41 STRUCTURAL PERFORMANCE OF CONCRETE BEAMS REINFORCED WITH DIAGONAL FRP BARS

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Abstract
To investigate the fundamental performance of reinforced concrete beams with diagonal FRP bars, five specimens were tested under the antisymmetrical cyclic load. The test parameter is the amount ratio of diagonal reinforcements to total longitudinal ones. All FRP reinforced specimens showed brittle behavior with shear failure and rupture of FRP bars. Obtained maximum strength increases as the amount ratio of diagonal reinforcements also increases. From the measured strain of longitudinal reinforcements, stresses of diagonal FRP bars behave similarly to those of parallel reinforcements at the ends of specimen. Taking account of these test results, a method to confirm the shear strength of beams with diagonal FRP bars is indicated.
Keywords: Diagonal reinforcement, Shear strength, Antisymmetrical load, Rupture, Stress distribution.

1 Introduction

Nowadays, many studies have been carried out to investigate the structural performance of FRP reinforced concrete members. In these studies, it is indicated that FRP reinforced concrete members fail without ductile behavior because of the rupture of FRP reinforcements.

On the other hand, it is well known that steel reinforced concrete members having diagonal longitudinal reinforcements show a good ductility under the antisymmetrical loads. It shows especially an improvement to use diagonal reinforcements for short span beams and columns, which have shear span ratio of 1. Reinforcements arranged diagonally make resistance to shear force directly. Besides bond conditions of the reinforcements to concrete have no influence on the members' behavior, because

compressive or tensile stresses take place uniformly along the reinforcements.

It is also considered that diagonal FRP bars can improve the brittle behavior of FRP reinforced concrete. However, there is no investigation concerned with diagonal FRP bars up to now. The main purpose of this research is to investigate the fundamental performance of FRP reinforced concrete beams with diagonal reinforcements under the antisymmetrical load.

2 Test outline

2.1 Specimens

Five beam specimens were tested. The list of specimens is shown in Table 1. Typical specimen with FRP diagonal reinforcements and details of cross sections are shown in Fig. 1. The cross section is 240 mm in width and 350 mm in depth, designed at half scale of actual size beams. Clear span length is 980 mm, and shear span ratio is 1.4.

Braided aramid fiber reinforcements are used in three specimens both for longitudinal and stirrups (APL, AX3L, AX7L). Main test parameter is the amount ratio of diagonal reinforcements to total longitudinal ones. These ratios are 0/6 (APL), 2/6 (AX3L) and 4/6 (AX7L). Stirrup ratio is 0.26% in three specimens. Two steel-reinforced beam specimens were also tested to compare the obtained behaviors of FRP reinforced specimens with those of steel reinforced specimens. Specimens NPL and NX7L have the same parameters with APL and AX7L, except for the type of reinforcements.

Table 1. List of specimens

Identification	Longitudinal reinforcement			Stirrup	
	Parallel rein.	Diagonal rein.	Ratio ρ (%)	Rein.	Ratio ρ_v (%)
APL	6-K256S	-	1.69	2-K32@80	0.26
AX3L	4-K256S	2-K256S	1.66	2-K32@80	0.26
AX7L	2-K256S	4-K256S	1.66	2-K32@80	0.26
NPL	6-D16	-	1.69	3-D6@120	0.33
NX7L	2-D16	4-D16	1.65	2-D6@80	0.33

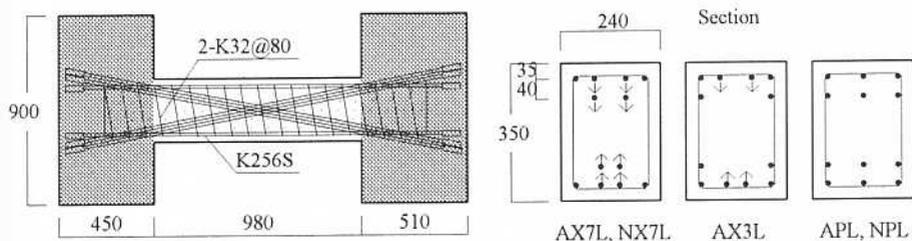| Identification	a: type of reinforcement	A≡aramid fib. N≡steel rebar
<u>A</u> <u>X</u> <u>7</u> <u>L</u>	b: arrangement	X≡diagonal P≡parallel
a b c d	c: amount ratio of diagonal to total rein.	3≡2/6 7≡4/6
	d: stirrup ratio	L≡lower level (about 0.3%)

Fig. 1. Typical specimen (AX7L) and details of section

Table 2.   Characteristics of reinforcements

Identification	Type	Sectional area (cm²)	Elastic modulus (GPa)	Tensile strength (MPa)	Remark
K256S	Braided ara-mid with sand	2.00	59	1320	for longitudi-nal rein.
K32	Braided aramid	0.25	59	1320	for stirrup
D16	Deformed steel	1.99	178	684	for longitudi-nal rein.
D6	Deformed steel	0.32	200	994	for stirrup

2.2   Material properties

Braided aramid fiber reinforcement and ordinary deformed steel bar were used for reinforcements. Sand is applied on the surface of the aramid fiber reinforcement, K256S. The characteristics of these reinforcements are shown in Table 2. Tensile strength and elastic modulus of aramid fiber reinforcements (K256S and K32) are 1320 MPa and 59 GPa, respectively. High strength steel rebar is chosen for specimens NPL and NX7L to compare the structural performance between FRP reinforced and steel reinforced concrete beams easily. Yield strengths of D16 and D6 are 528 MPa and 923 MPa, respectively. Stirrup shape is spiral type for specimens APL, AX3L and AX7L, and enclosed type using butt welding for specimens NPL and NX7L.

Normal-weight concrete with specified compressive strength of 35 MPa was cast horizontally from the top side of specimen. Measured compressive strength is 40.5 MPa for specimens APL, AX3L and AX7L, and 31.6 MPa for specimens NPL and NX7L.

2.3   Loading program and measurement

Antisymmetrical cyclic load was provided for all specimens using the antisymmetrical loading system as shown in Fig. 2. The loading was carried out by controlling
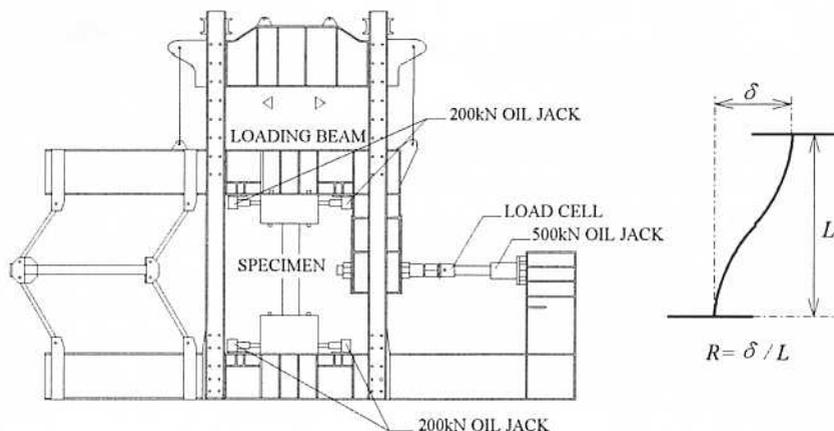

Fig. 2.   Antisymmetrical loading system

translational angle (R) that is defined as shown in Fig. 2. The loading history to be applied to all specimens is $R = \pm1/200$, $\pm1/100$, $\pm1/50$, $\pm1/33$ radians twice and $R = \pm1/20$, $+1/15$ radians once. Shear force, relative displacement between the upper and the lower stub and strains of longitudinal reinforcements were measured.

3 Test results

3.1 Failure progress
Shear force (Q) versus translational angle (R) curves are shown in Fig. 3. Crack patterns after loading are shown in Fig. 4. The failure progresses until the loading cycle to $R = \pm1/100$ radians were almost the same in all five specimens. First, bending cracks took place at the both ends of beams and they expanded as the displacement became larger. Next, shear cracks took place at the central portion of beams. After that, each specimen
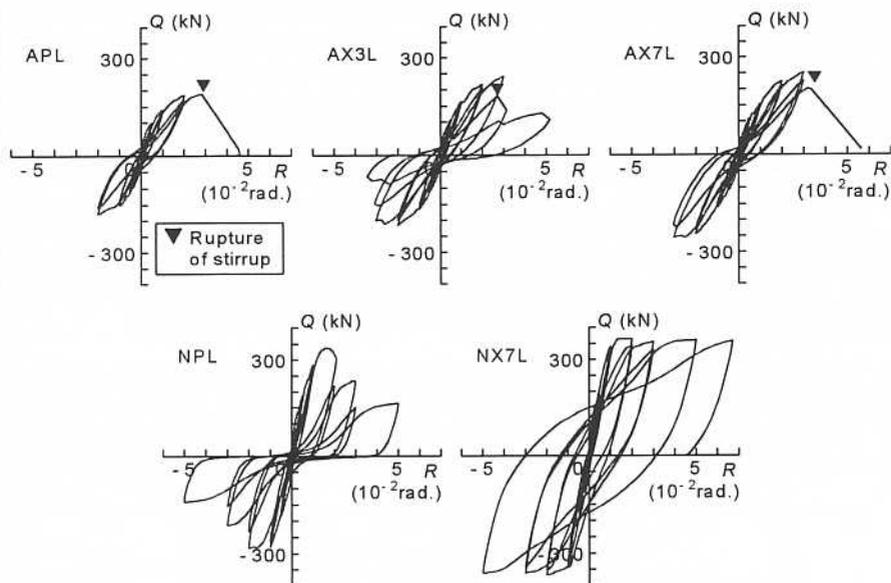

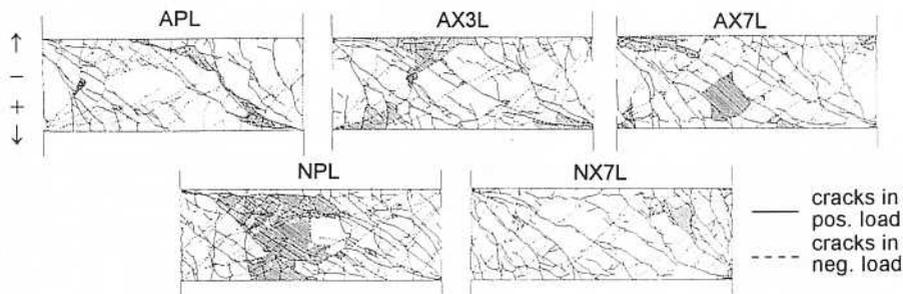Fig. 3.   Shear force - translational angle curves

Fig. 4.   Final crack patterns

showed different progress. Specimens NPL and NX7L gave longitudinal reinforcements (including diagonal ones) yielding at the ends of beams. Shear cracks took place and distributed widely in all specimens expect for NX7L, from the loading cycle of 1/50 to 1/33 radians. Specimen NPL also showed the decrease of peak loads. Specimens APL, AX3L and AX7L led the rupture of bent corner of stirrup(s) with the remarkable load decrease at the $R = 1/36$, $1/37$ and $1/30$ radians, respectively. The rupture of longitudinal reinforcements (including diagonal ones) followed in these specimens. On the other hand, specimen NX7L did not show the decrease of peak loads until the final loading cycle. It can be said that the final failure pattern of FRP reinforced specimens is shear failure with the rupture of FRP bars.

Observed maximum load is 182, 228 and 253 kN for specimen APL, AX3L and AX7L, respectively. It can be recognized that the shear strength of FRP reinforced specimens increases as the amount of diagonal reinforcement also increases.

3.2   Strain of longitudinal reinforcement

Shear force (Q) versus strain of longitudinal reinforcement at the end of specimen (ε) curves are shown in Fig. 5. The cross sections of each specimen are also shown in this figure, where the location of the reinforcements are indicated by black circles. In proportion as the shear force increases, strain also increases in case of tensile strain (positive strain). It can be recognized that the measured maximum strain is bigger as the obtained maximum shear force is also bigger. These phenomena are also noticed in diagonal reinforcements.

Table 3 shows the obtained strains of each layer reinforcement at the ends of specimens when the loads reached the maximum values. These strains are about 0.6% and 0.7% for specimens AX3L and AX7L, respectively. There is little difference in the maximum strains between parallel reinforcements and diagonal ones.
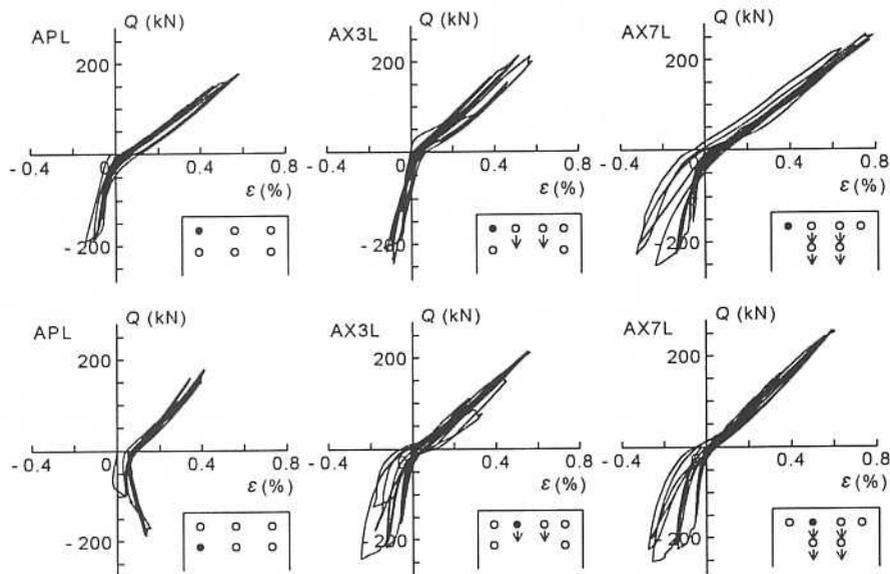

Fig. 5.   Shear force - strain of longitudinal reinforcement curves

Table 3.   Strains of longitudinal reinforcements at the maximum load   (unit : %)

	APL	AX3L		AX7L		NPL	NX7L	
		Parallel	Diagonal	Parallel	Diagonal		Parallel	Diagonal
1st layer	0.598	0.613	0.552	0.736	0.589	0.360	0.220	0.429
2nd layer	0.379	0.439	-	-	0.373	0.244	-	0.292

From these results, it is considered that both parallel reinforcements and diagonal ones carry the same stresses at the ends of specimens.

4   Shear strength of FRP reinforced beams with diagonal reinforcements

4.1   Adaptation of previous study

For ordinary steel-reinforced beams with diagonal reinforcements, shear strength is given as follows [1] :

$$V_n = V_c + V_s + A_v f_y \sin \alpha \tag{1}$$

where,

V_n : shear strength
V_c : shear strength provided by concrete
V_s : shear strength provided by stirrup
A_v : area of diagonal reinforcement
f_y : yield strength of diagonal reinforcement
α : angle between diagonal reinforcements and longitudinal axis of member

Because FRP reinforcement has no yield strength, it is necessary to consider the proper treatment of f_y. At first, obtained maximum load is compared with calculated shear strength by formula (1) using measured maximum strains shown in Table 3 for f_y. Following formulas are used for shear strengths V_c and V_s, standing on the previous study [2].

$$V_c = \frac{0.115 \cdot 0.82 \left(E_f / E_s \cdot 100\rho\right)^{0.23} \left(f_c + 180\right)}{M/Vd + 0.12} \cdot b \cdot \frac{7}{8} d \quad \text{(in kgf} = 9.81 \text{ N)} \tag{2}$$

$$V_s = 2.7 \sqrt{E_f / E_s \cdot \rho_v f_{vb}} \cdot b \cdot \frac{7}{8} d \quad \text{(in kgf} = 9.81 \text{ N)} \tag{3}$$

where,

E_f : elastic modulus of FRP
E_s : elastic modulus of steel
ρ : ratio of longitudinal reinforcement
f_c : compressive strength of concrete (in kgf/cm^2 = 0.0981 MPa)
M/Vd : shear span ratio
b : width of beam (cm)
d : effective depth of beam (cm)
ρ_v : ratio of stirrup

f_{vb} : strength of bent corner of stirrup (in kgf/cm^2 = 0.0981 MPa) [2]

A comparison between obtained maximum loads and calculated shear strengths is shown in Table 4. Though the calculated values are slightly bigger than the maximum loads, a good correlation is recognized between two values. Shear strength of beams with FRP diagonal reinforcements is predicted by formula (1) similarly to steel reinforced concrete beams.

Table 4   Comparison of shear strength

Specimen	Maximum load (kN)	Calculated value (kN)	Ratio of max. to cal.
APL	182	181	1.01
AX3L	228	239	0.95
AX7L	253	274	0.92

4.2   A method to predict stress of diagonal reinforcement

It is essential to know the value of f_v for determination of shear strength using formula (1). In the former section, measured stresses were used. However, this method is not reasonable. So, a method to predict stress of diagonal reinforcements is discussed in this section.

From the test results, it is considered that the maximum load is fixed by the rupture of reinforcements. Obtained maximum stresses of diagonal reinforcements are similar to those of parallel ones at the ends of specimens. Therefore, it is considered that the stress of diagonal reinforcement is equal to that of parallel reinforcement which is determined only by shear strength without diagonal reinforcement. This stress, f_v, can be assumed by the moment which is carrying the shear strength without diagonal reinforcement, using following formula.

$$\left(V_c + V_s\right)\frac{L}{2} = \left(A_s + A_v \cos\alpha\right)\cdot f_v \cdot \frac{7}{8}d \tag{4}$$

where,
  L : clear span length
  A_s : area of longitudinal tension reinforcement (parallel reinforcement)

Table 5 represents obtained maximum load (a), calculated strength by formula (1) ignoring the term of $A_v f_y \sin\alpha$ (b), calculated stress of diagonal reinforcement by formula (4) (c), calculated strength carried by diagonal reinforcement, $A_v f_v \sin\alpha$ (d), calculated shear strength (e), and ratio of maximum load to calculated strength (f). The

Table 5   Calculated shear strength

Specimen	a	b	c	d	e	f
	maximum load (kN)	$V_c + V_s$ (kN)	f_v (MPa)	$A_v f_v \sin\alpha$ (kN)	b + d (kN)	a / e
AX3L	228	169	264	56	225	1.01
AX7L	253	166	261	96	262	0.97

ratios are 1.01 and 0.97 for specimen AX3L and AX7L, respectively. Shear strength calculated by this method shows a very good correlation with the maximum load. The calculated stress of diagonal reinforcement is almost same between specimen AX3L and AX7L. It is recognized that the shear strength of beam with diagonal reinforcement increases as the area of diagonal reinforcement also increases. However, tensile stress of FRP reinforcement used in this study is 1320 MPa. The avoidance of rupture of bent corner of stirrup is essential to use FRP diagonal reinforcements effectively.

5 Conclusions

1. Specimens with FRP diagonal reinforcements failed by rupture of stirrups and longitudinal reinforcements. These specimens showed brittle behavior.
2. Shear strength of FRP reinforced specimens increases as the amount of diagonal reinforcement also increases.
3. It is considered that both parallel reinforcements and diagonal ones carry the same stresses at the ends of specimens.
4. A method to predict shear strength of beams with FRP diagonal reinforcements is indicated standing on the test results.

References

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