Accepted Manuscript

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PII: S0263-8223(18)33288-4
DOI: https://doi.org/10.1016/j.compstruct.2019.01.002
Reference: COST 10519

To appear in: *Composite Structures*

Received Date: 10 September 2018
Revised Date: 10 December 2018
Accepted Date: 2 January 2019

Please cite this article as: Chandrathilaka, E.R.K., Gamage, J.C.P.H., Fawzia, S., Numerical Modelling of Bond Shear Stress Slip Behavior of CFRP/Steel Composites Cured and Tested at Elevated Temperature, *Composite Structures* (2019), doi: https://doi.org/10.1016/j.compstruct.2019.01.002

Numerical Modelling of Bond Shear Stress Slip Behavior of CFRP/Steel Composites Cured and Tested at Elevated Temperature

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Abstract

This paper presents a numerical model developed to predict the bond characteristics of CFRP/steel composites cured under different curing conditions and their behaviour at elevated temperatures. The measured material properties and their degradation with the temperature exposure were considered. The predicted bond performance was in a good agreement with the test results. The strain variation in the CFRP sheet was used to develop the bond shear stress-slip variations. Parametric studies were also conducted to evaluate the effects of bond line parameters on the bond shear stress-slip relationship at elevated temperature. The results indicate that the maximum bond shear stress of the joint lies in the range between 25 MPa and 28 MPa at ambient conditions, irrespective of the curing type. A rapid decrease in the maximum bond shear stress appears with exposure to the elevated temperature. Maximum shear stress reaches 10 MPa when the bond line temperature exceeds 90 ^{0}C. The elevated temperature curing, exposed temperature during service and the bond thickness notably affects on the bond slip behavior.

Key words: Bond stress-slip, CFRP/steel, Bond line properties, Curing type, Elevated temperature

1. Introduction

Superior mechanical and thermal properties of Carbon Fiber Reinforced Polymer (CFRP) material has attracted the attention of the civil and construction industry. The use of elevated temperature curing conditions may improve the performance of CFRP strengthened structural members [1]. In this case, it is vital to understand the bond mechanism of the system cured under different curing conditions and their behavior at elevated temperatures.

Nguyen et al. [2,3] has observed the effects of curing conditions at ambient temperature and also the behaviour of ambient temperature cured joints at elevated temperature. They found a significant degradation of bond properties with the temperature exposure of the bond between CFRP and steel, cured under ambient conditions. Gamage et al. [4] also noted the similar behavior from CFRP/concrete composites cured at ambient conditions. Some research studies conducted on the CFRP/concrete joints indicated the negative influence on the substrate properties from elevated temperature curing [5-7]. However, these studies were conducted in a controlled environment. The curing was also done using a standard which are not practically feasible in civil engineering applications [3,8-10]. Chandrathilaka et al. [11] introduced a set of halogen floodlights for elevated temperature curing of the CFRP/epoxy/steel bond. They have exaggerated the feasibility of this system for the application in curing of large structures with high performance. Bond shear stress-slip variation is one of the key parameters which determines the bond behavior, irrespective from the geometrical properties of CFRP/steel composite. However, there is a lack of knowledge on the steel/CFRP bond slip behavior if it is both cured and exposed to elevated temperature. In general, collecting all required data from experiments is impractical and also not economical. In such cases, Finite Element Analysis (FEA) can be applied to predict the performance. Many researches have successfully applied FEA technology to predict the behavior of CFRP/steel composites [12,13]. Xia and Teng [14] has proposed a bi-linear bond slip model using experimental data which suitable for the CFRP/steel joints cured and tested at ambient conditions. However, developing a bond shear stress-slip model using experimental results require more resources and time [14-16]. Fawzia et al. [15] successfully used the bi-linear bond-slip model to evaluate the steel/CFRP bond performance using experimental and numerical data of the joints cured and tested under ambient conditions. However, the effects of bond line temperature were not discussed with the bond slip relationships. However, Fawzia et al. [15] has mentioned that CFRP/epoxy/steel bond length should higher than the effective bond length to have a bond shear stress-slip model to independent from CFRP/epoxy/steel bond length. Chandrathilaka et al. [11] has used higher bond length than the effective bond length in CFRP/epoxy/steel bond in the experiment.

Elevated temperature curing of epoxy adhesives increases the glass transition temperature (T_g) of polymeric resins [3]. Gamage et al. [4-6] indicated the improved service performance of the CFRP/concrete composites with an increased T_g of the polymeric bond and their bond shear stress-slip relationships. However, there is a lack of knowledge of the ways of raising the T_g of the joint between CFRP and steel, and its characteristics. Hence, it is important to evaluate the bond performances of steel/CFRP joints cured and tested at elevated temperature without an influence of geometric conditions of the joints. Therefore, this study is focused on the bond-slip behavior of the CFRP/steel joints cured under different levels of elevated temperatures. Effects of elevated temperature on bond-slip behavior is an another key aspect.

2. Overview of the test programme

CFRP/steel double strap joints were prepared at six different initial curing conditions as listed in Table 1. A schematic view of double strap joints with instrument setup is shown in Fig. 1. All the samples were cured for 7 days at ambient temperature after exposure to the initial curing under elevated temperature. Then the environmental temperature of the testing phase was increased till the bond line reaches different predetermined temperature levels; 30 ^{0}C (ambient temperature), 50 ^{0}C, 60 ^{0}C, 70 ^{0}C, 80 ^{0}C, 90 ^{0}C and 100 ^{0}C. When the joint temperature reaches a stabilized predetermined temperature level, a transient tension force was applied to the double strap joint till failure [Fig. 2]. The detailed experimental programme can be found in Chandrathilaka et al. [11].

3. Numerical modelling

Based on the dimensions and geometry of the double strap joint, either 2-D or 3-D modelling can be carried out to simulate the numerical analysis. Even though, the 2- D modelling is much easier to simulate and analyze in a normal computer, the results would have less accuracy and precision compare to 3-D modelling [12]. The controversy, the 3-D modelling will present more accurate results, although it would require more powerful computers and resources. Therefore, it will pose more difficulties when large scale structures are modelled and analyzed as 3-D models in normal computers. However, as the double strap joints are comparatively small, a 3-D modelling can be performed in a normal computer with a reasonable accuracy and precision [12]. Furthermore, reducing the scale and size of the model will encourage to reduce the analysis' computer resources. A computer with an 8 core processor, 8 GB RAM and 2 GB VGA was used for the current analysis.

3.1 FE mesh and Boundary conditions

As the double strap joint is consisted with three different types of materials, two different element types were assigned to create the numerical model using a commercially available finite element analysis software [17]. SOLID 185 element defined with 8 nodes was used to model the steel plate while SOLID 186 element defined with 20 nodes was used to model the adhesive and CFRP layers to achieve more precision. Node to node connection was used to connect the nodes with six degrees of freedom between different material layers [Fig. 3]. Mesh sensitivity analysis was carried out to check the accuracy of the results.

Axis-symmetric modelling of the specimen was considered. Hence, the constraints have to be assigned on the faces, as the symmetry of the model is identified in Fig. 4. There are three faces where the symmetry of the specimen is considered. Displacements were not allowed on X, Y and Z directions, respectively, on the face (a), (b) and (c). Rotations in all directions were restricted in the symmetry planes. A transient load was applied on the steel plate opposite to the joint as a transient displacement of 6 mm in 180 seconds with 50 steps. Approximately 1.5 hours were taken to solve the model.

3.2 Material Properties

Measured material properties at ambient temperature (30 ^{0}C) were used as listed in Table 2.

The bond behavior at elevated temperature was studied during the test programme. Since, the adhesive component is critical and sensitive to the temperature, degradation of material properties of adhesive bond with the temperature were considered [Fig. 5]. It was assumed that the variation of material properties of steel and CFRP is negligible compared to the mechanical properties degradation of adhesive bond within the considered temperature range for modelling, which is less than 100^{o}C.

4. Transient heat analysis

Transient heat analysis was performed using transient thermal tools in the software [17]. SOLID70, 8-node brick elements were used in each three materials with three different material properties [17].This element type contains single degree of freedom, temperature, at each node and suitable for modeling the mass transport of heat flow at constant velocity field. Programme controlled mesh was used after carrying out a mesh sensitivity analysis. Bonded connection was used between different material layers with node to node connection, with the same temperature value in the common node of different material layers. The thermal behavior of the CFRP/steel double strap joints was predicted for the variation of environmental temperatures (t_e) with time. Fig. 6 (a) shows the variation of bond line temperature for different environmental temperatures. It has shown that the bond line temperature reached the environmental temperature within 5 minutes of exposure to the temperature changes. Fig. 6 (b) indicates the uniformity of the temperature distribution within the bond line after saturation within a short period (<5 minutes). This is clearly indicating the non-insulation properties of CFRP as observed in CFRP/concrete composites [21]. The used material properties for transient heat analysis are shown in Table 3.

5. Thermo-mechanical analysis

Thermo-mechanical analysis was performed at low temperature range to identify the detailed bond mechanism which cannot be measured during testing for non-insulated CFRP/steel composites. ANSYS Mechanical APDL was used as the solver in thermos-mechanical analysis. The load, boundary conditions, elements and material properties were applied as described in section 3.1. Initially the transient heat analysis was performed.Then the temperature variation within the bond line was used to arrange the property degradation with the temperature. Finally, a transient load was applied to the joint till failure.

5.1 Model results and validation

Comparison between the average experimental joint capacities (P_{EXP}) and predicted load capacity (P_{FE}) results are shown in Fig. 7. It was observed that P_{FE}/ P_{EXP} ratios are in the range from 1.005 to 1.104 for all the models. Predicted results for each conditions have shown a slight higher value than the average experimental failure load in each scenario. The average deviation between predicted and experimented failure loads was less than 8%, for the exposed temperature varies between 30 ^{0}C and 100 ^{0}C. The average coefficient of correlation is 1.081. This clearly indicates the accuracy of a model for predicting the joint capacity. The temperature exposure beyond 100 ^{0}C were not considered in the analysis since the retained strength of joint at this temperature is less than 20%.

Measured and predicted strain variations in both X and Y directions at 35 mm from the joint, which exposed to 100^{0}C environmental temperature are shown in Fig. 8. Both predicted and experimental data have shown an elastic behavior at the beginning of the loading. The discrepancy between predicted and experimented values within this region are less than 10%. However, the start of the plastic behavior has begun at about 6 kN load level in the developed numerical model to simulate the bond characteristics, while experimental data have shown the start of plastic behavior at about 8 kN load level. Predicted average strain values in the CFRP sheet at 35 mm from the joint within the plastic range showed the difference lower than 10%, compared to the experimental results. Hence, the accuracy in strain behavior can also be expected.

The stress variation contours of the CFRP sheet and within the adhesive bond line near failure are shown in Fig. 9, at different bond line temperatures for the ambient temperature cured samples. The most common failure mode observed when the bond line temperature is less than 60 ^{0}C is the combination of CFRP rupture and the interface debonding. The predicted stress contours of samples tested below 60 ^{0}C also indicated the similar nature as shown in Fig. 9. In the test programme, the interface debonding failure was often observed for the samples tested above 60 ^{0}C. The predicted stress variations had also shown the evidence for the existence of high stress concentrations in the adhesive layer when the bond line temperature exceeds 60 ^{0}C.

5.2 Bond shear stress Vs. slip

The ultimate strength of a double strap joint can be used as a measurement for determining the performance of steel-CFRP joints. However, it is highly dependent on the geometric conditions of the bond. Hence, the bond -slip models were introduced to evaluate the bond performance independent from the geometry of the joint. Xia and Teng[14] has proposed a simple bi-linear bond-slip model for CFRP/steel composites as shown in Fig. 10. The initiation of bond slip graph is the elastic region where the bond shear stress increases while the bond slip increases. In the softening stage the shear stress starts to decrease while increasing the slip. At the end of the softening range the debonding occurs. Fawzia et. al. [15] has also successfully used bi-linear bond slip approximation for CFRP-steel double strap joints cured and tested at ambient conditions to evaluate the bond performances. In this study, a detailed bond-slip behavior is analyzed with respect to the curing conditions and also with the elevated temperature exposure.

The local slip of the bond is the relative displacement between the CFRP sheet and steel plate, which can directly measure from the FEA model. The shear stress represents the stress of the bond at the particular location where the slip was calculated. The location where the bond slip model is developed not particularly critical as the bond slip relationship is reasonably consistent between different locations of the bond [14]. However, using a location near to the joint has been shown more accurate than using a location far away from the joint. Therefore, all the bond slip models described in this paper were developed at 10 mm away from the joint.

5.2.1 Effects of bond line temperature

The temperature has influenced significantly on the bond slip relationship for all six specimen groups exposed to elevated temperature curing at different temperature levels as shown in Fig. 11. All the samples had indicated an average 0.17 mm initial slip, 0.43 mm maximum slip and 26 MPa maximum shear stress at 30 ^{0}C bond line temperature. When the bond line exposed to the temperature of 90 ^{0}C, the respective values (initial slip, maximum slip and maximum shear stress) have changed to 0.15 mm, 0.35 mm and 9 MPa. Therefore, when the bond line temperature increases from 30 ^{0}C to 100 ^{0}C, on average 17%, 60% and 25% reductions of initial slip, maximum shear stress and maximum slip, respectively were noted, irrespective of the curing condition. These reductions are negligible till the bond line reaches 50 ^{0}C for ambient temperature cured samples. The latter for elevated temperature cured samples were 60 ^{0}C. This clearly indicates the weaken bond properties with the exposure to the elevated temperature, which indicates the importance of providing an insulating layer for CFRP/steel composites cured under any condition.

5.2.2 Effects of curing condition

The behavior of CFRP/steel composites at different temperature levels with respect to their curing conditions is shown in Fig. 12. The curing condition has shown a minimum effect on the low bond line temperatures (<50 ^{0}C), while the maximum effects at the high bond line temperatures (80 ^{0}C, 90 ^{0}C and 100 ^{0}C). When the system exposed to ambient conditions (30 ^{0}C), the change in initial slip, maximum slip and maximum shear stress were 5%, 9% and 10%, respectively. When the bond line reaches the temperature higher than 70 ^{0}C, initial curing condition of the system starts to influence significantly on the bond line properties as shown in Fig. 12 (a) to 12 (g). However, at 100 ^{0}C the bond line temperature, initial and maximum slips and maximum shear stress values have decreased by 12%, 17% and 47%, respectively with the type of curing. Fig. 12 (g) indicates a considerable effect of curing conditions on bond line properties at relatively high temperature levels. This clearly indicates the importance of initial curing conditions on the performance of CFRP/steel composites exposed to elevated temperature.

6. Parametric study

6.1 Effects of adhesive layer thickness

Effects of adhesive layer thickness of the ambient temperature cured samples (A) and the samples with initial 75 ^{0}C temperature curing for 4 hours are shown in Fig. 13. Adhesive layer thicknesses at bond line; 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm were chosen for the study. On average 200% and 130% increase of initial slip and maximum slip, respectively has observed when the adhesive thickness increases from 0.5 mm to 2.0 mm for both curing conditions on the considered temperature exposure range. However, the maximum shear stress on the joint has not been affected by the thickness of the adhesive layer. The area enclosed by the bond shear stress-slip curve has increased with the elevated temperature curing. This means the fracture energy of the bond has increased when the system cured under elevated temperature result in more stable bond.

6.2 Effects of CFRP layer type

An another important aspect is to evaluate the bond properties at elevated temperature with respect to the curing conditions and the type of CFRP material used for strengthening. Three types of CFRP fabrics were chosen including the one used in the experiment (General purpose). The mechanical properties of the other two types (High modulus and Ultra high modulus) used in modelling are listed in Table 4.

Effects of CFRP fabric types on bond slip relationship are shown in Fig. 14 for bond line temperatures, 30 ^{0}C, 60 ^{0}C and 90 ^{0}C. A significant difference cannot be observed in the initial slip and maximum shear stress for different CFRP fabric types. The maximum shear stress in the bond slip relationship varies only with curing method. However, UHM CFRP fabrics have shown 4% less maximum slip compared to the GP and HM CFRP types at all levels of temperature exposure. The curing condition has also significantly affected on the bond slip model only beyond the temperature exposure of 60 ^{0}C.

6.3 Effects of CFRP layer thickness

To check the effect of CFRP layer thickness on bond slip relationship, three commercially available CFRP thicknesses for general purpose CFRP were used [26,27] as shown in Fig. 15. CFRP layer thickness had also shown a minimum effect on the initial slip and the maximum shear stress for all considered bond line temperature exposures and the curing method. The thickness of the selected CFRP sheet does not affect on the bond shear stress- slip behavior as shown in Fig. 15. This may due to low effects of temperature on CFRP material compared to epoxy adhesive [22,23]. The curing method had influenced only on the maximum shear stress of the composite. However, on average, a 7% difference has been observed in the maximum slip of bond slip relationship between all samples exposed to 30 ^{0}C and 60 ^{0}C bond line temperatures. This indicates the initial softening of the bond with exposed temperature, does not depend on the thickness of the CFRP layer. At 90 ^{0}C bond line temperature, CFRP layer thickness shows a negligible effect on the bond slip relationship. Hence, it can be concluded that the bond-slip behavior mainly depends on the bond line properties and the thickness of the adhesive layer.

Conclusions

A detailed numerical model was developed to simulate the bond characteristics of CFRP/steel joints cued at different conditions and their behavior with the elevated environmental temperature exposure. The following conclusions were drawn:

1. The transient heat analysis carried out to determine the thermal behaviour of CFRP/steel composites indicates the uniform and equivalent temperature profile within the bond line, which is similar to the exposed environmental temperature. The time taken to reach the uniform stabilized temperature within the bond line was less than 5 minutes. The model highlights the requirement of a provision of an insulation layer for the CFRP/steel composites.
2. The observed failure mode in the test programme was the combination of CFRP rupture and failure in adhesion layer for the specimens tested at low temperature exposure (< 50 ^{0}C). When the temperature exceeds 50 ^{0}C, pure bond failure was noted. The model predicted behaviour is also with a good agreement with this observed behaviour.
3. The discrepancy between model predicted and tested strain behaviour and the joint capacity is less than 12%. Hence, the model results are well agreed with the tested results.

4. Bond shear stress-slip relationships can be used to evaluate the bond characteristics which are independent from the geometry of the joint.
5. The samples which were both cured and tested at ambient temperature indicated 0.17 mm initial slip, 0.43 mm maximum slip and 25 MPa maximum shear stress. This is well agreed with the previous research conducted under these conditions.
6. A negligible variation in initial slip, maximum slip and maximum shear stress was noted from the ambient temperature cured sample exposed to the temperature less than 50 ^{0}C. The latter for the elevated temperature cured samples was 60 ^{0}C.
7. The initial curing condition of the joint influences significantly on the bond performance when the exposed environmental temperature exceeds 70 ^{0}C, irrespective of the type of curing.
8. The maximum bond shear stress does not depend on the thickness of adhesive layer when the system exposed to the temperature less than 100 ^{0}C.
9. The change in maximum shear stress, initial and maximum slips of CFRP sheet of the composite was negligible for all types of curing conditions for the considered exposure range of temperature (30 ^{0}C - 90 ^{0}C).
10. The initial softening of the bond with temperature does not depend on the type and thickness of the CFRP sheet.

Acknowledgement

A special thank goes to the staff in the computer laboratory of Department of Civil Engineering, University of Moratuwa for their valuable assistance. Senate Research Council of the University of Moratuwa has greatly acknowledged for arranging the necessary financial support (Grant No: SRC/LT/2016/19).

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Figures

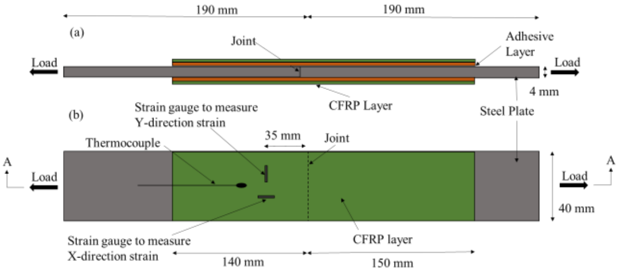


Fig.1. Schematic diagram of a double strap joint; (a) view A-A (b) plan view

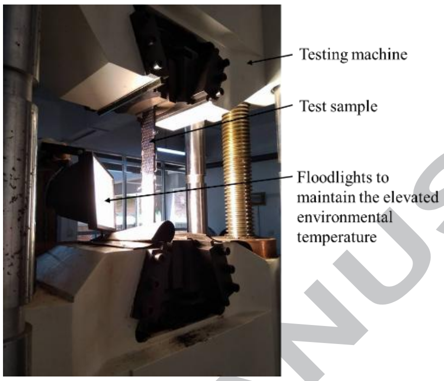


Fig.2. Test apparatus

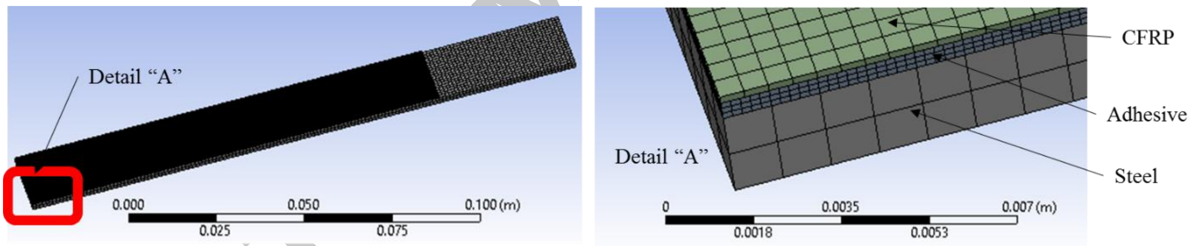


Fig. 3. FE mesh

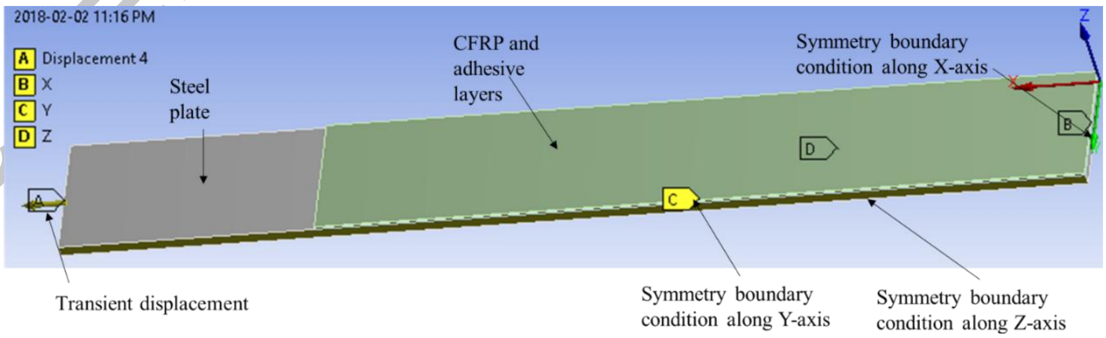


Fig. 4. Boundary conditions

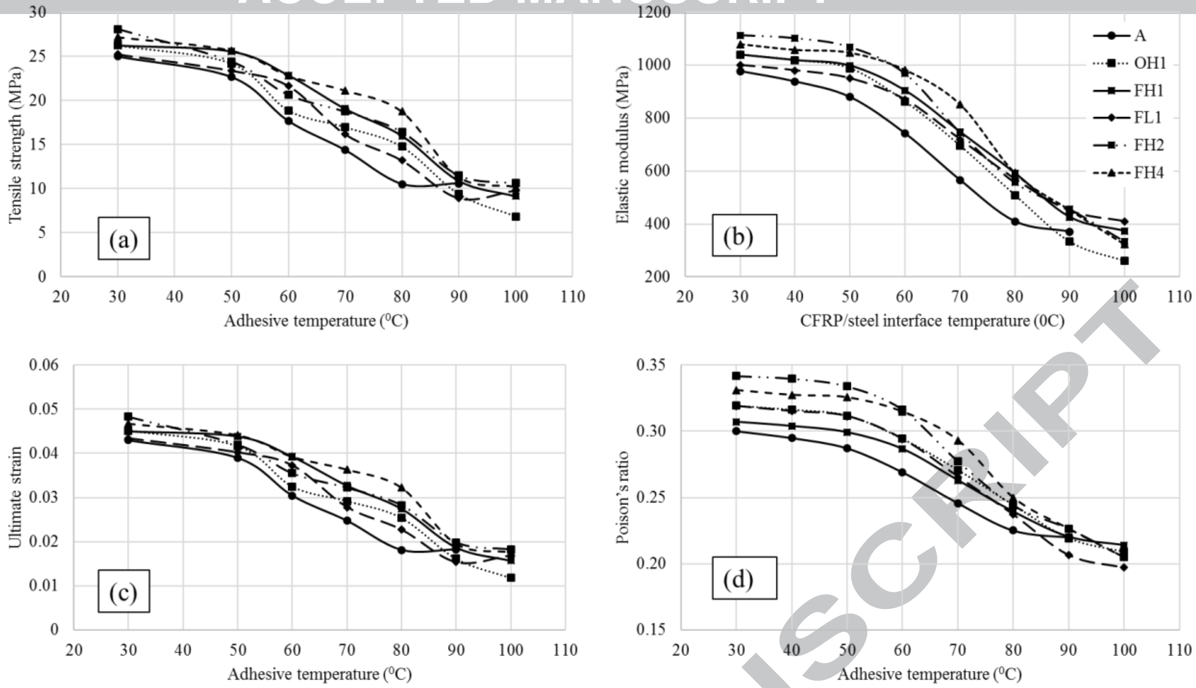


Fig. 5. Variation of adhesive properties with temperature (a) Tensile strength (b) Elastic modulus (c) Ultimate strain (d) Poison's ratio

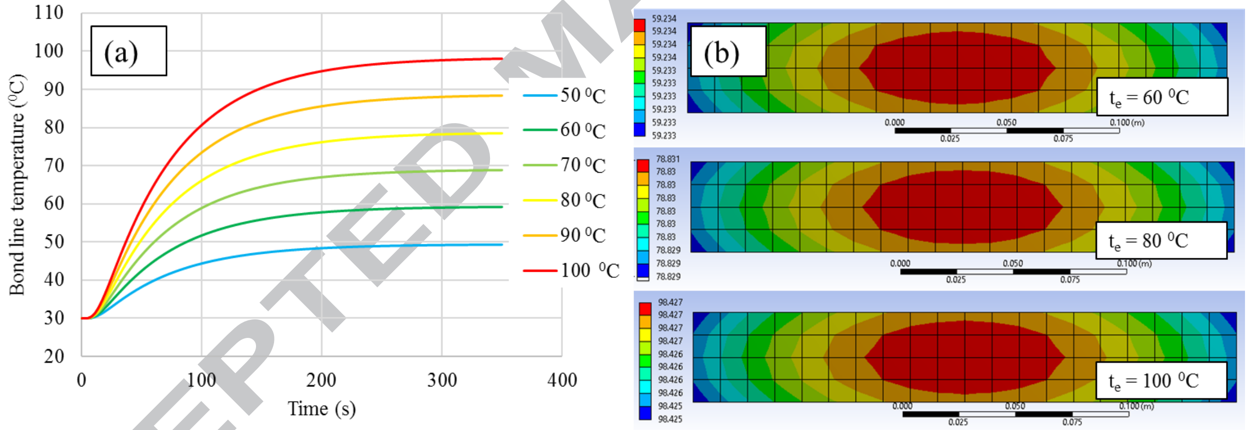


Fig.6. (a) Bond line temperatures of CFRP/steel joints for different t_e (b) Temperature contours of bond for different t_e

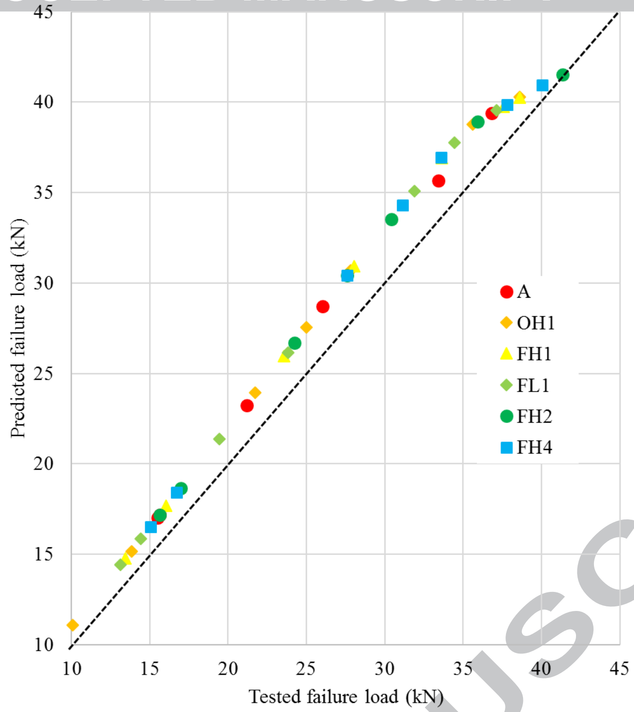


Fig. 7. Correlation between experimental and FEM failure loads

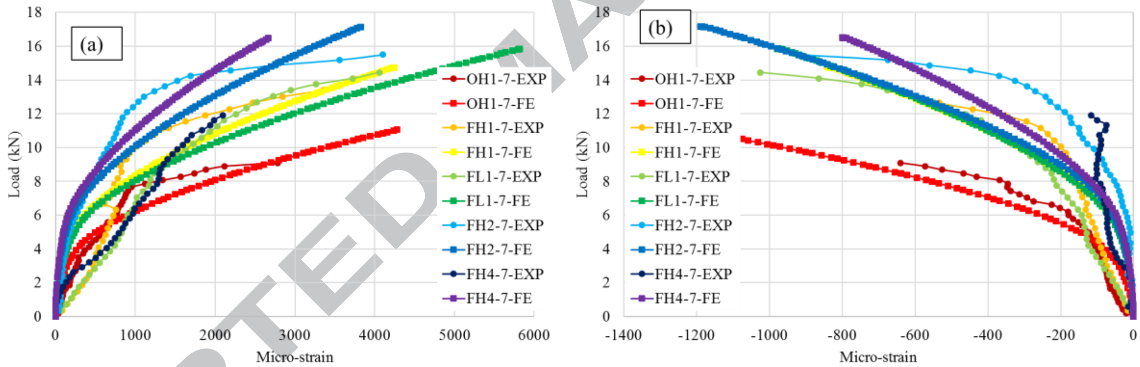


Fig. 8. Strain variation on CFRP at 100 ^{0}C bond line temperature for experimental and FEM results, (a) X (b) Y directions

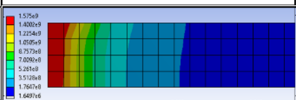
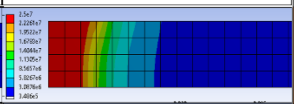
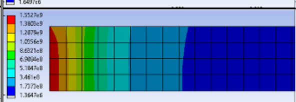
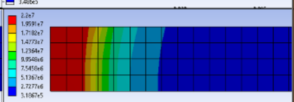
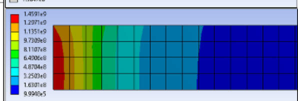
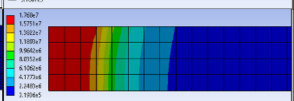
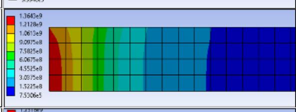
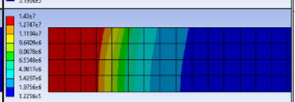
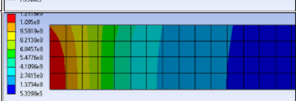
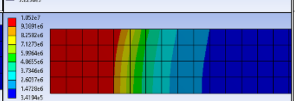
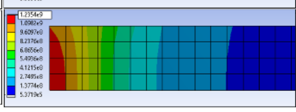
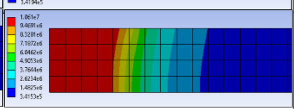
Bond line temperature (^{0}C)	CFRP layer stress (MPa)	Adhesive layer stress (MPa)	Predicted stress (MPa)		Remarks
			CFRP	Adhesive	
30			1575	25	Both CFRP and adhesive stresses have reached their ultimate values. Combined failure in CFRP and adhesive layers.
50			1552	22.6	Both CFRP and adhesive stresses have reached their ultimate values. Combined failure in CFRP and adhesive layers.
60			1459	17.6	Only adhesive layer stress has reached its ultimate value. Failure in adhesive layer.
70			1364	14.3	Only adhesive layer stress has reached its ultimate value. Failure in adhesive layer.
80			1231	10.5	Only adhesive layer stress has reached its ultimate value. Failure in adhesive layer.
90			1235	10.6	Only adhesive layer stress has reached its ultimate value. Failure in adhesive layer.

Fig. 9. Stress contours at near failure

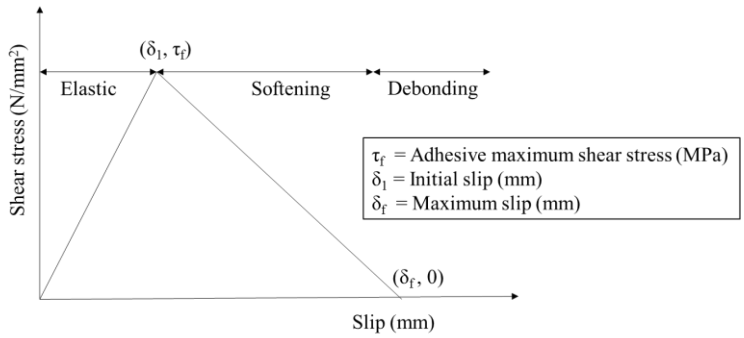


Fig. 10. Bilinear bond shear stress vs. slip approximation [14,15]

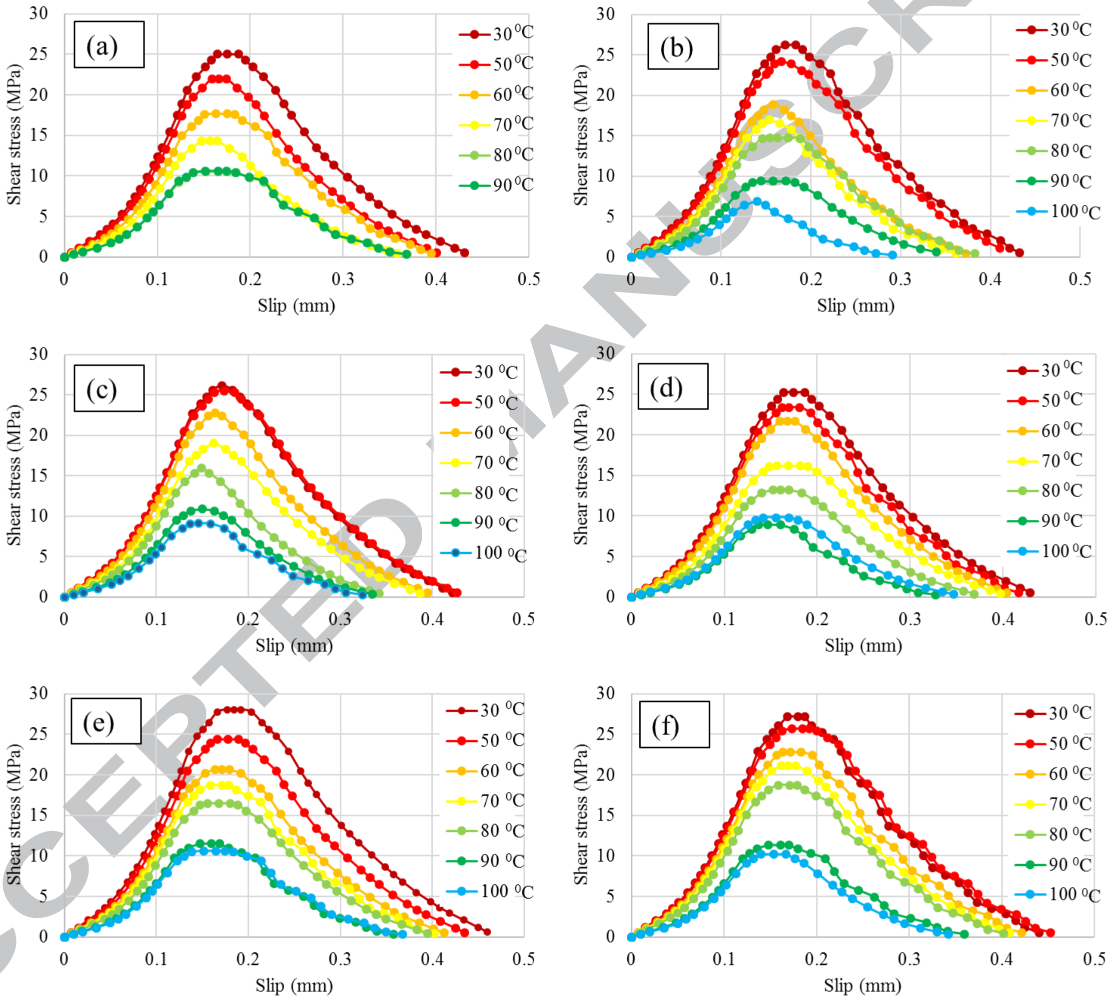


Fig. 11. Effect of bond line temperature on bond slip vs. shear stress for different curing conditions for specimen groups, (a) A (b) OH1 (c) FH1 (d) FL1 (e) FH2 (f) FH4

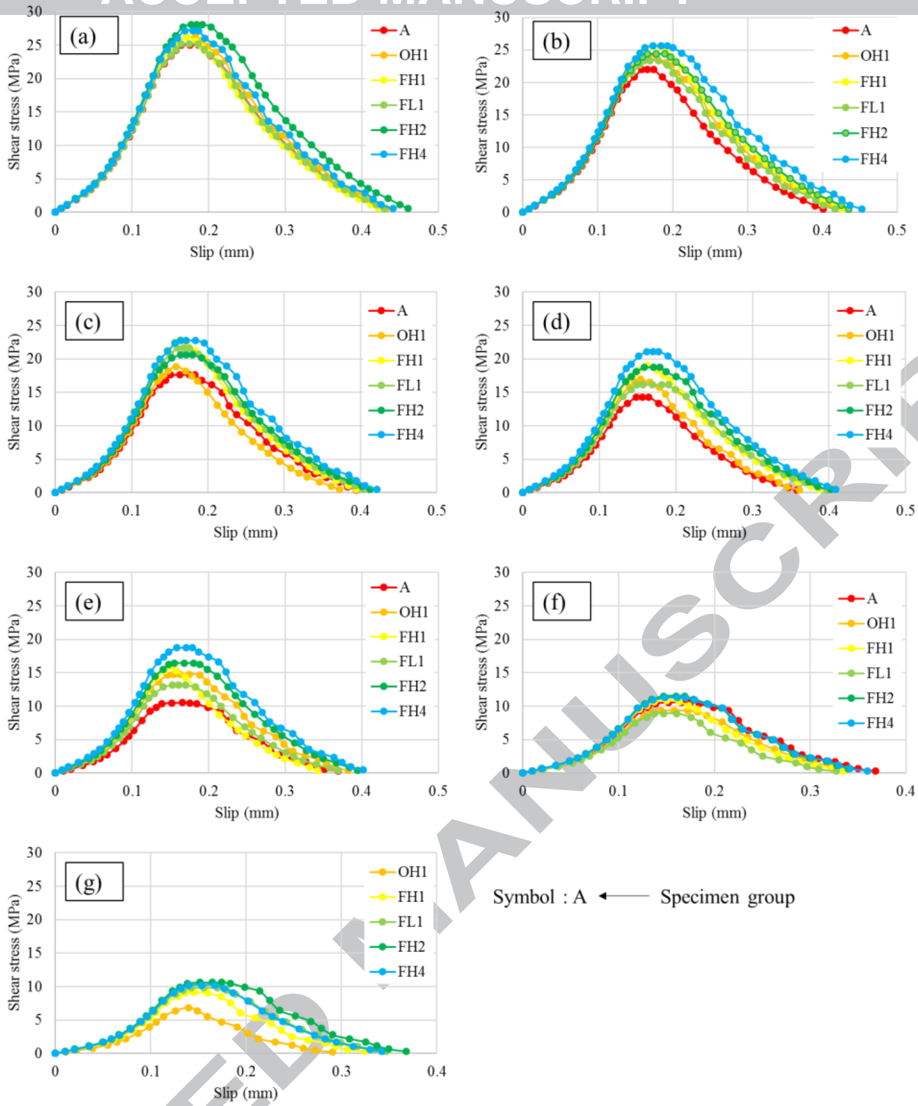


Fig. 12. Effect of curing conditions on bond slip vs. shear stress for bond line temperatures, (a) 30 ^{0}C (b) 50 ^{0}C (c) 60 ^{0}C (d) 70 ^{0}C (e) 80 ^{0}C (f) 90 ^{0}C (g) 100 ^{0}C

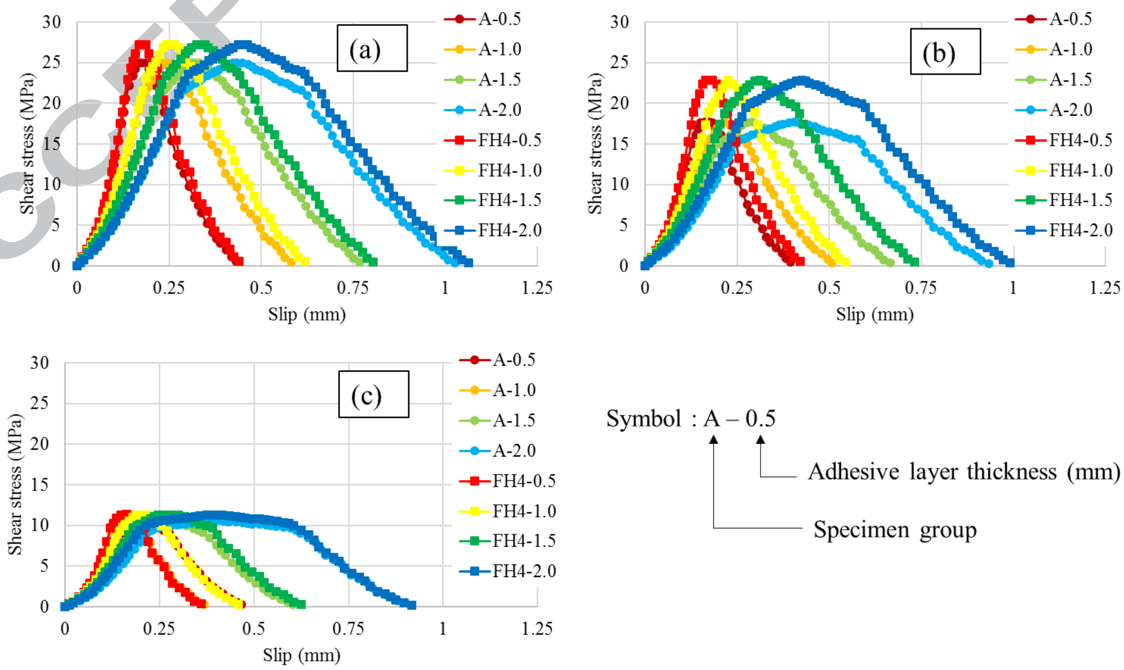


Fig. 13. Effects of adhesive layer thickness on bond slip vs. shear stress for bond line temperatures, (a) 30 ^{0}C (b) 60 ^{0}C (c) 90 ^{0}C

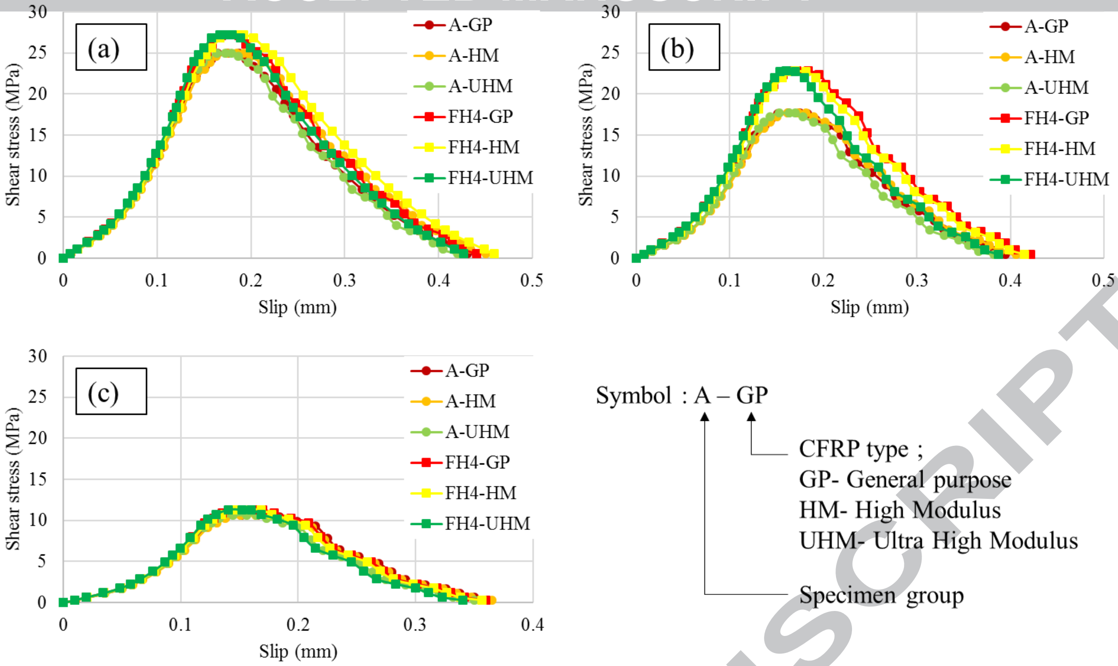


Fig. 14. Effects of CFRP type on bond slip vs. shear stress for bond line temperatures, (a) 30 ^{0}C (b) 60 ^{0}C (c) 90 ^{0}C

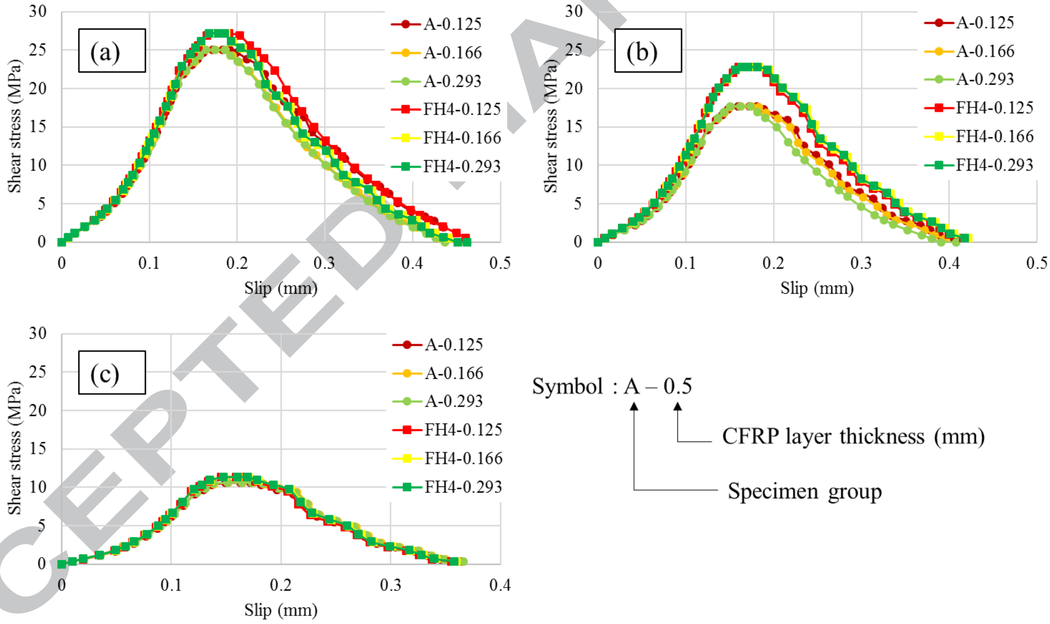


Fig. 15. Effects of CFRP layer thickness on bond slip vs. shear stress for bond line temperatures, (a) 30 ^{0}C (b) 60 ^{0}C (c) 90 ^{0}C

Tables

Table 1
Curing configuration

Specimen group	Elevated temperature Curing conditions			Total nos. of specimens
	Curing temperature (^{0}C)	Curing method	Initial curing time (hours)	
A	Ambient	Ambient	N/A	12
OH1	75	Oven	1	14
FH1	75±5	Floodlights	1	14
FL1	55±5	Floodlights	1	14
FH2	75±5	Floodlights	2	14
FH4	75±5	Floodlights	4	14

Table 2
Material properties at ambient temperature

Material Property	Steel [18]	Adhesive [19]	CFRP [20]
Average Tensile strength (MPa)	583	25	1575
Average Ultimate strain	0.065	0.043	0.009
Average Elastic Modulus (GPa)	200	0.579	175.62
Average Poison's ratio	0.3	0.3	0.3

Table 3
Material properties used in transient heat analysis [22-24]

Material	Thermal conductivity (W/m.^{0}C)	Specific heat (J/kg.^{0}C)	Density (kg/m^3)
Steel	60.5	511	7800
CFRP	0.6	1000	1800
Adhesive	0.6	1300	1100

Table 4
CFRP fabric properties [25]

CFRP type	Elastic modulus (GPa)	Ultimate strength (MPa)	Ultimate strain
High Modulus (HM)	330	2500	0.005
Ultra-high modulus (UHM)	600	2000	0.002
General purpose (GP)	175	1575	0.009