MATHEMATICAL MODELLING OF PIPELINE COMPOSITE REPAIR DESIGN USING FINITE ELEMENT ANALYSIS INCORPORATING PUTTY'S CONTRIBUTION

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor Degree of Civil Engineering.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Sistem pembaikian komposit yang terdiri daripada penggunaan komposit polimer diperkuat gentian *(FRP)* dan isian pakal-pakal telah terbukti efektif dalam membaiki talian paip keluli yang mengalami kerosakan. Walau bagaimanapun, kajian terdahulu termasuk kod dan piawaian reka bentuk telah mengabaikan sumbangan daripada pakal kerana mereka menganggap pakal hanya berfungsi untuk mengisi bahagian yang berkarat dan memindahkan beban daripada paip ke pembalut komposit. Ini telah membataskan usaha untuk meneroka sumbangan pakal dan prestasi pembalut komposit telah menjadi tumpuan utama dalam kajian terdahulu. Satu kajian yang baru-baru ini telah menunjukkan bahawa pakal tidak hanya terhad untuk memindahkan beban, tetapi ia juga berpotensi sebagai komponen galas beban. Oleh itu, kajian ini bertujuan untuk memodelkan sumbangan pakal dari segi keupayaan galas beban melalui analisis unsur terhingga *(FEA)* dan pemodelan matematik. Dua model FE telah digunakan untuk mengkaji prestasi dua pakal yang berbeza sifat bahan yang digunakan untuk membaiki paip yang berkarat luaran diikuti dengan analisis regresi. Hubungan antara tekanan letus paip dan pengagihan beban antara paip keluli, pembalut komposit dan pakal telah dikaji. Keputusan ujian menunjukkan bahawa penggunaan pakal yang berbeza sifat mempunyai pengaruh yang besar terhadap sifat dan seterusnya prestasi keseluruhan paip pembaikian komposit. Bagi pakal yang mempunyai kekuatan tegangan yang tinggi, ia dapat meningkatkan kapasiti letus paip yang diperbaiki dengan memberikan pengukuhan tambahan manakala pakal yang mempunyai modulus tegangan yang tinggi dapat mengurangkan pengubahan bentuk. Di samping itu, didapati bahawa dengan mengambilkira sumbangan kekuatan pakal, terdapat potensi untuk meningkatkan tekanan letus paip sebanyak 5%. Penemuan dalam kajian ini adalah penting kerana ia memberikan pemahaman yang komprehensif tentang sumbangan pakal dari segi keupayaan galas beban dalam paip pembaikian komposit di mana sumbangannya telah dikuantitikan dengan menggunakan dua jenis pakal yang berbeza sifat. Maka, kemasukan sumbangan kekuatan pakal harus diambil kira dalam penyelesaian tertutup reka bentuk pembaikian komposit. Ini boleh digunakan sebagai satu batu loncatan ke arah pengoptimuman reka bentuk pembaikian paip, seperti meminimumkan penggunaan pembalut komposit dan kemudiannya pembaikian tanpa pembalut komposit.

ABSTRACT

A composite repair system which consists of Fibre Reinforced Polymer (FRP) and putty as infill material has been proven effective in repairing pipeline system. However, previous studies including the design codes and standards are neglecting the contribution of putty as they assume putty is only functioned to fill the corroded section and to transfer loads from damaged pipeline to composite wrap. This has restricted the efforts to explore the contribution of putty that performance of wrapper became the main focus in the past research works. A recent study has pointed out that putty is not only limited to transfer the load, but it has the potential to serve as a load bearing component. Therefore, this research is aimed to model the contribution of putty in terms of load bearing capacity through finite element analysis (FEA) and mathematical modelling. Two finite elements models were utilized to study the performance of two different material properties of putties used to repair externally corroded pipeline followed by regression analysis. The relationship between burst pressure and stress distribution of steel, composite wrap and putty are investigated. Results revealed that different properties of putty have great influence upon the behaviour and subsequently the overall performance of a composite repaired pipe. A high tensile strength putty can increase the burst capacity that a repaired pipe can withstand by providing additional reinforcement while high tensile modulus of putty can help to reduce the deformation. In addition, it was found that by incorporating the strength contribution of putty, there are potential to increase the burst pressure by about 5%. The finding of this research is significant as it provides comprehensive understanding on the contribution of putty in terms of load bearing capacity in composite repaired pipeline where its contribution has been quantified with two different properties of putties. Hence, the inclusion of strength contribution of putty should be taken into account in the closed-form solution of composite repair design. This can serve as a stepping stone towards design optimization of pipeline rehabilitation, such as minimizing the usage of composite wrap and subsequently repair without composite wrap.

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LIST OF SYMBOLS

D	Diameter of pipe
E	Young's modulus
E_c	Tensile modulus of composite laminate (in circumferential direction)
E_s	Tensile modulus of pipe
P	Pressure
P_{live}	Live pressure
P_s	Maximum allowable operating pressure
P_{yield}	Internal pressure of the substrate pipe at yield
R^2	R Square
S	Yield strength in substrate pipe
t	Thickness of pipe, composite wrap and putty
t_{min}	Minimum repair thickness
t_s	Minimum remaining wall thickness
x_{i}, x_{ii}, x_{iii}	Independent variables
y	Dependent variable
ε	Strain
ε_c	Design allowable strain of composite
$\varepsilon_{elastic}$	Elastic strain
$\varepsilon_{plastic}$	Plastic strain
σ	Stress
σ_c	Composite wrap stress
σ_h	Hoop stress
σ_p	Putty stress
σ_s	Steel stress

LIST OF ABBREVIATIONS

DGEBA	Diglycidyl ether of bisphenol-A
Eq.	Equation
FEA	Finite element analysis
FRP	Fibre reinforced polymer
HES	Helicoid epoxy sleeve
IMPACT	International Measures of Prevention, Application and Economics of Corrosion Technology
MAOP	Maximum allowable operating pressure
MLR	Multiple linear regression
RGTSU	Regasification Terminal Sungai Udang
SMYS	Specific Minimum Yield Strength
USDOT PHMSA	U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration
VSD	Volumetric Surface defects

CHAPTER 1

INTRODUCTION

1.1 Overview

In the oil and gas industry, steel pipelines are regarded as the most effective, economic and safest way of transporting crude oil, natural gas and liquid petroleum products over a long distance (Kishawy & Gabbar, 2010; Shamsuddoha *et al.*, 2013a; Abdul Jalil *et al*., 2016). Owing to this reason, provision of their continuous work and accident-free operation is utmost essential (Barkanov *et al.*, 2018). However, these pipelines are subjected to damage and deterioration throughout their service life. These damages are generally caused by several factors, which include material and construction defects, natural forces, corrosion and also third parties' excavation (Kishawy & Gabbar, 2010; Azraai *et al.*, 2015). Referring to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (USDOT PHMSA), it can be summarized that about 21% of recent oil pipeline failures in the United States are caused by corrosion (Haladuick & Dann, 2018). Hence, a damaged pipeline can be very dangerous as it tends to reduce the strength of the steel pipelines and eventually its intended service life. This issue has become a big headache for the oil and gas industry since it can lead to pipeline failures such as loss of structural integrity, fire, explosion and leakage. All these failures require a significant amount of cost while bringing much inconvenience towards the industry and public as well.

As reported by NACE International in their two years of global study, International Measures of Prevention, Application, and Economics of Corrosion Technology (IMPACT), the global cost of corrosion is approximated at $2.5 trillion (NACE International, 2016). In addition, the average annual corrosion-related cost is estimated at $7 billion to monitor, replace, and maintain these gas and liquid transmission pipelines. The corrosion-related cost of operation and maintenance makes up 80% of this cost (Koch *et al*., 2002). In 2013, an explosion of an underground pipeline in Qingdao in eastern China killed at least 62 people and injured 136 which was caused by an ignition of vapours produced from oil leakage from a corroded underground pipeline (NACE International, 2014). Saeed *et al.* (2014) revealed that more than 60% of the pipelines from all over the world have been in service for more than 40 years. Even in our own country, Malaysia, Petronas Gas Berhad (2014) reported that more than 35% of the local onshore pipelines are more than 30 years old. In short, it can be concluded that there is an urge to repair all these pipelines so as to recover their desired operating capacity and to restore their in service performance. Hence, pipeline failure due to corrosion that can have large social, economic, and environmental consequences has gained attention from researchers worldwide and so its repair technique is kind of their main interest to ensure the pipelines are in good working condition (Shamsuddoha *et al.*, 2013a; Alexander, 2014).

1.2 Research Background

Nowadays, there are a wide variety of pipeline rehabilitation techniques that are available for the offshore platform and onshore processing plant. Traditionally, the most common repair method is done by replacing a new steel pipe entirely for the damaged pipe or by removing the localized damaged section and covered it with a welded steel patch. Alternatively, the repair method can be done by the installation of full encirclement steel clamp or steel sleeve. These conventional repair system use either bolting or welding method to join both external steel sleeve and damaged pipe. Nevertheless, there are several limitations of these kinds of techniques, which are pricey, time-consuming and bulky especially for underground pipelines (Shamsuddoha *et al.*, 2012). It is an obvious fact that heavy machinery is required to perform this cumbersome work. Additionally, welding poses a potential risk of explosion as it involves hot work. Besides, these techniques are mostly not applicable for joints or bends but more suitable for a straight section of pipe. Therefore, it is an urge for the researchers to find an alternative way of repairing that is relatively lightweight, cheaper, appropriate yet effective (Shamsuddoha *et al*., 2013a; Lim *et al*., 2016a).

In most recent years, Fibre Reinforced Polymer (FRP) composite has been justified as a useful approach in steel pipeline rehabilitation (Duell *et al*., 2008; Alexander, 2014). One of the reasons may be due to its capability in repairing steel pipelines which has been proven both experimentally and analytically. It is widely practiced in the industrial projects. Also, it does not require a stop of pipeline operation while eliminating the risk of fire or explosion due to welding during the repair that makes it a better choice (Duell *et al.*, 2008). Composite repair also prevented the growth of newer corrosion risk and it can be considered as a life time repair (Shouman & Taheri, 2011). Basically, FRP composite method can be categorized into few groups, which are pre-cured layered, pre-impregnated with the aid of resin, clamping, flexible tape and wet lay-up, which is similar to the concept of a bandage. Even though numerous companies have produced their own composite repair systems around the world which might have various performances, a composite material repair system generally consists of three parts: (i) a high strength of FRP composite wrap, (ii) a high curing speed of adhesive and (iii) an infill material with high compressive strength which transfers the load. Owing to the capability of restraining high pressure of pipeline from yielding, FRP composite wrap, together with putty have been selected in repairing steel pipeline (Trifonov & Cherniy, 2014).

Generally, a composite wrap is installed by wrapping few layers of a composite material over the defected location (Ariff *et al.*, 2014). An increase in wrapping thickness can help to prevent the premature yielding of pipeline especially at the damaged area and so it is rather important that a minimum thickness is done according to the existing design codes (Osella *et al.*, 1998). However, there is a trend to reduce the usage of composite wrapping as composite wrapper is more expensive than the infill material itself. Besides, some damaged pipes are situated in congested areas such as piping on offshore platforms, piping of boiler tank and underground pipelines that have only limited working space for the wrapping process to be done. This makes the only possible solution is to replace the whole damaged pipe to maintain its service life (Abdul Jalil *et al*., 2016).

1.3 Problem Statement

In composite repair system, putty is generally used as an infill material. Most of the researchers assume that the function of putty is only to fill the defected area and creating a smooth surface rather than sharing the load with an additional protection layer. In other words, putty or grout acts as a load transfer agent between a corroded pipe and composite wrap. It is essential for minimizing the outward distortion of the corroded part

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