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- Technical paper -

ULTIMATE DISPLACEMENT OF PIER REINFORCED BY CONTINUOUS FIBER WITH A LARGE FRACTURING STRAIN

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ABSTRACT: In this paper Polyacetal Fiber (PAF) has been demonstrated as a new continuous system of shear reinforcement replacing major parts of dense steel stirrups. Eight reinforced concrete piers were tested under reversed cyclic loading to study the hybrid performance of the new material in withstanding the very high shear without premature rupture. The rupture failure of PAF at the bent-portions has been avoided. The desirable confinement was acquired with the core concrete and consequently ductility was enhanced.
KEYWORDS: flexible shear reinforcement, polyacetal fiber, FRP, RC pier.

1. INTRODUCTION

The outcome of 1995 Kobe Earthquake Disaster provided a lot of damages caused by poor workmanship, improper construction, deprived precautions for anchorage of lateral reinforcement and lap spliced ties in cover concrete. The code specified details for lateral reinforcements are difficult to realize in practice due to complexity of construction work. The inbuilt strength of pier needs acute-angled hook at the end of steel tie surrounding longitudinal reinforcement embedded in the concrete. To restrain buckling of longitudinal reinforcement and to utilize sufficient confinement action in the concrete pier, major seismic design codes in the world specify huge amount of lateral reinforcements around the potential plastic hinge region. Regarding the huge amount of lateral reinforcements for seismic protection, there is always a demand for workable, efficient and economical shear reinforcing system. The authors have demonstrated a highly workable shear reinforcing system using high performance in-situ resinated continuous carbon fiber for concrete piers [1][2]. Conversely, carbon fiber has high strength but low straining capacity. To the amount of carbon fiber they used, which was 0.2% as reinforcement ratio, rupture failure at the bent-portions was reported to be the cause for terminal loss in load carrying capacity of the pier. What if the high rupture strain of the fiber is emphasized instead of high strength and stiffness?

Non-metallic fibers have been regarded as the state of the art materials for rehabilitation of aging RC infrastructures. As the materials of new hybrid construction technology, the use of high performance fiber, as shear reinforcement is remarkably sluggish. Mostly, it was limited for stress concentration at the bent-portions that could yield the premature triggering rupture of the fiber. PAF is a new kind of fiber composite being used in Reinforced Concrete (RC) structures, compared with existing fibers like carbon fiber, aramid fiber or glass fiber [2][3]. It is stable and at the same time flexible enough to be shaped into desired forms of shear reinforcement. It has appealing engineering properties like high tensile strength, light weight, electric insulation, corrosion resistance etc. It has high rupture strain capacity of about 6-9%. Unlike Continuous Carbon Fiber Flexible Reinforcement [4], PAF is a thermoplastic resin and needs no in-situ resin injection after arranging into desired shape. Therefore, PAF can be an element of swift and efficient construction technology as contrasted with to the conventional steel stirrups having constructional difficulties at regions of crowded arrangements such as potential plastic hinge regions of RC piers and beam-column joints.

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2. OUTLINE OF EXPERIMENTAL WORK

2.1 PARAMETER

There were three parameters. The first was pitch and amount of PAF. The objective was to demonstrate the ability of PAF as continuous shear reinforcement system for a seismic design. The second was tie reinforcement ratio and configuration of the shear reinforcement. The objective was to demonstrate the performance comparable to that given by conventional steel shear reinforcement. The last was shear span.

2.2SIZE OF SPECIMEN

Some specimens consisted of a 250 × 250 × 1000 mm column cast monolithically with a 1000 × 700 × 500 mm footing, the other consisted of same pier cast with changed height. The column part of the specimen represents the part of single column cantilever type bridge pier. The core size measured from the center of the perimeter tie was kept constant at 200 × 200 mm in all eight specimens. **Fig. 1** shows the short column specimen. The material properties of the reinforcements are shown in **Table 1**. The details of specimens are shown in **Table 2**.

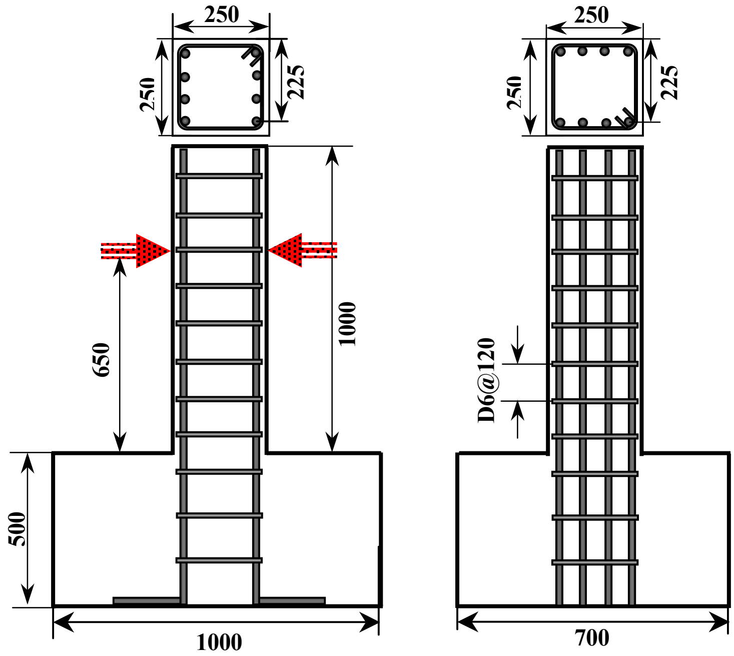

Fig.1 Dimensions of specimen

Table 1 Material properties

item	Cross sectional area (mm^2)	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Ultimate strain (%)
D6	31.67	149	293	-	-
D19	286.5	187	384	-	-
PAF	0.60585	40	-	1760	6~9

Table 2 Details of specimen

Specimen	Amount of PAF P_{paf}(%)	Pitch of PAF (mm)	Amount of Stirrup P_s(%)	Pitch of Stirrup (mm)	Total reinforcement ratio P_w(%)	Shear span (mm)	Shear span ratio
S1	0.20	190	0.21	120	0.41	650	2.88
S2	0.41	175	0.21	120	0.61	650	2.88
S3	0.60	50	0.21	120	0.81	650	2.88
S4	0.30	110	0.32	80	0.62	650	2.88
S5	0.20	190	0.42	60	0.62	650	2.88
S6	-	-	0.63	40	0.63	650	2.88
S7	0.20	0.41	0.21	120	0.61	550	2.44
S8	0.20	0.41	0.21	120	0.61	750	3.33

2.3ARRANGEMENT OF PAF

Proper anchorage of PAF extremities under the applied loading system means effective use of continuous system of shear reinforcement. Then a simple clamp system was developed, tested and used to anchor the PAF extremes, and PAF as shear reinforcement was arranged in every side of specimen in the same way. **Figs. 2** and **3** show the PAF arrangement in S1

2.4 APPLYING LOAD

All specimens were tested under reversed cyclic inelastic lateral displacement simulating earthquake loading. Appling load was continued over the ultimate displacement when the load drops below yielding load level, until at least 9δ_y.

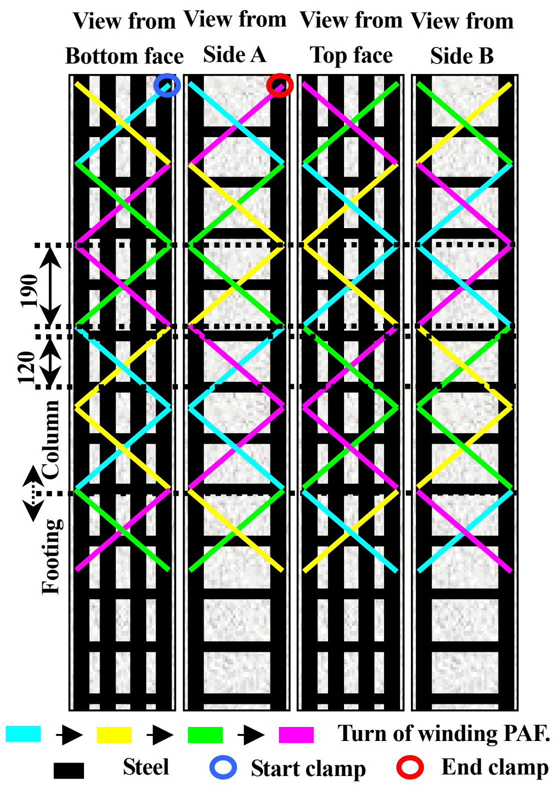

Fig.2 Arrangement of PAF

3. RESULTS OF EXPERIMENT

3.1 FAILURE MODE AND DUCTILITY

(1) Effect of amount of PAF

Fig. 4 shows the load - displacement envelope curve for piers of S1 and S2, S3. In the pier S1, flexural yielding was immediately followed by shear failure, but the others are followed by shear failure after flexural yielding. In all specimens, maximum load is almost same (see **Table 3**). Additional PAF does not enhance maximum load. Here, ductility is ultimate displacement when the load drops below yielding load level, divided by yielding displacement. Ductility of S1 is 2.69, that of S2 is 6.60, that of S3 is 7.65. So increasing the amount of PAF means that we can have good ductility.

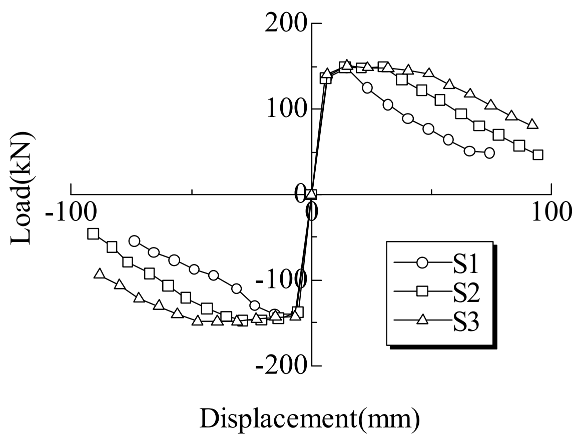

Fig.4 Load displacement curve

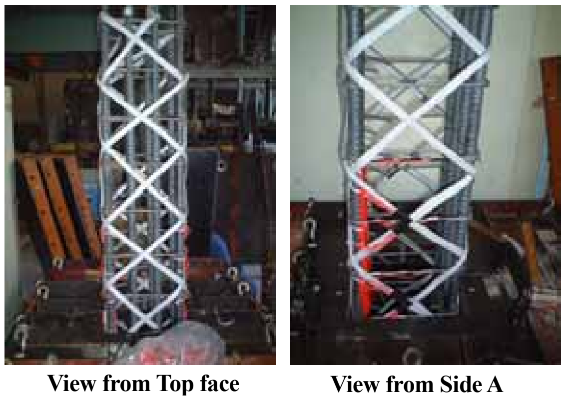

Fig.3 Arrangement of PAF

Table3 Results of S1, S2 and S3

Item	Yielding load (kN)	Yielding displacement (mm)	Ultimate displacement (mm)	Maximum load (kN)	Displacement at maximum load (mm)
S1	138.6	6.55	17.65	148.5	14.69
S2	136.6	5.73	37.88	149.4	13.89
S3	141.8	6.59	50.48	150.9	14.95

(2) Effect of replacement of steel by PAF

Figure 5 shows the load - displacement envelope curve for piers of S2, S4, S5 and S6. In all specimens, flexural yielding was followed by shear failure. The capacity reduction did not reach to the yielding load till the six times yielding displacement. **Tables 4** and **5** shows the shear stiffness and maximum load and ductility. The stiffness of shear reinforcement is obtained multiplying Young's modulus (GPa) of material to reinforcement ratio (%). From **Tables 4** and **5**, the greater shear stiffness is, the greater maximum load we can get. Ductility of S2, S4 and S6 is quite similar, while that of S5 is slightly less. It means that PAF has effects as good as steel stirrup on enhancement of maximum load and ductility. When the load – displacement envelopes in **Fig.5** are compared carefully, the reduction rate in load after the peak is the largest in S6 with only steel stirrup.

Table 4 Results of S2, S4, S5 and S6

Item	Yielding load (kN)	Yielding displacement (mm)	Ultimate displacement (mm)	Maximum load (kN)	Displacement at maximum load (mm)
S2	136.6	5.73	37.88	149.4	13.89
S4	142.8	5.69	37.15	160.1	29.93
S5	147.1	5.86	31.63	160.4	22.87
S6	142.6	6.01	39.64	169.9	30.38

Table 5 Shear stiffness and ductility

Item	Shear stiffness ($Es*P_s+Epaf*P_p$)	Ductility
S2	47.69	6.60
S4	59.68	6.52
S5	70.58	5.39
S6	93.87	6.58

Es : Young's modulus of steel (GPa)
P_s : Reinforcement ratio of steel (%)
Epaf : Young's modulus of steel (GPa)
P_p : Reinforcement ratio of PAF (%)

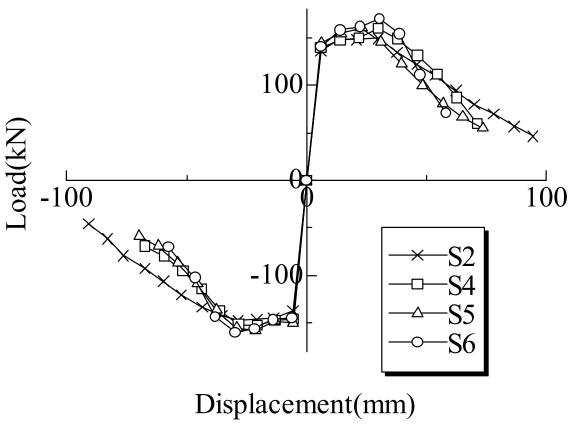

Fig.5 Load displacement curve

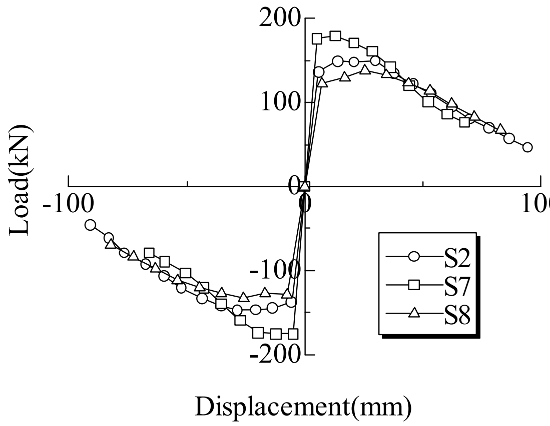

Fig.6 Load displacement curve

Table 6 Results of S2, S7 and S8

item	Yielding load (kN)	Yielding displacement (mm)	Ultimate displacement (mm)	Maximum load (kN)	Displacement at maximum load (mm)
S2	136.6	5.73	37.88	149.4	13.89
S7	175.6	5.03	14.86	178.8	12.94
S8	125.1	7.37	40.04	132.8	34.51

(3) Effect of shear span

Figure 6 and **Table 6** shows the load - displacement envelope curve for piers of S2, S7 and S8. In all specimens, flexural yielding was followed by shear failure. The maximum load is greater and the corresponding displacement is smaller for the smaller shear span to depth ratio. The load reduction rate after the maximum load is quite similar among those specimens. PAF is effective regardless to shear span.

3.2 CRACK PATTERN

(1) Effect of amount of PAF

Figure 7 shows crack pattern of S1 at first yielding, and **Fig. 8** shows crack pattern of S3 at first yielding. **Fig. 9** shows crack pattern of S1 at $4\delta_y$, and **Fig. 10** shows crack pattern of S3 at $4\delta_y$. At first yielding displacement, crack pattern of S1 is not quite different from that of S3. At 4δy, cover concrete peels off clearly in S1, but it does not in S3. It means that the additional PAF could confine the core concrete after diagonal cracking, maintaining shear carrying capacity of concrete despite progressive opening of the diagonal crack. It provides the supplementary shear capacity as shear reinforcement.

(2) Effect of Replacement of Steel by PAF

Figure 11 shows crack pattern of S2 at first yielding, and **Fig. 12** shows crack pattern of S6 at first yielding. **Figure 13** shows crack pattern of S2 at $5\delta_y$, and **Fig. 14** shows crack pattern of S6 at $5\delta_y$. It is clear that crack pattern is different between S2 and S6 even at first yielding displacement. However, at $5\delta_y$, cover concrete spalls off in both specimens. Since not every steel stirrup has yielded yet at the first yielding displacement, cracks can be restrained firmly. After that the steel stirrups yield and the crack arrest effect fades away at $5\delta_y$. For early displacement to which the steel stirrup has not yielded, it can be said that the effect of steel stirrup to prevent cracks from opening is better than that of PAF. In addition, it can be seen that region where crack is progressing is different between S2 and S6 from **Figs. 13** and **14**. The crack progressing region in S2 is larger than that in S6. While the crack is progressing beyond the range of beam sectional height (D) in S2, the crack is progressing in the range of beam sectional height in S6.

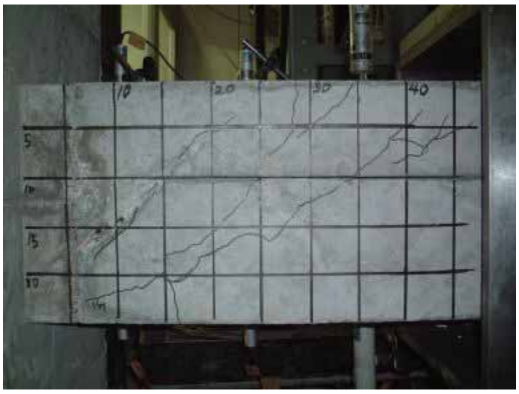

Fig.7 Crack pattern at $1\delta_y$ in S1

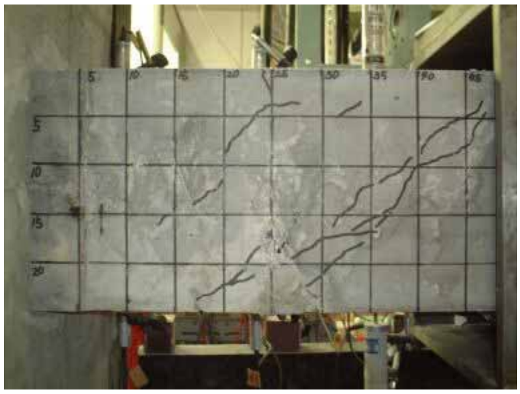

Fig.8 Crack pattern at $1\delta_y$ in S3

Fig.9 Crack pattern at $4\delta_y$ in S1

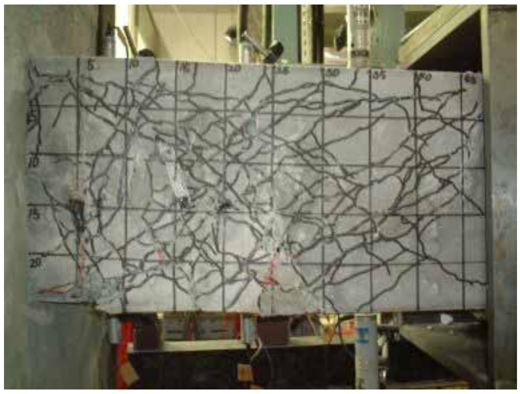

Fig.10 Crack pattern at $4\delta_y$ in S3

3.3 PAFORMANCE OF POST PEAK

(1) Effect of Amount of PAF

After the maximum load, as for all specimens, load fell slowly. Comparison of S1 with S3, it can be seen that the reduction of post-peak load-carrying capacity in S3 is more slowly than that in S1. Contribution of PAF to resisting shear force is different due to the different amount of PAF. It can be said that the additional PAF supplies the mechanism to make the concrete contribution to shear resistance more slowly decrease.

(2) Effect of Replacement of Steel by PAF

From **Fig. 5**, it can be seen that difference in the reduction rate of post-peak load-carrying capacity between S6 and the other specimens. Although the shear force decreases immediately after the maximum load in S6, it does not decrease immediately in the other specimens where steel stirrup was partially replaced by PAF. In S6, when the applied load reached maximum load, the steel stirrup yielded. While the steel stirrup also yielded at the maximum load in the other specimens, PAF did never yield. PAF can continue to carry shear force more efficiently after the steel stirrup yielding. Because of this fact, the core concrete is highly restrained against dilation and enhances overall performance of S2 in comparison with S6. The configuration of continuous shear reinforcement without hook anchorage like in steel tie reinforcement must have a positive effect reducing likely problems of hook anchorage failure at high displacement. Additional point to be raised is that PAF has no rupture in all specimens, which could avoid abrupt loss of load carrying capacity.

Fig.11 Crack pattern at 1δ_y in S2

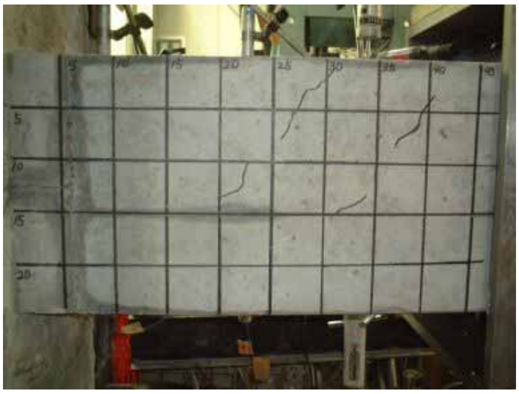

Fig.12 Crack pattern at 1δ_y in S6

Fig.13 Crack pattern at 5δ_y in S2

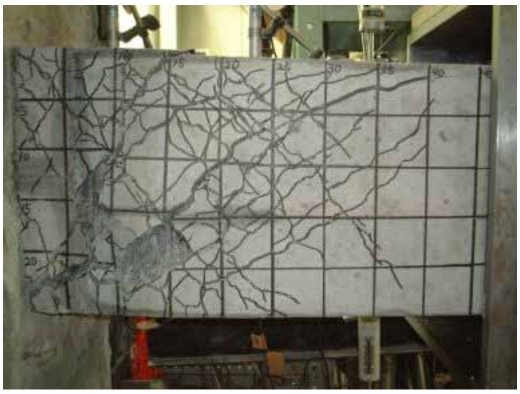

Fig.14 Crack pattern at 5δ_y in S6

4. CONCLUSION

Structural member level experiments were performed on short columns with PAF as hybrid shear reinforcement under alternating displacement reversals. The experiment furnishes the following main conclusions.

(1) The shear strength and ductility of short columns can be enhanced with hybrid PAF continuous shear reinforcement.
(2) PAF can replace majority of steel shear reinforcement and provide even better performance in ductility in terms of the post-peak slope in load – displacement curve.
(3) PAF reinforcement without hook anchorage and its high fracturing strain are also reasons for good performance in ductility.
(4) Steel stirrup can provide better effect in inhabiting crack, comparing with PAF at early displacement.

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