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MECHANICAL CHARACTERIZATION OF CFRP/STEEL BOND CURED AND TESTED AT ELEVATED TEMPERATURE

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Abstract

Glass transition temperature (T_g) of the bond between CFRP and steel influences on the service and fire performance of strengthened members. A total of eighty-two CFRP/steel double strap joints were prepared and tested under elevated temperature. They were cured under a range of elevated temperature conditions in the control laboratory environment and in the open environment which is practically feasible in large civil engineering structures. The test results showed a similar trend of reductions in the bond strength, Poisson's ratio and Elastic modulus of CFRP/steel joint with the exposure to the elevated temperature. More than 50% reduction in the Poisson's ratio, elastic modulus and the bond strength was noted when the bond line temperature exceeds T_g + 15 ^{0}C, irrespective of the curing time and curing conditions. Initial elevated temperature curing also causes for shifting the curves in the right-skewed direction. A significant increase in T_g of bond was noted with 4 hours initial curing at 75 ^{0}C, i.e. T_g +20 ^{0}C.

Key words: CFRP/steel, Elevated temperature curing, Glass transition temperature, Fire, Bond characteristics

1. Introduction

The use of Carbon Fiber Reinforced Polymer (CFRP) composites is increasing in recent years in the construction industry due to its superior properties. CFRP applications in steel structures can widely be seen in outdoor structures such as bridges and towers. These structures directly expose to the environment. Hence, it is important to investigate the possible alternatives to enhance the service performance of the composites.

Nguyen et al. [1] investigated the behavior of CFRP/steel composite when it is exposed to the elevated temperature. Effects of elevated temperature on the CFRP/steel joints cured at ambient conditions were investigated with respect to the different CFRP layer types, adhesive types, exposure conditions etc. [2-7]. However, the effects of elevated temperature curing in the range of temperatures around the glass transition temperature (T_g) of polymeric bonds of the steel/CFRP double strap joints and their behaviour at elevated temperature had not been investigated in the latter studies. A significant degradation of bond properties was noted. Most of the polymeric adhesives which are commercially available have a very low T_g which is less than 60 ^{0}C [8,9]. Curing condition of the epoxy adhesive has a significant effect on glass transition temperature of the polymeric matrix. The T_g of epoxy adhesive can be increased with elevated temperature curing [10], result in improved service performance [11]. However, these investigations were only focused on the T_g of pure epoxy adhesive, rather than the T_g of CFRP/epoxy/steel bond. Nguyen et al. [12] showed the strength improvement in steel/epoxy/CFRP double strap joints when it cured under elevated temperature. However, the curing method which was used in all the above investigations is not practical enough to use in large structures.

Gamage et. al. [8,9,13,14] studied the bond characteristics of CFRP/epoxy/concrete when the composite subjected to long term effects of cyclic temperatures, humidity and sustained loading. A heavy strength degradation was noted when the environmental temperature reaches 10 ^{0}C less than the T_g of bond. This study provides evidence for the sensitivity of the epoxy bond to the external environment when the surrounding temperature is 10 ^{0}C less than the T_g of epoxy bond. They further concluded the evidence for the neutrality of the bond between CFRP and steel even for high humidity exposure under sustained loading when the environmental temperature is 20 ^{0}C lower than the T_g. Hence, the improvement of T_g of bond between CFRP and steel may improve the service performance of the composite.

Mobility of polymers in the bond increases around the T_g of the polymeric bond [15]. This increased mobility during the curing phase may cause for proper bond between CFRP and steel. It will enhance the mechanical properties of the composite system. Elevated temperature curing may be a good alternative to enhance the short-term and long-term performance of the composite. In general, the majority of research studies have been conducted in the control environment. Since Civil engineering structures are large, the practical applications in the standard control environment are impossible. Therefore, the technique used to enhance such performance should be able to apply in the practical environment condition. This study is focused on the effects of elevated temperature curing on the CFRP/epoxy/steel bond. A practically feasible method is investigated and comparison is also done with the control environmental testing.

2. Test Programme

A detailed test programme was conducted to determine the glass transition temperature (T_g) and bond characteristics of the steel/epoxy/CFRP joints cured under ambient conditions and a range of elevated temperatures. In general, the majority of experimental studies have been conducted in the control laboratory environments [1-7,10-12]. Since the Civil engineering structures are large, evaluating the possibilities for the application of certain techniques in a practical environment is important. Therefore, two types of elevated temperature curing techniques were considered for the comparison purpose.

2.1 Material properties

Three materials were involved in the test programme: steel, Carbon Fiber Reinforce Polymer (CFRP) and two-part epoxy adhesive. The measured and manufacturer provided material properties [16,17] are listed in Table 1. The steel coupon test was conducted in accordance with ASTM 370-03a [18] to determine the mechanical properties of steel substrate. Adhesive properties were measured using five tensile coupon test samples [19]. The tensile tests were conducted to determine the CFRP properties in accordance with ASTM D 3039/3039M [20]. The average values are listed in Table 1. All measured properties were considerably lower than the manufacturer provided values. There are huge discrepancies in the range between60% to 55% were noted between the measured and manufacturer provided tensile strength and ultimate strain values of CFRP. This clearly indicates the importance of measuring mechanical properties rather than relying on the manufacturer provided properties.

2.2 Specimen preparation

CFRP steel double strap joints were prepared [21]. All the steel segments were 40 mm wide and 4 mm thick [Fig. 1]. The effective bond length of the double strap joints with the same dimensions and materials were determined experimentally and numerically [Fig. 2]. Therefore, one side of the double strap joint was maintained at 140 mm while the other side was maintained at 150 mm as shown in Fig. 1 for the detailed test programme. Type K thermocouples with 1 mm diameter was installed in the middle of the bond line to measure the temperature reading during the curing process as well as for the testing under elevated temperature. All thermocouples were calibrated before use.

Five elevated temperature initial curing conditions were considered [Table 2]. In the elevated temperature curing, one of the series was cured using an oven, while other series were cured using a system of halogen floodlights with 1000 W capacity, which is a practically feasible method. All the specimens were kept under ambient temperature (30 ^{0}C) for 7 days after the initial elevated temperature curing at considered temperature levels for the relevant period. While curing using the floodlights, bond line temperature could maintain at ±5 ^{0}C margin from the desired curing temperature. Fig. 3 shows the details of the both curing systems.

2.3 Testing

Initially, the environmental temperature was raised till the bond line temperature reaches the required temperature level. Then the specimen was kept at the same temperature for 10 minutes till the bond line temperature becomes stable and uniform as predicted [22] in Fig. 4(a). The transient tensile load was applied to the specimens by maintaining the saturated temperatures at bond line as 30 ^{0}C (ambient temperature), 50 ^{0}C, 60 ^{0}C, 70 ^{0}C, 80 ^{0}C, 90 ^{0}C and 100 ^{0}C. The universal testing machine with 1000 kN capacity was used to apply the tension on the double strap joints [Fig. 4(b)].

2.4 Test results

2.4.1 Failure load and mechanisms

The measured failure loads are listed in Table 3. Elevated temperature curing at temperatures slightly higher (75 ^{0}C) than the glass transition temperature (55^{0}C) of polymer adhesive [17] showed increased strength than the samples cured at temperature lower (55 ^{0}C) than the T_g of epoxy adhesive. Mobility of polymer particles increases around the T_g of polymeric matrix [23]. This increased mobility may cause for proper rearrangement of polymer molecules during the initial curing stage, which result in the highest bond strength. When the specimens expose to the temperature near the T_g, the strength of all the samples had decreased, irrespective from the curing condition. A considerable strength reduction (70%) was noted when the bond line temperature reaches T_g + 40 ^{0}C. This may due to the weaken load transfer ability of the CFRP/steel joint due to the softening of epoxy adhesive bond. Similar behaviour was also noted from the concrete/epoxy/CFRP joints [8,9,13].

Three major failure modes were identified during testing: (a) CFRP fiber rupture, (b) Adhesive-steel interface debonding and (c) mix failure mode (CFRP fiber rupture and adhesive steel interface debonding) as shown in Fig. 5. CFRP fiber rupture failure mode was observed in the samples which were tested at 30 ^{0}C temperature, i.e. at environmental temperature. This provides evidence for a sound bond between CFRP and steel in the operating environment. Adhesive-steel interface debonding failure mode was observed only in the specimens which were tested at temperatures greater than 60 ^{0}C. This may due to the fact that softening of polymeric adhesive bond when it reaches its T_g. In the specimens failed due to a mix failure of CFRP fiber rupture and adhesive steel interface debonding, tested temperature was less than 80 ^{0}C [< (T_g + 25 ^{0}C)]. When the tested bond line temperatures were less than 60 ^{0}C [< (T_g + 5 ^{0}C)], specimens were tending to fail due to a CFRP fiber rupture. This indicates the lesser mobility of polymer particles when the bond line temperature is less than T_g result in a sound bond between CFRP and steel. Gamage et. al. [9] noted the similar behaviour in CFRP/concrete composites when the joint exposes to the elevated temperature.

2.4.2 Effects of curing temperature on bond strength

Fig. 6 shows the strength of CFRP/steel joint when the bond line is exposed to the different temperature levels. These specimens were identically cured at two levels of elevated temperatures (50 ^{0}C and 75 ^{0}C) for one hour before fully cured under the environmental temperature. These three graphs show a similar trend of degrading material properties which can be seen in polymeric adhesive bonds [24].

The strength reductions when the composite is exposed to different temperatures have decreased with elevated temperature curing. This implies the evidence for increased glass transition temperature with the initial curing temperature. Increased T_g may cause for more stable bond even though it exposes to the elevated temperature. When the bond line temperature exceeds 90 ^{0}C, almost similar behaviour can be seen from all specimens irrespective from the curing conditions. On average, 70% strength reduction was noted when the bond line temperature becomes 100 ^{0}C. This shows the evidence for softening of bond when it exceeds the temperature beyond T_g + 40 ^{0}C. Nguyen et al. [12] had also observed similar effects of the CFRP/steel double strap joints cured at ambient temperature (30 ^{0}C).

2.4.3 Glass transition temperature of CFRP/epoxy/steel bond

Glass transition temperature (T_g) for the double strap joints was calculated as shown in Fig. 7 for the samples which exposed to the different curing conditions. The definition used by Gamage et. al. [8] was used to define the T_g. It is found that the T_g of the CFRP/epoxy/steel bond cured under ambient condition is about 50 ^{0}C. This is 9% lower than the T_g of epoxy adhesive [17] cured under the same conditions. This provides the importance of identifying T_g of bond rather than relying on the T_g of adhesive component.

The graphs indicate the evidence for increased bond properties with elevated temperature curing. Initial curing at elevated temperature for one hour has caused to 10% increase in T_g, irrespective of the exposed temperature level and the environmental condition, whether control or open nature. The period exposed to initial curing considerably affect on the bond performance. This clearly shows by the improved T_g from 10% to 20% with 1 hour to 4 hours of curing at the same temperature level. With high temperature curing the rigidity of the polymer chain of epoxy tends to increase [24]. This may happen with the four hours curing, while it partially occurs with the 1-hour curing at elevated temperature.

Gamage et. al. [14] showed the increased resistance to long term environmental exposures to cyclic temperature, humidity and sustained loading with increased T_g. They further indicated the neutrality of bond for external environmental factors when the operating environment temperature is less than T_g + 20 ^{0}C of the bond. Hence, increased T_g of bond will enhance the service performance of the composite. Fire testing carried out by Ranasinghe et. al. [25] showed the effectiveness and economical application of an insulation layer for CFRP/concrete composites with increased T_g of the bond. Hence, it can be concluded that there is a possibility of increasing fire performances with increases T_g of the CFRP/steel bond.

2.4.4 Effects of Curing period at elevated temperature

The specimens shown in Fig.8 were exposed to the elevated temperature curing at 75 ^{0}C for 1,2 and 4 hours. All these specimens cured at elevated temperature indicated higher strength than the ambient temperature cured specimens till the bond line temperature reaches 90 ^{0}C. This may due to the effect of high mobility of polymer chains at higher temperatures [15] result in a more stable bond arrangement. Similar behaviour was noted from all the specimens tested by maintaining the bond line temperature more than 90 ^{0}C. This provides convincing evidence for degrading bond performance when the bond line temperature reaches 90 ^{0}C; i.e. 35^{0}C higher than the glass transition temperature of epoxy adhesive bond (T_g + 35^{0}C).

2.4.5 Comparison between practical and experimental approaches for elevated temperature curing

In general, the majority of research work has been conducted in the controlled environments. In this study, curing the CFRP/steel composites in a standard oven to evaluate the effects of elevated temperature curing on bond characteristics is one of an example. However, the nature of practical applications in civil engineering structures is completely different from the control environmental applications. Therefore, the comparison between these two approaches may help to understand the similarities or discrepancies in both cases.

Fig. 9 shows the joint capacities of ambient temperature cured and elevated temperature cured samples (at 75 ^{0}C for 1 hour) which were cured in the open environment using the halogen flood light system and in the control environmental chamber. Specimens from both techniques showed the similar trend in strength degradation. However, the samples cured in the practical approach indicated a slightly higher strength (17%) than the specimen cured under the control environment. This may due to the fact that elevated temperature allowed a ±5 ^{0}C margin when curing under open environment due to non-controllable nature. Due to this margin the temperature in the bond line could rise up to 80 ^{0}C while curing. Therefore, the use of research properties tested under the control environment can be taken as an indication of actual performance.

2.4.6 Strain variation in CFRP sheet

Strain gauges were attached to the CFRP layer of double strap joints to measure the strain variation in both X and Y directions, 35 mm from the joint as shown in Fig. 1. Strain measurement in X and Y directions when the bond line reaches the average temperature about 100 ^{0}C is shown in Fig. 10. Elastic region of the epoxy adhesive has increased with the curing temperature and curing time. The ultimate strain in CFRP of the elevated temperature cured samples has increased from 20% to 50%. However, all the tested samples had shown a plastic behaviour to rapid increase in the strain readings near failure.

2.4.7 Variation of Poisson's ratio

Fig. 11 shows the variation of poisson's ratio of the CFRP/epoxy/steel joint with the temperature in the CFRP /steel interface. At a low temperature level which is below 60 ^{0}C, the Poisson's ratio has a significant change with the curing temperature and curing time of the specimen. The Poisson's ratio had increased with the curing temperature and the curing period. When the curing temperature increases from 55 ^{0}C to 75 ^{0}C, the Poisson's ratio increases up to 4%. One-hour increase of curing time had caused for 7 % increment in the Poisson's ratio. When the temperature is more than 70 ^{0}C [$\geq$ (T_g + 15 ^{0}C)] all the specimens indicated a high rate of reduction of the Poisson's ratio in the similar manner.

2.4.8 Variation of elastic modulus

The variation of elastic modulus of the bond with the bond line temperature is shown in Fig. 12. Elevated temperature curing has a significant effect on the elastic modulus up to the bond line reaches 80 ^{0}C. On average, 50% increase in elastic modulus has found from the composites cured at 75 ^{0}C for four hours. However, the variance of elastic modulus has grown thin when the bond line temperature reaches 80 ^{0}C. The effect of curing temperature and curing time had not considerably affect on the elastic modulus of the bond when the interface temperature exceeds 80 ^{0}C.

Conclusions

Steel/epoxy/CFRP double strap joints were prepared. They were exposed to six different initial elevated temperature curing conditions. The bond strength was determined under the elevated environmental temperature exposure. The mechanical properties and glass transition temperatures of the bond were evaluated. The following conclusions were made:

1. The failure modes of CFRP/steel double strap joints were shifted from CFRP fiber rupture to CFRP/steel interface debonding with the transient elevated heat condition of the bond line.
2. Failure loads were directly influenced by the bond line temperature and about 70% of strength reduction was noted when the bond line temperature reaches T_g + 25 ^{0}C.
3. The initial curing temperature of the joint directly influences on the mechanical properties of the bond. A high rate of bond degradation appears when the bond line reaches the range of temperatures between 55 ^{0}C and 80 ^{0}C, i.e. T_g ^{0}C and T_g + 25 ^{0}C. When the bond line temperature reaches 90 ^{0}C (T_g + 35 ^{0}C), the retained bond properties were almost similar irrespective from the curing time and curing conditions.
4. On average, 16% difference was noted between the glass transition temperature (T_g) of the bond and pure epoxy adhesive. By increasing the curing temperature from 30 ^{0}C to 55 ^{0}C and 75 ^{0}C, T_g increases about 10% between each category. Curing time influences significantly on T_g when compared to the curing temperature. With increasing curing time from 1 hour to 4 hours, T_g increases on average from 10% to 20%.
5. Ultimate strain of the bond increases about 50% with elevated temperature curing within the considered range.
6. When the bond line exposes to the elevated temperature, the properties such as elastic modulus, Poisson's ratio, bond strength decreases in a similar manner.
7. Degradation of mechanical properties was appeared when the bond line exposes to the temperature T_g – 10 ^{0}C.
8. A flood light system with suitable capacity can be used for elevated temperature curing of CFRP strengthened steel members.
9. It is quite safe to use the bond characteristics of samples tested in the control environment as an indication of practical performance.

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10. It is important to measure the material properties for applications rather than relying on the manufacturer provided properties because of the noted huge discrepancy between two figures.

Acknowledgements

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Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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Figures

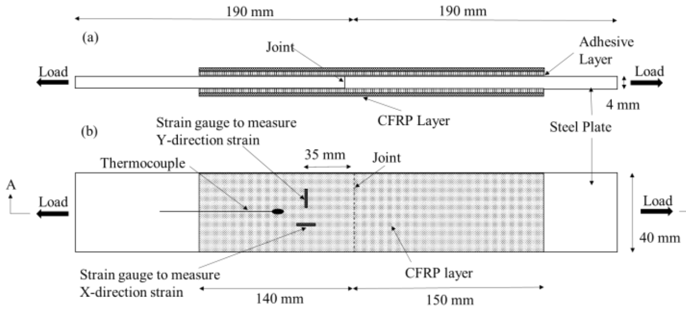

Fig. 1. Schematic diagram of a double strap joint; (a) view A-A (b) plan view

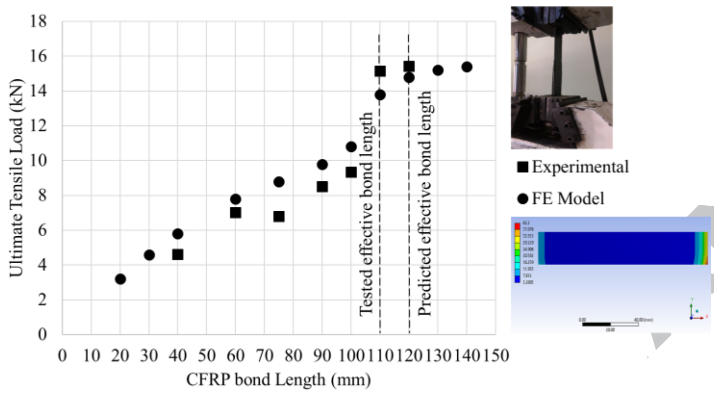

Fig. 2. Comparison between predicted and experimental loads vs CFRP bond length

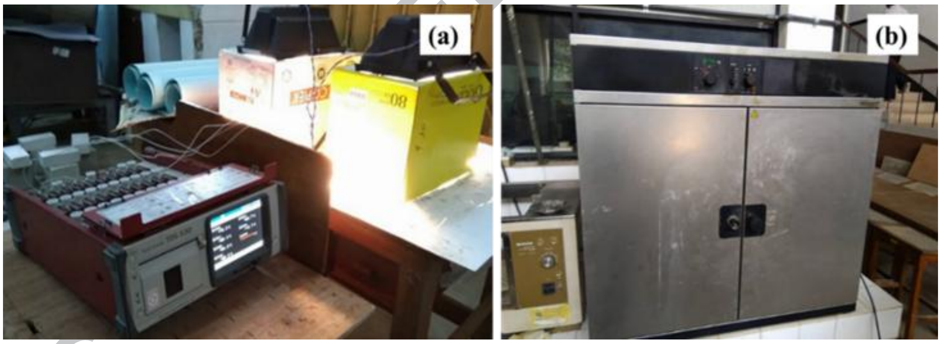

Fig. 3. Elevated temperature curing using (a) halogen floodlights (b) standard oven

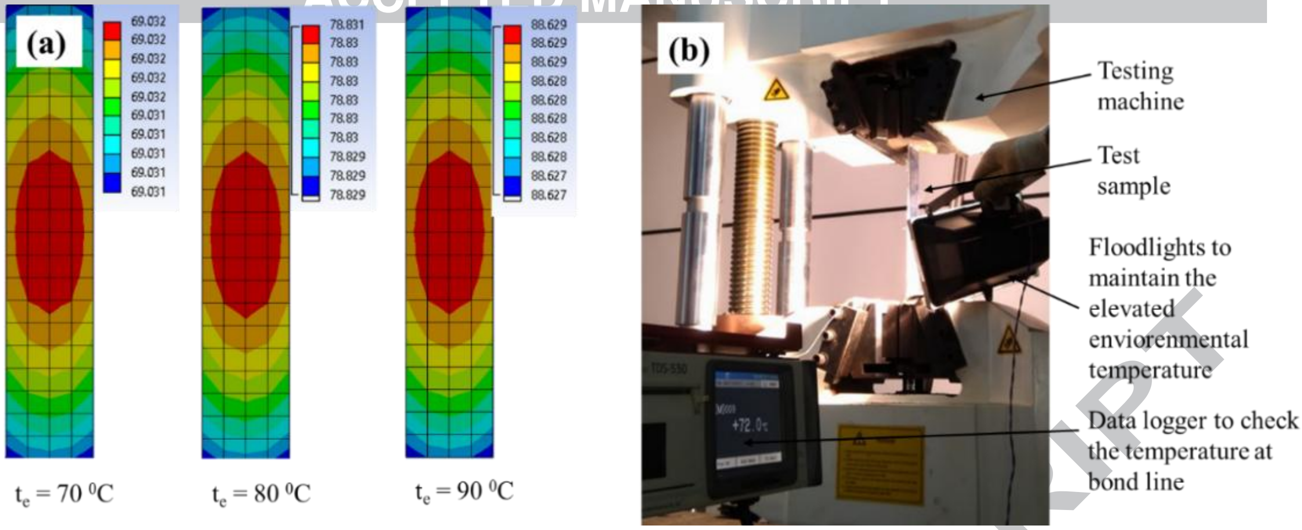

Fig. 4. (a) Predicted temperature profile after 10 min exposure to elevated environmental temperature (t_e) (b) Test setup

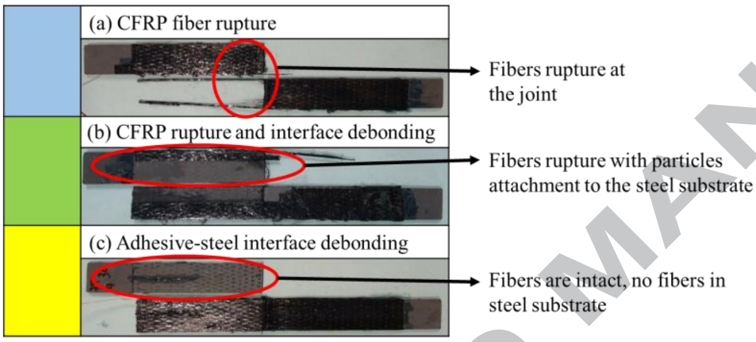

Fig. 5. Failure modes

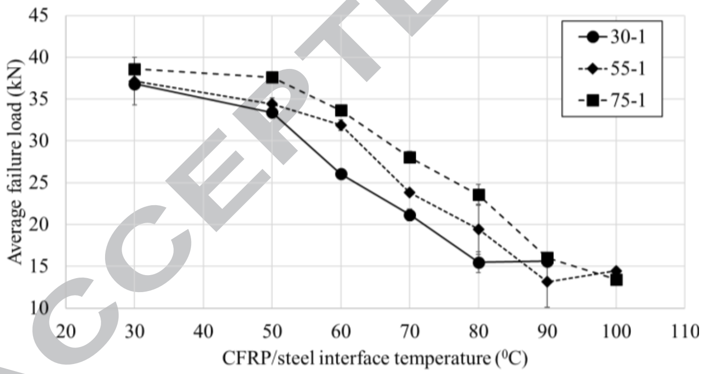

Fig. 6. Effects of curing temperature on average failure load

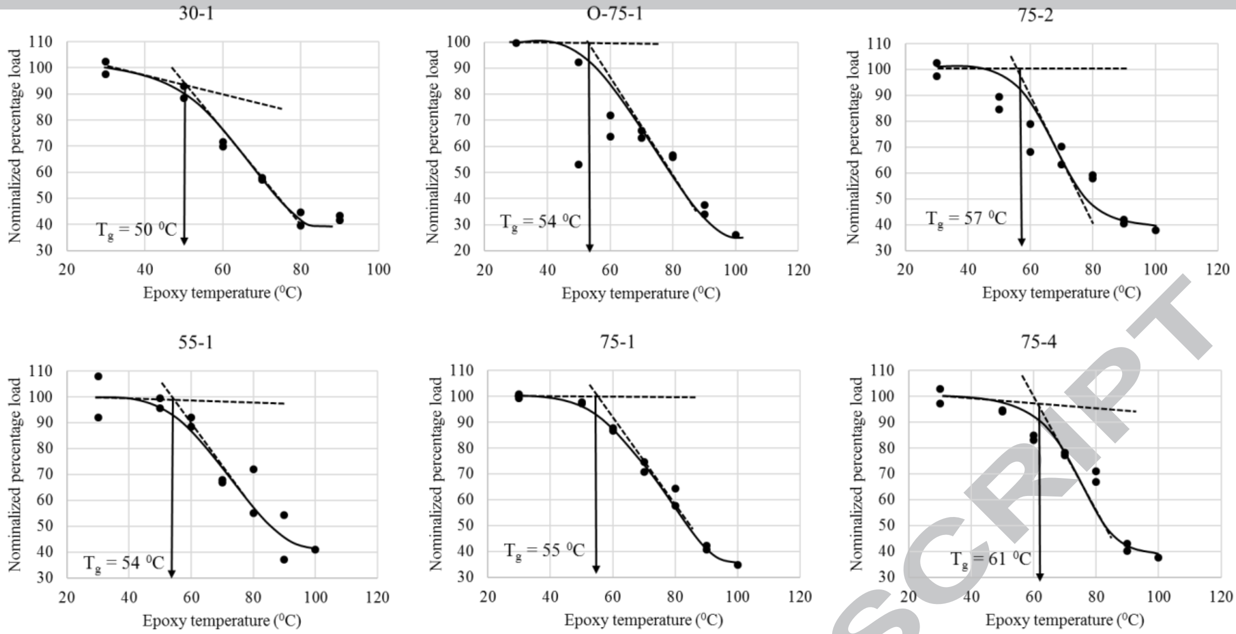

Fig. 7. Glass transition temperature for specimen groups

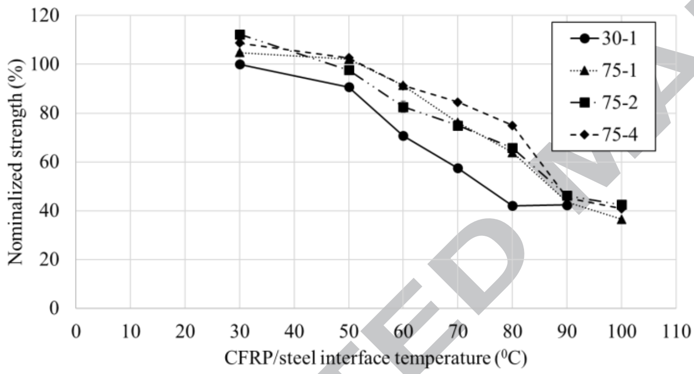

Fig. 8. Effects of curing period on average failure load

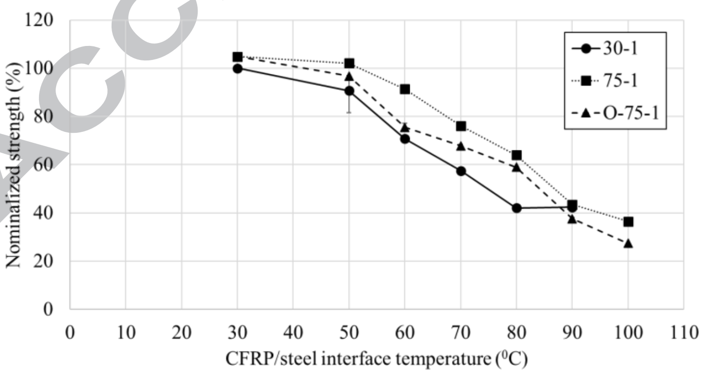

Fig. 9. Comparison of elevated temperature curing using an oven and floodlights

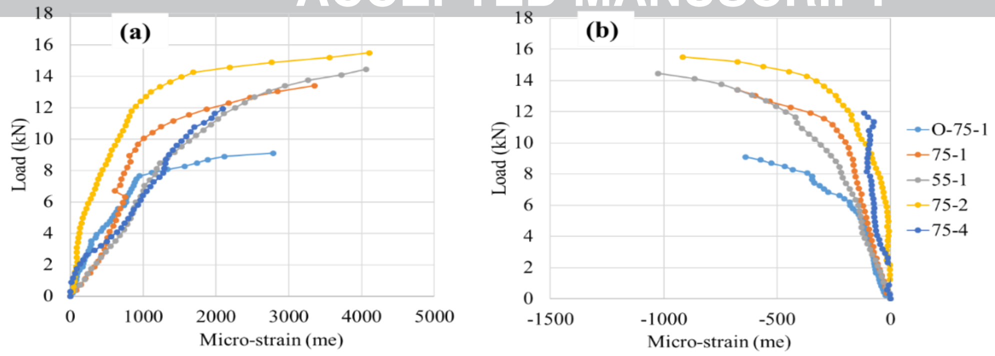

Fig. 10. Strain variation on CFRP at 100 ^{0}C bond line temperature, (a) X (b) Y directions

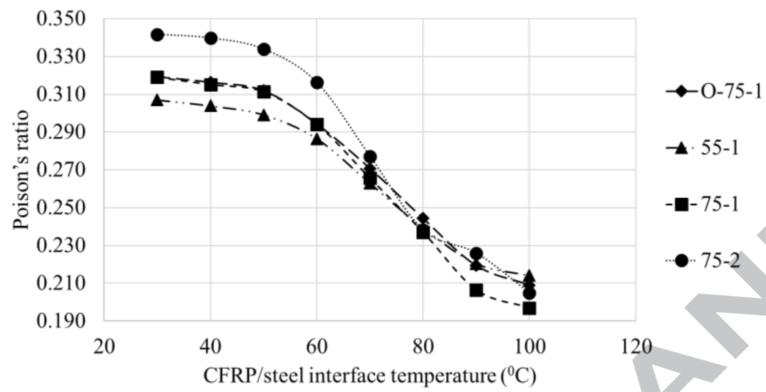

Fig. 11. Variation of Poison's ratio with bond line temperature

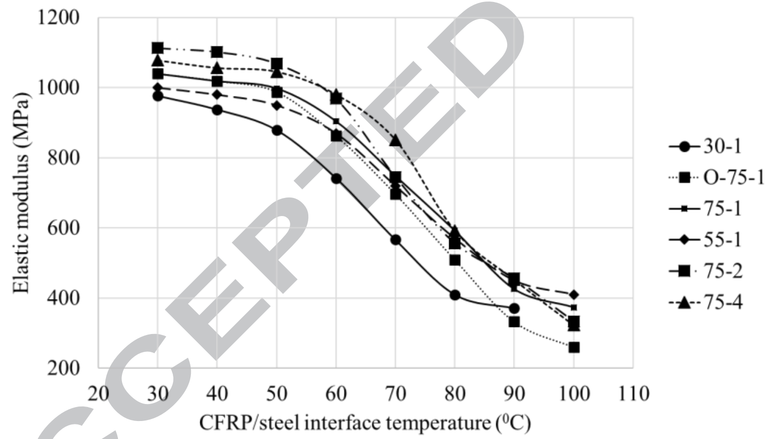

Fig. 12. Variation of Elastic modulus with bond line temperature

Tables

Table 1: Material Properties

Material Property		Steel	Adhesive Value	Adhesive % diff.	CFRP Value	CFRP % diff.
Average Tensile strength (MPa)	Measured	583	25	13	1575	60
	Manufacturer provided	-	29		4000	
Average Ultimate strain	Measured	0.065	0.043	6.5	0.009	55
	Manufacturer provided	-	0.046		0.02	
Average Elastic Modulus (GPa)	Measured	200	0.977	35	175.62	26
	Manufacturer provided	-	1.495		240	
Average Poisson's ratio	Measured	0.3	0.3	0	0.3	0
	Manufacturer provided	-	0.3		0.3	

Table 2: Curing configuration

Specimen group	Elevated temperature Curing conditions: Curing temperature (^{0}C)	Curing method	Initial curing time (hours)	Total nos. of specimens
30-1 to 30-6	Ambient	Ambient	N/A	12
O-75-1-1 to O-75-1-7	75	Oven	1	14
75-1-1 to 75-1-7	75±5	Floodlights	1	14
55-1-1 to 55-1-7	55±5	Floodlights	1	14
75-2-1 to 75-2-7	75±5	Floodlights	2	14
75-4-1 to 75-4-7	75±5	Floodlights	4	14

Table 3: Average failure loads (kN)

Bond line temperature at failure (^{0}C)	Specimen group: 30-1	O-75-1	75-1	55-1	75-2	75-4
30	36.83	38.63	38.6	37.15	41.35	40.05
50	33.4	35.62	37.6	34.43	35.95	37.8
60	26.05	26.2	33.65	31.9	30.4	33.6
70	21.18	25	28.05	23.83	27.6	31.13

	80	15.5	21.73	23.55	19.45	24.23	27.6
	90	15.63	13.83	16.03	13.15	17	16.7
	100		9.1	13.45	14.45	15.65	15.05