Modelling failure pressure of pipeline composite repair design using finite element analysis incorporating putty's contribution

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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 as it can structurally reinforce the damaged steel pipes and potentially prevent external corrosion. However, previous studies including the design codes are neglecting the contribution of putty as they assume putty is only functioned to fill the corroded section. A recent study has pointed out that putty is not only limited to transfer the load, but it can serve as a load bearing component. Thus, the purpose of this research is 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. 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 can serve as a stepping stone towards design optimization of pipeline rehabilitation.

1 Introduction

Steel pipelines are regarded as the most effective, economic and safest way of transporting oil and natural gas over a long distance [1-3]. However, these pipelines are subjected to damage and deterioration which are caused by material and construction defects, natural forces, third party damage and corrosion [4-6]. A corroded pipeline can be dangerous as it tends to reduce the strength of steel pipelines and eventually its intended service life and so its repair technique is one of the prime interests of researchers worldwide [7-12]. Recently, Fibre Reinforced Polymer (FRP) has been accepted as a legitimate repair material towards conventional material, steel in the pipeline rehabilitation through the development of design codes and standards, including ASME PCC-2 [13] and ISO/TS 24817 [14]. Figure 1 shows

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a typical composite repair system for pipeline rehabilitation. Previously, most of the researchers assume that the function of infill material is to fill the damaged area and creating a smooth surface rather than sharing the load [15-18]. This has led to the negligence of the contribution of putty and performance of wrapper became the main focus in the past research works. Even in the design codes and standards, strength contribution from the putty was neglected in the closed-form solution when determining the minimum repair thickness, where it only accounts for minimum remaining wall thickness of steel pipe and additional strength of composite wrap and this may lead to a conservative calculation.

The global oil price is currently fluctuating between USD50 and USD70, which means a smaller profit margin for oil and gas producers. Therefore, asset integrity management and optimization has become a major concern for oil and gas producers and researchers to save maintenance costs. Owing to that, few researchers have started looking into optimization of composite pipeline repair [6, 19, 20]. In addition, oil and gas industry have commenced their interest in reducing the usage of composite wrap as it is more expensive than the infill material. Furthermore, some damaged pipes are located in congested areas such as piping on offshore platform, piping of boiler tank and underground pipelines and so they only have limited working space for wrapping process. Previous studies have revealed that the usage of composite wrap can be minimized by increasing the performance of infill materials [18, 20, 21]. Therefore, this research has taken an initial step to quantify the contribution of putty in terms of load bearing capacity towards burst capacity of externally corroded steel pipelines with different properties of putties through finite element analysis.

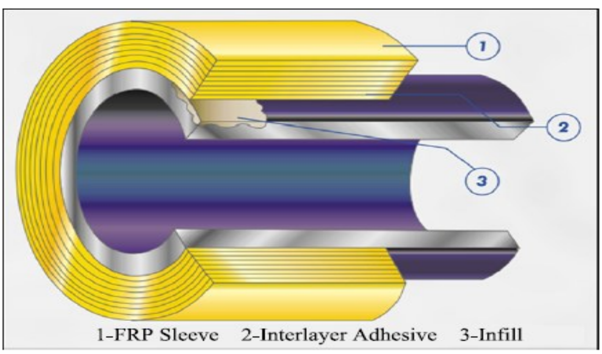

Fig. 1. Typical arrangement of composite repair system.

2 Methodology

A commercial finite-element software package was used to create the model, generate meshes, and perform finite element (FE) calculations to simulate the burst tests. The pipe and putty were meshed as reduced integration, 8-nodes linear brick elements of type C3D8R, while the composite shell was modelled as a reduced integration, 4-nodes shell element of type S4R. The analysis duration was set to 500 s with a linear increase in pressure to 50 MPa, which simulates a loading rate of 0.1 MPa/s. The non-linear effects concerning large displacement have been considered in this analysis.

Two finite element models corresponding to two different material properties of putties were utilized which serve as important inputs for the mathematical modelling. Model A is used to propose a closed-form solution of composite repair design incorporating the contribution of putty while Model B is used for validation purpose. The base geometry of the steel pipe is 168.3 mm diameter with 1200 mm length and 7.11 mm thick. A 50% of metal loss was simulated where the defect geometry was 100 mm (hoop) x 100 mm (axial) x

3.56 mm (depth). A total of three layers of composite wrap with 300 mm width and thickness of 1mm per layer were laid out across the defected pipe. Table 1 summarizes the material properties of steel, composite wrap and two different types of putties. Meanwhile, for the mathematical modelling, Model A serves as a base model while Model B acts as a validation model. Two types of analysis were conducted for both models, which are analysis of with and without the consideration of putty into the closed-form equation. For each model, various ranges of input values were taken into account in the analysis, which are full range, yield strength of steel and yield stress composite repaired pipe. The purpose of considering such ranges is to determine how much the putty can contribute towards the burst pressure prediction provided different nature of system were considered.

Table 1. Material properties of steel, composite wrap and putties.

Material Properties	Steel	Composite Wrap	Putty (Model A)	Putty (Model B)
Young's Modulus (GPa)	222.00	14.30	19.90	2.61
Ultimate Tensile Strength (MPa)	557.66	241.27	20.02	39.90
Yield Strength (MPa)	293.27	-	-	-

3 Results and Discussions

3.1 Base model of with and without putty

Table 2 presents the comparison between base model of with and without putty in terms of adjusted R^2 of multiple regression models and R^2 value of actual versus predicted pressure. It can be concluded that equation with the input of putty is more accurate than the equation without putty. This is done according to the adjusted R^2 and also R^2 value. As seen in Table 2, both adjusted R^2 and R^2 values are greater for the models with putty's input except for Model 2. However, it is slightly lower that not much visible effects can be governed where the percentage difference is 0.4% only. Generally, the higher the adjusted R^2, the higher the accuracy of the result is. In other words, a better fit will be if the adjusted R^2 is close to 1.0. Similar to R^2 value, higher value of it will be more advantageous in predicting the burst capacity that a pipe can withstand since it was a comparison between actual pressure and predicted pressure.

Table 2. Comparison between base model of with and without putty.

Model		Equation	Adjusted R^2 of MLR	R^2 value of actual vs predicted pressure
With putty	Full range (Model 1)	$P = 0.0483\sigma_s + 0.2799\sigma_p + 0.0104\sigma_c$	0.9964	0.9548
	Yield strength of steel (Model 2)	$P = 0.0476\sigma_s + 0.0194\sigma_p + 0.0915\sigma_c$	0.9375	1
	Yield stress composite repaired pipe (Model 3)	$P = 0.0151\sigma_s + 0.6182\sigma_p + 0.0493\sigma_c$	0.9943	0.9756

Without putty	Full range (Model 4)	$P = 0.0588\sigma_s + 0.0159\sigma_c$	0.9959	0.9399
	Yield strength of steel (Model 5)	$P = 0.0480\sigma_s + 0.1075\sigma_c$	0.9412	1
	Yield stress composite repaired pipe (Model 6)	$P = 0.0556\sigma_s + 0.0243\sigma_c$	0.9917	0.9327

3.1.1 Model 1

Relationship between actual and predicted burst pressure for Model 1 is shown in Figure 2. As can be seen, the obtained R^2 value was 0.9548, revealing that about 95.5% of the pressure values were predicted accurately. At the beginning and ending part of the graph, most of the points were approximately similar with the trend line, indicating that the values were predicted precisely. However, at the pressure of 4 MPa, the difference has started to deviate where the equation has overestimated the capability of the repaired pipe. This trend was continued until 23 MPa. Oppositely, from 23 MPa to 27 MPa, the system was under predicted by the equation. The actual burst pressure obtained by FEA is 32.8178 MPa while the predicted burst pressure is 32.5196 MPa. Considering the fact that predicting burst pressure is the most critical aim, the proposed model has shown a very good prediction where the percentage difference between actual burst pressure and predicted burst pressure is only 0.91%.

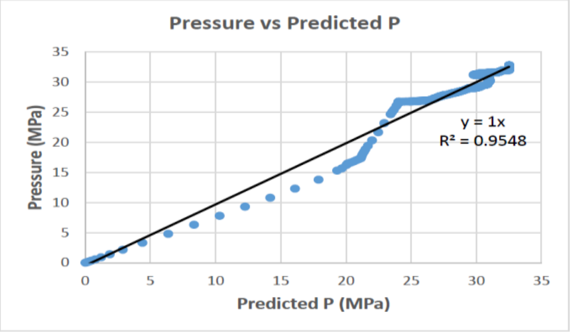

Fig. 2. Actual versus predicted pressure of Model 1.

3.1.2 Model 4

Figure 3 illustrates the relationship between actual and predicted burst pressure for Model 4. It can be noticed that the obtained R^2 value was 0.9399, implying that about 94% of the pressure values were predicted accurately. At the beginning and ending part of the graph, it is an obvious fact that the predicted pressure values were precise since they were coincided with the trend line. However, at pressure of 7 MPa, the equation has over-predicted the ability of the repaired pipe to withstand the burst pressure. This over-prediction was continued until 19 MPa. In contrast, the system was underestimated between 20 MPa and 27 MPa. Briefly, the proposed model shows a very good prediction that the actual burst pressure obtained by FEA and the predicted burst pressure are 32.8178 MPa and 32.7651 MPa respectively, together with percentage difference of 0.16%.

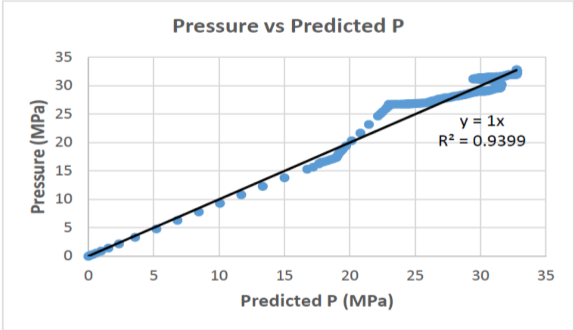

Fig. 3. Actual versus predicted pressure of Model 4.

3.1.3 Comparison between base models with putty

As can be seen from Table 2, Model 2 produces more accurate result than Model 1 and Model 3 in burst pressure prediction due to its highest R^2 value. This is because steel behaves linear-elastic before it reaches its yield strength. Besides, the multiple linear regression is a statistical approach that used to explain linear relationship between variables. Nevertheless, such result is applicable in the aspect of linear-elastic region only. Obviously, steel produces non-linear stress and strain after reaching its yield strength and so the regression analysis may produce less precise result. While for Model 3, the regression analysis took into account until the yield of composite wrap. In other words, the non-linear deformation of steel was considered and this makes the R^2 value to be slightly decreased. Model 1 has lowest R^2 value owing to the consideration of all linear and non-linear deformations of steel, composite wrap and putty.

3.2 Validation model of with and without putty

Table 3 presents the comparison between validation model of with and without putty in burst pressure prediction which compared between predicted burst pressure and actual burst pressure by R^2 value. It can be noticed that analyses without putty input have higher R^2 value compared to analyses with putty input. However, this happened due to different material properties of putty that the stiffness of putty in validation model was far lesser than that in base model, which are 2.61 GPa and 19.9 GPa respectively. In general, a lower stiffness of putty results in a lower stiffness of the whole composite repaired pipe that comprises stiffness from steel, putty and composite wrap. In fact, this stiffness is important in governing the strain reduction at damaged pipe section. When deformation occurs within the pipe, it also allows deformation to be happened in the putty since putty was used to fill the defected area and creating a smooth surface.

Table 3. Comparison between validation model of with and without putty

Model		Equation	R^2 value of actual vs predicted pressure
With putty	Full range (Model 7)	$P = 0.0483\sigma_s + 0.2799\sigma_p + 0.0104\sigma_c$	0.9678
	Yield strength of steel (Model 8)	$P = 0.0476\sigma_s + 0.0194\sigma_p + 0.0915\sigma_c$	0.9993
	Yield stress composite repaired pipe (Model 9)	$P = 0.0151\sigma_s + 0.6182\sigma_p + 0.0493\sigma_c$	0.8352
Without putty	Full range (Model 10)	$P = 0.0588\sigma_s + 0.0159\sigma_c$	0.9822
	Yield strength of steel (Model 11)	$P = 0.0480\sigma_s + 0.1075\sigma_c$	0.9992
	Yield stress composite repaired pipe (Model 12)	$P = 0.0556\sigma_s + 0.0243\sigma_c$	0.9858

3.2.1 Model 7

Figure 4 shows the graph of actual pressure versus predicted pressure for model 7 where the latter was computed using equation that has been obtained from the base model. It can be noticed that about 97% of the pressure values were predicted accurately. At the beginning part, most of the points were coincided with the trend line until the pressure of 14 MPa. However, between 15 MPa and 27 MPa, the regression equation has underestimated the ability of the repaired pipe. In contrast, from 32 MPa until the end of the graph, the system was being overestimation by the equation, where the predicted pressure was higher than the actual pressure. Briefly, FEA determined 32.2147 MPa as the actual burst pressure while the predicted burst pressure obtained is 39.8993 MPa with about 23.85% percentage difference. This large difference is due to the smaller stiffness value possessed by the putty and subsequently resulting in a totally different behaviour of composite repaired pipe. This further justifies the importance of considering the contribution of putty in the closed-form solution.

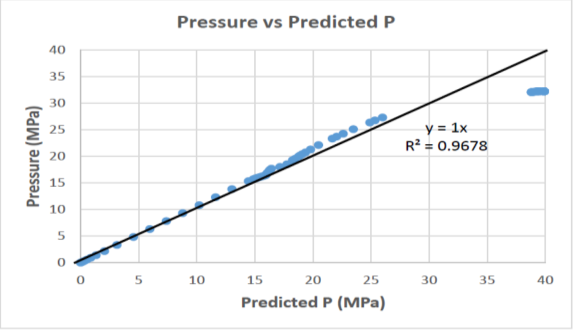

Fig. 4. Actual versus predicted pressure of Model 7.

3.2.2 Model 10

Figure 5 reveals the graph of actual pressure versus predicted pressure for model 10. Regression equation from the base model was used to compute the predicted pressure. As can be seen, about 98% of the pressure points were predicted precisely with respect to the actual pressure since the obtained R^2 was 0.9822. It can also be noticed that pressure points from 0 MPa to 20 MPa were approximately similar with the trend line. However, the ability of the system to resist the burst pressure was under predicted between 21 MPa and 27 MPa. On the other hand, the equation has over-predicted the system's ability towards the end where the actual burst pressure obtained by FEA is 32.2147 MPa while the predicted burst pressure is 35.5386 MPa with percentage difference of 10.32%.

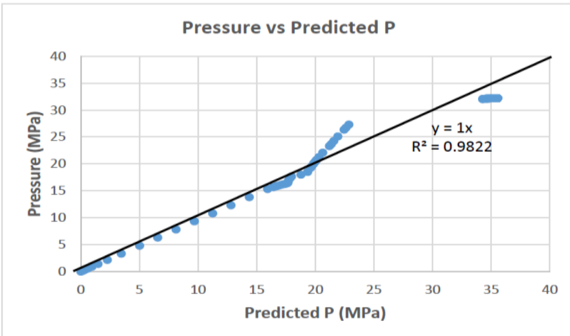

Fig. 5. Actual versus predicted pressure of Model 10.

3.3 Understanding the contribution of putty

Putty has significant influence towards the burst capacity that can be resisted by a repaired pipe. As can be seen from the results of base model, the difference between models of with and without putty can achieve up to 5% where the tensile strength of putty was 20.02 MPa only. Therefore, mathematically, as the tensile strength of putty increases, the stress being exerted also increases and finally the overall performance of a composite repaired pipe, mainly the burst capacity can be increased as well. Also, results of validation model revealed that the properties of putty can affect the behaviour and subsequently the performance of a composite repaired pipe. Hence, the inclusion of strength contribution from putty should be taken into account in the closed-form solution of composite repair design as putty is part of the composite repair system in order to reduce the conservativeness of current design philosophy.

4 Conclusions

This study has successfully modelled the contribution of putty in the aspects of load bearing capacity in pipeline composite repair design through finite element analysis. Two composite repaired pipes with different material properties of putties have provide fruitful explanations on the contribution of putty in composite repair system, mainly the burst capacity. Different models of with and without the inclusion of putty can results in about 5% difference in predicting the failure pressure. In addition, the best model was found to be model with the inclusion of putty's contribution in predicting the stresses experienced by the repaired pipe up to the yield strength of steel. Finally, this study has further proven that putty can serve as a load bearing component that it could act as a one step ahead to explore the potential ways of repairing without composite wrap.

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