INFLUENCE OF TEMPERATURE ON CLEAVAGE BONDING PROPERTIES BETWEEN CFRP SHEETS AND CONCRETE

Dr. Kimio FUKUZAWA, Ibaraki University, Ibaraki, JAPAN
Dr. Masakazu MITSUI , Ibaraki University, Ibaraki, JAPAN
Dr. Tatsuya NUMAO, Ibaraki University, Ibaraki, JAPAN

Introduction

Recently, the FRP adhesion method which uses carbon or aramid fiber sheets for the strengthening of the flexural concrete members of buildings or bridges has lately become a subject of special interest. The bonding properties between the FRP sheets and concrete influence the structural properties of the concrete members which are strengthened by this method. Therefore, it is necessary to grasp the bonding properties between FRP sheets and concrete for the appropriate strengthening design. The bonding properties may be affected by factors related to the properties of concrete or FRP sheets. The resin is a high molecular weight material which has viscoelastic properties such as temperature dependency or time dependency. Furthermore, materials used in civil and architectural structures must be durable against circumferential temperature change as it is exposed to the open air and the direct solar radiation for long time. Therefore, it is important to evaluate the influence of temperature on the bonding properties between FRP sheets and concrete. However, there has been only a few papers published concerning this subject. This paper concerns the influence of the temperatures of FRP sheet by changing the temperature of specimens and circumferential air at the test on the cleavage bonding properties between FRP sheets and concrete. The effect of bonding and curing temperature on the properties is also examined. The compact tension test (CT test) was used in the experiments to evaluate the cleavage bonding properties. The bond softening diagram, fracture energy and toughness index are derived from the test data as the cleavage bonding properties.

Experimental procedures

Type of resin and CFRP sheets

The type of resin, the bonding and curing temperature T_{bc} and the testing temperature T_t were selected as factors in the experiments. The epoxy resin and the MMA resin were used as the bonding agent for the FRP sheets. Considering the distribution situation in the market, one-directional carbon fiber sheets were used to reinforce epoxy resin, and plain woven undirectional carbon fiber sheets were used to reinforce MMA resin. Two epoxy resins whose viscosity and pot life were changed to adapt the bonding and curing temperature. As for the MMA resin, the mixing ratio of hardener and promotion auxiliary was changed to adapt to the bonding and curing temperature. Physical properties of each resin are shown in **Table 1**. An epoxy system primer and MMA system primer were used in theses experiments.

Table 1. The physical properties of carbon fiber sheet and resin.

		CFS with epoxy		CFS with MMA	
	T_{bc}	20	5	20	5
Carbon fiber sheet CFS					
	Fiber areal weight, g/m^2	200		200	
	Tensile strength, MPa	4273		4200	
	Elastic modulus, GPa	230		230	
Resin					
	Rightness temperature, °C	15 ~ 25	5 ~ 15	30 ~ -10	
	Coefficient of viscosity, Pa-s	20	10	0.20 ~ 0.35	
	Pot life, hour	7.0	5.0	0.5	

Bonding and curing temperature T_{bc} and testing temperature T_t

As shown in **Table 2**, the bonding and curing temperature T_{bc} was changed to 5 and 20 °C. All works of the bonding were carried out in a thermostatic room which was set to 5 or 20 °C. All materials, components of the specimen, continuous fiber sheets, resins and concrete blocks, were stored for 24 hours preceding the bonding. The testing temperature, T_t is 5 levels of -15, 0, 20, 40 and 60 °C as shown in **Table 2**. All specimens were stored in the thermostatic chamber set at the testing temperature T_t 6 hours before the CT test. The experiments were done combining these factors as shown in **Table 2**. Two specimens were tested at each combination.

Table 2. Test program.

Type of resin	Bond/curing temp. T_{bc}, °C	Testing temp. T_t, °C				
		-15	0	20	40	60
Epoxy	20	●	●	●	●	●
	5	●	●	●	●	●
MMA	20	●	●	●	●	●
	5	●	●	●	●	●

Testing arrangement

Specimens

The specimen for CT test is shown in **Figure. 1**. The specimens were made by bonding an upper part and a lower part, setting continuous fiber sheets with resin between them. The stainless steel pipes in specimen were set to prevent breakage fracture due to stress concentration at the loading point. The concrete mix proportion used for making the upper and lower parts is shown in **Table 3**. The concrete was removed from form after one day and it was cured in water for 28 days. The bonding surfaces of an upper and a lower part of specimen were treated using diskgrider after the two days of air drying. Bonding the two blocks was done after one day of primer application on the bonding surfaces. At the time, the pre-crack between FRP sheet and concrete was formed by setting a non-adhesive film (thickness of 0.05mm and length of 10mm) at the notch tip, as it is shown in **Figure. 1**. Preceding the bonding, all materials for specimens, such as concrete block or adhesives, were stored for one day at the bonding and curing temperature. Bonding was also done in a chamber set at the temperature. Specimens were cured in the chamber (setting temperature of 20 ° C and humidity of 60%RH) for one month.

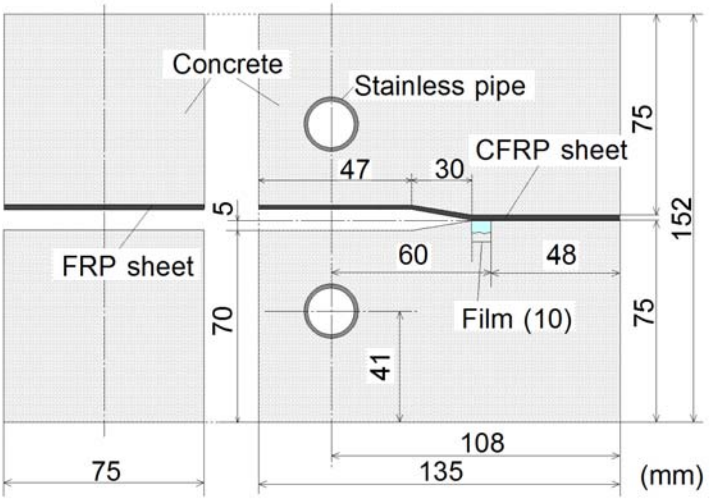


Figure. 1. Detail of CT specimen

Table 3. Concrete mixture.

W/C %	Unit mass, kg/m^3					Slump cm	Air %	Com. strength in 28d., MPa
	W	C	S	G	Ad.*			
42.0	170	405	742	991	1.00	10.5	4.0	51.2

Test procedures

The testing arrangement is shown in **Figure. 2**. A 100kN displacement controlled universal testing machine attached a temperature controllable box from -35 to 250 ° C. All tests were done at the displacement rate of 0.5mm/min. The opening displacement at a notch tip of specimen *CMOD* was measured by clip type displacement transducer whose sensitivity was 1000μ/mm. The clip type displacement transducer suitable for the low testing temperature was used in the low testing temperature at 0 and -15 ° C. Measurements of tensile load *P* and *CMOD* were done about 150 times/min. using a high-performance strain measuring instrument in order to grasp the peak in the *P-CMOD* curve.

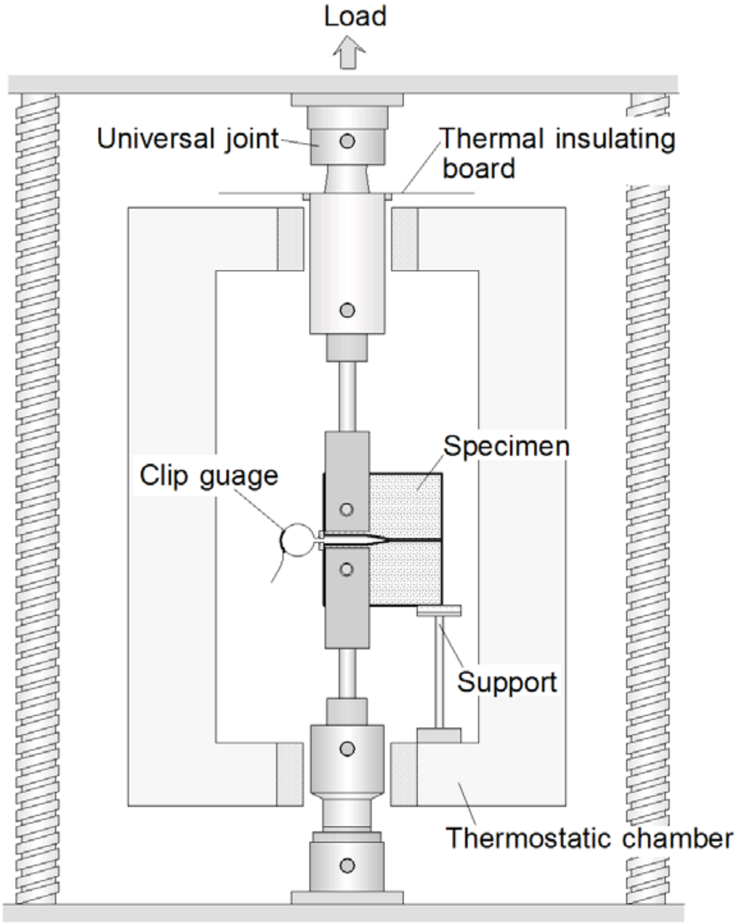
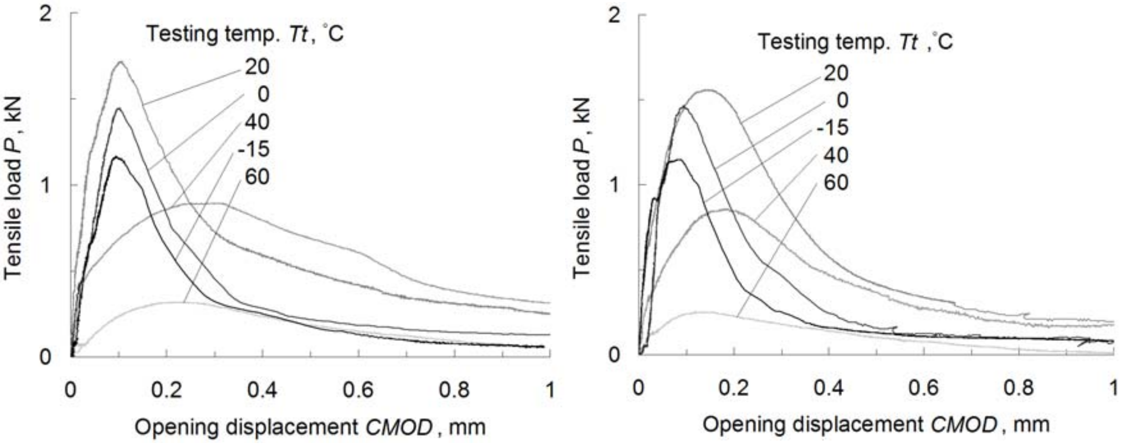


Figure. 2. Testing arrangement.

Results

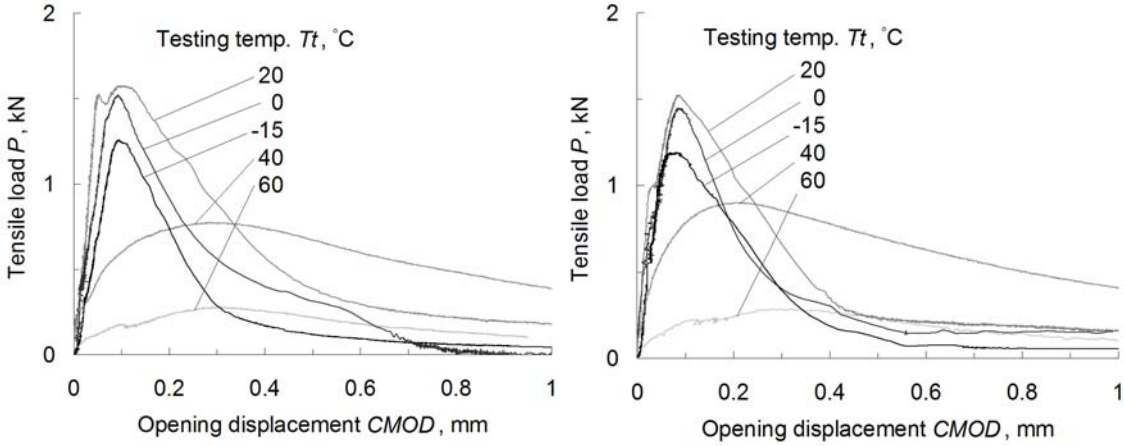
P-CMOD curves

The tensile load and the opening displacement of a notch tip (*P-CMOD*) curves are shown in **Figure. 3, 4**. Results of specimens used epoxy resin is shown in **Figure. 3** and results used MMA resin is shown in **Figure. 4**. In Fig.s, (a) shows the results that the bonding and curing temperature T_{bc} is 20 ° C and (b) shows the results that the T_{bc} is 5 ° C. Regardless of the type of resin and the bonding and curing temperature T_{bc}, it is apparent that the effect of the test temperature T_t is remarkable from the comparison of (a) and (b) of each figure. Under the low testing temperature of 0 and -15 ° C, the decrease in *P* as the *CMOD* increases is remarkable after the tensile force reached to the maximum tensile load *Pmax*. On the contrary, under the testing at 40 and 60 ° C, *Pmax* and decreasing rate of the load are smaller than that are gained at the testing temperature of 0 and -15 ° C. *Pmax* showed the largest value when the testing temperature T_t is 20 ° C.



(a) T_{bc} of 20 ° C (b) T_{bc} of 5 ° C

Figure. 3. P-CMOD curves using epoxy.



(a) T_{bc} of 20 ° C (b) T_{bc} of 5 ° C

Figure. 4. P-CMOD curves using MMA.

Observations of the fracture surface

Fracture positions classification using the five links theory is shown in **Figure. 5**. "A type" is a case where the fracture happened in the concrete. "B type" is a case that the fracture in concrete body and failure at the concrete/resin interface happen simultaneously. "C type" is a case where the failure happens at the concrete/resin interface without the failure occurring in the concrete. "D type" is a case where the fracture in the resin and failure at the concrete/resin interface happen simultaneously. And "E type" is a case where the failure happens in the resin only. These classifications of the fracture surface of all specimens are shown in **Table 4**. Also in **Table 4**, the effect of the bonding and curing temperature T_{bc} on the fracture surface can be seen. It is not recognized regardless of the type of resin since the fracture position classifications were similar for the T_{bc} of 20 ° C and the T_{bc} of 5 ° C. However, the effect of the type of resin and testing temperature T_t is large. At the testing temperature T_t of 20, 0 and -15 ° C, many specimens showed "A type", when the epoxy resin was used as shown in **Figure. 6** (b), (c). The fracture type changes with the increase in the testing temperature T_t. At the testing temperature of 60 °C, "D type" increases (see **Figure. 6**(a)). The glass transition temperature T_g of the epoxy resin is within 25 to 40 °C. Therefore, it can be verified that the transformation of glass-like resin into rubber-like resin, in the testing temperature T_t which exceeded the glass transition temperature T_g, affects the fracture type between CFRP sheets and concrete. When the testing temperature T_t was 20, 0 and -15 °C, the concrete fracture ("A type") and multiple failure in concrete ("B type") are observed when the MMA resin is used. Almost all specimens showed the fracture of "D type" when testing temperature T_t was 40 and 60 °C. The failure type at each testing temperature using the MMA resin agrees with the failure type when the epoxy resin is used. The observations on the fracture type of the MMA resin used specimens almost coincide with that of the epoxy resin used specimens at each testing temperature. The above can be explained because the glass transition temperature T_g of the MMA resin is equivalent to the T_g of epoxy resin.

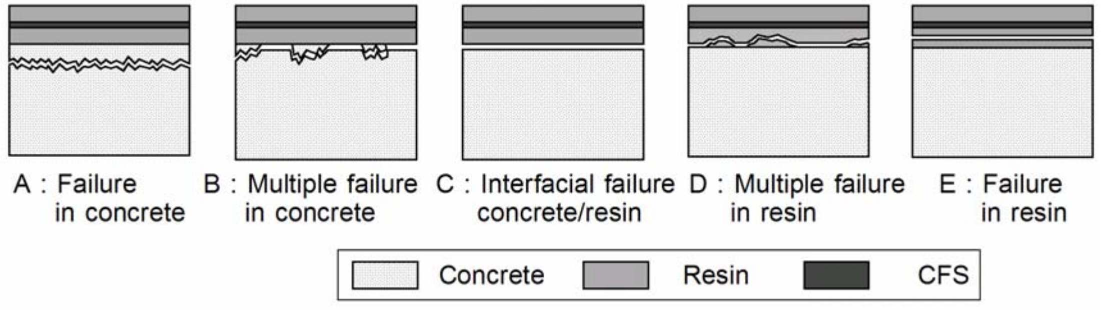
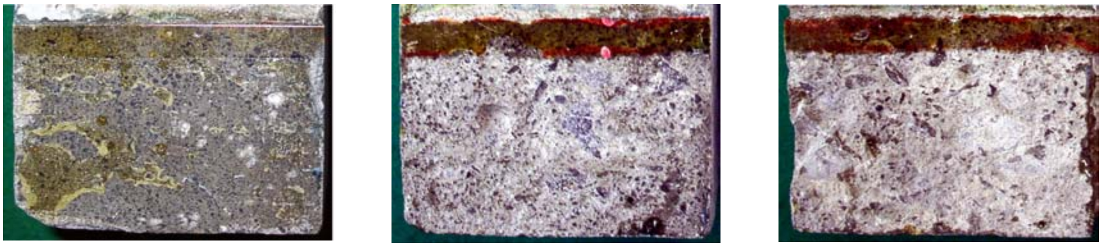


Figure. 5. The classification of fracture position based on the five links theory.

Table 4. Summary of classifications

Type of resin	Bond/curing temp. T_{bc}, °C	Testing temp. T_t, °C				
		-15	0	20	40	60
Epoxy	20	A, B	A, A	A, A	B, C	D, E
	5	A, A	A, B	A, A	B, B	D, D
MMA	20	B, B	B, C	B, B	C, D	D, E
	5	B, C	B, C	B, B	D, D	E, E



(a) T_{bc} of 60 °C (b) T_{bc} of 20 °C (c) T_{bc} of -15 °C

Figure. 6. The observation of the fracture surface using epoxy.

Bond softening properties

Estimation method of bond softening diagrams

Concrete is not brittle material represented by glasses, but a quasibrittle material that the fracture gradually develops generating many microcracks at the fracture front area with the increase in deformation. The tension softening diagram which shows the tensile behavior after the maximum tensile stress is one of important properties of quasibrittle material, especially in the simulation of the fracture mechanism with the crack progress of the concrete. Generally, the tension softening diagram is expressed in the relationship between cohesive stress and the assumed crack width. In this paper, the bond softening diagrams were determined through the poly-linear approximation method (Kitsutaka (1995)) combined with the finite element analysis with fictitious crack model at the CFRP sheet/concrete interface (see **Figure. 7**). The poly-linear approximation method is used in the estimation of the tension softening diagram of plain concrete. In this method, the coordinates of each point of softening diagram are determined step by step with the development of the fictitious crack in the FE analysis, so that the analytical *P-COMD* curve agrees with the experimental *P-CMOD* curves shown in **Figure. 3** or **4**. Elastic modulus and Poisson's ratio from the concrete cylindrical specimens which were tested at the normal temperature were used in the FE analysis. This is based on the preceding papers that the properties are not influenced by the temperature in the temperature range of the experiments (-15 to 60 ° C).

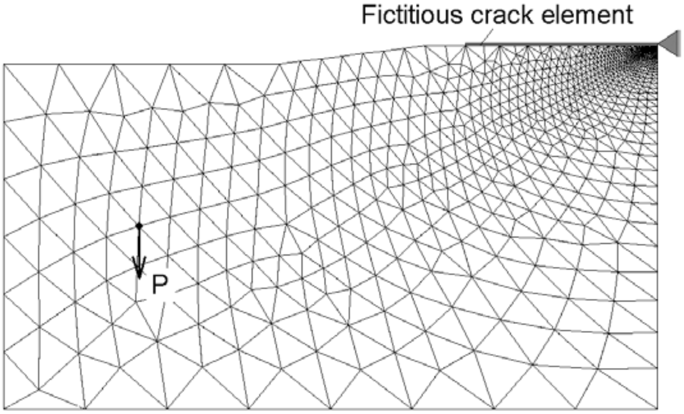
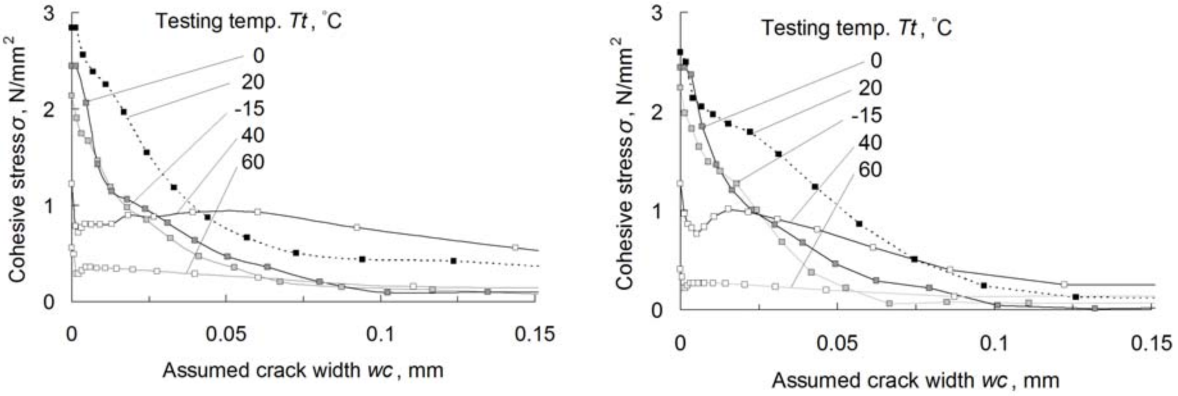


Figure. 7. FE analytical model and meshing division.

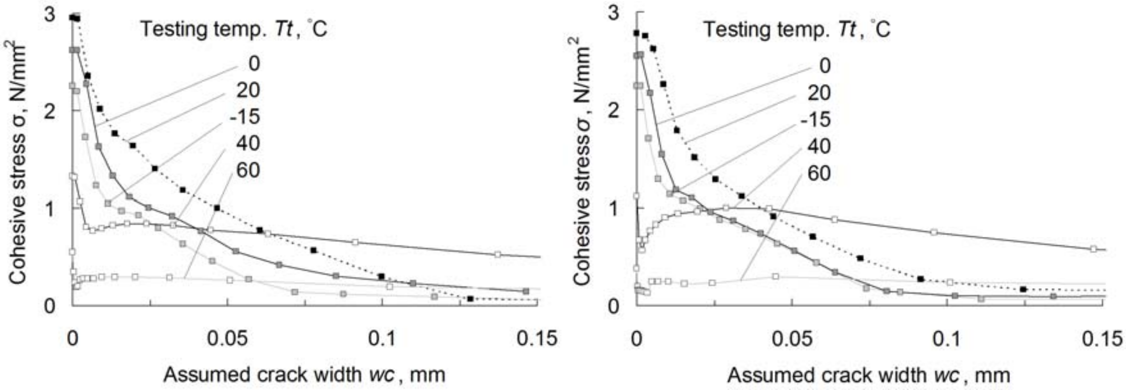
Temperature dependency of the bond softening diagrams

The bond softening diagram between CFRP sheets and concrete is shown in **Figure. 8** and **Figure. 9**. The bond softening diagrams of the specimen using the epoxy resin are shown in **Figure. 8** and the diagrams of the specimen using the MMA resin are shown in **Figure. 9**. From each figure, it is proven that the bond softening diagrams are affected by testing temperature T_t. It is confirmed that the start point of cohesive stress at the bond softening diagram remarkably decreases in the high testing temperature. The maximum cohesive stress decreased remarkably at the high temperature; the bonding strength at 40 °C decreased to about 50% of that at 20 °C and the bonding strength at 60 °C decreased to about 20% of that at 20 °C. The bond softening diagram where the at high testing temperature shows the toughness ductile that decreases in the load to the increase in crack width *wc* is small. The start point stresses of testing temperature T_t of 0 and -15 °C are almost equal to that of testing temperature of 20 °C. The bond softening diagram where the low testing temperature shows the brittle behavior that decreases in the load to the increase in crack width, *wc* is large. Those bonding properties, as well as the change in the fracture surface, where decided by whether the testing temperature T_t is higher or lower compared to the glass transition temperature T_g of both resins.



(a) T_{bc} of 20 °C (b) T_{bc} of 5 °C

Figure. 8. Bond softening diagrams using epoxy.



(a) T_{bc} of 20 °C (b) T_{bc} of 5 °C

Figure. 9. Bond softening diagrams using MMA.

The temperature dependency of fracture energy

The fracture energy G_f is the non-recoverable energy consumed as the crack progresses in the CFRP sheets/concrete interface. It is calculated as an area surrounded in bond softening diagram and horizontal axis (in the range between 0 and 0.1mm) as shown in **Figure. 10**. It is well known that the cleavage bonding property between CFRP sheets and concrete is improved with the increase of fracture energy G_f. An example of relation between fracture energy G_f and testing temperature T_t is shown in **Figure. 11**. The influence of the resin type on the fracture energy G_f is shown in **Figure. 11**(a) and the influence of adhesion and curing temperature T_{bc} is shown in **Figure. 11**(b). The largest fracture energy is obtained at the testing temperature of 20 ° C and it decreases with the decrease or increase in testing temperature irrespective of the type of resin, bonding and curing temperature T_{bc}.

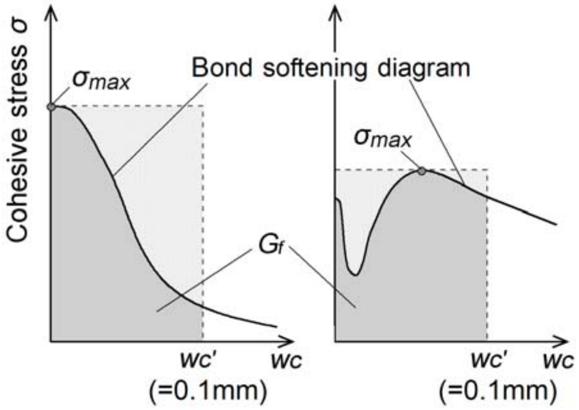
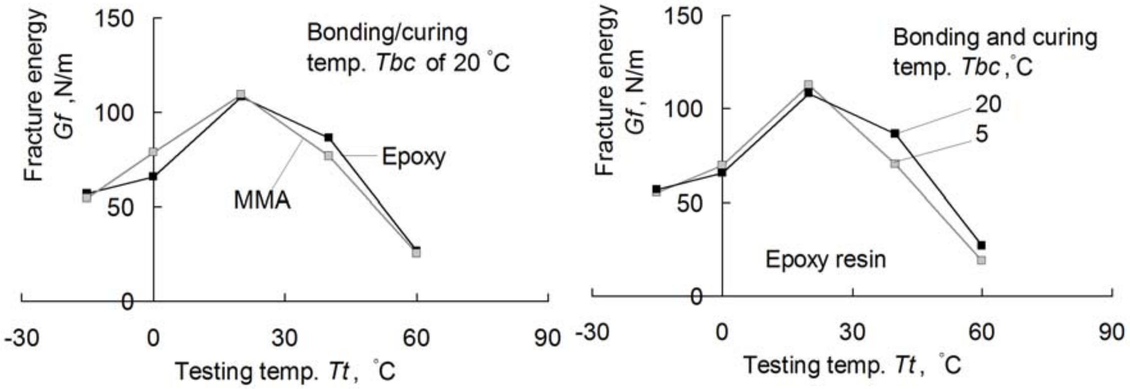


Figure. 10. Fracture energy G_f



(a) Influence of resin type (b) Influence of T_{bc}

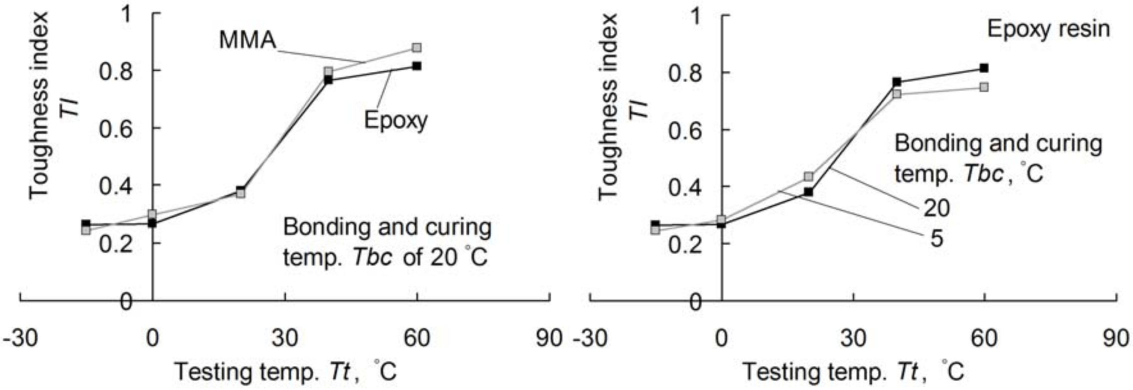
Figure. 11. Temperature dependence of fracture energy G_f.

The temperature dependency of the toughness index

Toughness index *TI* is introduced as an index which quantifies whether the cleavage bonding property is ductile or brittle. The toughness index *TI* is calculated from equation (1) that is a ratio of fracture energy G_f to the product of the maximum cohesive stress s_{max} and the crack width limit w_c' as is shown in **Figure. 10**(a) or (b).

$$TI = G_f / (s_{max} \times w_c') \quad (1)$$

The toughness index is measured from zero to one. As the index moves closer to zero, the bond softening behavior becomes more brittle and it becomes more ductile as the index moves closer to one. An example of the relationship between toughness index *TI* and testing temperature T_t is shown in **Figure. 12**. **Figure. 12** shows that the toughness index *TI* increases as the testing temperature T_t increases irrespective of the type of resin and bonding and curing temperature T_{bc}. The relationship between the toughness index *TI* and the testing temperature T_t shows to be an upward convex when T_t is high and a downward convex when T_t is low. These relationships are approximated by cubic curves and the inflection point is to be calculated around 25 ° C irrespective of the type of resin. The toughness index *TI* at the testing temperature T_t of 25 ° C is about 0.5. These results seem to explain why the cleavage bonding property between CFRP sheet and concrete changes from brittle behavior to ductile behavior as the temperature increases.



(a) Influence of resin type (b) Influence of T_{bc}

Figure. 12. Temperature dependence of toughness index *TI*.

Conclusions

Experiments on the cleavage bonding property between CFRP sheet and concrete were carried out to verify the influence of the type of resin, bonding and curing temperature and testing temperature. The conclusions from the experiments are as follows:

(1) The cleavage bonding properties between CFRP sheet and concrete are remarkably affected by the temperature of the specimen. Resin type, and bonding and curing temperature has little influence on the cleavage bonding properties.

(2) The maximum value of the cohesive stress at the CFRP sheets/concrete interface is obtained at the testing temperature of 20 ° C and it decreases as testing temperature increases or decreases. The maximum cohesive stress decreases remarkably at a high temperature; the bond

strength at 40 °C decreases to about 50% of that at 20 °C and the bonding strength at 60 °C decreases to about 20% of that at 20 °C.

(3) The largest fracture energy between CFRP sheet and concrete is obtained at the testing temperature of 20 °C and it decreases as testing temperature increases or decreases.

(4) The cleavage bonding properties becomes ductile as the testing temperature increases and it becomes brittle as the temperature decreases. The boundary of testing temperature of peeling characteristics change from brittle behavior to ductile behavior is estimated to be 25 °C, irrespective of resin type and bonding and curing temperature.