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Modulus Effect on Local Load Distribution for FRP /Steel Bonded Joint

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Abstract. Rehabilitation of piping system has been a major concern in the oil and gas industries. Fibre reinforced polymers (FRPs) have been introduced as an alternative approach and increasingly used in repairing oil and gas pipeline. However, performance of pipeline repair system is decided by its load transfer ability and for FRPs, this led to the debonding issue which has been studied by many researchers. This paper describes a series of double strap shear tests under tensile load to investigate the bond performance between FRP sheets and steel plates. Adhesive failure at the steel-adhesive interface was observed to be the dominant failure mode for both glass fibre reinforced polymer (GFRP)-Steel and carbon fibre reinforced polymer (CFRP)-Steel DSJ due to its higher modulus ratio compare to FRP-adhesive interface. Strain distribution along the bond length shows that GFRP offer larger extension before debonding compared to CFRP. CFRP-Steel DSJ withstand higher ultimate load and possessed better load transfer ability compare to GFRP-Steel DSJ. The load spread throughout the CFRP-Steel DSJ bond length while only 50% of GFRP-Steel bond length were effective. The experimental result shows that the FRP type and bond area of a rehabilitated pipeline need to be taken into consideration during pipeline strengthening.

1.0 Introduction

In Malaysia, there are approximately more than 10,000 kilometres of high pressure liquid and gas pipelines with average age between 15 to 20 years. Some of these pipelines are more than 30 years in operation and may require rehabilitation for continued operation in good condition [1]. The deterioration mechanisms, such as corrosion and erosion may lead to further damages such as reducing of pipe thickness, surface cracks, or even worse, a complete failure [2]. The industry, as of today, has developed various non-metallic materials for pipeline repair and rehabilitation especially for oil and gas transportation application such as reinforced thermoplastic, thermo-composites, polymer composites etc. [3]. Industry analysis shows that composite repair systems are, on average, 73% cheaper than completely replacing the damaged section of the steel pipe and 24% cheaper than welded steel sleeve repairs system [4]. In related to bond performance of a composite repair system, lap shear test is one of the most common methods used by adhesive technologists, particularly to measure the performance of an adhesive joint, where it is necessary to determine the stress and strain under a certain load and predict the failure potential [5].

The unique properties of FRPs offer many possibilities in civil infrastructure applications ranging from repair and rehabilitation to developing new structural elements. They are corrosion resistant and suitable for harsh environment application like having a direct contact with corrosive soils and marine, light weight and having high specific strength/modulus. Moreover, it easy to manufacture and install due to FRPs formability. Application of the unidirectional laminates allows strengthening of the structural elements in the required direction, give a much better control over the desired strength and modulus [6]. Unfortunately, they are some disadvantages. Since FRPs are exposed to vandalism, fire and impact, they are susceptible to damage and they have low modulus and tensile strength compared to steel [7]. The investigation of the probability damage happen in the system can be see through lap joint test and analysis.

However, performance of a pipeline repair system is decided by its load transfer ability and for FRPs, this led to the debonding issue which has been studied by many researchers [8-14]. This paper describes a series of double strap shear tests under tension to investigate the bond performance in term of load distribution between FRP sheets and steel plates.

2.0 Materials and Sample Preparation

Pipeline rehabilitation involved the process of wrapping FRP onto the defected steel pipe. Therefore, bond performance between FRP and steel pipe become a major concern. In this study, two type of samples, namely GFRP-Steel DSJ and CFRP-Steel DSJ were used in the bond test. Double strap joint (DSJ) configuration was used as a simplification of the wrapped pipeline structure. The properties of materials associated in this study were further discussed.

2.1 Materials

There are three main materials involved in this study, namely; steel, FRP and epoxy adhesive. The details of the materials background and properties is shown in Table 1.

Table 1: Research materials details

Type	Material	Tensile Strength (MPa)	Extension at Maximum load (mm)	Tensile Modulus, E (GPa)	Remarks
Steel	ASTM A36	528.20	15.29	182.56	
Strengthening materials	GFRP	783.46	6.57	40.37	Reinforcing fibre S Glass supplied by Sika Malaysia Sdn. Bhd.
	CFRP	1834.35	6.47	140.62	Reinforcing fibre Carbon UD300 supplied by Polymer Technologies Pte Ltd., Singapore
Laminating Matrix	Epicote 2175	22.21	-	2.13	Supplied by Polymer Technologies Pte Ltd., Singapore
Bonding agents	Sikadur 330 Epoxy	35.65	2.56	3.21	Supplied by Sika Malaysia Sdn. Bhd.

2.2 Sample Preparation

The design guidelines for Double Strap Joint (DSJ) test samples is according to ASTM D3528. In this study, the sample size was modified in order to meet the testing requirements. In this experimental programme, each sample group consist of three specimens and was prepared according to strict bonding procedure.

ASTM A36 structural steel was used as inner adherend with 7.11 mm average thickness. The steel plate surface quality was machined using universal milling machine and surface grinding machine. In order to produce a high quality bonding surface, the steel bond surface was undergone sandblasting process to produce surface roughness in the range of 50 to 70 microns profile height. In order to remove any impurities and contaminations, acetone was used to clean the bond surface prior bonding process.

GFRP and CFRP were used as the outer adherend with average thickness of 1.05 mm and 1.10 mm respectively. Both materials system were prepared by vacuum infusion technique with 8 hours curing time.

Sikadur 330 epoxy was used as the bonding agent in DSJ fabrication process. The dimension of the specimen is shown in Figure 1. A special-designed jig was used by which four specimens can be produced at one time. The 1 mm adhesive thickness was controlled using Teflon tape.

In order to determine the strain along the bond length, ten strain gauges were installed onto FRPs outer surface, with the directions parallel to the applied load. The locations of the strain gauges is shown in Figure 1.

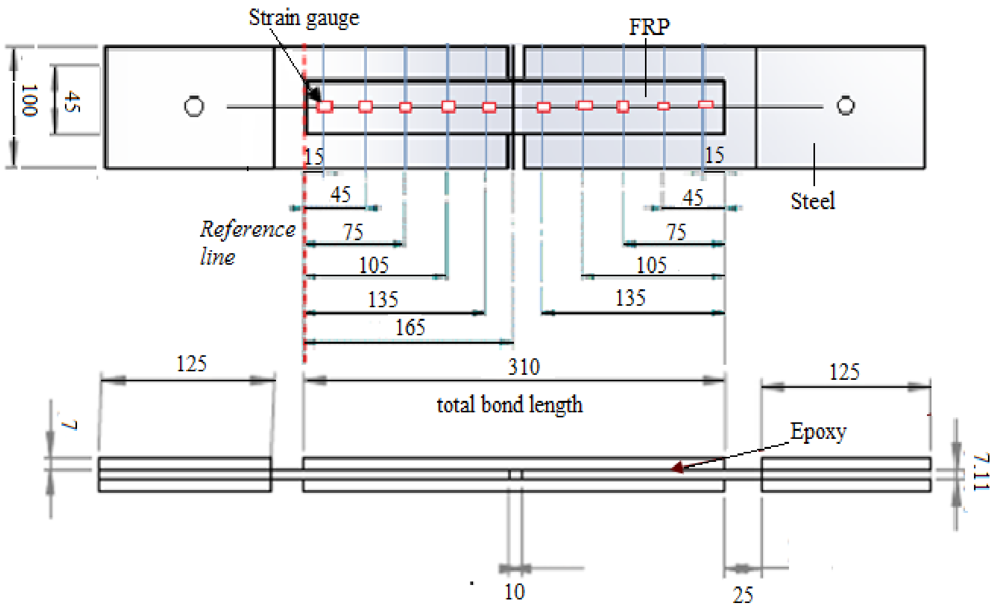

Figure 1: Schematic diagram of DSJ specimen geometry

3.0 Test Method

The experimental and investigation of bond performance for shear test under applied tensile load was carried out according to ASTM D3528 standard.

3.1 Bond Load Test

The Universal Testing Machine model INSTRON 100 kN was used to apply external load to the test samples using a pull-out test rig. The test rig was developed in a research study done by Shukur (2007) [15]. The test was conducted with the crosshead speed of 0.5 mm/min. The samples were subjected to loading up to failure as shown in Figure 2.

The objective of this test is to determine the maximum ultimate load, local load distribution, maximum bond strength, and effective bond length of the double strap joint samples together with its failure mode analysis.

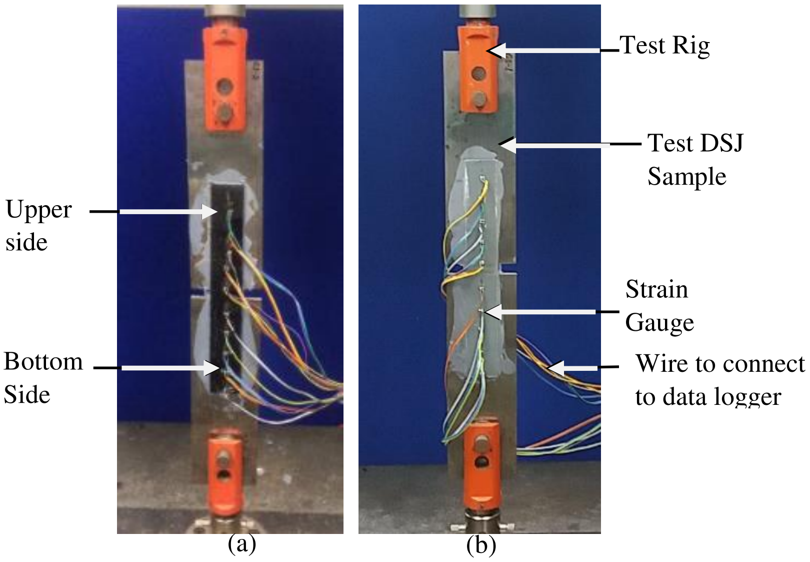

Figure 2: Sample double strap joints (DSJ) under tensile load for (a) CFRP-Steel and (b) GFRP-Steel

4.0 Results and Discussion

The load versus displacement curves for both GFRP and CFRP steel DSJ samples are presented in Figure 3. The bond test showed that both DSJ samples have the same elastic-plastic behaviour as we could observe from the graphs. However, the tensile strength for both samples are different. The Results acquired from the Instron Universal Tensile Machine test shows that the CFRP-Steel DSJ possess a better ultimate load with an average maximum load value of 30kN compares to 24.3kN of GFRP-Steel DSJ. CFRP-Steel DSJ also have bigger tensile modulus value compare to GFRP-Steel DSJ. However, GFRP-Steel DSJ have a bigger strain value that can be seen by its larger displacement on the graph. The maximum displacement value of GFRP-Steel DSJ is 1.58 mm compared to 1.20 mm for CFRP-Steel DSJ.

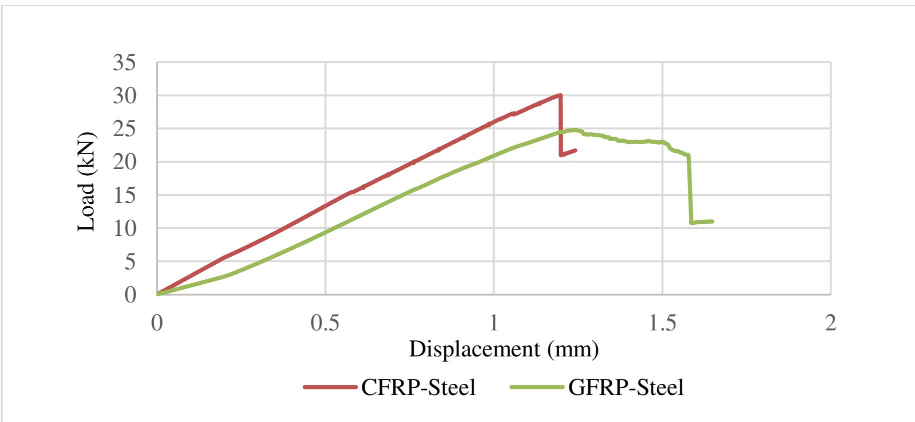

Figure 3: Graph of Load versus Displacement for FRP-Steel DSJ

CFRP-Steel DSJ have a better shear strength and maximum load while GFRP-Steel DSJ undergo further extension before break. This can be explained by the load-displacement curve of both DSJs where CFRP-Steel DSJ possessed higher strength and stiffness to withstand larger shear stress and load applied compare to GFRP-Steel DSJ. Meanwhile, high strain-to-failure properties of GFRP resulted larger extension at the maximum load of GFRP-Steel DSJ compare to CFRP-Steel DSJ.

4.1 Strain and Load Distribution

Strain distribution along the bonded length can be obtained from the strain gauge reading at the top surface layer of the fibre. Assuming there is no stress variation occurs along fibre thickness, Figure 4 and Figure 5 shows the strain readings at the epoxy layer of both GFRP-Steel and CFRP-Steel samples under different load levels respectively.

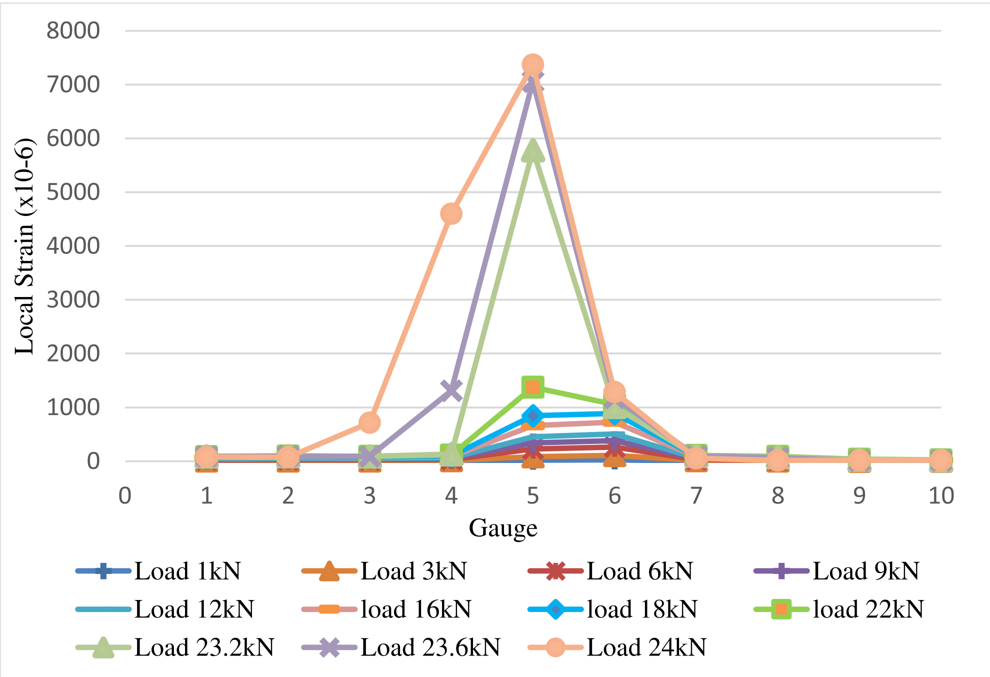

Figure 4: Graph of Local Strain Distribution versus Bond Length for GFRP-Steel DSJ

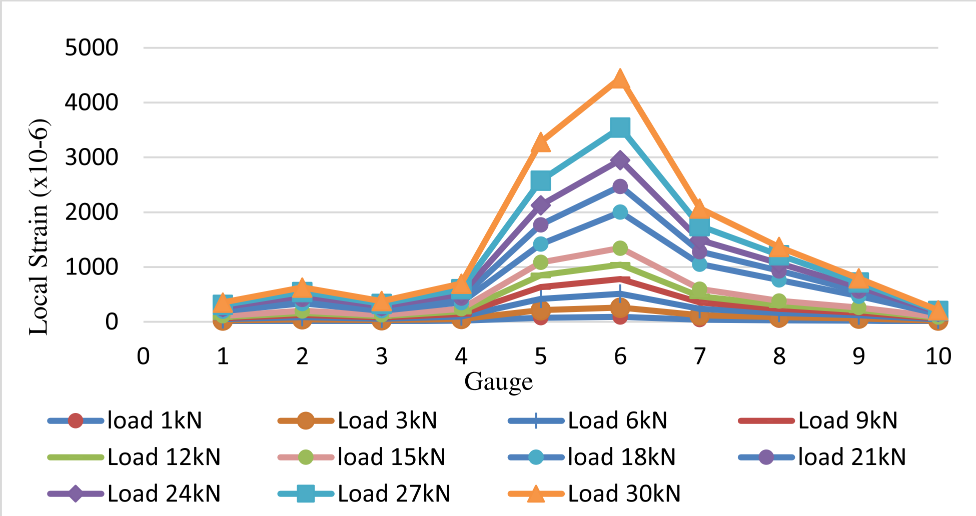

Figure 5: Graph of Local Strain Distribution versus Bond Length for CFRP-Steel DSJ

It is clear from Figure 4 and 5 that the strain generally decreases from the middle towards the ends of the joints. The strain distribution for CFRP-Steel DSJ seems to be perfectly linear and reached the furthest strain location from the centre compare to GFRP-Steel DSJ where the outer strain gauges readings are too small and almost zero. The increment of strain for each load are also seems to be linear for both samples at every strain location. However, approaching the ultimate load, there was sudden increases in strain value at the middle gauge of GFRP-Steel sample which most likely cause by initial cracking and slip occurred at the epoxy-steel interface. Smaller strain values also were obtained for CFRP-Steel DSJ, which is probably corresponding to its stiffer properties.

4.1.1 Local Load Distribution

Figure 6, Figure 7 and Figure 8 show the comparison of local load distribution between GFRP-Steel DSJ and CFRP-Steel DSJ at 3 kN, 12 kN, and 24 kN applied load respectively. CFRP-Steel DSJ shows better load transfer ability through the epoxy where the maximum local load at 3kN, 12kN, and 24kN applied load are 70.98%, 71.25%, and 72.65% of the applied load respectively.

Meanwhile, for the GFRP-Steel DSJ, the maximum local load only around 6.07 % of 3 kN applied load, 7.22 % of 12 kN applied load, and 52.76 % of 24 kN applied load where the failure occurs. These local loads are theoretically affected by the modulus differences between the adherends. On CFRP-Steel DSJ, the modulus difference is small, so a huge amount of load can be transfer from the steel to CFRP as there is not much displacement occurs between them. On the other side, due to low stiffness of GFRP, the load is accumulated in the steel and only a little amount of load is transferred to the GFRP to prevent the GFRP from further displacement.

The load also spread throughout the bonded area of CFRP-Steel DSJ where the furthest strain location from the centre experienced an average of 6 % of the applied load. For the GFRP-Steel DSJ, the load only spread until the third strain location from the centre for both side with the exception during breaking point where the load spread all the way to the end of the debonded part. Table 2 listed the average test result of both samples GFRP-Steel DSJ and CFRP-Steel DSJ.

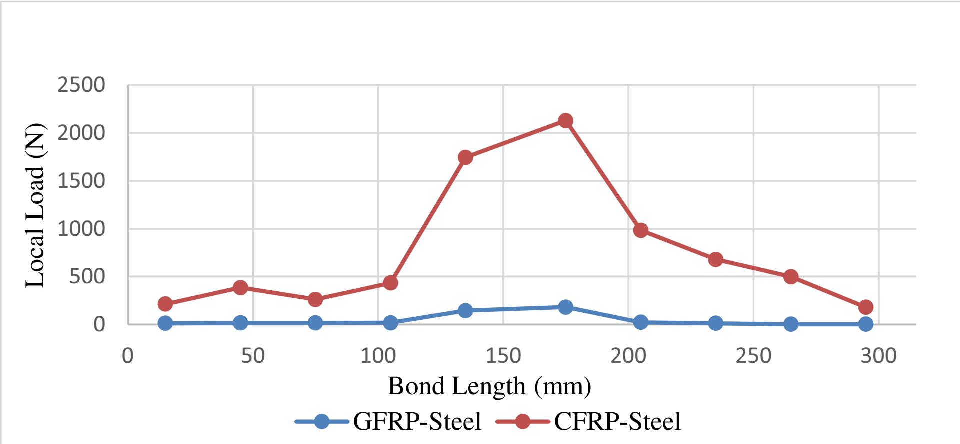

Figure 6: Comparison of Local Load between GFRP-Steel and CFRP-Steel at 3 kN Applied Load

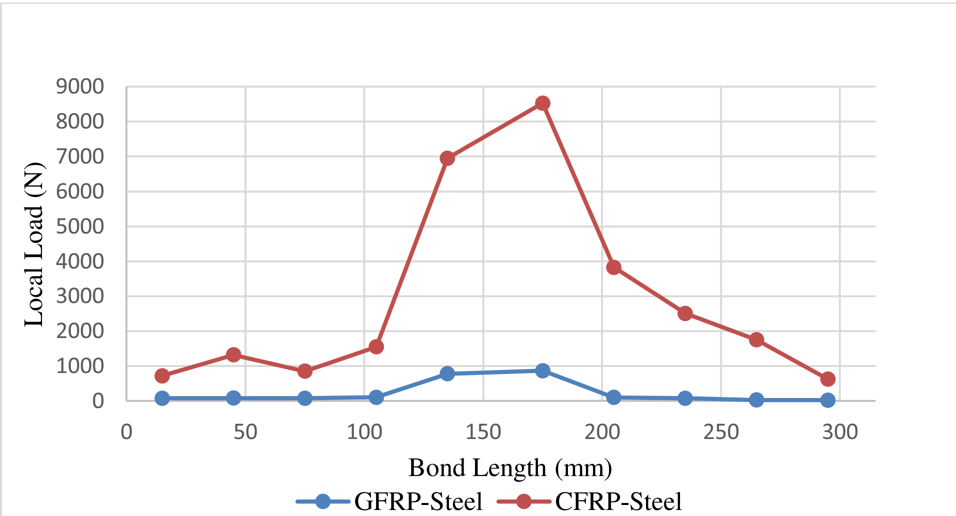

Figure 7: Comparison of Local Load between GFRP-Steel and CFRP-Steel at 12 kN Applied Load

Table 2: Average bond test result for double strap joint samples

Sample	***Shear strength, (MPa)***	***Extension at Max Load [mm]***	***Max load (kN)***	***Modulus Difference (Fibre/Steel)***
GFRP-Steel DSJ	2.01	1.58	24.32	0.2211
CFRP-Steel DSJ	2.22	1.20	30.01	0.7703

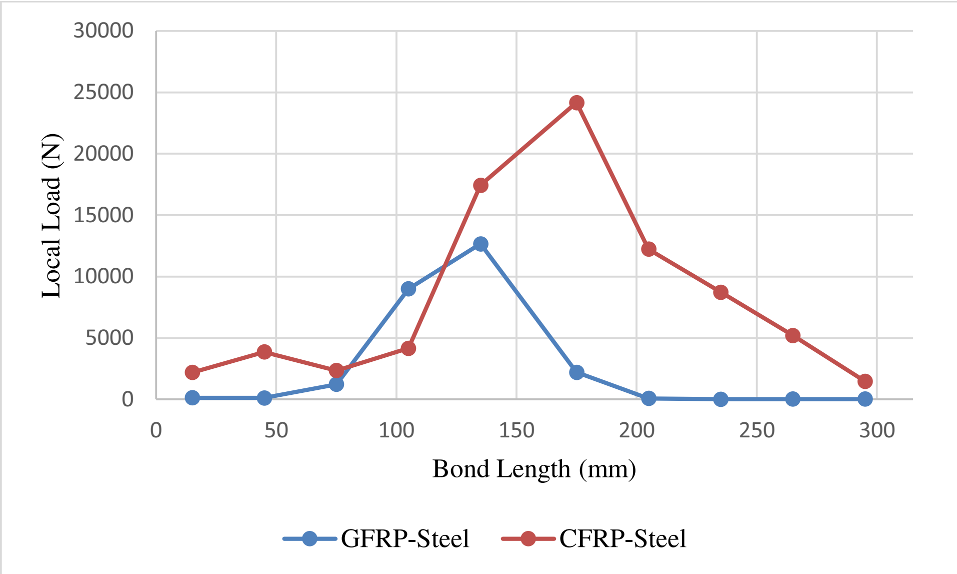

Figure 8: Comparison of Local Load between GFRP-Steel and CFRP-Steel at 24kN Applied Load

4.2 Failure Mode

GFRP-Steel DSJ debonded at the upper side of the sample while CFRP-Steel DSJ debonded at the lower side of the sample as shown in Figure 9. Almost 90% of adhesive failure was observed for GFRP-Steel DSJ at the epoxy-steel interface. This shows the shear strength of epoxy-GFRP interfacial bond and the epoxy itself exceed the strength of epoxy-steel interfacial bond, probably due to a huge modulus ratio between Sikadur 330 epoxy and steel. On the other hand, there was mixed-mode failure (cohesive and adhesive failure) was observed on the CFRP-Steel DSJ samples even though adhesive failure at the epoxy-steel interface still become the major failure. There was no sign of fibre break or steel cracking observed on all specimens which concluded that all the failures occur at the adhesive layer and its interfaces. The modulus ratio of epoxy to steel and epoxy to CFRP are close in value, provide almost an equal strength at both interfacial bonds.

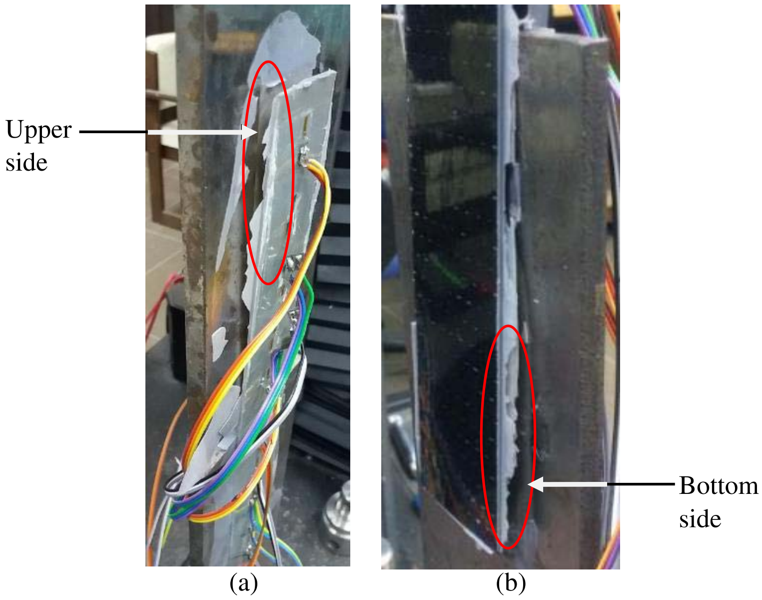

Figure 9: Sample failure mode for (a) GFRP-Steel DSJ and (b) CFRP-Steel DSJ

5.0 Conclusion

A series of bond test on double strap joints in tension were carried out to investigate the bond performance of GFRP-Steel DSJ and CFRP-Steel DSJ. The conclusions are made based on the observations and test results. Different debonded area were observed for GFRP-Steel DSJ (upper side) and CFRP-Steel DSJ (bottom side). Mix mode failure was observed for both DSJ with adhesive failure as the dominant failure. However, 90% of the failure mode on GFRP-Steel DSJ was adhesive failure at the steel-epoxy interface due to huge differences between its modulus ratio and epoxy to GFRP modulus ratio.

CFRP-Steel DSJ possessed higher ultimate load (30kN) and modulus compare to GFRP-Steel DSJ (24.3kN). Both DSJs show similar shape of strain distribution which the value decreases from the centre towards the end of the joints. The strain increment as the load increases for both DSJs also seems to be in linear pattern even though there were sudden increases during the failure point of GFRP-Steel DSJ. However, higher strain value was obtained with the maximum of 7372 $\mu\varepsilon$ for GFRP-Steel DSJ compared to CFRP-Steel DSJ (maximum 4446 $\mu\varepsilon$). CFRP-Steel DSJ with smaller modulus difference between adherends shows better load transfer ability with the average of 71 % of maximum local load compare to the average of 7 % of maximum local load for GFRP-Steel DSJ. The load also spread through the entire bonded area of CFRP-Steel DSJ while only 50 % of the GFRP-Steel DSJ bonded area experienced the same load level.

GFRP-Steel DSJ able to withstand a high ultimate load even though its load transfer ability is low. The load accumulated at epoxy-steel interface as shown by the 90 % of adhesive failure occurred. CFRP-Steel DSJ on the other hand possessed both high ultimate load and load transfer ability make it more suitable to overcome the debonded problem in piping rehabilitation. Plus, the adhesive failures were almost balanced on steel-epoxy and

CFRP-epoxy interface due to close modulus ratio between them. This provide higher bond strength to overcome shear as both adherends were too stiff to displace compare to GFRP in GFRP-Steel DSJ.

As suggestion, a number of bond test should be made with different epoxy and fibre should be made for further understanding the correlation between the material properties and performances of the bond made.

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References:

[1] Nazmi, M. *Corrosion-Free Pipeline: NACE East Asia & Pacific Area Conference*. Malaysia (2016)
[2] D. G. Pavlou, J. Offshore Mech. Arct. Eng., **137**, 6 (2015).
[3] R Kristen. Master's thesis, University of Stavanger, Norway (2016)
[4] Agarwal, A., Foster, S.J. and Hamed, E., Comp. Part B: Eng., **99**, 235-247 (2016)
[5] Broughton, B. and Gower, M., *Measurement good practice guide,* **47** (2001)
[6] M. Ehsani, *V. M. Karbhari, Ed. Cambridge*: *Woodhead Publishing*, ,39–59 (2015)
[7] Saad, S.M., Patel, I.N. and Shah, M.J., Int J Eng Res Gen Sci, **3**, 686-688 (2015)
[8] Dawson, D.). *Corrosion-resistant aramid fiber/thermoplastic liner gives new life to deteriorating steel subsea pipelines* (2015)
[9] J. Kou, a. W. Yang, *(ICPTT)*, 1285-1292 (2011)
[10] A. Al-Shawaf, R. Al-Mahaidi & X.L. Zhao, *Australian Journal of Structural Engineering*, **10:1**, 63-74 (2015)
[11] W.K. Goertzen, M.R. Kessler, Comp. Part B: Eng., **38**, 1-9 (2006)
[12] Md Shamsuddoha, Luke P Djukic, Md Mainul Islam, Thiru Aravinthan and Allan Manalo, J. of Comp. Mat., **0**, 1–13 (2016)
[13] M.Y. Tsai, J. Morton, Int. J. of Solids and Struc., **47**, 3317–3325 (2010)
[14] Houssam Toutanji, Sean Dempsey, J. Thin-Walled Struct, **39**, 153–165(2001)
[15] S. Abu Hassan, PhD’s thesis, Universiti Teknologi Malaysia, 103 (2007)