and load transfer mechanism of a composite repaired pipe is yet to be fully established. Therefore, more research is needed to understand the role of infill material. This is crucial in providing a better understanding of the behaviour of composite repair systems. In addition, it can serve as an initial step towards optimizing current design, such as reduces conservativeness in current closed-form solution, minimizing the usage of composite layers and subsequently design a repair without composite layers. Therefore, this study has taken initial step to harvest more information on the behaviour of infill material and its contribution in composite repair systems through detailed material characterization, hydrostatic burst tests and numerical analysis.

1.3 Research Objectives

The main aim of this research is to investigate the behaviour and performance of epoxy grouts in terms of load transfer mechanism and load bearing capacity of pipeline composite repair system using detailed material characterization, hydrostatic burst test and finite element analysis (FEA). The objectives of this study are:

1. To characterize the mechanical and thermal properties of existing epoxy grouts and to determine its behaviour as a “stand-alone” material.

2. To investigate the detailed load transfer mechanism and behaviour of infill materials as part of composite repair systems through full-scale pipeline hydrostatic burst tests and comparison made with finite element analysis.

3. To propose a modified infill material by modifying composition and adding graphene nanoplatelets to investigate its potential in improving the performance of composite repair system.

1.4 Research Scope

This study investigates the behaviour of infill materials in composite repair systems for repairing damaged steel pipe. The type of damage is limited to external corrosion defects of 50% metal loss, and 100mm (hoop) by 100mm (axial) defect. Internal corrosion, through wall thickness defect and defect geometries are not covered in this study. The mechanical properties and stress-strain behaviour of the infill materials were investigated under various loading conditions including compression, tensile, flexural and lap shear. Experimental hydrostatic burst test and numerical analyses of non-defective pipe, defective pipe and repaired pipes using two types of infill materials were done to evaluate the performance and behaviour of the infill materials. Enhancement on the performance of infill material was done by modifying the properties of existing infill. However, no development of new material is covered by this research.

1.5 Importance of Study

Several companies in the oil and gas pipeline industry are keen in reducing the usage of composite wrap since it can directly reduce the repair cost of repair material and other issues related to usage of composite wraps (i.e.: logistic, congested area). One of the main challenges in improving the current pipeline repair system is the lack of information on the behaviour of composite repaired damaged pipes. The role of infill materials is very significant to ensure satisfactory repair performances; hence it is of utmost importance to understand the behaviour of infill materials and its contribution towards overall repair performance. If the required properties and behaviour of infill materials can be determined in detail, it would benefit the industry by improving the design for composite repair systems. It also could serve as a stepping stone for future research in order to achieve the above mentioned aim. Ultimately, it is hoped that in the future, repair works can be done without composite wrapping.

1.6 Overall Research Methodology

Laboratory test and numerical analysis were conducted in this study. It consists of three stages: infill material characterization, pipeline hydrostatic burst tests and finite element analysis (FEA). The first stage required extensive laboratory tests including compression, tensile, flexural, and lap-shear test to provide detail understanding of the fundamental properties and behaviour of existing and modified infill material under different loading conditions as stand-alone material. The next stage aims to evaluate the effect of infill material as part of composite repair system. Full scale pipeline hydrostatic burst tests were carried to determine the behaviour and performance of four steel pipes. The first specimen is a bare pipe, representing the original strength of a newly installed pipe. A defect was machined onto the second specimen resembling an external corrosion to determine the strength reduction due to the wall loss. A defect similar to the second specimen was machined onto the third and fourth specimens. Both third and fourth specimens were repaired using a similar composite wrap but with different infill material as such the effect of infill can be evaluated. The final stage involved comprehensive finite element analysis to investigate the overall behaviour and performance all tested steel pipe specimens, focusing on the infill material. In addition, sensitivity analyses were carried out to numerically investigate the role and contribution of infill material as part of composite repair system.

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