NUMERICAL ANALYSIS ON BONDING STRESS OF CARBON FIBRE REINFORCED EPOXY / STEEL

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ABSTRACT

The application of fibre reinforced polymer (FRP) composites in pipelines repairing and rehabilitation process revolutionizes the whole oil and gas industry especially in a condition which repair technique is hard to be implemented. The bond strength between FRP and the pipeline metal is the major element in determining the system strength. Numerous researchers studied the adhesion failure between FRP and metal using both experimental work and finite element (FE) simulation. However, the evaluation of bond strength has been specifically constraint within the bonding system and materials used only. This study aimed to simulate the pipeline repair system and investigate the adhesion shear stress acting at the joint using FE analysis. Double strap joint (DSJ) samples consisted of carbon fibre reinforced epoxy (CFRE) and ASTM A36 steel as the adherend were prepared to model the repairing system using SIKADUR 330 epoxy as the adhesive. A number of parametric tests was performed to obtain material data input for FE simulation. FE model of the DSJ samples was developed using ABAQUS software and a linear cohesive zone model was applied to model the behaviour of the cohesive layer. Laboratory tensile test was also conducted to validate the FE simulation results. The maximum load value in simulation result showed 9.8% higher than the result from experimental work while deeper analysis in stress distribution data provided an estimation of 69.1% effective length of the bonded area. A parametric study was conducted to evaluate the effect on the bond strength by varying adherend's thickness and elastic modulus. For CFRE cases, the maximum applied load increased non-linearly with average increments of 2.08% and 1.25 % respectively, while adhesive horizontal displacement non-linearly decreased with average decrements of 6.16% and 5.62%, respectively as its thickness and modulus increased. Meanwhile, for ASTM A36 steel cases, a slight decrement was observed for maximum applied load with average decrements of 0.33% and 0.16%, while adhesive horizontal displacement non-linearly decreased with average decrements of 2.21% and 2.37 % respectively as its thickness and modulus increased. In conclusion, the stiffness of the bonded structure was influenced by both parameters, which beneficial in structural design.

ABSTRAK

Penggunaan komposit polimer bertetulang gentian (FRP) dalam proses pembaikan dan pemulihan saluran paip merevolusikan keseluruhan industri minyak dan gas terutamanya dalam keadaan yang mana teknik pembaikan sukar dilaksanakan. Kekuatan ikatan antara FRP dan logam saluran paip adalah elemen utama dalam menentukan kekuatan sistem tersebut. Ramai penyelidik telah mengkaji kegagalan lekatan antara FRP dan logam sama ada secara eksperimen mahupun analisis unsur terhingga (FE). Namun begitu, penilaian kekuatan ikatan terkekang secara spesifik dalam sistem ikatan dan bahan yang digunakan sahaja. Tujuan kajian ini adalah untuk membuat simulasi sistem pembaikan saluran paip dan menyiasat tegangan ricih yang bertindak pada sendi lekatan menggunakan FE. Sampel sendi berganda (DSJ) yang terdiri daripada komposit epoksi bertetulang gentian karbon (CFRE) dan keluli ASTM A36 disediakan sebagai perekat untuk memodelkan sistem pembaikan menggunakan SIKADUR 330 sebagai pelekat. Sejumlah ujian berparameter telah dijalankan untuk mendapatkan data masukan bahan bagi simulasi FE. Model zon jelekat lelurus digunakan untuk memodelkan tingkah laku lapisan jelekat. Ujian tegangan makmal juga telah dijalankan untuk mengesahkan data simulasi FE. Nilai daya maksimum keputusan FE menunjukkan 9.8% lebih tinggi berbanding dengan hasil kerja dalam eksperimen sementara analisis yang mendalam terhadap data taburan tekanan memberikan anggaran panjang berkesan sebanyak 69.1% dari kawasan lekatan. Satu kajian parametrik telah dijalankan untuk menilai kesan terhadap kekuatan sendi dengan memvariasikan ketebalan dan modulus elastik perekatan. Bagi kes CFRE, beban tertumpu maksimum meningkat secara tidak lelurus dengan purata peningkatan masing-masing sebanyak 2.08% dan 1.25%, manakala anjakan melintang pelekat berkurang secara tidak lelurus dengan purata pengurangan masing-masing sebanyak 6.16% dan 5.62% apabila ketebalan dan modulus CFRE meningkat. Bagi kes keluli ASTM A36 pula, pengurangan kecil beban tertumpu maksimum dapat dilihat dengan purata pengurangan masing-masing sebanyak 0.33% dan 0.16%, manakala anjakan melintang pelekat berkurang secara tidak lelurus dengan purata pengurangan masing-masing sebanyak 2.21% dan 2.37% apabila ketebalan dan modulus keluli meningkat. Kesimpulannya, kekukuhan struktur melekat dipengaruhi oleh kedua-dua parameter, yang mana memberi manfaat dalam mereka bentuk struktur.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
CFRE	-	Carbon Fibre Reinforced Epoxy
CZM	-	Cohesive Zone Model
DSJ	-	Double Strap Joint
ESDU	-	Engineering Science Data Unit
FE	-	Finite Element
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
FRP	-	Fibre Reinforced Polymer

LIST OF SYMBOLS

N	-	Newton
MPa	-	MegaPascal
GPa	-	GigaPascal
mm	-	millimeter
N/mm	-	Newton per millimeter
s	-	second

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Research Background

Carbon steel remains the main material used in pipeline manufacturing today [1]. During their service life, pipelines are subjected to various deterioration factors, such as erosion and corrosive environments. If unattended, these types of deterioration may cause further damage to the pipe such as thickness reduction, surface cracking or, worse still, complete failure. However, pipeline monitoring and assessment are now used practically worldwide, often to give a prior assessment of the required repairs and replacements [2]. The use of fibre-reinforced polymer (FRP) composites in repairing and strengthening pipelines is increasing in both onshore and offshore applications. The advantages of using FRP for repairing pipes include its versatility in making repairs without the need for a pipeline shutdown, as well as the elimination of explosion risk due to welding [3]. These attributes compensate for the reasons to use a simpler repair process. Additionally, FRP is also viable due to its high-tensile strength, light weight and non-corroding attributes [4].

The unique properties of FRP offer many possibilities in civil infrastructure applications, ranging from repair and rehabilitation to the development of new structural elements [5][6][7]. FRPs are generally resistive to corrosion and highly suitable for harsh environment applications, including subsea locations and corrosive soils. Transportation costs can be reduced greatly as the low weight properties of FRP eliminate the need for heavy equipment during installation. Its high strength-to-weight ratio also makes FRP an effective strengthening material for use in rehabilitated structures, where extra load might be a threat. FRP also provides engineers with the option of decreasing the dimension changes of any repaired structure, as FRP with high specific strength or modulus is also available in thin strips. Other unique advantages of FRPs include their formability and their easy manufacture and installation. The unidirectional laminates application of FRP also provides better control of specific direction strengthening in any structural application.

Wet layup is one method that can be employed in the FRP manufacturing process. The formability of FRP increases the capability to use it with any structure, even if unevenly shaped. Fibre is also available in many forms, including strips with numerous width differences, which are formed by stitching long fibres next to each other. This minimises any material waste as FRP can be formed to the specific size needed in the application.

However, FRP still possesses some drawbacks [8]. Despite the advantages listed, FRP is vulnerable to damage from impact, fire, or vandalism. To eliminate these threats, a type of cover should be used as a protection medium for the FRP. Moreover, the FRP matrix resin is still susceptible to degradation caused by heat or other environmental factors. The most serious drawback to the FRP repair technique is that sufficient information is lacking on the long-term durability of FRP, making any service lifetime prediction unavailable.

1.2 Problem Statement

Load transfer ability is the main criterion for determining the performance of an FRP composite in any repair and strengthening system of a metallic structure. To achieve that, the proper selection of material has been the focus of both the industrial and academic worlds, since a structure’s strength generally derives from the material properties themselves. Adhesive with a high curing speed and performance has become a necessary form of load transfer medium, together with high-strength fibre, as reinforcing materials, especially in extreme environment applications. The current wet lay-up and fibre-wrapping techniques used in composite repair and strengthening systems have encountered many technical difficulties, resulting in a poorly bonded structure. This would lead to the formation of voids at the bond interface, affecting the structural integrity and load transfer capability of the bonded structure itself. Many studies have been conducted to improve the quality of composite repair systems and, in terms of structural capabilities, the bond between the fibre and its connected substrate has always been the primary focus. Joint debonding is the primary failure mode of an FRP/metal-bonded structure and this issue is becoming a major concern in the design and application of composite repair and strengthening systems.

Although the fibre-wrapping technique is considered new in repair and strengthening systems, its analysis began in 1940, since when joint analysis has become a key discipline in structural analysis. Over the years, researchers have devised numerous analytical and numerical methods of predicting the lifetime of a joint such that this aligns with the fundamental wrapping technique. However, while analytical analysis has limitations and employs too many assumptions, numerical studies are hampered by their complexity and the deep understanding required, even though these approaches actually provide more accurate data than analytical analysis. Although laboratory experiments are ideal for determining many critical properties of FRP/metal composite bonded structures, their applicability is limited to certain geometric sizes and a small number of material properties variations. Experimental work on composite structures with various combinations of different parameters is both difficult and uneconomical. As the complexity of bonded structure applications increases, computerised and numerical work (including the finite element method) are becoming major analysis tools and an integral part of structural engineering. With the correct understanding and method, numerical work can model a specimen as small as a grain of sand or as large as a building, while it can also predict the outcome after loads and displacements have been applied. In addition, with a non-linearity problem exhibited in the analysis due to surface contact and traction, numerical analysis in joint strength should be encouraged, particularly on FRP/metal bonded structures, as they are useful in practical terms and in industry.

Despite the numerous designs and applications of FRP/metal bonded structures, most FRP repair and strengthening activities have been undertaken with carbon steel as it is widely used in structural applications, including construction and pipelines. Therefore, the focal point of this research centred on the development of a numerical model for an FRP/steel bonded specimen using ABAQUS finite element analysis software, which was used to evaluate its mechanical behaviours. FE analysis on FRP/steel bonded samples has been performed frequently by researchers worldwide. However, with numerous material and design configurations available for application, the analysis of FRP/steel bonded structures is a considerable challenge since different configurations usually produce different performance and mechanical data. The usage of brittle epoxy, such as Sikadur 330, as the adhesive on FRP/steel bonded structures is widely recognised in industrial applications. However, little thorough experimental or numerical analysis is available on its mechanical behaviour and performance. As a major industrial applicable configuration, understanding the structural debonding behaviour of an FRP/steel adhesively bonded structure is important and has been highlighted in this study. An FRP/steel double-strap joint (DSJ) model was developed with Sikadur 330 as the adhesive. After the model had been calibrated using experimental data, it was used to conduct a parametric study. The geometrical and material effects on the load transfer capability and structural integrity are discussed in depth. The parameters evaluated were the thicknesses and elastic modulus of the FRP, adhesive and steel.

As the numerical approach has become a major tool for evaluating the mechanical behaviour of bonded structures, accuracy has become a concern. Problems arise when the plastic behaviour and damage mechanism play a substantial role in debonding failure. Many models have been proposed to describe the failure mechanism of a bonded surface through numerical simulation. In the last decade, cohesive zone modelling (CZM) has been extensively used by researchers to describe the adhesion properties of a bonded surface. CZM was initially developed by Barrenblatt in describing the fracture between two surfaces as a material separation. Such material separations revolve around the concept that crack propagation is prevented by some cohesive force that exists before the crack occurs. The description of material separation is defined by traction-separation laws, which regard traction as a function of separation and determine the constitutive behaviour of cohesive zone models. In computational CZM, material separation and degradation are assumed to occur in a discrete plane; this is represented using cohesive elements. These failure and degradation mechanisms are embedded into the constitutive law, which relates cohesive traction to local separation. Its effects on load transfer capability and structural integrity are later discussed in depth.

1.3 Objectives of the Research

The research aim is to improve an existing polymer composites strengthening/repairing materials system that can be applied in oil and gas structural applications (e.g., gas pipes) due to variations in the subjected load. To fulfil the project aim, the objectives are as follows:

i. To conduct finite element (numerical) analysis on a double-strap joint model of a steel pipe strengthened with an FRP system under adhesion shear.
ii. To evaluate the bond performance and shear stress distribution on the adhesive layer of the joint numerically using FE analysis.
iii. To investigate numerically the effects of geometrical and material parameters on the joint strength using FE analysis.

1.4 Research Scope

The scope of the research covers the understanding of the overall need for the project through a literature review; a parametric study of materials systems, such as identifying their mechanical and physical properties; the development of a numerical model for finite element analysis; and a numerical analysis of the model when subjected to adhesion shear based on experimental and analytical analysis using ABAQUS software. A double-strap joint configuration will be used in the numerical model to better simulate a real application. The structural bond performance and shear stress distribution will be investigated and discussed. The data from the analysis will be compared with the experimental work.

1.5 Research Questions

i. Can a finite element model predict the bond performance and structural integrity of a CFRE-steel strengthening system within an acceptable range of errors?
ii. How is shear stress distributed on the joint overlaps and how does this affect the bond integrity?
iii. How do different parameters - such as the adherend's thickness and elastic modulus - affect the bond strength of a double-strap joint system?

1.6 Significant of the Research

This research will predict data and results concerning the performance of a CFRE plate bonded system under adhesion shear which is, at present, the major concern in real-world applications. The research finding is vital and will be used as a standard reference in the design and quality control of composite repairs made to strengthen pipelines. The data prediction will also be used to provide directions for further analysis, as well as a more effective repairing and strengthening system.

is time consuming, the other option seems unnecessarily costly, and is difficult to perform in the subsea or hazardous areas. Still, in both cases, a long downtime and revenue losses will occur as the pipeline must be shut down and emptied before any work could been done.

During early 1970s, a development of full encirclement steel sleeves was made for pipeline repair [9]. These repair system were done by wrapping the damaged pipe with a length of pipe that possessed same diameter, wall thickness, and grade. The steel sleeves are then welded using butt or fillet welded techniques produced a type A or type B sleeve condition. However, type A sleeves are incapable of containing pressure and not suitable to be used for any through-thickness defects and any defects that are deeper than 80% of wall thickness. For these cases, type B sleeves are more suitable to be applied. However, the repairing required full drained or depressurized of the pipe to allow any fillet welding process being made.

Other conventional methods of repair include weld overlays, fillet welded patches, flush welded patches and welded leak box mechanical clamps [3].

2.2.2 FRPs Wrapping Technique

The interest of FRP as a materials for structural purposes was started way back in the 1950s and 1960s, where their high specific modulus and strength was very welcome in the structural application. Military industry was the earliest usage of FRP materials as high strength FRP was firstly introduced in fighter aircraft. It was only until 1980s, the first development of FRP pipeline repair system was made [9]. Through time, a number of different repair systems for internal and external pipeline repair existed for commercial used, and the development of a better repairing system continue to progress until today [10].

Low weight and flexibility are the major advantages of FRP materials in pipeline repair application [3] [4]. Adding the corrosive issue, FRP wrapping solve the problem of pipeline repair in corrosive environment as they are corrosive resistant

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Appendix A Material Properties for FE Simulation

Fibre

E1	E2	E3	Nu1	Nu2	Nu3	G12	G13	G23
300000	10000	10000	0.0058	0.0058	0.3	26500	26500	3700

Steel

Elastic	**Young Modulus**	**Poison Ratio**
	251602.1	0.26
Plastic	**UTS**	
	726205.1	

LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. Dani, Airul & Jamaluddin, Nor & Hassan, Shukur & Yahya, Mohd. (2019). Modulus Effect on Local Load Distribution for FRP/Steel Bonded Joint. IOP Conference Series: Earth and Environmental Science. 220. 012060. 10.1088/1755-1315/220/1/012060. (**Indexed by SCOPUS**)