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Flexural Behavior of Concrete Beams Reinforced With Hybrid FRP Bars and HRB Bars

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Abstract: This paper reports and compares experimental studies on flexural performance of concrete beams reinforced with hybrid fiber reinforced polymer (FRP) and steel HRB bars with this study and other literatures. The objective of this study is to examine the effect of hybrid FRPs on structural behavior of retrofitted RC beams and to investigate if different sequences of BFRP and GFRP bars of the hybrid FRPs have influences on improvement of strengthening RC beams, Total 3 steel reinforced concrete beams and 8 hybrid reinforced beams were designed using only HRB steel bars and hybrid G/BFRP-steel bars respectively. The flexural bearing capacity, the maximum crack width and the deflection of the test beams were obtained and analyzed. Results show that the ultimate bending moment of hybrid reinforced is slightly less than that of steel reinforced concrete beam with the same reinforcement ratio. It can be concluded that it is feasible to replace the corner steel bars of concrete members with FRP bars without reducing the flexural bearing capacity. However, the deflection and maximum crack of hybrid reinforced concrete beams are much higher than those of steel reinforced concrete beams at the same load levels. The theoretical calculation method can effectively predict the flexural bearing capacity, crack spacing, maximum crack width and deflection of hybrid reinforced concrete beams, which can be used in engineering design reference.

Keywords: FRP bar, hybrid reinforced, flexural capacity, deflection, crack

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I. INTRODUCTION

The durability of reinforced concrete (RC) structures is regarded as a major concern due to the corrosion of steel reinforcement. Reduction of mechanical strength of RC structures and poor bond behavior between steel and concrete are often caused by the corrosion of steel reinforcement. Significant efforts have been devoted in recent years to overcome the problems associated with the corrosion of steel reinforcement including the use of galvanized steel reinforcement[1]or addition of rust inhibitor in concrete[2].Besides, Fiber Reinforced Polymer (FRP) bar is considered as an ideal alternative to steel bar[3]. Compared to the traditional steel bars, FRP bars have the characteristics of corrosion resistance, high specific strength and superior manufacturability[4]. However, the stress-strain behavior of FRP bars is linear without any obvious yield point. Also, FRP bar reinforced concrete members usually fail in a brittle manner. Furthermore, compared to steel reinforcing bars, the modulus of elasticity of the FRP bar is significantly low and the bond between FRP bar and concrete is relatively weak. Thus, large deflection and crack width are often observed in FRP bar reinforced concrete structures[5]. Due to the linear stress-strain behavior and low modulus of elasticity of the FRP bar, the design of FRP bar reinforced concrete structures is usually controlled by the serviceability limit state requirements[6]. To mitigate the disadvantages of FRP bars, new FRP bar and FRP reinforcement system were investigated in a few research studies. For example, hybrid FRP bars were fabricated with different continuous fibers. Herris et al[7] reported that stress-strain behavior of steel can be simulated by hybrid FRP bars which combined different types of fibers. The ductility of hybrid FRP bar reinforced concrete beams was found to be close to the corresponding steel bar reinforced concrete beams. A new reinforcement system consisted of FRP bars and steel bars was also proposed in Qu et al[8]. It was reported that reinforcing concrete beams with both FRP bars and steel bars was an effective way for improving the serviceability and ductility of FRP bar reinforced concrete beams. Recently, in a few research investigations, it was observed that the deflection and crack width of FRP bar reinforced concrete beams were restrained and the ductility was improved by the addition of randomly distributed fibers[9,10]. There are many researches on the pure FRP reinforced concrete beam, Theoretical calculation is mostly based on the design specifications and guidelines of ordinary reinforced concrete beams or pure FRP reinforced concrete beamsand the research on flexural performance, crack width and deflection of hybrid reinforced concrete beams is not sufficient.

Therefore, it is very important to study the flexural performance of hybrid reinforced concrete beams with FRP and steel bars. This paper carried out the flexural performance test of 8 FRP bars and HRB bars reinforced concrete beams (hereinafter referred to as "hybrid reinforced concrete beams") and 3 steel reinforced concrete beams.Which analyzed the characteristics of the ultimate flexural moment, deflection and crack development of the hybrid reinforced concrete beams.The experimental results are also compared with steel reinforced concrete beams.Theoretical values of flexural capacity, average crack spacing, maximum crack width and deflection of hybrid reinforced concrete beams were compared with the experimental values. The relevant results can provide some reference for the practical engineering application of hybridreinforced concrete members

II. EXPERIMENTAL INVESTIGATION

2.1 Component design

The cross-sectional dimensions of all beams designed and manufactured here are 180mm×300mm and the length is 1800mm.The concrete cover was 30 mm. The spacing of the stirrups was 100mm. The reinforcement method and section parameters of the test beams are shown in Fig.1. The cross section parameter of test beamsare shown in Table1.

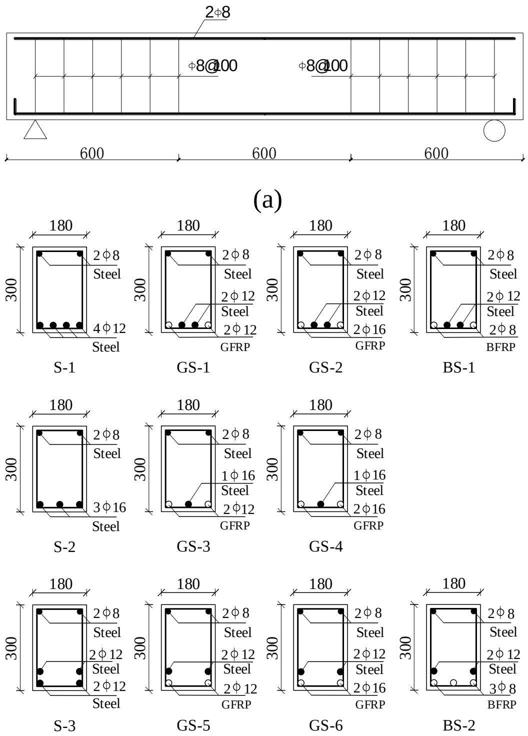


Figure1: Schematic diagrams of test beams: (a) details of beam's reinforcements and (b) details of beams' section.

Table 1: The cross section parameter of test beams

Test piece number		Tensioned longitudinal reinforcement	A_s/mm^2	A_f/mm^2	Reinforcement ratio $\rho_{h,s}$/%
Single layer form	S-1	4S12	452	0	0.98
	GS-1	2G12+2S12	226	226	0.87
	GS-2	2G16+2S12	226	402	1.26
	BS-1	2B8+2S12	226	101	0.67
	S-2	3S16	603	0	1.31
	GS-3	2G12+1S16	201	226	0.80
	GS-4	2G16+1S16	201	402	1.17
Double layer form	S-3	4S12	452	0	1.06
	GS-5	2G12+2S12	226	226	0.94
	GS-6	2G16+2S12	226	402	1.36
	BS-2	3B8+2S12	226	151	0.82

Note: G is GFRP, B is BFRP, S is HRB; 12, 16 is gluten diameter; A_s is the area of reinforced steel in the pull zone; A_f is the area of FRP reinforcement in the tensile area; and the reinforcement rate is uniformly used $\rho_{h,s}$ in the analysis of the test results.

2.2 Material properties

The concrete design strength grade is C30 and the mix ratio design is shown in Table 2. The concrete cube compressive strength is 32.2MPa. The steel bars in the tension zone are HRB400 bars with a diameter of 12 and 16 mm. The mechanical properties are shown in Table 3. FRP bars are glass fiber (GFRP) bars and basal fiber (BFRP) bars produced by a company in Nanjing. The mechanical properties of the FRP bars are shown in Table 4.

Table 2: Concrete mix ratio and its mechanical properties

Water cement ratio	Cement /(kg·m^{-3})	Water / (kg·m^{-3})	Sand/ (kg·m^{-3})	Stone/ (kg·m^{-3})	f_{cu}/MPa
0.49	449	220	615	1116	37.9

Table 3: Mechanical properties of HRB bars

Types	Diameter /mm	Elongation rate /%	f_y/MPa	f_u/MPa
HRB400	12	15.8	517	631
HRB400	16	15.6	540	643

Table 4: Mechanical properties of FRP bars

Types	Diameter /mm	f_u /MPa	E_f/GPa
BFRP	8	1299.6	42.03
GFRP	12	868.22	40.06
GFRP	16	958.2	45.70

Figure2: FRP bars used in this study

2.3 Experiment test equipment and loading system

A 50 ton load is applied, test set-up is shown in Fig.3. 11 beams are tested under four point test configuration with a clear span of 1600mm. The applied load was monitored by means of load cell located on top of the spreader beam. Five linear variable displacement transducer (LVDT) was placed at the soffit of the beam to measured the deflection at midspan. The flexural moment, crack width, strain gauges and deflection of the test beams were recorded.

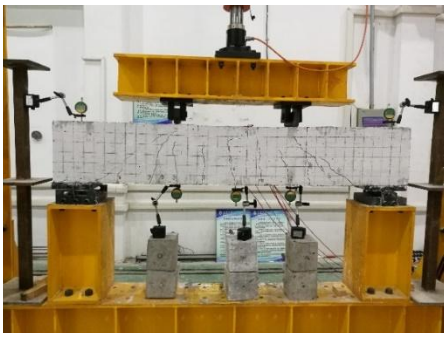


Figure3: Loading set of test beam

III. MIXEDREINFORCEMENT RATIO

Since FRP bars have greater tensile strength and lower elastic modulus than steel bars, consider the coordination ability of the two in the hybrid reinforcement beam.Defining reinforcement rate of hybrid reinforced concrete beam$\rho_{h,s}$as follow [11].

$$\rho_{h,s} = \frac{A_s}{bh_0} + \frac{f_{fd}}{f_y}\frac{A_f}{bh_0} = \rho_s + \frac{f_{fd}}{f_y}\rho_f \quad (1)$$

Where,f_y is the yield strength of the steel, MPa;$f_{fd}$is the tensile strength of the FRP, MPa; b is the width of the section, mm; h_0 is the effective height of the section, mm.

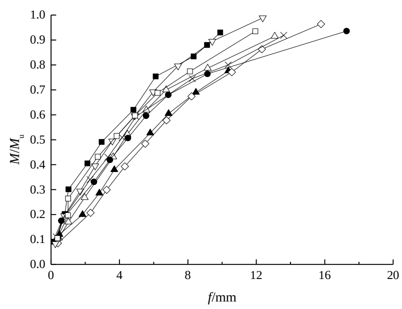
IV. EXPERIMENTANALYSIS

4.1 Experiment process

Fig.4 shows the load-deflection curve of some test beams. Fig.5shows the crack distribution of some test beams. According to the load-deflection curve, the bending process of the hybrid reinforcement concrete beam can be divided into the following three sections:

In the early stage of cracking, the deformation characteristics of hybrid reinforced concrete beams are characterized by linear elasticity. When the mid-span bending moment is increased to (0.1~0.15) M_u^e (M_u^e measured value of ultimate flexural moment), one or more cracks appear near the bottom of the corresponding beam, the crack width is small, the height is 2/18~5/18 of the beam height, the crack width of the reinforced concrete beam is less than 0.03mm. Under the same load level, the deflection of the hybrid reinforced concrete beam is larger than that of the steel reinforced concrete beam. The ratio between the two is 1.2～1.94. When the mid-span flexural moment is increased to (0.5-0.6) M_u^e the maximum crack width of the hybrid reinforced concrete beam has exceeded 0.5 mm.

When the mid-span flexural moment is increased to (0.8-0.87) $M_u^e$the hybrid reinforced concrete beam steel first yields. Due to the presence of FRP bars, the deflection continues to increase with the increase of the load and the steel reinforced concrete beam will continue to increase even after the load is applied, even if the load no longer increases the deflection, so the load-deflection curve of the hybrid reinforced concrete beam at this time unlike steel reinforced concrete beams.



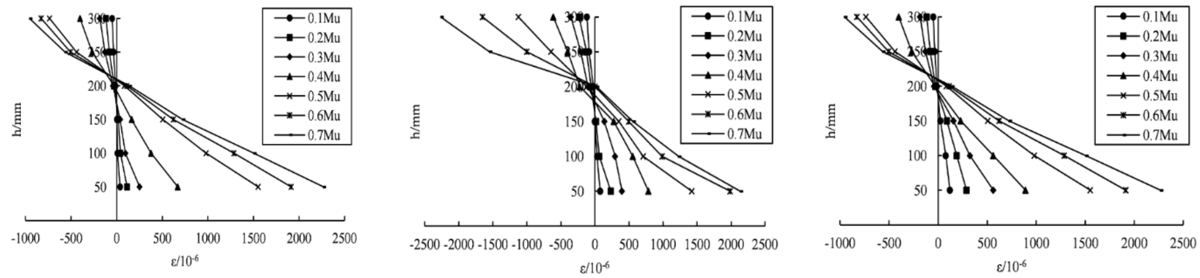
—■—S-1 ; —△—GS-1 ; —▲—GS-2 ; —●—GS-3 ;
—◇—GS-4 ; —▽—GS-6 ; —×—BS-1 ; —□—BS-2。

Figure4: Load-deflection curve of several test beams

Figure5: Crack distribution of BS-1 beam

4.2 Verification of plane section assumption

Comparison of steel concrete beam S-1 and hybrid concrete beams GS-1 and BS-1 of this study. From fig.6, it can be seen that both-hybrid reinforced concrete beams and steel reinforced concrete beams satisfy the plane section assumption.



(a) S-1 (b) GS-1 (c) BS-1

Figure6: Strain distribution of test beam

V. RESULTS AND ANALYSIS

5.1 Flexural capacity

According to the simplified material constitutive model[14] and the basic assumptions and the curve stress pattern of the concrete in the compression zone is replaced by the equivalent rectangular stress pattern, the height and ultimate bending moment of the cross section of the hybrid reinforced concrete beam M_u is calculated according to equations (3) and (4), respectively.

$$\alpha_1 f_c bx = f_y A_s + E_f \varepsilon_f A_f \qquad (2)$$

$$\xi = \frac{(A-B) \pm \sqrt{(A-B)^2 + 3.2B}}{2\alpha_1} \qquad (3)$$

$$M_u = \alpha_1 f_c b h_0^{\,2} \xi \left(1 - \frac{\xi}{2}\right) \qquad (4)$$

Where:$A=f_y\rho_s/f_c$;$B=\varepsilon_{cu}E_f\rho_f/f_c$;$\varepsilon_f=\varepsilon_{cu}(\beta/\xi -1)$;$\varepsilon_{cu}$is the ultimate compressive strain of the concrete.

It can be seen from Table 5 that the theoretical calculated values of the ultimate bending moment of the hybrid reinforced concrete beam are in good agreement with the experimental values. The mean value of the two values is 0.893 and the coefficient of variation is 0.09, which indicates that the theoretical value obtained by the formula (6) of the limit bending moment of the hybridreinforced concrete beam can be better in agreement.Compared with the limit bending moment of the two groups of hybrid reinforced concrete beams, GS-1, GS-2, BS-1, GS-3 and GS-4, the ultimate bending moment of hybrid reinforced concrete beams in the form of single-layer reinforcement increases with the increase of the mixed reinforcement ratio, which is consistent with the experimental results of the literature [16]. For double-layer reinforcement hybrid reinforced concrete beams, this phenomenon is not obvious and still needs further study.

Table 5: The bearing capacity analysis of test beam of this study and other literatures

Literature	Specimen name	M_u^c/(kN·m)	M_u^e/(kN·m)	M_u^c/M_u^e
This study	S-1	53.80	59.12	0.910
	GS-1	50.19	57.5	0.873
	GS-2	60.64	63.30	0.958
	BS-1	41.87	52.00	0.805
	S-2	69.22	60.25	1.149
	GS-3	49.25	56.37	0.874
	GS-4	59.84	66.70	0.897
	S-3	51.97	60.77	0.855
	GS-5	45.14	53.79	0.839
	GS-6	54.20	50.56	1.072
	BS-2	41.31	50.01	0.826
[15]	FS1	68.9	74.4	0.94
	FS2	68.8	73.5	0.96
	FS3	68.7	72.8	0.97
	F1	66.5	67.6	1.01
	S1	69.8	67.9	1.02

5.2 Crack spacing

Combined with the test and literature [17], the average crack spacing test value of 14 hybridreinforced concrete beams is obtained and the test data are shown in Table 6,the k_1, k_2 value in the regression analysis is obtained in the formula (5)， k_1=2.5， k_2=0.04， The formula for calculating the average crack spacing is (6).

$$l_{\mathrm{m}} = k_1 c_{\mathrm{s}} + k_2 \frac{d_{\mathrm{eq}}}{\rho_{\mathrm{te}}} \quad (5)$$

$$l_{\mathrm{m}}^{\mathrm{c}} = 2.5 c_{\mathrm{s}} + 0.04 \frac{d_{\mathrm{eq}}}{\rho_{\mathrm{te}}} \quad (6)$$

For the accuracy of the validation of formula (6), the literature [18,19] test results are collected, as shown in table 6 by formula (6) .The mean value of $l_{\mathrm{m}}^{\mathrm{c}}/l_{\mathrm{m}}^{\mathrm{e}}$is 1.001 ,the variation coefficient is 0.119 ,which indicates that the average crack spacing of the hybrid reinforced concrete beams calculated by using formula (6) is in better agreement.

Table 6 Average crack spacing test data

Literature	Specimen name	FRP Gluten Types	Surface form of reinforced material	Steel	FRP Gluten	b /mm	h /mm	c /mm	$l_{\mathrm{m}}^{\mathrm{e}}$ /mm	$l_{\mathrm{m}}^{\mathrm{c}}$/mm	$l_{\mathrm{m}}^{\mathrm{c}}/l_{\mathrm{m}}^{\mathrm{e}}$
This study	GS-1	GFRP	Spiral Winding Ribs	2S12	2G12	180	300	30	114	128.8	1.13
	GS-2			2S12	2G16	180	300	30	122	124.6	1.02
	GS-3			1S16	2G12	180	300	30	128	137	1.07
	GS-4			1S16	2G16	180	300	30	131	131.4	1.003
	GS-5			2S12	2G12	180	300	30	145	128.8	0.888
	GS-6			2S12	2G16	180	300	30	114	124.65	1.09
	BS-1			2S12	2G8	180	300	30	143	134	0.937
	BS-2			2S12	3G8	180	300	30	111	153.41	1.382
[17]	GF1	GFRP	Surface Sand Blasting	2S12	2G12.7	180	250	15	96	85.33	0.89
	GF2			1S16	2G15.9	180	250	15	89	86.99	0.98
	GF3			2S16	2G9.5	180	250	15	91	83	0.91
	GF4			2S16	2G12.7	180	250	15	88	80	0.91
	GF5			1S12	2G9.5	180	250	15	105	108.82	1.04
	GF6			2S16	2G15.9	180	250	15	78	78.63	1.01
[18]	FS1	BFRP	Spiral Winding Ribs	4S10	6B8	200	300	25	106	103	0.97
	FS2			5S10	5B8	200	300	25	95	102.5	1.08
	FS3			6S10	4B8	200	300	25	93	101.4	1.09
[19]	A1	AFRP	Spiral Winding Ribs	2S8	2A7.5	150	200	13	72	55.41	0.77
	A2			2S8	2A10	150	200	13	81	78.22	0.97
	A3			2S12	3A10	150	200	13	77	69.36	0.901
	C1			2S8	2A7.5	150	200	13	83	81.31	0.98

5.3 Crack width

For the crack at the horizontal position of the longitudinal beam of the test beam, refer to the crack width calculation formula [20] in the ACI specification. The formula for calculating the maximum crack width of the hybrid reinforced concrete beam under short-term load is:

$$w_{\mathrm{s,max}}^{\mathrm{c}} = k_{\mathrm{g}} \varepsilon_{\mathrm{f}} \beta' \sqrt[3]{d_{\mathrm{c}} A} \quad (7)$$

Where, d_{c} is the distance from the center of the longitudinal reinforcement at the bottom of the beam to the edge of the concrete in the tension zone, mm; A is the average effective area of the tensile concrete around each longitudinal reinforcement, mm^2; β' the distance from the edge of the tension zone to the neutral axis. $k_{\mathrm{g}}$is a function reflecting the influence of the bond strength of the tensile main rib in the hybrid reinforced concrete beam on the crack width, defined as $k_{\mathrm{g}} = k_1 \chi$， k_1=0.4[21]

The relationship between the calculated short-term maximum crack width calculation value $w_{\mathrm{cs,max}}$of the hybrid reinforced concrete beam calculated by the formula (7) and the measured value $w_{\mathrm{s,max}}^{\mathrm{e}}$ is shown in Fig.7. The mean value of the $w_{\mathrm{cs,max}}/w_{\mathrm{s,max}}^{\mathrm{e}}$is 0.996 and the coefficient of variation is 0.112. It can be seen that the maximum crack width of the hybridreinforced concrete beam is suitable by the formula (7).

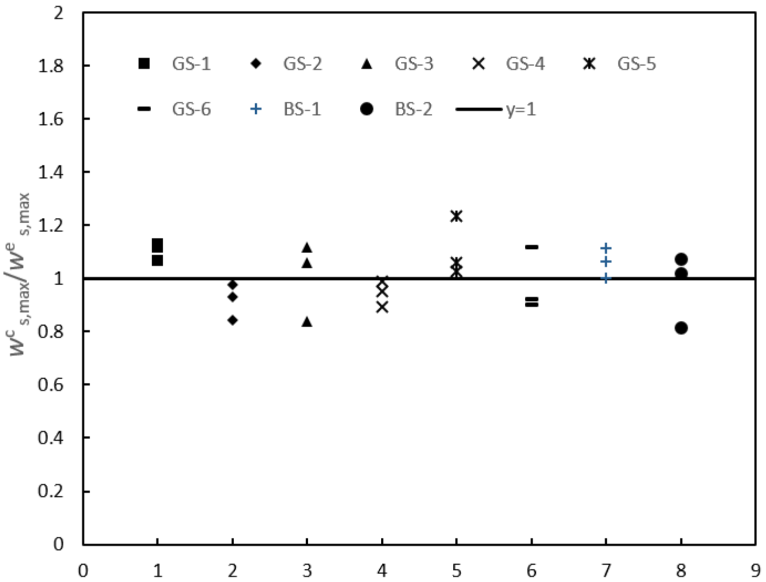


Figure 7: Comparison of short-term maximum crack width

5.4 Mid-span deflection calculation

The effective inertial moment of hybridreinforced concrete beams I_e is calculated as follows:

$$I_e = \beta \frac{I_{cr}}{1-\eta\left(\frac{M_{cr}}{M}\right)^2} \quad (8)$$

$$\eta = 1 - \frac{I_{cr}}{I_g} \quad (9)$$

Where,$M_{cr}$for cracking bending moment, kN·m;Mbending moment for the corresponding moment with deflection, kN·m. βisthe reduction coefficient,β=0.64[22].

After obtaining the effective inertial moment, the deflection of the hybrid reinforced concrete beam is calculated by using the method of structural mechanics and the calculation formula of the midspan deflection of the four-point loaded hybridreinforced concrete beam is as:

$$f = \frac{Pa}{48E_cI_e}\left(3L^2 - 4a^2\right) \quad (10)$$

Where ,*L is* to calculate the span, m； *a is* distance of load point for support distance, m。

In order to verify the accuracy of β values, a comparison of the theoretical values obtained by collecting some scholars at home and abroad with formula (10) is shown in Fig.8. In the Fig.8, f^c_m is the theoretical calculation value of midspan deflection and $f^e_m$is the test value of midspan deflection. As can be seen from Fig.8, the theoretical value of midspandeflection of hybridreinforced concrete beams calculated by formula (10) is in good agreement with the measured value, the mean value of f^c_m/f^e_m is 0.995 and the coefficient of variation is 0.096.It is concluded that it is appropriate to calculate the deflection by type (10) under the short-term load of the hybrid reinforced concrete beam.

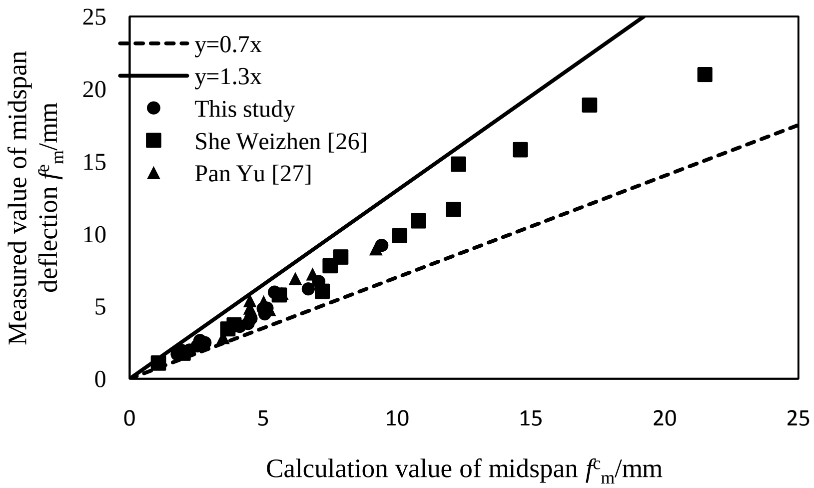


Figure8: Comparison of deflection of some scholars experiment

VI. CONCLUSION

(1) Using hybrid FRPs is effective in improving the ultimate strength and stiffness of a strengthened beam.

(2) The normal section of the hybrid reinforced concrete beam still conforms to the flat section assumption. The crack development process is basically the same as that of the steel reinforced concrete beam. The load-deflection curve is divided into three sections and the inflection point of the corresponding curve is the cracking load and the yield load of the steel bar.

(3) The ultimate bending moment of hybrid reinforced concrete beam of the theoretical formula is in good agreement with the experimental value, which can be used for engineering design. For the hybridreinforced concrete in the form of single layer reinforcement when the $\rho_{h,s}$is in the range of 0.67%-1.26% and the same tensile reinforcement is arranged, the ultimate bending moment of the beam increases with the increase of the mixed reinforcement ratio.

(4) The calculation formula of the average crack spacing of steel reinforced concrete structures is still applicable to hybridreinforced concrete beams. The calculated values of the short-term maximum crack width and the mid-span deflection theoretical formula of the hybridreinforced concrete beams agree well with the experimental values.

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