- Technical Paper -

FLEXURAL PERFORMANCE OF FRP SHEET STRENGTHENED CONCRETE BEAMS THROUGH VARIOUS BONDING SYSTEMS

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ABSTRACT

Flexural performance of notched concrete beams externally bonded with carbon fiber (CF) sheets through various bonding systems was experimentally evaluated. Two types of sheet geometries (conventional sheet and new strand sheet) and three types of adhesive bonding systems (normal adhesive bonding, ductile adhesive bonding, and a hybrid use of two of them) were applied. The new CF strand sheet proves its superiority to the conventional CF sheet. In addition, the hybrid bonding system can achieve optimized flexural performance at both the serviceability and ultimate states.

Keywords: Carbon strand sheet, concrete beam, flexural strengthening, hybrid bonding, ductile adhesive, serviceability, ultimate state

1. INTRODUCTION

Flexural strengthening of reinforced concrete (RC) member with externally bonded fiber reinforced polymer (FRP) sheet has become a popular application nowadays. Stress transfer between the externally bonded FRP and RC member is usually achieved through adhesive bonding system. However, the brittle debonding failure at the FRP to concrete interface usually precedes to the flexural shear or shear failure of the strengthened member. As a result, the role of bond between concrete and FRP has become a hottest concern for the FRP strengthening technology over the last decade.

With respect to the debonding failure, a fortunate thing is that good understanding has been achieved on the failure modes and mechanisms in the FRP flexural strengthened RC members. Also, recent advancing in bonding modeling has enabled reasonable prediction of the structural performance of FRP strengthened RC members and numerous models have proved their successes in predicting the debonding strength for the FRP-concrete interface either at element or at member level. Accordingly, design guidelines for predicting the flexural capacity of FRP strengthened members with consideration of the interface debonding have been developed in many nations [e.g. 1-3]. However, it is hard to recognize that the debonding problem has been solved in nature because structural designers still confront a dilemma to discount heavily the high strength advantage of FRP to meet the demand for a safe strengthening design. For actual structures with large dimensions, to improve the member stiffness or strength even a little usually requires a relatively large amount of FRP. But the reality is, the larger amount of FRP required for the design, the lower its material strength we can utilize for design and the less member ductility at the ultimate state. To solve this problem, several researchers tried to use flexible and ductile adhesives with relatively low elastic modulus for improving the interface bond between concrete and FRP [4-6] and gained successes in achieving higher ultimate flexural strength and improved ductility at the ultimate stage. However, the flexible or ductile bonding system mainly contributes the strength enhancement after steel yields and hardly improves the member serviceability. This is not favored when concerns are also needed to control crack width, member deformation, and stress level in steel reinforcement under an increased design load. This paper aims to develop a better configuration for the FRP sheet to concrete bond from both geometrical and mechanical points of view so that an optimized FRP flexural strengthening effect can be realized with a simultaneous consideration of the serviceability and ultimate limit state performance.

2. TEST PROGRAMS

2.1 Materials

Concrete used in this study had the compressive strength of 33.7MPa at the time of testing. Two types of CF sheets shown in Fig.1 were used. One was conventional CF sheet which is being popularly used nowadays. Another was a new type named CF strand sheet, in which CF fibers were pre-cured to FRP strands and then the strands were woven in sheet format. In the current study both two types of sheets were made of the same fiber amount and had the same design tension stiffness (see Table 1). Two types of adhesives were used as the bonding materials (see Fig.2). One was normal adhesive A1 that has a linear material property. Another was ductile adhesive A2 that has a non-linear material property. The elastic modulus of A1 and A2 is

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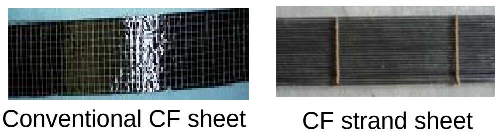
2.41GPa and 0.39GPa, and their fracturing strains are 1.85% and 60%, respectively. Different from the flexible adhesive (see Fig.2) which has a very low elastic modulus but a linear material property, the ductile adhesive has a yielding phenomenon as shown in Fig.2.

Conventional wet lay-up processes were applied for both CF conventional sheet and CF strand sheet implementations. Adhesives used for the bonding layer and for the impregnating matrix of FRP sheets were different when the ductile adhesive A2 was used. Also, adhesives used for the impregnating matrix of FRP sheets were different when different sheet geometries were used. In the conventional CF sheet case, adhesive A1 was used for the impregnating matrix. However, in the CF strand sheet case, epoxy putty was used instead since the CF sheet had already been pre-cured. The selected epoxy putty had the similar mechanical properties with A1 but much higher viscosity than A1. The thickness of FRP layer in the CF strand sheet case was much larger than that in CF conventional sheet case. Consequently, the thickness of bonding adhesive layer achieved during CF strand sheet implementation was much larger than that achieved during conventional CF sheet implementation because the epoxy putty in fact also acted as the bonding layer between CF strand and concrete.



. Fig.1 Geometry of used FRP sheet

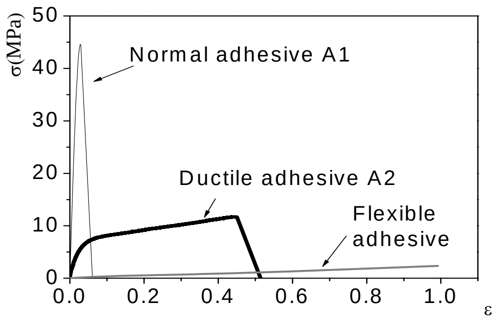


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Fig.2 Tensile stress - strain curves of adhesives

Table 1 Properties of FRP sheet

Type	Conventional CF sheet	CF strand sheet
ρ_f (g/m^3)	400	400
f_t (MPa)	> 3,400	>3,400
E_f (GPa)	245	245
t_f	0.222mm	0.555mm^2
A_f (mm^2)	13.32	13.32
E_fA_f (kN/mm)	54.39	54.39

Note: ρ_f = fiber density; f_t = tensile strength; E_f = elastic modulus; t_f = design thickness of CF sheet or section area of a single CF strand; A_f = design sectional area; and E_fA_f = tension stiffness.

.2.2 Information of Specimens

In total, 18 concrete beams of 900mm in length and 100×150mm in cross-sectional area were prepared. Beam geometry is shown in Fig.3. All tested beams were notched in the mid-span with a depth of 50mm. In the pure bending zone, the CF sheet was un-bonded with concrete substrate to improve the measurement of strain in the sheet over there. The above-mentioned two types of CF sheets were externally bonded to the bottom of beams. After that U-shape end anchorage was applied at the end area of one shear span (see Fig.3). Through a combined use of different types of CF sheet and adhesive materials, five bond configurations were prepared for the tests (see Fig.4 and Table 2). Among them there was a hybrid use of normal and ductile adhesives in the same specimens (see A-3-1 and A-3-2 in Table 2). The background for applying this hybrid bond was that use of low elastic modulus will decrease the stiffness of the interface bond and consequently may ruin the serviceability of the flexural strengthened member [7]. Since a ductile adhesive usually has smaller elastic modulus, it was expected that the loss of bond stiffness due to using ductile adhesives would be compensated through the hybrid bonding system. To understand the most critical part which may require the use of ductile adhesive, the ductile adhesive A2 was applied in the shear-dominating zone and flexure-dominating zone (see Fig. 4) in test series A-3-1 and A-3-2, respectively. The remained parts were applied with the normal adhesive A1.

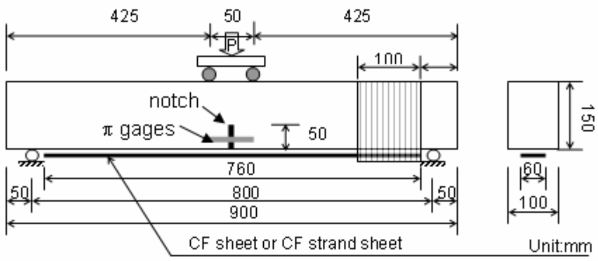


Fig.3 Geometry of specimens

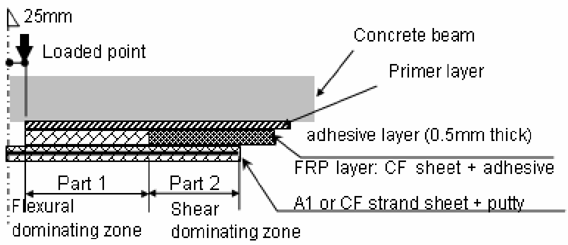


Fig.4 Profile of bonding configuration

Table 2 Different bonding configurations

Beam code	Type of sheet	Adhesive		Length (mm)	
		Part 1	Part 2	Part 1	Part 2
A-1	CCFS	A1	A1	355	0
A-2	CCFS	A2	A2	355	0
A-3-1	CCFS	A1	A2	165	190
A-3-2	CCFS	A2	A1	165	190
A-4	CFSS	A1	A1	355	0
A-5	CFSS	A2	A2	355	0

Note: CCFS = conventional CF sheet; and CFSS = CF strand sheet.

2.3 Measurement

Among the three specimens characterized with the same test variables, one was mounted with a lieu of strain gages on FRP with the interval of 20mm in the shear span without U anchorage. During the loading tests, besides the load and mid span deflection, the opening of notch induced at the mid span was monitored at the height of 5mm, 25mm, and 55mm from the bottom of tested beams using three π gages at front and back beam sides, respectively (refer to Fig.3).

3. TEST RESULTS AND DISCUSSIONS

3.1 Strength and Ductility

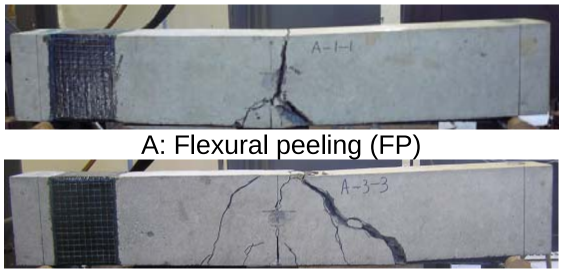
Two types of failure modes were observed in the tests. One was interface peeling failure between FRP and concrete due to the opening of flexural cracks in concrete beams (see A in Fig.5) and another was interface peeling failure due to the opening of flexure/shear cracks (see B in Fig.5) in concrete beams. In the latter parts, these two modes are called flexural peeling (FP) and flexural/shear peeling (F/SP), respectively. As listed in Table 3, even with the similar flexural/shear peeling mechanism, the ultimate strength of strengthened concrete beams varies between 16.8kN and 32.8kN, indicating the significant influences of bonding configurations on controlling the opening of flexural/shear cracks. In general the failure of flexural/shear peeling occurred at relatively high loading levels. One exception is the A-3-2 test series, in which the ductile adhesive and normal adhesive were used in the flexure-dominating zone and shear dominating zone, respectively. Two of the three tested specimens in series A-3-2 were subjected to flexural/shear peeling failure and had relative low ultimate strength at 16.8kN and 18.3kN, respectively. It was expected that the ductile adhesive at the flexural dominating zone would alleviate the stress concentration at the vicinity of flexural cracks while delaying the debonding process. The current test result, however, indicates that the debonding at the flexural dominating zone may not be critical for the ultimate failure of the strengthened system.

Figs.6 and 7 present the load versus mid span deflection ($P \sim \delta$) curves of strengthened concrete beams. The effects of sheet geometry and mechanical property of adhesives are included. As shown in the figures series A-2 and A-5 have much higher ultimate load-carrying capacity and ductility than test A-1 and A-4 series, respectively, indicating that the ductile bonding is superior to the normal bonding in terms of

Table 3 Summary of test results

Code	P_{max} (kN)	δ_{max} (mm)	ε_{max} (μ)	Average of three P_{max}	Average of three δ_{max}	Average of three ε_{max}	Failure mode
A-1-1	15.5	3.63	5445	16.8	3.69	5999	FP
A-1-2	18.3	3.99	6282				FP
A-1-3	16.5	3.44	6269				FP
A-2-1	21	3.78	7499	22.1	4.99	7095	FP
A-2-2	22.2	4.38	7109				F/SP
A-2-3	23.0	6.81	6676				F/SP
A-3-1-1	19.5	4.36	6839	19.5	5.48	6765	FP
A-3-1-2	19.5	7.72	6557				FP
A-3-1-3	19.5	4.36	6899				FP
A-3-2-1	18.3	3.46	8047	17.8	3.00	6448	F/SP
A-3-2-2	16.8	2.52	5705				F/SP
A-3-2-3	18.3	3.02	5592				FP
A-4-1	19.7	3.22	5198	20.7	4.56	5689	FP
A-4-2	20.8	4.9	6164				F/SP
A-4-3	21.7	5.57	5706				F/SP
A-5-1	30.5	10.4	9061	29.9	7.92	8772	F/SP
A-5-2	32.8	7.89	9795				F/SP
A-5-3	26.5	5.47	7461				F/SP

Note: P_{max}, δ_{max} = maximum load-carrying capacity and deflection of the strengthened beam, respectively; and ε_{max} = maximum strain in FRP at ultimate state.



A: Flexural peeling (FP)

B: Flexural/shear peeling (F/SP)

Fig.5 Failure modes of CF sheet strengthened concrete beams

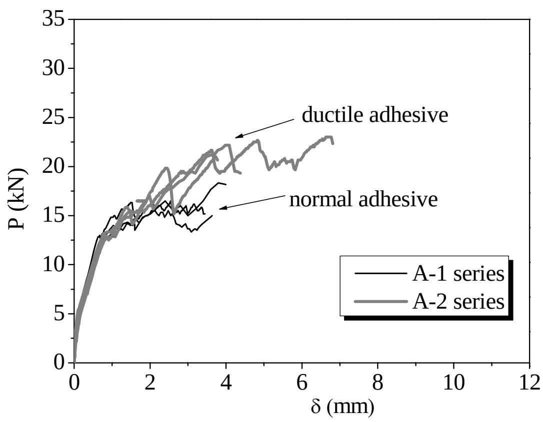


Fig.6 P ~ δ curves of CCFS strengthened beams with unique adhesive bonding

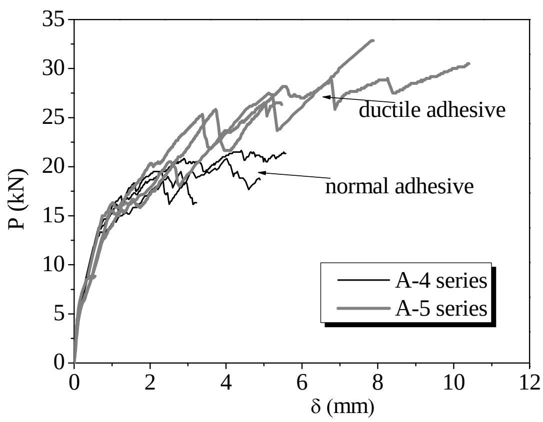


Fig.7 P ~ δ curves of CFSS strengthened beams with unique adhesive bonding

the ultimate state performance of strengthened members. On the other hand, series A-4 and A-5 tend to achieve higher ultimate load-carrying capacity and ductility than series A-1 and A-2, respectively, indicating that CF strand sheet performs better than conventional CF sheet although two types of sheets have the same tension stiffness (see Table 1). Therefore, use of the CF strand sheet together with ductile bonding would be ideal for optimizing the flexural performance of strengthened beams in terms of the ultimate strength and ductility.

Figs.8 and 9 present the effect of hybrid bonding system on the $P \sim \delta$ curve. In Fig.8 the hybrid bonding is realized by arranging the normal and ductile adhesives at the flexural and shear dominating zone, respectively, while in Fig.9 the situation becomes contrary. Compared the hybrid bonding system to the normal or ductile bonding system, it is shown that test series A-3-1 and A-2 have almost the same strength and ductility at the ultimate state (see Fig.8). On the other hand, test series A-1 and A-3-2 have the similar ultimate state performance (see Fig.9). As indicated in Table 2, the same adhesive A2 and A1 were used in shear dominating zone for A-3-1 and A-2 series, and A-3-2 and A-1 series, respectively. As a consequent, it can be concluded that the ultimate strength and ductility are mainly influenced by the mechanical properties of the adhesive used for the shear dominating zone.

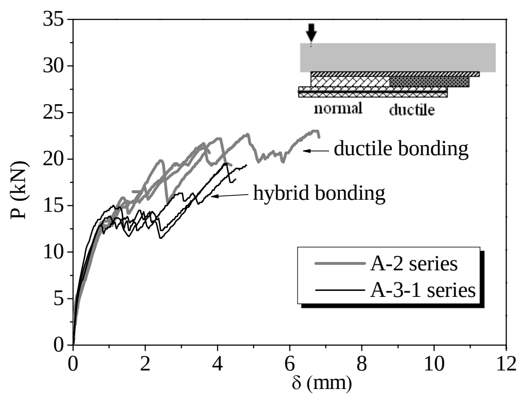


Fig.8 P ~ δ curves of strengthened beams with the hybrid use of two adhesives

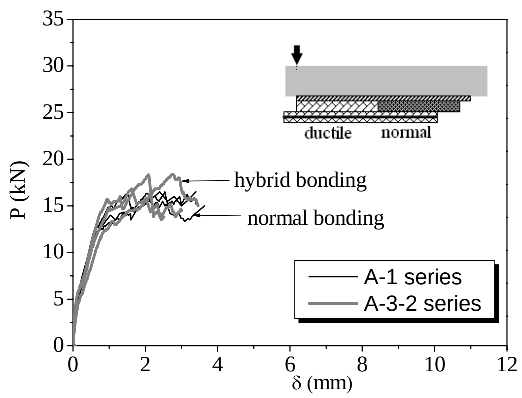


Fig.9 P ~ δ curves of strengthened beams with the hybrid use of two adhesives

3.2 Member Stiffness

Fig.10 presents the stiffness performance of strengthened members with different bonding configurations under serviceability state. The mid span deflection of all the strengthened beams under the same external load, which is assumed to be 10kN, is used to evaluate the effects of bonding configuration on the global stiffness of the strengthened beams (see Fig. 10). It is clearly seen that deflections in test series A-2, A-3-2, and A-5 series are approximately the same, while the deflections in the remaining series are also almost the same at the given load level 10kN. As has been indicated in Table 2, ductile adhesive was used in the full spans of series A-2 and A-5 and only in the flexural dominating zone of series A-3-2. On the other hand, normal adhesive was used in the full span of series A-1and A-4 and only in the flexural dominating zone of series A-3-1. It can be concluded, therefore, the global stiffness of strengthened beams is mainly influenced by the mechanical properties of adhesive within the flexural dominating zone. Usually, use of ductile adhesive in the flexural dominating zone will decrease the global stiffness of the strengthened beams and hence increase the deflection of the strengthened members (see series A-2, A-3-2, and A-5 in Fig. 10).

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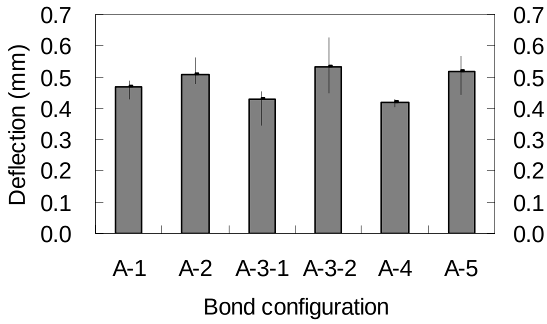

Fig. 10 Member deflection at P = 10 kN

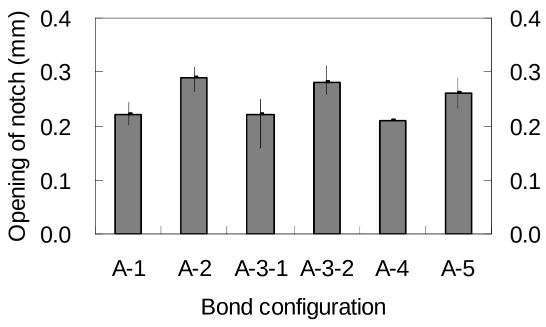

Fig. 11 Crack performance at P = 10 kN

3.3 Crack Width

The opening of mid-span notch, which was obtained from the π gage at the height of 5mm from the bottom of tested beams, was presented in Fig.11 to see how the bonding configuration influences the development of the maximum crack width in the strengthened members. It is shown in Fig.11 that test series A-2, A-3-2, and A-5 have the similar notch opening, while tests series A-1, A-3-1, and A-4 have the similar notch opening at the given load 10kN. It is understandable that use of ductile adhesive in the flexural dominating zone causes larger maximum crack width in the strengthened beam (series A-2, A-3-2, and A-5). Comparatively small crack width can be seen in test series A-2, A-3-2, and A-5, where the normal adhesive was used in the flexural dominating zone. Considering that the ductile adhesive can improve the ultimate state performance in terms of the member strength and ductility as discussed in Section 3.1, it is necessary to employ a hybrid use of normal and ductile adhesives in the same strengthening system to achieve optimized serviceability and ultimate state performance simultaneously. The different sheet geometry, the CF strand sheet and the conventional CF sheet, seems not to influence noticeably the global stiffness (see series A-1, A-4 and A-2, A-5 in Fig.10) and the maximum crack width (see series A-1, A-4 and A-2, A-5 in Fig.11) of strengthened member.

3.4 Strain Development in FRP

Fig.12 presents the development of maximum strain in FRP with the mid span deflection in cases of different bonding configurations. In the figure the maximum strain in FRP is the average of three specimens characterized with the same test variables. It is shown that, after the initial peeling of FRP (see

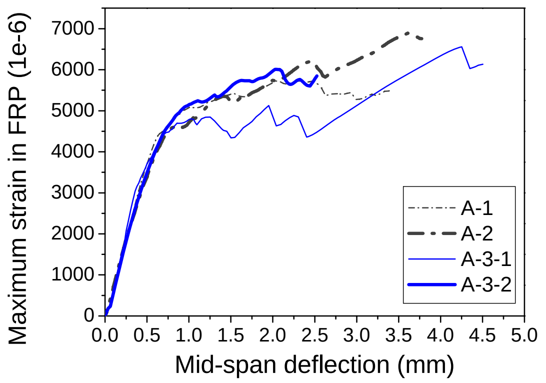

Fig.12 Strain development in FRP: comparison between unique and hybrid adhesive bonding

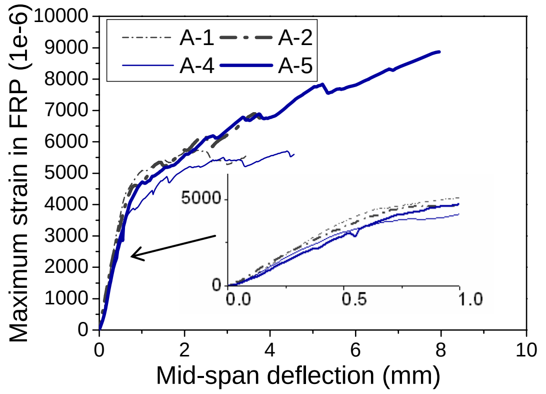

Fig.13 Strain development in FRP: comparison between CCFS and CFSS system

those peaks in the linear ascending braches in Fig.12), series A-1, A-2, and A-3-2 show the similar manner although A-2 achieves the greatest maximum strain in FRP, in other words, the greatest strengthening efficiency. Again, this benefits from the use of ductile adhesive in the full member span. However, use of ductile adhesive only in the flexural dominating zone hardly can improve the maximum strain in FRP at the ultimate state (see A-3-2 in Fig.12). When a hybrid use of the normal adhesive and ductile adhesives was applied in flexural and shear dominating zones, respectively (see A-3-1 in Fig.12), the strain in FRP seems clearly to be smaller compared to other bond configurations at the same mid-span deflection. In addition, the maximum strain in FRP stops increasing soon after the initial peeling load, implying an early debonding occurring near the initial crack (notch). So stiff bond at the mid-span accompanied with ductile bond at the end anchorage part may lead to an early occurrence of debonding at the mid-span area. Fortunately, this early debonding does not stop the significant increase of strain in FRP afterwards since the ductile adhesive in the shear dominating zone governs the ultimate state performance. Considering the good serviceability performance achieved in series A-3-1 as discussed in Sections 3.2 and 3.3, the bonding configuration used for A-3-1 consequently proves to be an optimal one for flexural strengthening.

Fig.13 also presents the development of maximum strain in FRP with the mid-span deflection in cases of different sheet geometries (CCFS and CFSS). The measured surface strain in CFSS system seems always smaller than that observed in CCFS system at the same mid-span deflection (see the enlarged view in Fig.13). This difference is considerably attributed to the relative shear displacement between the CF strand and the surrounding putty. The FRP layer in CFSS system is much thicker than that in CCFS system. Because of this the measured strain is on the surface of putty rather than on the surface of strand itself. This strain difference may explain why CF strand sheet is more efficient than conventional CF sheet as concluded in Section 3.1. The deformability in shear of the thick putty layer can enhance the shear force transfer between FRP layer and concrete. It is hard to achieve a bond layer rich in shear deformability in conventional sheet bonding system. However, the CF strand sheet bonding system makes this possible.

3.5 Strain Distribution in FRP

To have better understanding on the debonding processes in cases of different bonding configurations. Figs.14 to 16 present the strain distribution in FRP at different load levels. Only the optimal hybrid bond configuration used for series A-3-1 is presented compared to unique normal (A-1) and ductile (A-2) bonding systems. The main difference between the normal (see Fig.14) and ductile adhesive bonding (see Fig.15) seems to be the magnitude of effective bonding area between the FRP and concrete. Here the effective bonding area is described as the active bonding area with a monotonic decreasing strain gradient in FRP by neglecting the local zigzag variations caused by concrete cracks. In the ductile bonding system the effective bonding area is large so that the overall strain gradient becomes smaller and the local bond stress concentration can be alleviated. Owning to this the overall bonding interface can consume more fracture energies over a larger interfacial shear softening zone. Of course, the wide effective bonding area means a wide range of strain distribution in FRP, which increases the relative slip between the FRP sheet and concrete. This slip is balanced with the crack width at crack locations hence the increased effective bond area is not favored for controlling the crack width. However, once an optimal hybrid bonding system is used as shown in Fig.16, the normal adhesive in the flexural dominating zone makes it possible to have a shorter effective bonding area at a relatively small load level (serviceability state) and consequently the local slip between FRP and concrete at the notch (crack) position is suppressed. At a larger load or deformation, the increased effective bond area contributes increased interfacial energy absorption, which is desirable at the ultimate state when the crack is no longer the concern.

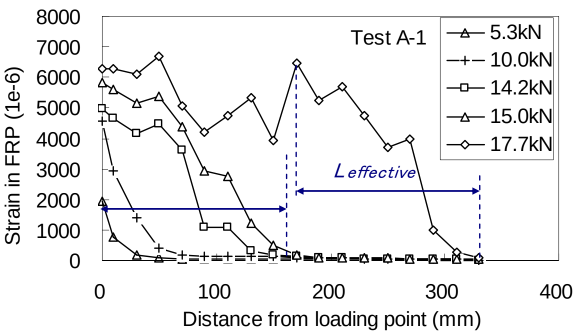

Fig.14 Strain distribution in FRP: A-1

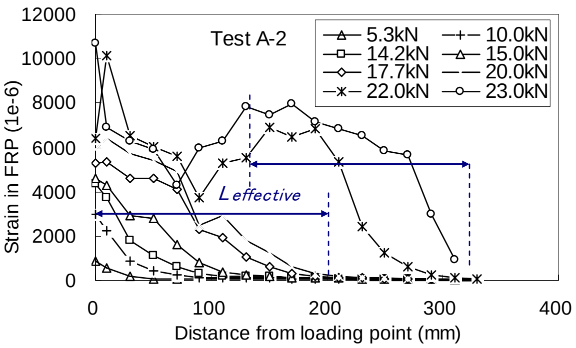

Fig.15 Strain distribution in FRP: A-2

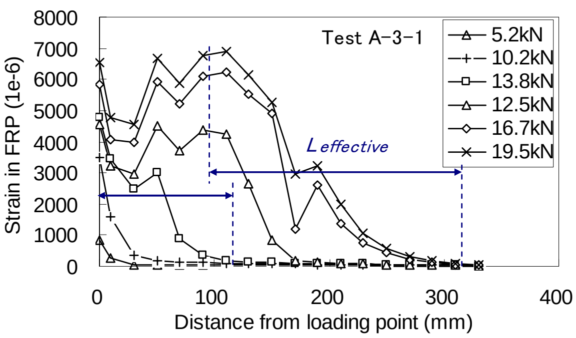

Fig.16 Strain distribution in FRP: A-3-1

4. CONCLUSIONS

(1) The new type of sheet geometry, CF strand sheet, achieves improved strengthening effects than conventional CF sheet although both two types of sheets were designed with the same tension stiffness.

(2) Sheet strengthened beams with ductile adhesive bonding achieve much better ultimate state performance than those strengthened through normal bonding system. Use of strand sheet together with the ductile adhesive bonding seemed to be an optimal solution for achieving best ultimate strength and ductility.

(3) Use of ductile bonding system has some demerits particularly concerning the crack width of the strengthened members for serviceability. A hybrid use of normal and ductile adhesive bonding in the flexural dominating and shear dominating zone, respectively, can compensate this shortcoming. This new type of bonding system may become an optimal solution for flexural strengthening if considering the serviceability and ultimate state performance simultaneously.

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