Scientific paper

Mechanical Properties of Newly Developed Heat-Resistant FRP Bars

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Abstract

This paper presents a basic research into newly developed heat-resistant fiber reinforced polymer (FRP) bars. The heat resistance of commercially available FRP bars is low because of the low heat resistance of the resins used for the matrix such as epoxy (EP), unsaturated polyester (USPE) and vinyl ester (VE). The authors investigated new heat-resistant resins suitable for the production of FRP bars, and resol type phenolic (PH) and M type cross-linked polyester-amide (CP) resins were selected for bar fabrication and testing. Six different types of FRP bars made with carbon fiber or aramid fiber and PH, CP or EP matrix resin were prepared. The heat resistance of each bar was evaluated by tensile tests during and after heating. To assert the durability of the bars, an alkaline resistance test was performed. Pull-out tests and flexural tests of concrete members reinforced with the newly developed FRP bars and those with steel bars were also performed at normal temperature (20°C) and high temperatures. The test results indicate that the heat resistance of the FRP bar specimens made with PH or CP matrix resin was higher than that of the specimens made with EP matrix resin, and that the heat resistance of reinforcing fiber was essential for improvement of the heat resistance of the matrix resin. Of particular note is the fact that the heat resistance of FRP bars made with carbon fiber and PH matrix resin was found to be almost the same as that of steel bars.

1. Introduction

Many studies on the mechanical properties of FRP bars at normal temperature (20°C) have been conducted in recent years, (JSCE 1992, Machida 1997, JSCE 1997, ACI Committee 440 2000). Tamura (1993) and Okamoto *et al*. (1993) summarized case histories of FRP bars applied as a replacement for steel bars and external tendons in pre-stressed concrete members. Kumahara *et al*. (1993) and Wang *et al*. (2003) demonstrated that the heat resistance of an FRP bar made with epoxy (EP), unsaturated polyester (USPE) or vinyl ester (VE) matrix resin is low. Sumida *et al*. (2001) also demonstrated that the glass transition temperature (GTT) of matrix resins used for commercially available FRP bars is lower than 180°C. When such FRP bars are employed as a steel bar replacement for buildings, a thick insulator on the surface of concrete structures is required to protect the FRP bars from high temperatures, but this increases cost and decreases architectural space. Therefore, Bisby *et al*. (2005) suggested that there is a strong need for high-heat-resistant FRP bars.

It is quite obvious that the EP, USPE and VE resins typically used in commercially available FRP bars have restrictive limits on service temperature. Therefore, heat resistant resins (i.e. GTT>200°C) industrially acceptable as a matrix resin for FRP bars were studied, and water-soluble resol type PH and aromatic diamine containing methanol-soluble M type CP resins were selected for higher heat resistance, easier solvent removal, and less decomposition during curing. The establishment of an economical production system for voidless FRP bars made with PH or CP matrix resin was difficult because PH and CP resins are dissolved in a solvent and they generate solvent vapor and decomposition products during curing. Polyimide and polyamide-imide resins, which have very high heat resistance, were also tried, but it was impossible to use them as matrix resins because of high viscosity, low polymer concentration, difficulty of solvent removal and extensive decomposition during curing.

After identifying promising resins, four new types of heat-resistant FRP bars made with carbon fiber or aramid fiber and PH or CP matrix resin were prepared. Conventional FRP bars made with carbon fiber or aramid fiber and EP matrix resin were also prepared for comparison purposes. Tensile tests at normal temperature (20°C), during heating and at normal temperature (20°C) after heating were conducted. An alkaline resistance test was also conducted. Pull-out tests at normal (20°C) and high temperatures were carried out. Lastly, flexural tests of concrete beams reinforced with each type of FRP bar or steel bar were carried out at normal (20°C) and high temperatures to demonstrate the fundamental heat resistance of the newly developed FRP bars in practice.

2. Evaluation of commercially available FRP bars

Table 1 shows the design of commercially available FRP bars in Japan and the properties of each applied resin.

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FRP bars and matrix resin samples, which were supplied by respective FRP bar makers, are shown in **Fig. 1**.

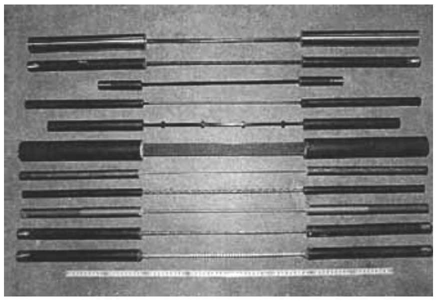
2.1 Heat resistance of resins

The glass transition temperature (GTT) and modulus of the matrix resin were measured by the method recommended by Suppliers of Advanced Composite Materials Association (SACMA). Both ends of the resin test piece were mounted on the two grips. One end of the grip was a transducer to detect displacement of a sample and the other was a transducer to detect stress in the sample. While an actuator induced a vibration in the sample and heat was applied with a heating ratio of 10°C/minute in air, the displacement and stress were measured and recorded. The GTT was measured as the temperature at which the inclination between temperature and stress was the highest. The GTT of the resin samples was less than 180°C and the modulus of each resin dropped sharply when the resin test specimen was heated above the GTT as shown in **Table 1**.

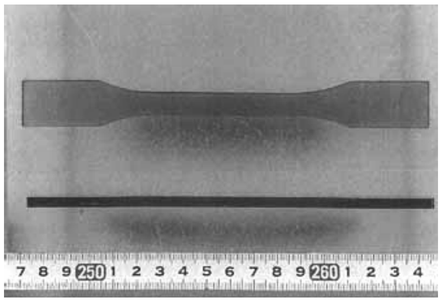
The weight loss behavior of each resin was thermogravimetrically measured with a heating ratio of 10°C/minute in air. **Fig. 2** shows instances of the TG-DTA curve. Each resin sample began to decompose at about 300°C as shown in **Table 1**.

2.2 Tensile properties of FRP bars

R-D for carbon fiber and R-I for aramid fiber were selected for the tensile test because these bars were made with typical epoxy or vinyl ester matrix. A test specimen for the tensile test was formed by inserting an FRP bar 800 mm in length into a steel pipe 22 mm in internal diameter and 200 mm in length. Epoxy resin and steel balls 1 mm in diameter were poured into the pipe and cured. The tensile test was conducted at normal temperature (20°C) according to "Test Method for Tensile



(a) FRP bars



(b) Resin specimen

Fig. 1 Specimens.

Table 1 Design and properties of commercially available FRP bars.

Sample number	Design				Properties of matrix resin					
	Shape*1)	Diameter	Fiber*2)	Resin*3)	GTT*4)	Tw*5)	Modulus			
							20℃	100℃	150℃	200℃
		(mm)			(℃)	(℃)	(GPa)	(GPa)	(GPa)	(GPa)
R－A	C S	9.6	CF	E P	126	293	1.7	1.3	0.018	0.016
R－B	C D	8.0	CF	E P	99	286	1.8	0.45	0.043	0.027
R－C	C S	7.5	CF	E P	---	319	---	---	---	---
R－D	C S	5.0	CF	E P	140	300	1.9	1.2	0.11	0.019
R－E	C L	4.7	CF	V E	---	244	---	---	---	---
R－F	C P	11.0	CF	E P	177	283	2.1	1,5	0.83	0.037
R－G	A D	3.0	AF	E P	---	---	---	---	---	---
R－H	A B	7.3	AF	E P	176	279	2.3	1.6	1.3	0.046
R－ I	A D	6.0	AF	V E	126	279	2.0	1.6	0.017	0.014
R－ J	G D	8.0	GF	E P	---	286	---	---	---	---
R－K	V D	8.0	VF	E P	93	269	2.0	0.32	0.045	0.033

*1) R: Rod, S: Strand, B: Braided, L: Lattice, P: Rectangular (Plate)

*2) C: Carbon fiber (CF), A: Aramid fiber (AF), G: Glass fiber (GF), V: Vinylon fiber (VF)

*3) EP: Epoxy, VE: Vinyl ester

*4) Glass transition temperature (GTT)

*5) Weight loss initiation temperature (Tw)

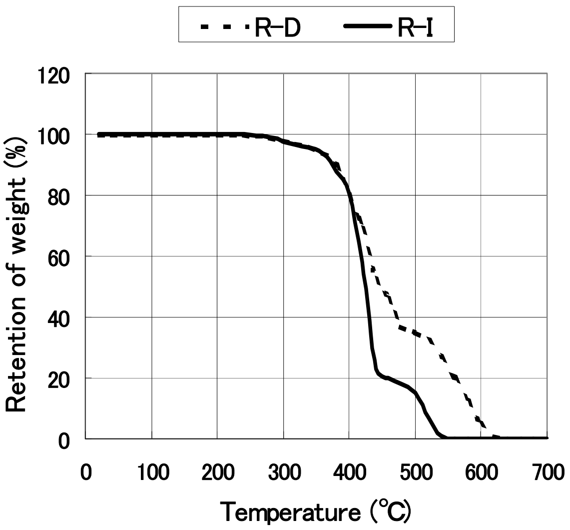


Fig. 2 TG-DTA curve.

Properties of Continuous Fiber Reinforcing Materials (JSCE-E 531-1995)" established by the Japan Society of Civil Engineers.

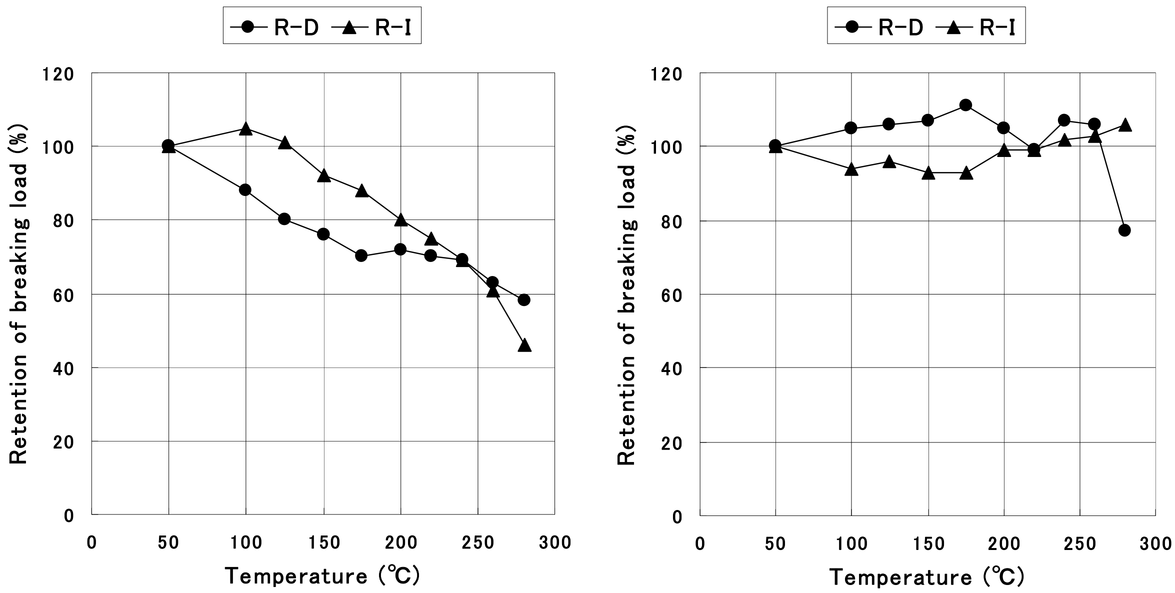
A test specimen, R-D or R-I, for "during heating" was mounted on the tensile tester with an electrically heated furnace where the temperature reached the target. The specimen was heated for 30 minutes. At the end of this period, the tensile test was conducted while the target temperature was maintained. The relationship between the testing temperature and the retention of breaking load is plotted in **Fig. 3(a)**. The retention of breaking load of FRP bars made with carbon fiber or aramid fiber decreased at a temperature higher than 150°C which corresponds to the GTT of each FRP bar. This was assumed to arise from the low glass transition temperature (GTT) of each matrix resin.

A test specimen R-D or R-I for "after heating" was heated for 30 minutes at a target temperature. After cooling, the tensile test was conducted at normal temperature (20°C). **Figure 3(b)** shows the test results of the relationship between heat treatment temperature and the retention of breaking load. The retention of breaking load of FRP bars made with carbon fiber or aramid fiber was almost 100% within 260°C. The reason was assumed to be high weight loss initiation temperature (Tw) of each matrix resin.

2.3 Pull-out test

Figure 4 shows the details of the test specimen. **Figure 5** shows the preparation procedure for the test specimen. The bond length was 44 mm. The FRP bar was left protruding from the concrete 26 mm to allow evaluation of bar slip.

The test was conducted according to JSCE-E 539-1995. The test specimen was heated in a mantle electric heater to each target temperature. While still at the target temperature, the specimen was fitted into the testing equipment and a pull-out test was conducted as shown in **Fig. 6**. Bar slip was measured with a displacement gauge. **Figure 7** shows the retention of the bond strength of R-D and R-I. The bond strength decreased drastically with an increase in temperature because of the low GTT of the epoxy or vinyl ester resin. Therefore the heat resistance of the matrix resin is assumed to be the most essential factor for bond strength.



(a) During heating **(b) After heating**

Fig. 3 Retention of breaking load.

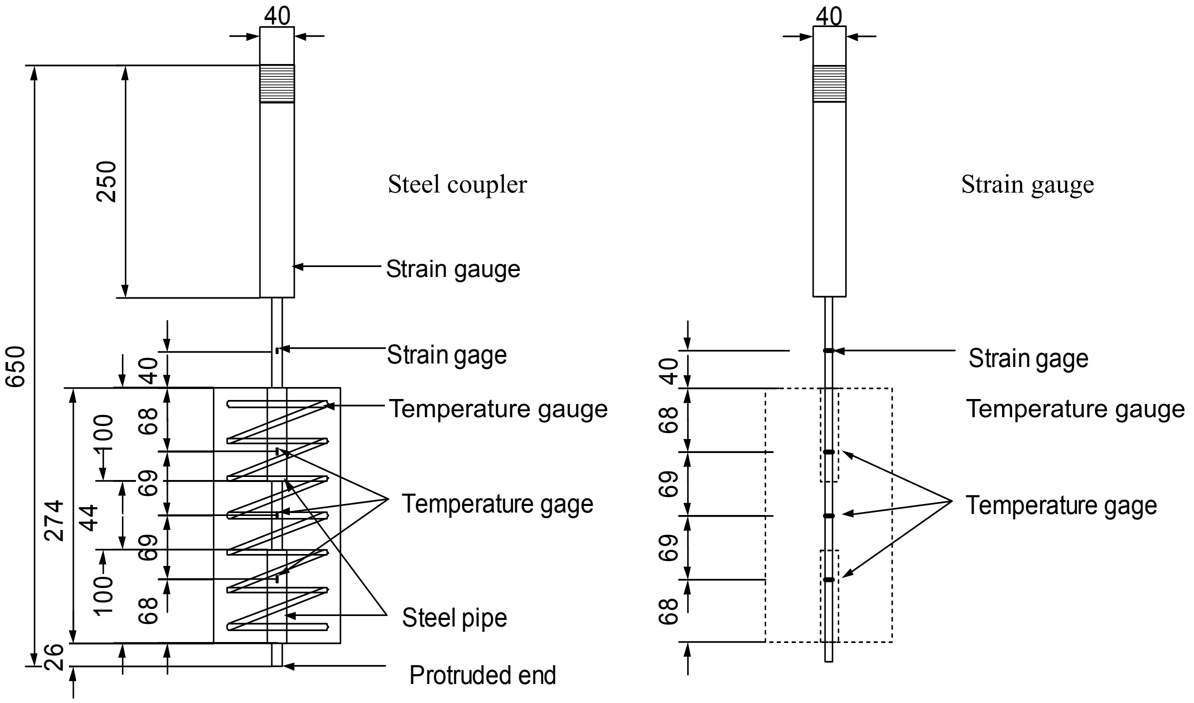
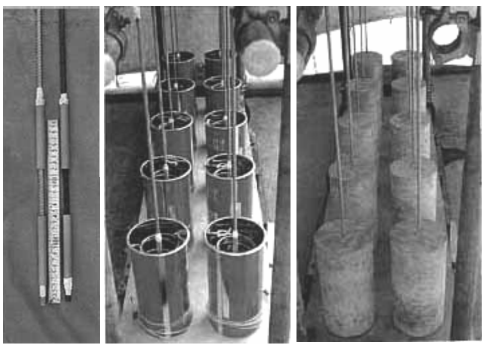


Fig. 4 Design of test specimen.



Test sample Placing of concrete Test specimen

Fig. 5 Preparation of test specimen.

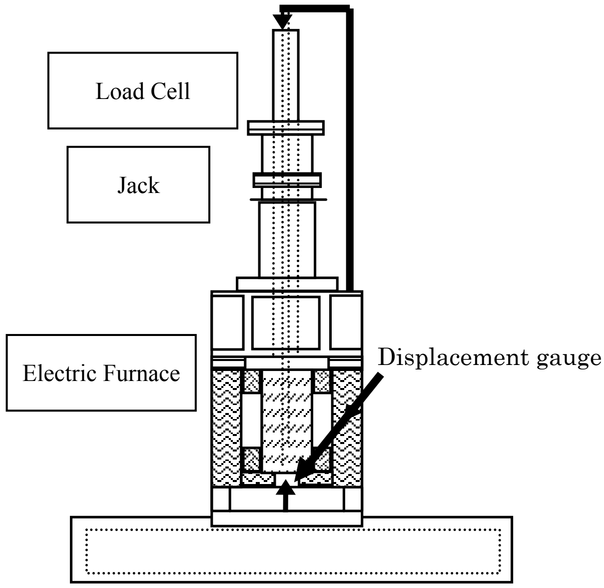


Fig. 6 Testing equipment.

3. Development of high-heat-resistant FRP bars

3.1 Materials

Table 2 lists the properties of carbon fiber and aramid fiber, the continuous fibers commonly used for reinforcement. Since the test results of commercially available FRP bars indicated that the heat resistance of the matrix resin is essential, below is the standard of resin selection.

- Glass transition temperature (GTT) :Higher than 200°C
- Weight loss initiation temperature (Tw) : Higher than 200°C

From the viewpoint of commercial production of FRP bars, the viscosity of the resin or resin dope as well as the resin concentration and boiling point of solvent are also essential. Below is the standard of resin selection.

- Resin concentration : Higher than 30% by weight
- Viscosity : Lower than 10 Pa·s
- Boiling point of solvent : Lower than 150°C

Table 3 lists the properties of selected resol type phenolic resin (PH) and aromatic diamine containing M type cross-linked polyester-amide resin (CP) as demonstrated by Sumida *et al*. (2006). Polyimide and polyamide-imide resins could not be applied because of low resin concentration, high viscosity, and high boiling point of the used solvent.

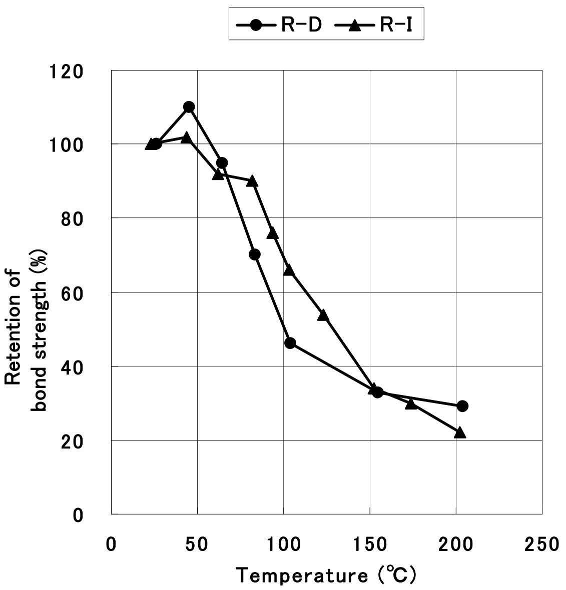


Fig. 7 Retention of bond strength.

Table 2 Properties of fiber.

Fiber	Tensile strength	Elastic modulus	Heat resistance in air
	(MPa)	(GPa)	(℃)
Carbon	7000	230	450
Aramid	3500	110	200

Table 3 Properties of resin.

Resin		Solvent	Concentration
Abbreviation	Name		(%)
PH	Phenol	Water	78
CP	Cross-linked polyester-amide	Alcohol	50
EP	Epoxy	None	100

3.2 Manufacture of FRP bars

Table 4 summarizes how FRP bars of various shapes are commercially produced. The protrusion, pre-pregged yarn wiring and braided yarn systems have been used to produce commercially available FRP bars. Since epoxy (EP), unsaturated polyester (USPE), and vinyl ester (VE) resins do not generate any solvent vapor or decomposition products during curing, it is easy to produce FRP bars without voids. However, PH and CP generate solvent vapor and decomposition products during curing, so a voidless fabrication system is needed to produce FRP bars made with these resins. Therefore, the braided yarn system was chosen because of the ease with which removal of solvent vapor and decomposition products can be achieved. FRP bars each 7 mm or 13 mm in diameter were prepared as shown in **Fig. 8**. During the early development stage of FRP bar manufacturing, some voids were observed. However, this problem was overcome by improving the resin system of PH and CP as well as adjusting the curing temperature profile and time. Additionally, FRP bars made with PH matrix resin were post-cured for an extended period with a slow temperature increase to prevent void generation.

3.3 Properties of FRP bars

3.3.1 Heat resistance

Table 5 lists the glass transition temperature (GTT) and the weight loss initiation temperature (Tw) of each FRP bar. The order of the magnitude of GTT and Tw for each FRP bar was phenolic resin (PH) > >cross-linked polyester-amide resin (CP) > epoxy resin (EP).

3.3.2 Breaking load at normal temperature

Table 6 shows the experimentally obtained breaking load of FRP bars 7 mm in diameter and 800 mm in length at normal temperature (20°C). Five test specimens made with each type of FRP bar were subjected to the test procedure described in 2.2. The retention of breaking loads for FRP bars made with PH or CP matrix resin was similar to that for bars made with EP matrix resin. The standard deviation of breaking loads for FRP bars made with PH or CP matrix resin was also similar to that for FRP bars made with EP matrix resin. The standard deviation of breaking loads of generally used FRP materials is less than 5%. Voids inside FRP tend to decrease the tensile strength and increase the standard

Table 4 Shape and production method of FRP bars.

Shape	Adhesion with concrete	Production method				Void	Productivity
		Fiber	Resin impregnation	System	Cure		
Circular	Poor	Arrangement	Dip	Protrusion	Die + hot air	Much	Poor
Square	Poor	Arrangement	Dip	Protrusion	Die + hot air	Much	Poor
Wire	Good	Prepreg yarn	Dip	Wiring	Hot air	Little	Poor
Braid	Good	Braided yarn	Dip	Braid	Hot air	Little	Good

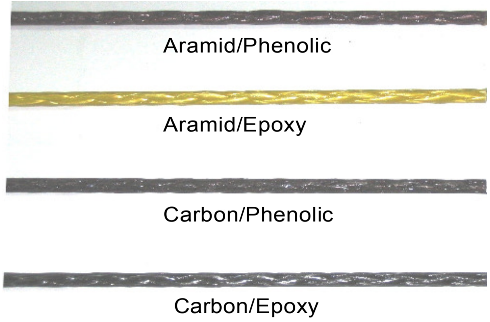


Fig. 8 Newly developed FRP bars 13 mm in diameter.

Table 5 Heat resistance of FRP bars.

Fiber	Resin	Glass transition temperature GTT (°C)	Weight loss initiation temperature Tw (°C)
Carbon	PH	>401*	401
	CP	185	330
	EP	73	295
Aramid	PH	>418*	418
	CP	173	330
	EP	72	341

*Not detected because GTT was higher than Tw

Table 6 Breaking load at normal temperature.

Fiber \ Resin		Unit	PH	CP	EP
Carbon	Average	kN	96	106	103
	Deviation	%	3.2	2.4	3.0
Aramid	Average	kN	58	60	69
	Deviation	%	9.1	3.3	1.6

deviation. Therefore, it was assumed that FRP bars made with PH or CP matrix resin contain few voids.

3.3.3 Breaking load during heating

The aim of this test is to evaluate the breaking load of FRP bars during a fire. Each test specimen was inserted in an electrically heated steel pipe and a tensile test was conducted according to the test procedure described in 2.2.

Figure 9 shows the retention of breaking load as the average of five FRP bars at each temperature. The order of retention of each FRP bar was phenolic resin (PH) > cross-linked polyester-amide resin (CP) > epoxy resin (EP). In particular, the retention of breaking load of FRP bars made with carbon fiber and PH matrix resin was approximately the same as that of a steel bar (Architectural Institute of Japan 2004). On the other hand, in the case of aramid fiber, the retention of breaking load of FRP bars made with PH matrix resin decreased at 250°C. The authors assume that this difference is due to the different heat resistance of carbon fiber (450°C) and aramid fiber (200°C).

3.3.4 Breaking load after heating

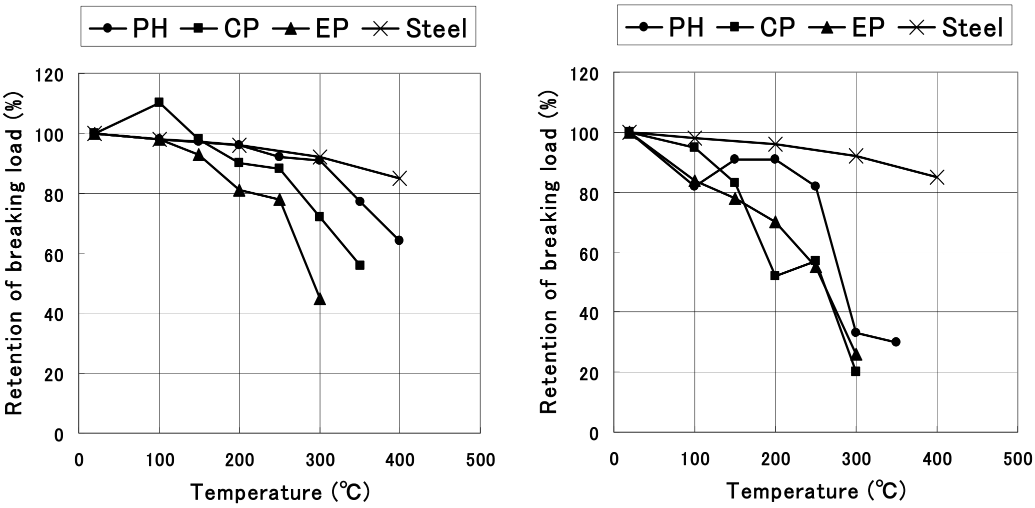
The aim of this test was to measure the residual breaking load of FRP bars after a fire. FRP bars were heated to each target temperature for 30 minutes and cooled to normal temperature (20°C), and then a tensile test was conducted according to the test procedure described in 2.2.

Figure 10 shows the retention of breaking load as the average of five FRP bars at each temperature. In the case of carbon fiber, the retention of breaking load of FRP bars made with carbon fiber and PH, CP or EP matrix resin was approximately 100% at 300°C. Above 300°C, PH and CP retain a greater breaking load than EP because the weight loss initiation temperature (Tw) of PH and CP is higher than that of EP. For aramid fiber, the retention of breaking load of PH, CP and EP was approximately 100% at 250°C. Above 250°C, PH retained a greater retention of breaking load than CP and EP. The difference in the retentions of carbon fiber FRP bars and aramid fiber FRP bars is assumed to come from the difference in heat resistance of carbon fiber (450°C) and aramid fiber (200°C). As the weight loss initiation temperature (Tw) is higher than the glass transition temperature (GTT), the retention of breaking load after heating is higher than that during heating. In other words, the breaking load under heating tends to smaller.

3.3.5 Elastic modulus during heating

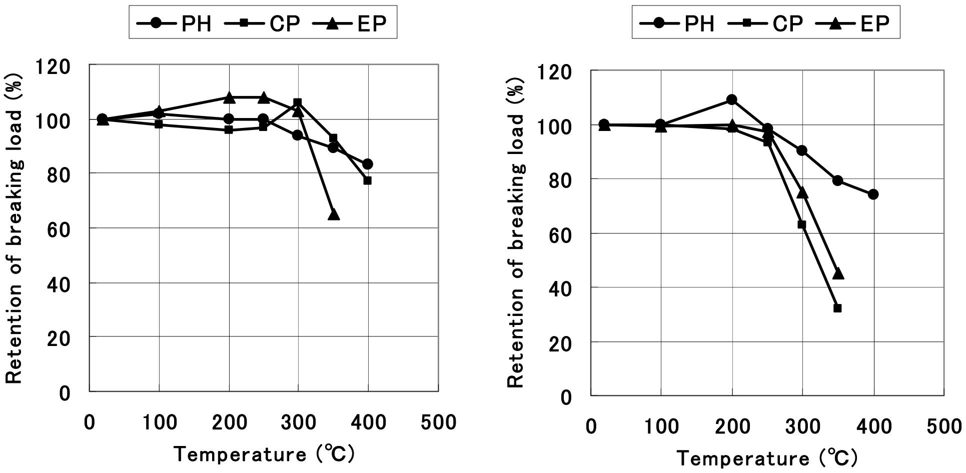
If the elastic modulus of FRP bars decreases at high temperature, concrete beams and slabs may be easily bent and cracked when loaded. To measure the elastic modulus, an FRP bar 13 mm in diameter and 2000 mm in length was prepared with two aluminum rods for measurement of elongation over a length of about 700 mm. This assembly was inserted in an electrically heated pipe 200 mm in diameter and 1000 mm in length as shown in **Figure 11**. Elongation during heating was then measured at each load. Since the fiber bundle, which is composed of braided yarns, is not straight, the elastic modulus of the FRP bar will decrease when the matrix resin softens at high temperature.

Figure 12 shows the relationship between elongation and load for each type of FRP bar at different temperatures. As expected, FRP bars made with carbon fiber and PH matrix resin had approximately the same elastic modulus at normal temperature (20°C) and 400°C as shown in (a) Carbon fiber-PH. This relationship was dramatically improved in comparison with that previously reported (Bisby *et al*. 2005). On the other hand, the elastic modulus of the FRP bar made with carbon fiber and EP matrix resin became lower at temperatures higher than the glass transition temperature (GTT) of the resin,



(a) Carbon fiber (b) Aramid fiber

Fig. 9 Retention of breaking load during heating.



(a) Carbon fiber (b) Aramid fiber

Fig. 10 Retention of breaking load after heating.

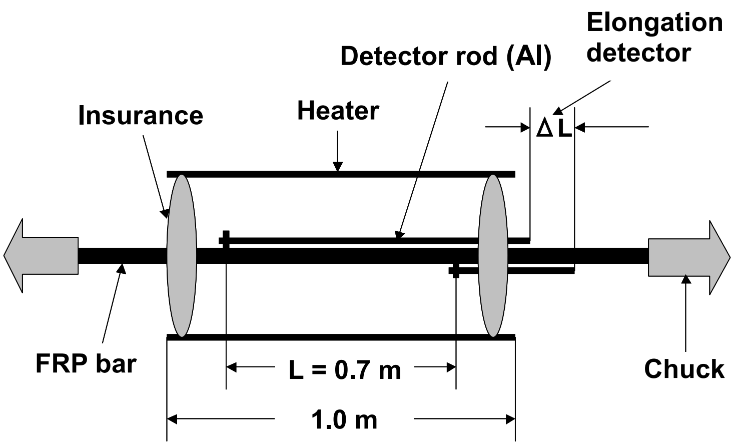
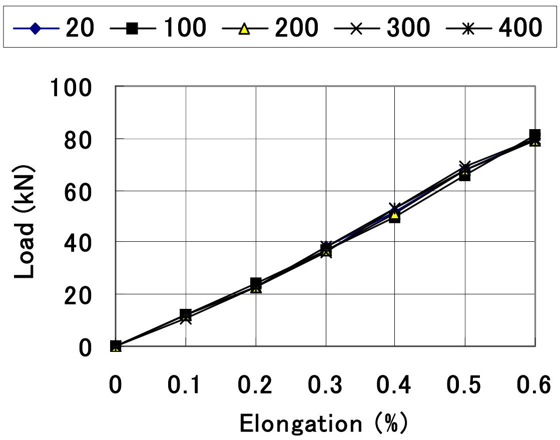
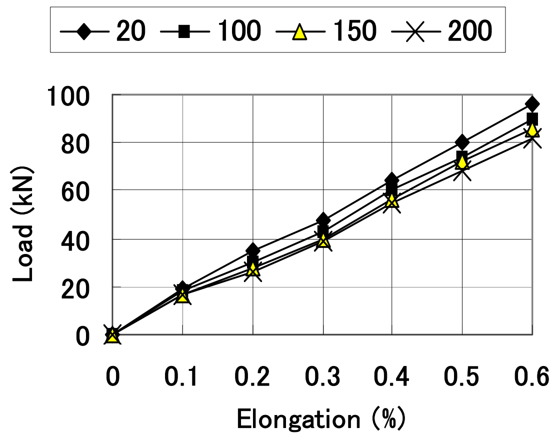


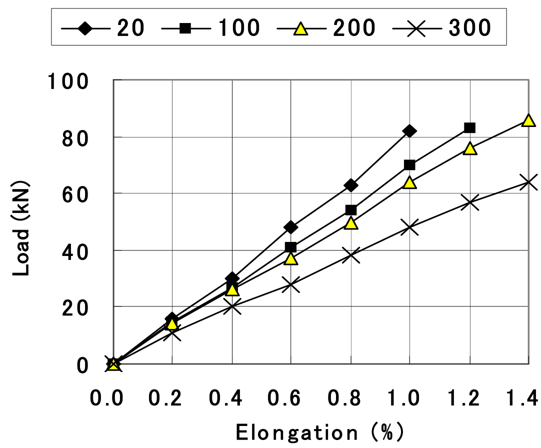
Fig. 11 Testing equipment.



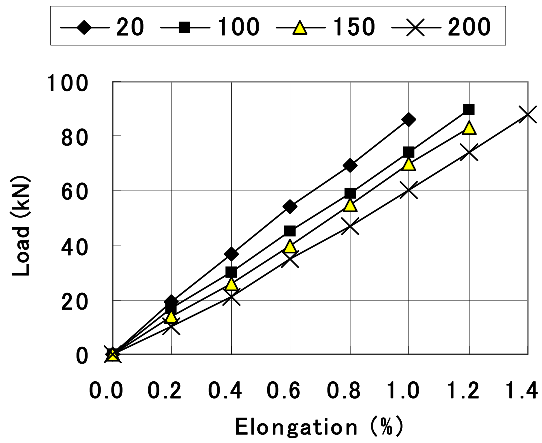
(a) Carbon fiber-PH bar



(b) Carbon fiber-EP bar



(c) Aramid fiber-PH bar



(d) Aramid fiber-EP bar

Fig. 12 Relationship between elongation and load.

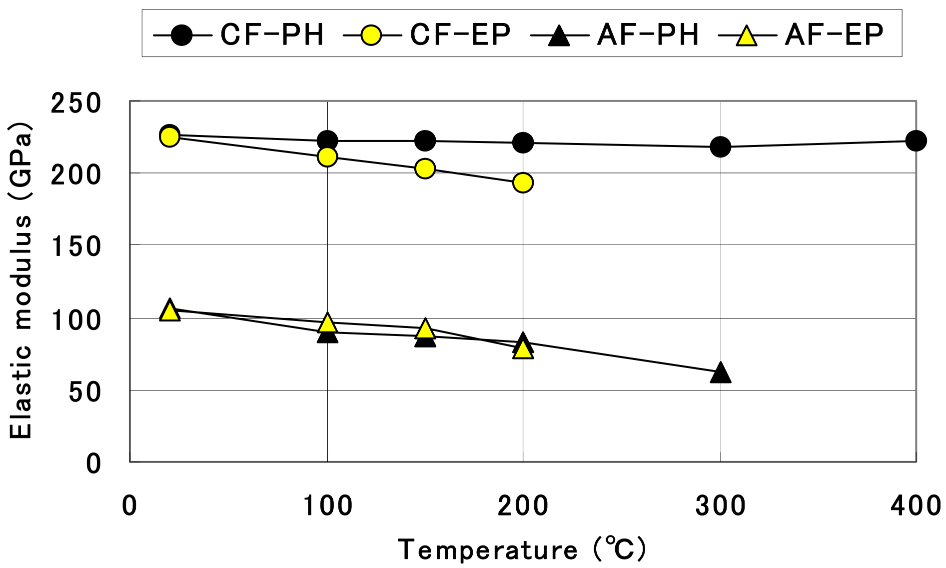


Fig. 13 Elastic modulus under heating.

73°C, as shown in (b) Carbon fiber-EP. The elastic modulus of each FRP bar made with aramid fiber and PH or EP became lower at higher temperature, as shown in (c) Aramid fiber-PH and (d) Aramid fiber-EP. The elastic modulus of FRP bars made with carbon fiber and PH matrix resin was constant at room temperature and high temperature but that of FRP bars made with aramid fiber and PH matrix resin became lower at higher temperature as shown in **Fig. 12(a)** and **(c)**, because the heat resistance of carbon fiber is higher than that of aramid fiber. **Figure 13** shows the relationship between testing temperatures and elastic modulus of each combination of fibers and matrix resins. It was also supposed that the GTT of matrix resin and the heat resistance of reinforcing fiber are essential.

3.3.6 Alkaline resistance

Durability of FRP bars in service is very important. The alkaline resistance test based on JSCE-E531-1999 was performed to compare the durability of FRP bars. Each group of five FRP bars was immersed in alkaline water having a PH of 13 at 60°C for one month. Then tensile tests were performed and the average of the breaking load and its retention before and after treatment were evaluated as shown in **Table 7**. According to JSCE-E531-1999, the specimens are acceptable if the strength retention is greater than 90%. Mutsuyoshi *et al.* (2001) reported that commercially available FRP bars made with carbon fiber or aramid fiber met or exceeded this requirement. The retention of FRP bars made with carbon fiber or aramid fiber and PH or CP matrix resin almost met or exceeded 90% retention. PH is said to be weak in an alkaline solution. However, PH changed thermally to a resin with alkaline resistance because FRP bars made with PH matrix resin were post-cured at a high temperature of 250°C.

Mutsuyoshi *et al.* (2001) also demonstrated that the breaking strength of aramid fiber dropped as the result of immersion in alkaline water having a PH of 13 at 60°C for one month. However no such drop was observed in the case of FRP bars made with aramid fiber and PH matrix resin. Therefore, it was also assumed that FRP bars made with PH matrix resin contained few voids.

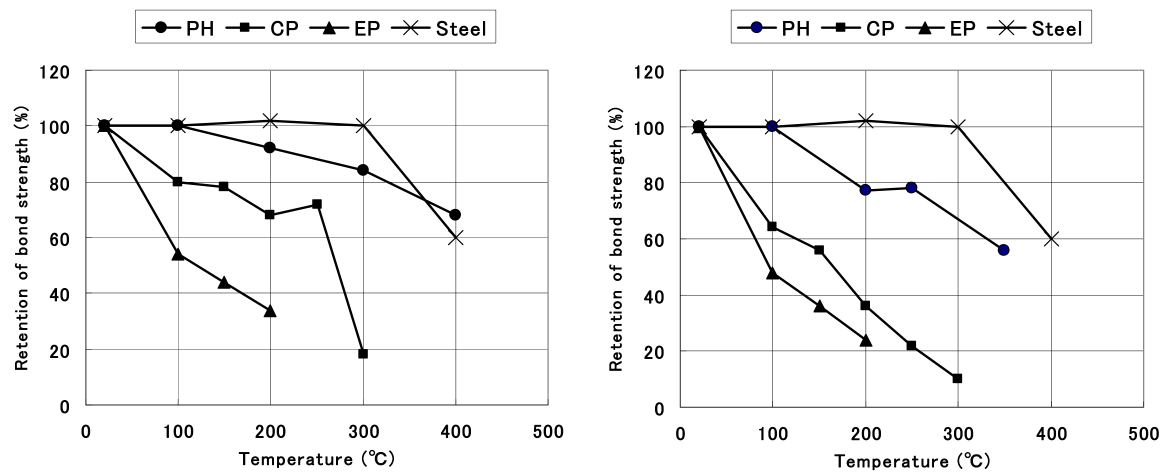
3.4 Pull-out test

The bond strength of the six types of FRP bars 13 mm in diameter made with carbon fiber or aramid fiber and a matrix resin of phenolic (PH), cross-linked polyester-amide (CP) or epoxy (EP) was tested. The bond strength of deformed steel bars 13 mm in diameter was also tested. The compressive strength of concrete at the time of the pull-out test was 42-50 N/mm^2. Target temperatures ranged from normal temperature to 450°C.

Table 8 lists the maximum bond strength at normal temperature (20°C). The issue is to improve the bond strength of the FRP bars, which is lower than that of steel bars at normal temperature (20°C). **Figure 14(a)** and **(b)**

Table 7 Breaking load and retention results of alkaline resistance test.

Fiber	Phenol (PH)			Cross-linked polyester-amide (CP)			Epoxy (EP)		
	Alkali treatment		Retention	Alkali treatment		Retention	Alkali treatment		Retention
	Before	After		Before	After		Before	After	
	(kN)	(kN)	(%)	(kN)	(kN)	(%)	(kN)	(kN)	(%)
Carbon	96	98	102	106	114	108	103	103	100
Aramid	69	70	101	60	52	87	69	70	101



(a) Carbon fiber FRP bar (b) Aramid fiber FRP bar

Fig. 14 Relationship between temperature and retention of bond strength.

Table 8 Maximum bond strength.

Resin / Fiber	PH (N/mm^2)	CP (N/mm^2)	EP (N/mm^2)
Carbon	10.8	10.9	13.7
Aramid	8.53	7.17	8.95
Steel	17		

show the relationship between measured temperature and the retention of bond strength. The retention of bond strength of FRP bars made with PH matrix resin, which had a high glass transition temperature (GTT), was higher than that of FRP bars made with CP or EP matrix resin. The retention of bond strength of carbon fiber-PH FRP bars was approximately the same as that of steel bars at high temperature. The bond strength of aramid fiber-PH FRP bars at high temperature was lower than that of carbon fiber-PH FRP bars, because the heat resistance of aramid fiber is lower than that of carbon fiber.

It has been demonstrated by others that the bond strength of FRP bars strongly depends on the glass transition temperature (GTT) of a matrix resin (Freismanis *et al.*1998, Katz *et al.* 1999, Katz *et al.* 2000, Mutsuyoshi *et al.* 2004, and Dai *et al.* 2006). In addition to the results of previously reported papers, the heat resistance of the fiber itself will be important when the heat resistance of the matrix resin is improved.

3.5 Flexural test of concrete beams

The flexural properties of concrete beams containing respectively carbon fiber-PH, carbon fiber-EP, aramid fiber-PH or aramid fiber-EP FRP bars 13 mm in diameter and those containing deformed steel bars 13 mm in diameter were evaluated as referred to in the papers (Wang *et al.*1995, Tanano *et al.*1997, Williams *et al.* 2004, Kodur *et al.* 2005). **Figure 15** shows the structure of a concrete beam specimen. The beam specimen was 2000 mm long and 100 mm by 200 mm in cross section. The concrete cover over the FRP bar was 40 mm at the bottom and 25 mm at the sides. Stirrup steel was set at a pitch of 55 mm within the two fulcrums and 100 mm outside of the fulcrums. The compressive strength of the concrete at the time of the flexural test was 40-49 N/mm^2. Electrical heaters were installed on all four planes of the concrete beam, with two heaters in parallel to keep the temperature uniform as shown in **Fig. 16**. The heating rate was controlled within 50°C/hour by the capacity of the electric heaters. When the average of surface temperatures on the FRP bars reached the target temperature, the heaters on the upper and lower planes were removed and the beam was installed in the test equipment, heating the side planes. Load and deformation measurements were taken at the center of the concrete beam. The temperature level for the flexural test was selected in accordance with the heat resistance of FRP bars and the pull-out test. The obtained results are listed in **Table 9**.

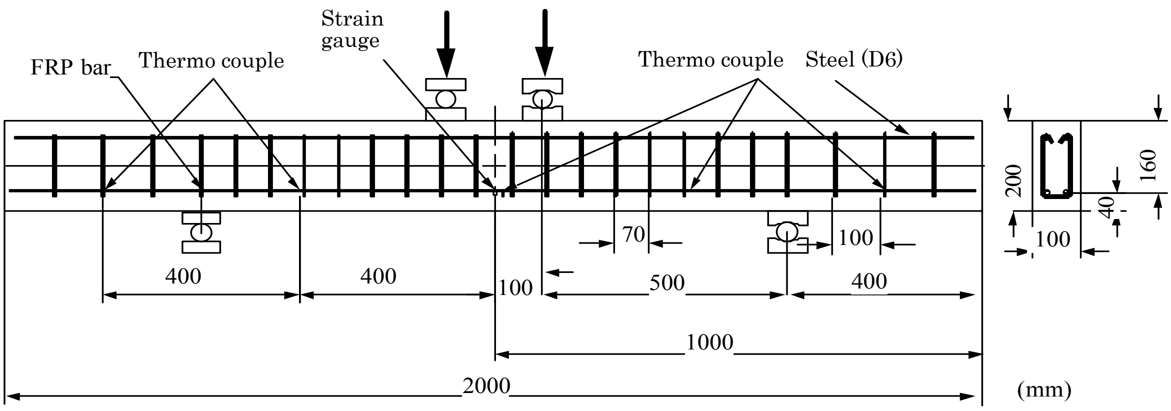
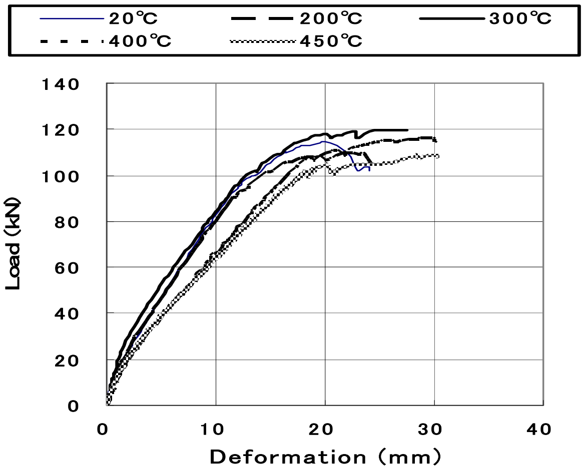


Fig. 15 Structure of concrete beam.

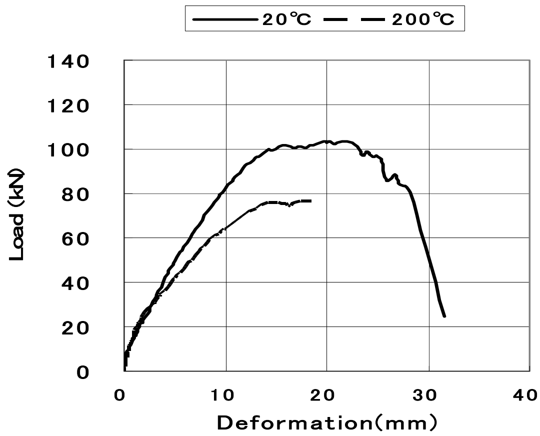
Fig. 16 Concrete beam with electric heaters.

Table 9 Maximum flexural load (kN).

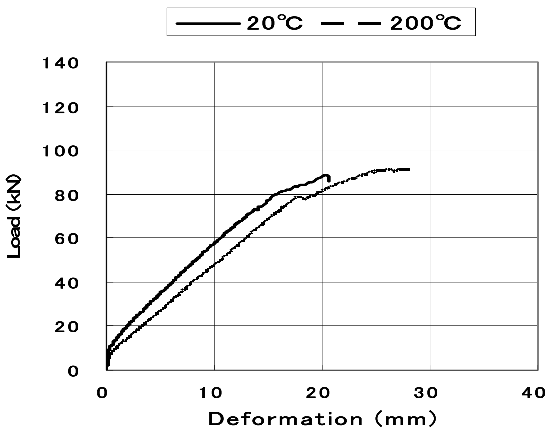
Fiber	Resin	Testing level (°C)				
		20	200	300	400	450
Carbon	PH	116	110	120	115	110
	EP	105	78	—	—	—
Aramid	PH	86	92	—	—	—
	EP	70	30	—	—	—
Steel		55	—	62	60	58



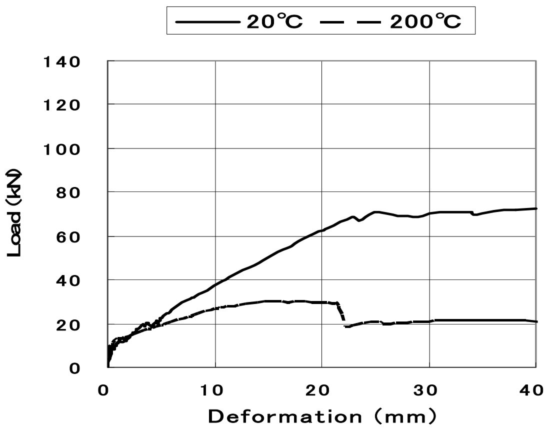
(a) Carbon fiber-PH



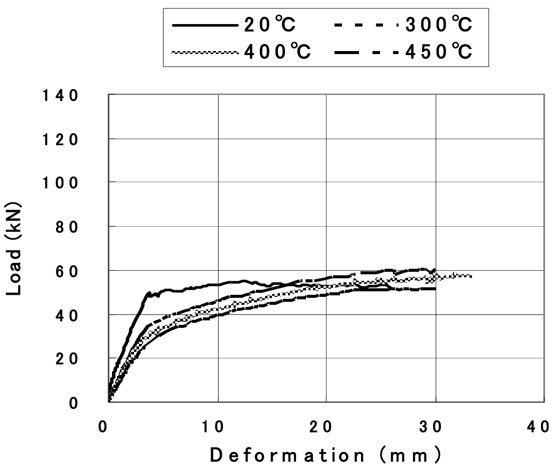
(b) Carbon fiber-EP



(c) Carbon fiber-PH



(d) Carbon fiber-EP

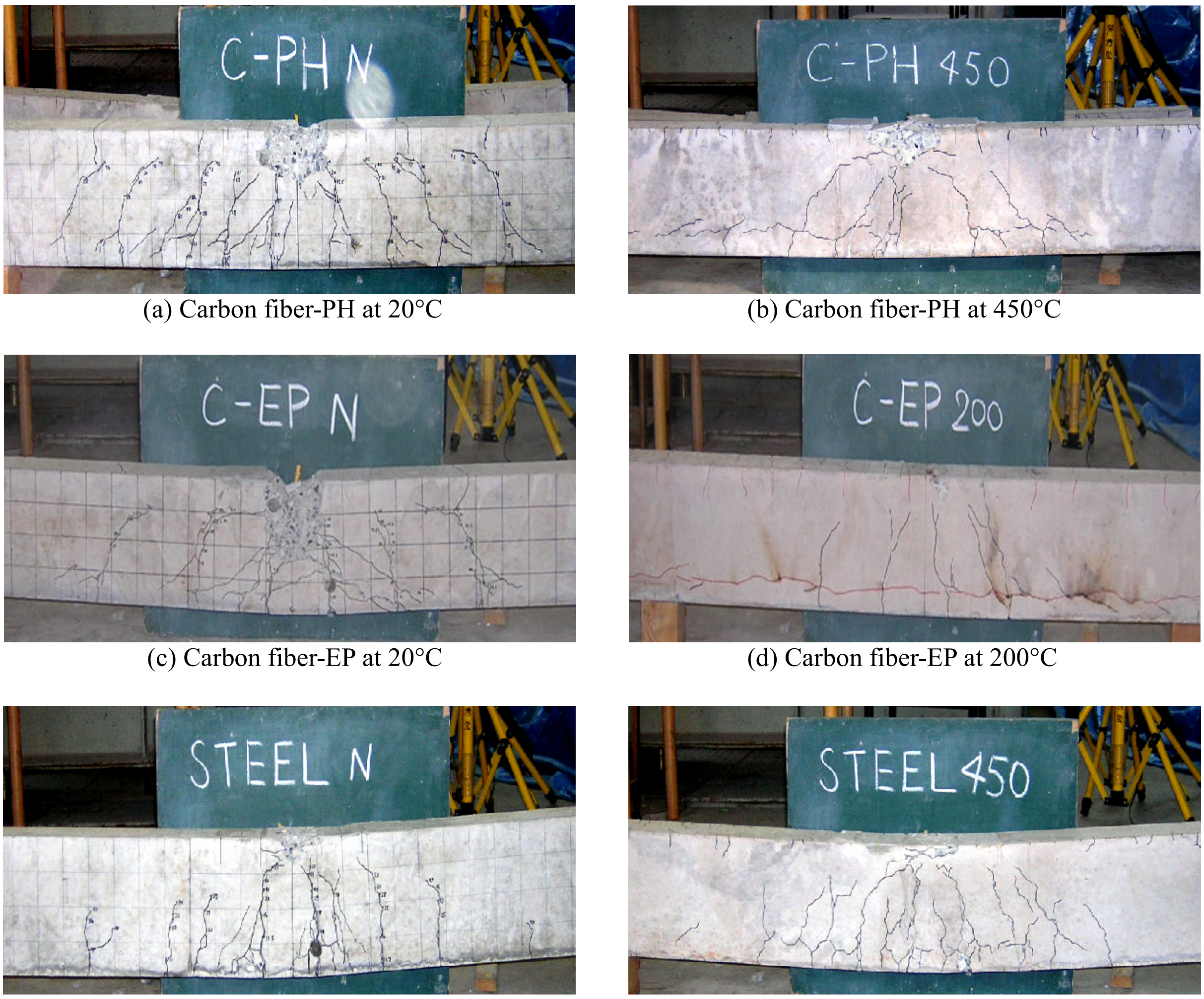


(e) Steel

Fig. 17 Load-deformation.

Figure 17 shows the relationship between load and deformation for the five types of beams. For the FRP bars made with carbon fiber and PH, the slope of the relationship at 450°C changed slightly gentle compared with that at 20°C as shown in (a) Carbon fiber-PH**.** For the FRP bars made with carbon fiber and EP, the slope of the relationship at 200°C became gentler compared with that at 20°C as shown in (b) Carbon fiber-EP**.** In the case of FRP bars made with aramid fiber and PH, the slopes of the relationship at 20°C and at 200°C were almost the same as shown in (c) Aramid fiber-PH**.** However, in the case of the FRP bars made with aramid fiber and EP, the slopes of the relationship at 20°C and 200°C greatly differed, and only a little increase in flexural load was observed as shown in (d) Aramid fiber-EP. For the steel bars, the slope of the relationship at 450°C changed slightly gentle compared with that at 20°C as shown in (e) Steel. The flexural load of each concrete beam reinforced with CF-PH or steel bars was different, but each concrete beam reinforced with carbon fiber-PH FRP bars or steel bars exhibited approximately the same load-deformation relationship at 20°C and 450°C, as shown in (a) Carbon fiber-PH and (e) Steel.

Figure 18 shows the crack pattern on the surface of concrete beams reinforced with carbon fiber-PH and carbon fiber-EP FRP bars as well as deformed steel bars after flexural tests at normal temperature and at the highest temperature. None of the FRP bars and steel bars broke at the ultimate failure. The ultimate failure of concrete beams reinforced with carbon fiber-PH or steel bars occurred with crushing of the concrete in the compression zone at 20°C and 450°C, as shown in (a) carbon fiber-PH at 20°C, (b) carbon fiber-PH at 450°C, (e) Steel at 20°C and (f) Steel at 450°C. No slippage between the FRP bars or steel bars and concrete was observed. The ultimate failure of concrete beams reinforced with carbon fiber-EP also occurred with crushing of the concrete in the compression zone at 20°C. However, no crushing of the concrete in the compression zone and slippage between carbon fiber-EP FRP bars and concrete were observed at 200°C, which is higher than the GTT (73°C). This demonstrates that the retention of bond strength



(a) Carbon fiber-PH at 20°C (b) Carbon fiber-PH at 450°C

(c) Carbon fiber-EP at 20°C (d) Carbon fiber-EP at 200°C

(e) Steel at 20°C (f) Steel at 450°C

Fig. 18 Crack pattern.

deteriorated due to high temperature and this slippage phenomenon resulted from the lack of heat resistance of EP matrix resin.

4. Conclusions

The following conclusions are drawn from the study.

(1) Resol type phenolic resin (PH) and M type cross-linked polyester-amide resin (CP) were selected as heat-resistant and industrially available matrix resins. The heat resistance of FRP bars made with PH or CP matrix resin cleared the target. The breaking load of FRP bars made with PH or CP matrix resin was a little lower than or approximately the same as that of FRP bars made with epoxy (EP) at normal temperature (20°C). The retention of breaking load of FRP bar specimens made with PH matrix resin, which have higher heat resistance, was high during heating. In particular, it was shown that the retention of breaking load of FRP bar specimens made with carbon fiber and PH matrix resin was close to that of deformed steel bar specimens. The alkaline resistance was shown to be satisfactory.

(2) The retention of bond strength was observed to strongly depend on the glass transition temperature (GTT) of the matrix resin. FRP bar specimens made with PH matrix resin exhibited high retention of the bond strength at high temperatures. In particular, the results showed that the retention of bond strength of the carbon fiber-PH FRP bar specimens was close to that of deformed steel bar specimens. It was also shown that the heat resistance of the fiber itself is important when the heat resistance of the matrix resin is improved. However, the bond strength of all FRP bar specimens at normal temperature (20°C) was lower than that of the deformed steel bar specimens.

(3) It was confirmed that the relationship between load and deformation of the concrete beams as well as the ultimate fracture mode and crack pattern were affected by the bond strength between the matrix resin of FRP bar and the concrete. Concrete beam reinforced with FRP bars made with PH matrix resin gave approximately the same load-deformation relationship at both normal (20°C) and high temperature. In particular, it was demonstrated that the heat resistance of the concrete beam reinforced with the carbon fiber-PH FRP bars was close to that of a concrete beam reinforced with deformed steel bars.

(4) It is concluded that the heat resistance of FRP bars made with PH matrix resin is much higher than that of conventional FRP bars made with EP matrix resin. Carbon fiber is preferable for use as a reinforcing fiber for PH-FRP bars than aramid fiber because the heat resistance of carbon fiber is higher than that of aramid fiber.

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References

American Concrete Institute (ACI) Committee 440 (2000). "*Guide for the design and construction of concrete reinforced with FRP bars.*"

Architectural Institute of Japan (2004). "*Guide book for fire-resistive performance of structural materials.*" 85-93

Bisby, L. A., Williams, B. K., Kodur, V. R. K., Green, M. F. and Chowdhury, E. (2005). "Fire performance of FRP systems for infrastructure: A state-of-the-art report." *Queen's University, Kingston and National Research Council, Ottawa, Canada Research Report*, 179.

Dai, J., Ueda, T. and Sato, Y. (2006). "Unified analytical approaches for determining shear bond characteristics of FRP-concrete interfaces through pullout tests." *Journal of Advanced Concrete Technology, Japan Concrete Institute,* 4(1), 133-145.

Freismanis, A. J., Bakis, C. E., Nanni, A. and Gremel, D. (1998). "A comparison of pullout and tensile behaviors of FRP reinforcement for concrete." *Proceedings of the Second International Conference on Composites in Infrastructure (ICCI-98)*, Tucson, Arizona, 2, 52-65.

Japan Society of Civil Engineers (JSCE) Subcommittee on Continuous Fiber Reinforcement (1992). "*Proceedings of the utilization of FRP-rods for concrete reinforcement*."

Japan Society of Civil Engineers (JSCE) (1997). "Recommendation for design and concrete structures using continuous fiber reinforcing materials." *Concrete Engineering Series*, 22.

Katz, A., Berman, N. and Bank, L. C. (1999). "Effect of high temperature on bond strength of FRP rebars." *Journal of Composites for Construction,* ASCE, 3(2), 73-81.

Katz, A. and Berman, N. "Modeling the effect of high temperature on the bond of FRP reinforcing bars to concrete." *Cement & Concrete Composites*, 22(2000), 433-443.

Kodur, V. K. R., Bisby, L. A. and Simon, H.-carbon fiber, (2005). "Thermal behavior of fire-exposed concrete slabs reinforced with fiber-reinforced polymer bars." *ACI Structural Journal*, 102, 799-807.

Kumahara, S., Masuda, Y. and Tadano, Y. (1993). "Tensile strength of continuous fiber bar under high temperature." *Proceedings of Fiber-Reinforcement for Concrete Structures, A. Nanni and W.E. Dolan, American Concrete Institute*, Detroit, 731-742.

Machida, A. (1997). "Issues in developing a design code for concrete structures with FRP." *Proceedings of the*

Third International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3), Sapporo, Japan, 2, 511-518.

Mutsuyoshi, H., Sumida, A. and Uomoto, T. (2001). "Alkali resistance of fibers, FRP rods and epoxy resins." *Proceedings of the 5th. International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-5),* University of Cambridge, UK, 1, 479-488.

Mutsuyoshi, H., Zin, T. and Sumida, A. (2004). "Development of new heat-resistant FRP bars." *4th. International Conference on Advanced Composite Materials in Bridges and Structures*, Calgary, Alberta.

Okamoto, T., Matsubara, S., Tanigaki, M. and Hasuo, K. (1993). "Practical application and performance of PPC beams reinforced with braided FRP bars." *Proceedings of Fiber-Reinforced-Plastic Reinforcement for Concrete Structures, SP-138, Nanni, A., and Dolan, C. W., ACI,* Farmington Hills, MI., 875-894.

Sumida, A., Fujisaki, T., Watanabe, K. and Kato, T. (2001). "Heat resistance of continuous fiber reinforced plastic rods." *Proceedings of the 5th. International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-5)*, University of Cambridge, UK, 1, 557-565.

Sumida, A. and Mutsuyoshi, H. (2006). "Research and development of new heat resistant FRP bars." *Concrete Research and Technology*, 17(3), 13-23. (in Japanese)

Tamura, T. (1993). "FiBRA, Aramid fiber-reinforced-plastic (FRP) reinforced for concrete structures: properties and applications." *Developments in Civil Engineering, A. Nanni,* Ed., Elsevier, Amsterdam, 42, 291-303.

Tanano, H., Masuda, Y., Sakashita, M., Oono, Y., Nonomura, K. and Satake, K. (1997). "Tensile properties at high temperatures of continuous fiber bars and deflection of continuous fiber reinforced concrete beams under high-temperature loading." *Proceedings of the 3rd. International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3)*, Sapporo, Japan, 2, 43-50.

Wang, N. and Evans, J. T. (1995). "Collapse of continuous fiber composite beam at elevated temperatures." *Composites*, 1, 56-61.

Wang, Y. C., Wong, P. M. H. and Kodur, V. K. R. (2003). "Mechanical properties of fibre reinforced polymer reinforcing bars at elevated temperatures." *ASCE-SFPE Conference: Designing Structures for Fire*, Baltimore, MD.

Williams, B. K., Kodur, V. K. R., Bisby, L. A. and Green, M. F. (2004). "The performance of FRP-strengthened concrete slabs in fire." *Proceedings of the fourth. International Conference on Advanced Composite Materials in Bridges and Structures*, Calgary, Alberta.