Article no. 30

THE CIVIL ENGINEERING JOURNAL 3-2018

EVALUATION OF FLEXURAL CAPACITY AND DUCTILITY ON HIGH-STRENGTH CONCRETE BEAMS REINFORCED WITH FRP REBAR AND STEEL FIBER

Jinzhang Li[1,2]

1. *University of Tongji, Faculty of Civil Engineering, Department of Geotechnical Engineering, Siping Road 1239, Shanghai, China*
2. *University of Tongji, Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Siping Road 1239, Shanghai, China; 1310300@tongji.edu.cn*

ABSTRACT

C60 class of concrete is produced with addition of hooked-end steel fibres at dosages of 0kg/m^3, 39kg/m^3, 78kg/m^3, 117kg/m^3, and its compressive strength and split tensile strength are measured. The flexural behaviour of high-strength concrete beams containing basalt fibre reinforced polymer (BFRP) rebars and steel fibres is investigated in the present study. An experimental program was set up and seven reinforced concrete beams have been tested, including one series with steel fibres content of 0%, 0.5%, 1.0%, and 1.5% in volume, and one series with ratio of BFRP rebars from 0.38%, 0.57% to 0.76%, 0.95% and tested under four-point flexural loading condition. The result revealed that with the addition of steel fibre, crucial properties of working performance, ductility, and bearing capacity is improved. By increasing BFRP rebar reinforcement ratio, desired ultimate strength is anticipated. Considering the deformability and energy dissipation, a synthesis ductility index for FRP and steel fibre reinforced beams was proposed; while a synthesis ductility index for FRP reinforced flexural structure was also advised. The model of the synthetic ductility index coefficient is verified by relevant experimental data, and was expected to give an insight into the problem of deformability and ductility for the FRP rebar (and steel fibre) reinforced flexural concrete member.

KEYWORDS

BFRP rebar, Steel fibre, High-strength concrete, Flexural capacity; Ductility

INTRODUCTION

The application of fibre reinforced polymer（FRP）bars on reinforced concrete structure has been restricted by its specific characteristics of the lower elastic modulus which is the ratio of elastic stress to strain, linear elastic response and bond performance with concrete. In order to reduce crack width, deflection and mitigate contradiction between durability and workability of FRP structural member, several engineering measures such as mixed reinforcement, pre-stressing technique and fibre concrete has been advised by many scholars to improve the bearing capacity of normal service limit state and ductility. Review of literature shows that limited number of studies were undertaken to investigate the behaviour of concrete beams reinforced with FRP rebar and steel fibre. This paper deals with the flexural capacity of high-strength concrete beams reinforced with BFRP bars and steel fibres, ratio of FRP bars and steel fibre volume fraction is the main study parameter. The variation in steel fibre volume fraction and ratio of FRP bars that affect the working performance, failure mode and ductility of the specimens was studied and discussed. Furthermore, a synthetic ductility index to evaluate and analyse the ductility of FRP and steel fibre reinforced concrete beam was presented, which can provide a new method to estimate relative ductility of FRP (and steel fibre) reinforced concrete flexural member.

THE WORKABILITY AND DUCTILITY OF STEEL FIBER REINFORCED FLEXURAL CONCRETE MEMBER

For the purpose of getting ideal workability and ultimate bearing capacity and limiting deflection and crack width of FRP reinforced concrete structure, some scholars have suggested several engineering measures as follows: improving the property of concrete, adopting hybrid fibre reinforced plastic rebar, applying pre-stressing force on FRP, configuring different modulus of FRP or steel rebar et al. Alsayed and Alhozaimy [1] found that the ductility index increase as much as 100% with the addition of 1% volume steel fibres. Wang and Belarbi [2] tested flexural beams reinforced with fibre-reinforced-concrete. The detailed results showed that addition of fibre improve the flexural properties by increasing the ductility level more than 30% compared with companion specimen. The ductility indices for all the beams were above the minimum requirement of 4. Harris et al. [3] found that the ductility capacity of beams reinforced with hybrid FRP bar were close to that of beams reinforced with steel. Wierschem and Andrawes [4] studied the property of damping and dynamics about SMA-FRP bars. According to test of cantilever beams reinforced with SMA-FRP rebar, the components have good performance of energy dissipate and ductility. SMA-FRP will give a well application foreground when structures applied with dynamic load.

APPRAISAL INDEX ON DUCTILITY OF FRP REINFORCED CONCRETE STRUCTURE

The workability and bearing capacity of FRP reinforced concrete flexural member is limited by some disadvantages such as more wider crack width and larger deflection. Furthermore, ultimate bearing capacity of flexural structure was dominated by FRP strain, bond-anchor property, concrete performance and reinforcement ratio and so on. Through analysis of theory and experiment, scholars proposed three main ductility index and calculation method named energy criterion, deformation and energy-deformation criterion to evaluate the performance of deformation and ductility for FRP reinforced concrete structure.

(1) Energy criterion

Spadea et al. [5] studied several flexural beams designed to failure by FRP rupture. The results are given of theoretical and experimental investigation, which failure mould release large amount of energy. The ductility appraisal index which is the ratio of total energy to elastic energy was advised. The calculation formula was that:

$$\mu_{\mathrm{E}} = \frac{E_{\mathrm{tot}}}{E_{0.75\mathrm{u}}} \tag{1}$$

Where E_{tot} is the total energy, equivalent to the total area under the load-deflection curve up to the failure load, $E_{0.75u}$, the elastic energy, can be estimated from the load-deflection curve of 75% ultimate load.

Naaman and Jeong [6] proposed a ductility index, μ_E, based on the conventional ductility definition, and expressed in terms of a ratio of energies, Equation 2. The total energy, E_{tot}, can be computed as the area under the load deflection curve up to the failure load such as maximum load, failure load, and 80% maximum load so on. E_{ela}, can be estimated from unloading test.

$$\mu_{\mathrm{E}} = \frac{1}{2}\left(\frac{E_{\mathrm{tot}}}{E_{\mathrm{ela}}} + 1\right) \tag{2}$$

If the unloading data are not available, E_{ela} can be calculated as the area of the triangle formed at the failure load by a line with slope S computed by Equation 3.

DOI 10.14311/CEJ.2018.03.0030

$$S=\frac{P_1S_1+\left(P_2-P_1\right)S_2}{P_2} \tag{3}$$

Where P_1 is the cracking load, and P_2 is the yielding load，S is the slope of the unloading branch, S_1, the first line slope, S_2, the second line slope.

(2) Deformability criterion

Jaeger et al. [7] proposed that the ductility could be measured by the ratio of deformation at ultimate and service limit. The ductility index μ_D must take into account of strength and deflection (or curvature), produced by the strength factor C_s and deflection factor C_d (or curvature factor C_c), the strength (or deflection curvature) factor expressed as the product of moment (or deflection, curvature) at ultimate, M_u (or Δ_u, ψ_u), to the moment (or deflection, curvature) at service limit state, $M_{0.001}$ (or $\Delta_{0.001}$, $\psi_{0.001}$) respectively. Also, the service limit state refers to a concrete strain at the compression marginal zone of 0.001. Detailed formula was shown in Equation 4.

$$\begin{gathered}\mu_{\mathrm{D}}=C_{\mathrm{s}}\cdot C_{\mathrm{d}}\ \ (\text{or } C_{\mathrm{c}})\\ C_s=\frac{M_{\mathrm{u}}}{M_{\varepsilon=0.001}};\ \ C_d=\frac{\Delta_{\mathrm{u}}}{\Delta_{\varepsilon=0.001}};\ \ C_c=\frac{\psi_{\mathrm{u}}}{\psi_{\varepsilon=0.001}}\end{gathered} \tag{4}$$

(3) Energy-deformation criterion

Oudah and El-Hacha [8] developed a new ductility model that relates to the deformability of reinforced concrete structure strengthened by using FRP. Through dividing the applied loading into static and monotonic, relevant ductility calculation model was established based on the tri-linear load-deflection response and a bi-linear trend. The ductility can be expressed as the product of the deformability ratio and a compatibility factor defined in Equation 5.

$$\begin{gathered}\mu_{\mathrm{E\text{-}D}}=\frac{E_{\mathrm{tot}}}{E_{\mathrm{ela}}}\cdot\frac{\Delta_{\mathrm{u}}}{\Delta_{\mathrm{y}}}\cdot\frac{\Delta_{\mathrm{y}}}{\Delta_{\mathrm{u}}}=\mu_{\mathrm{d}}\beta;\ \ \mu_{\mathrm{d}}=\frac{\Delta_{\mathrm{u}}}{\Delta_{\mathrm{y}}};\ \ \beta=\frac{E_{\mathrm{tot}}}{E_{\mathrm{ela}}}\cdot\frac{\Delta_{\mathrm{y}}}{\Delta_{\mathrm{u}}}\\ \beta=\begin{cases}\dfrac{S\Delta_{\mathrm{y}}\left[P_{\mathrm{y}}\left(\Delta_{\mathrm{u}}-\Delta_{\mathrm{c}}\right)+P_{\mathrm{u}}\left(\Delta_{\mathrm{u}}-\Delta_{\mathrm{y}}\right)+P_{\mathrm{c}}-\Delta_{\mathrm{y}}\right]}{P_{\mathrm{u}}^2\Delta_{\mathrm{u}}};\ \ \mathrm{S}=\dfrac{P_{\mathrm{y}}-\Delta_{\mathrm{c}}}{\Delta_{\mathrm{y}}-\Delta_{\mathrm{c}}}\\ \dfrac{S\Delta_{\mathrm{y}}\left[P_{\mathrm{y}}\Delta_{\mathrm{u}}+P_{\mathrm{u}}\left(\Delta_{\mathrm{u}}-\Delta_{\mathrm{y}}\right)\right]}{P_{\mathrm{u}}^2\Delta_{\mathrm{u}}};\ \ S=\dfrac{P_{\mathrm{y}}}{\Delta_{\mathrm{y}}}\end{cases}\end{gathered} \tag{5}$$

Where Δ_u is the ultimate deflection, Δ_c is the cracking deflection, Δ_y is the yield deflection, P_u is the ultimate capacity, P_y is the yield capacity, μ_d is the traditional ductility index of deflection, S is the slope of the unloading branch that can be obtained from experimental test or use approximate formula, $\mu_{E\text{-}D}$ is the ductility index, β is the optimum ductility. More information refers to the relevant literature.

As different evaluation indexes of ductility were adopted, the value of ductility index of FRP reinforced concrete flexural member differ considerably. So, the existing problem urges us to understand and evaluate deeply the ductility performance of FRP reinforced structure, forming a relative unified formula of ductility index.

METHODS

Beams specifications

In this research, seven high-strength concrete beams reinforced with BFRP bar and steel fibre were tested monotonically under four point bending. All the beams had a constant crosssection of 150×300 mm and length of 2100 mm. The distance between supports was 1800 mm, and the shear span 600 mm, so the distance between loads was 600 mm shown in Figure 1. The shear span was reinforced with steel stirrups (ϕ6mm/75mm) in order to avoid shear failure and minimize shear effects. In the pure bending zone no stirrups and reinforcement were provided. As a top reinforcement, 2ϕ6 steel rebars were used to hold stirrups in the shear span zone.

The variables of FRP bar ratio and volume fraction of steel fibre were studied by using four different amounts of longitudinal reinforcement and three steel fibre content. One reinforced beam B0 without steel fibre were used for comparison. The geometric and reinforcement details of the beam are shown in Figure 1 and Table 1.

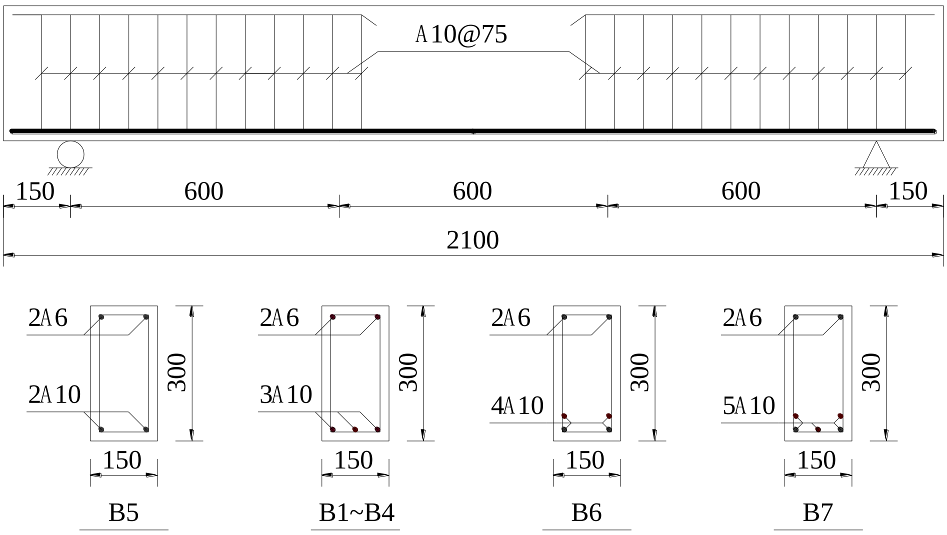

Fig. 1 - Geometric and reinforcement details

Tab. 1 - Geometric characteristics of sections and properties of concrete

Beam ID	B (mm)	H (mm)	Volume Fraction of Steel Fiber (%)	Main Rebar	Compressive Strength fc (MPa)	Splitting Tensile Strength (MPa)
B1	150	300	–	3ϕ10	68.0	3.0
B2	150	300	0.5	3ϕ10	76.2	6.7
B3	150	300	1.0	3ϕ10	81.6	8.9
B4	150	300	1.5	3ϕ10	80.4	10.8
B5	150	300	1.0	2ϕ10	79.6	7.6
B6	150	300	1.0	4ϕ10	80.0	8.0
B7	150	300	1.0	5ϕ10	81.7	8.2

Materials property

High-strength concrete reinforced with steel fibres with 60MPa compressive cubic strength at 28 days were utilized to cast the concrete beams. Table 2 shows the concrete's adopted composition. Cubic specimen having dimensions of 150 mm×150 mm×150mm were also in-situ casted for each beam to perform compressive and splitting tests. The hooked-end steel fibres used in the study were 30 mm in length and 0.55 mm in diameter, aspect ratio 65, and they were known as "Dramix ZP305", whose tensile strength is greater than 1345 MPa, and elastic modulus 200 GPa. BFRP rebars were used as flexural reinforcement. Plain round steel rebars HRB400 were used as top reinforcement and stirrups. The mechanical properties of these rebars were obtained by a uniaxial tension test and are shown in Table 3.

Tab. 2 - Mix proportion of high-strength concrete reinforced with steel fibre

Concrete Strength	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Steel Fiber (kg/m^3)	Superplasticizer (kg/m^3)
C60	146	487	618	1199	–	7.3
CF60	156	520	710	1064	39	7.8
CF60	164	547	696	1043	78	8.2
CF60	164	547	696	1043	117	8.2
CF60	172	573	720	985	156	8.6

Tab.3 - Mechanical properties of BFRP and steel rebar

Material	Diameter (mm)	Elastic Modulus(MPa)	Yield Strength(MPa)	Tensile Strength(MPa)	Elongation (%)
BFRP	10	4.408×10^4	–	951.9	–
HRB400	6	2.020×10^5	512.2	465	0.21

Experimental setup and instrumentation

Each beam was simply supported by reaction frame shown in Figure 2. A hydraulic jack transmitted the load to the test beam by a spreader beam. The load was applied in displacement control mode, and all data was collected by a data acquisition system. Every 5 kN of applied load before beam cracking and 10 kN after cracking, the load applier was paused 10 minutes for the purpose of measure and take note of crack width.

Seven transducers (LVDT and strain gauge based transducers) were used: one at each support, one in the mid-span section, two at 600 mm and two at 800 mm distance from the supports. The mid-span section was instrumented with five concrete strain gauges at side surface of the beam (distributed evenly with 75 mm) to verify the theory of plane-section hypothesis. An instrument of concrete crack width observation was used to measure the development of crack width. Strain gauges were also adopted on the surface of BFRP rebar. These strain gauges were distributed over the shear span length and concentrated in the mid-span zone. All data were automatically measured and stored in the data-acquisition system. The details of test beams and test set-up were shown in Figure 2.

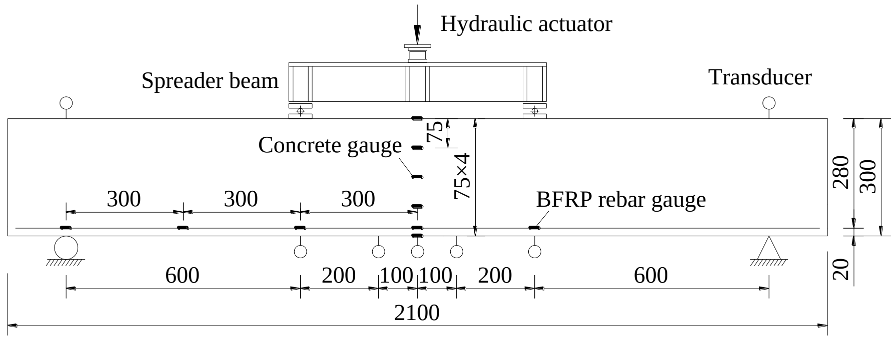

Fig. 2 - Details of test beam and setup

RESULTS

Failure mode analysis

Because of BFRP bars do not exhibit yielding, flexural failure of high-strength concrete beams reinforced with FRP rebar and steel fibre is characterized by either concrete crushing (over-reinforced case) or FRP bar rupture (under-reinforced case).

Under-reinforced failure case B2 ~ B6, BFRB reinforced beams with reinforcement ratio less than balanced reinforcement ratio, their failure started due to increasing of deflection followed by BFRP rupturing. On the other hand, the beam B8 was over-reinforced section which failure mode was duo to concrete crushing, with deflections reaching values more than 50 mm. Tensile rupture of the reinforcing BFRP and concrete crush were depicted in Figure 3.

(a) *B2~B6 BFRP rupture*

(b) *B7 concrete crush*

Fig. 3 - Typical failure mode of beams tested

The flexural capacity with different steel fibre volume fraction

An experimental load–deflection relation derived from the measurement of midspan transducer is shown in Figure 4 and Table 4, indicates the comparison of high–strength concrete beams with steel fibre and plain concrete beam. With the addition of steel fibre, concrete beams show steeper slope in the ascending part of the load-displacement, which means the beams possess higher flexural rigidity. When increase steel fibre volume fraction with 0.5%, 1.0% and 1.5%, the series of B2 ~ B4 revealed that percentage increase in flexural capacity of the high-strength concrete beams reinforced with BFRP rebars and steel fibre are 2.1%, 23.6% and 16.8%, percentage increase in servicing capacity is 75%, 100% and 125%, and percentage increase in cracking load is 25%~50%, through contrast with plain concrete reinforced beam B1 respectively.

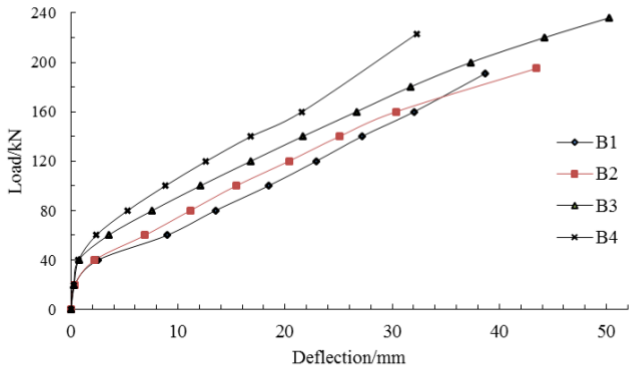

Fig. 4 - Load-deflection relationship for different dosages of steel fibre

Tab. 4 - Cracking load, servicing load and flexural ultimate strength

Beam ID	Dosage of Steel Fibre(kg/m^3)	Main Rebar	Cracking load (kN)	load refer to crack width 0.7mm (kN)	Ultimate strength (kN)
B1	–	3ϕ10	20	40	191
B2	39	3ϕ10	30	70	195
B3	78	3ϕ10	30	80	236
B4	117	3ϕ10	25	90	223
B5	78	2ϕ10	25	60	167
B6	78	4ϕ10	30	83	260
B7	78	5ϕ10	25	105	310

The flexural capacity with different reinforcement ratio of FRP bars

As shown in Figure 5 and Table 4, with the increase of BFRP reinforcement ratio 0.38%, 0.57%, 0.76% and 0.95%, the ultimate loads of the high-strength concrete beams reinforced with BFRP rebar and steel fibre increase from 167 kN to 195 kN, 260 kN and 310 kN respectively, while the servicing loads increase from 60 kN to 70 kN, 83 kN and 105kN, respectively.

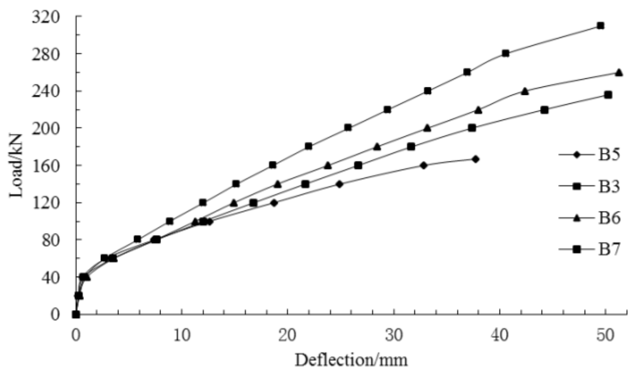

Fig. 5 - Load-deflection relationship for different reinforcement ratio of BFRP bars

SYNTHESIS DUCTILITY COEFFICIENT

Analysis on deformity and ductility of FRP reinforced flexural concrete member

From the viewpoint of mechanics, FRP bars and concrete bear the applied loading together before cracking. After cracking, the stress shifts from the concrete to FRP bar rapidly. There is a sudden change on the stress of FRP bar. The deformability and bearing capacity of FRP structure is mainly controlled by the strain of FRP. Accompanying with load-deflection curve appears inflection point, the deformation rate grows steadily. Before failure, the performance of structure on bond and anchor gradually degraded. Deformation rate of structure become larger and tend to presents unsteady growth. The ultimate bearing capacity mainly depended on the properties of concrete and FRP bar. In addition, FRP bar has a weak shear capacity and bond stress, implying less influence on the circumference concrete. The fatigue is interior fabricate-dependent. So, the influence factor mentioned above increases the complexity of ductility analysis.

From the viewpoint of bond performance, the property of deformation and ductility for FRP reinforced structure substantially depend on the bond behaviour between FRP and concrete. Cosenza and Manfredi et. al. [9-10] put forward that bond stress was transferred by means of the mechanical interlocking of the concrete and steel, and the bond action depending on the coefficient of friction. Bi [11] explored anchorage length, type and diameter of FRP bar, and concrete strength grade upon the bond performance and degrade trend for FRP reinforced concrete structure. The result reveals that these factors mentioned above can influence parameter of deformability and ductility for flexural member relatively. Belarbi [12] discovered that fiber reinforced concrete could improve the degrading trend of FRP bar and concrete remarkably. Especially bond property closely related to the tensile strength of FRP.

From the viewpoint of failure model, brittle fracture was found when different loading applied on FRP reinforced structure. It was obvious that the failure model of FRP reinforced structure which will dissipate large elastic energy. The failure process was dramatic. The bearing capacity of structure lost rapidly, it cannot provide sufficient warning. The other failure model of concrete crushing, due to the concrete property of elastic-plastic, proportional energy was dissipated gradually present preferable ductility. Large deformation of FRP reinforced structure does not imply better performance of ductility contrast to conventional steel reinforced concrete beam. Conventional evaluation model cannot be applied to FRP reinforced flexural member. Consequently, Taniguchi [13] proposed that the failure model of concrete crushing gained a better ductility, which provided apparent sufficient warning compared to FRP fracture.

Synthesis ductility coefficient for FRP and steel fibre reinforced beams

Research showed that the steel fibre substantially enhances the flexural property, toughness and crack resistance in the service limit state. Some tensile loads can be transferred across the cracks by the bridging function of fibre, which make the process of stress transferring from concrete to FRP bar more smoothly, so it is beneficial to gain better workability and ideal failure model of concrete crushing.

The synthetic ductility model for FRP and steel fibre reinforced beams is based on full analysis of research achievements and expressed as the product of deformability factor μ_Δ, the ratio of deflection at ultimate, Δ_u, to the defection at service limit state, Δ_w=0.7 mm, and energy factor and the ratio of total energy, E_{tot}, can be calculated as the area under the load-deflection curve up to the load defined as the failure load, while the elastic energy, E_{ela}, can be estimated from unloading test. The service limit state corresponds to crack width at the tensile marginal zone for concrete was defined as 0.7mm.

Typical load-deflection curve for FRP rebar and steel fibre reinforced flexural concrete member was adopted, shown in Figure 6. The synthetic ductility index for FRP rebars and steel fibre reinforced beams defined as follows:

$$\begin{cases} \mu_s = \mu_\Delta \cdot \mu_e \\ \mu_\Delta = \dfrac{\Delta_u}{\Delta_{w=0.7}}; \quad \mu_e = \dfrac{E_{ela}}{E_{tot}} \\ E_{tot} = \dfrac{1}{2}\left[P_c \cdot \Delta_c + (P_c + P_u)\cdot(\Delta_u - \Delta_c)\right] \\ E_{ela} = \dfrac{1}{2}\cdot\dfrac{P_u^2}{S}; \quad S = \dfrac{P_{w=0.7}S_1 + (P_u - P_{w=0.7})S_2}{P_u} \end{cases} \tag{6}$$

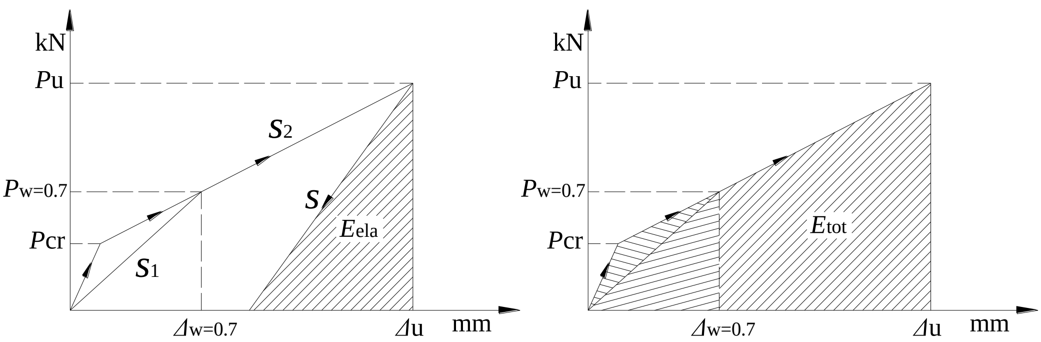

Fig. 6 - Typical load-deflection curve for FRP rebar reinforced flexural concrete member

Where μ_s is the synthetic ductility index, μ_Δ is the deformability factor, μ_e is the energy factor, Δ_u is the deflection of ultimate load (mm), Δ_c is the deflection for cracking load (mm), $P_{w=0.7}$ is the load for service limit state corresponds to mid-span crack width at the tensile marginal zone for concrete was defined as 0.7 mm (kN), P_u is the ultimate bearing capacity (kN), E_{ela} is the dissipated elastic energy of FRP, obtained from unloading experiment (kN·mm), E_{tot} is the total energy (kN·mm), virtually the area of load-deflection curve, S is the slope of the unloading branch, S_1 is the first line slope, S_2 is the second line slope.

Experimental data of load-deformation was gathered and analysed, which revealed the different influence factors of steel fibre volume fraction and ratio of FRP rebar. Based on data collected, the synthetic ductility index of high-strength concrete beams reinforced with BFRP rebars and steel fibre was communicated and presented respectively. Detailed results were shown in Table 5.

Tab. 5 - The synthetic ductility index for BFRP rebars and steel fibre reinforced beams

Beam ID	$P_{w=0.7}$ (kN)	P_u (kN)	$\Delta_{w=0.7}$ (mm)	Δ_u (mm)	μ_Δ	S	E_{tot} (kN.mm)	E_{ela} (kN.mm)	μ_e	μ_s	Failure model
B2	70	195	9.02	43.45	4.82	5.11	3712.4	4128.3	0.90	4.34	FR
B3	80	236	7.59	50.26	6.62	5.99	5235.8	5879.2	0.79	5.24	--
B4	90	223	7.04	32.28	4.59	8.30	3242.6	3557.6	0.84	3.86	--
B6	83	260	8.69	51.25	5.90	5.88	5978.3	6587.8	0.87	5.15	--
B7	105	310	9.66	49.57	5.13	7.08	7107.1	7643.5	0.89	4.56	CC

Note: CC: concrete crushing, FR: FRP rupture.

The reasons of improving ductility for high-strength concrete beams reinforced with BFRP and different dosage of steel fibre could be explained exactly that: the steel fibre can take proportional stress, which delayed the development trend of crack width, remarkably improved the service capacity. For BFRP reinforced beams which contain constant 1% volume ratio of steel fibre, the ductility improved through increase the ratio of FRP reinforcement. After balanced reinforcement, BFRP-reinforced beams have the trend to degrade ductility, because fail model is controlled by the property of steel fibre reinforced concrete.

Synthesis ductility coefficient for FRP reinforced beams

The synthetic ductility factor takes into account the factor of nonlinear characteristics of concrete and FRP rebar, state of stress delivery from FRP to concrete and potential ultimate bearing etc. The energy factor is related to the storage of elastic energy, the tendency of bond deterioration and nonlinear property of the compression zone. Essentially, the deformability and ductility for FRP reinforced concrete beams highly depends on the property of FRP, elastic-plastic property for concrete and bond performance between them. While such factor of failure mode of concrete crushing and reasonable FRP ultimate strain is help for the better deformability and ductility of FRP reinforced concrete flexural member. Thus, the synthetic ductility index model relates to the deformability and the energy dissipated more reasonably.

The formula of synthetic ductility index for FRP reinforced concrete beams is similar to Equation 6, only two parameters $P_{w=0.7}$ and $\Delta_{w=0.7}$ are changed with $P_{\varepsilon=0.001}$ and $\Delta_{\varepsilon=0.001}$, which defined as the load and defection at service limit state. The service limit state corresponds to concrete strain at marginal tensile zone was defined as 0.001 mm. If relevant data are not available, for normal concrete, $P_{\varepsilon=0.001}$ can be estimated in the following Equation 7, Where f_{cu} is the cubic concrete compressive strength, based on the test of compressive strength.

$$P_{\varepsilon=0.001}=1.9f_{cu}^{3/4} \quad P_{\varepsilon=0.001}=3.0f_{cu}^{2/3} \quad P_{\varepsilon=0.001}=4.1f_{cu}^{2/3} \tag{7}$$

When the value of $P_{\varepsilon=0.001}$ is got, then calculate the values of Δ_c and $\Delta_{\varepsilon=0.001}$ respectively. Detailed procedures refer to the Equation 8 and current code ACI 440.

$$\begin{cases} \Delta_{c,\varepsilon=0.001} = \dfrac{Pa}{24E_c I_e}(3L^2 - 4a^2) + \dfrac{Ph^2 a}{10GI_e} \\ I_e = I_g \quad \text{when } M_\alpha \le M_{cr} \\ I_e = \left(\dfrac{M_{cr}}{M_a}\right)^3 \beta_d I_g + \left[1 - \left(\dfrac{M_{cr}}{M_\alpha}\right)^3\right] I_{cr} \le I_g \quad \text{when } M_\alpha > M_{cr} \end{cases} \tag{8}$$

Also E_{tot} can be calculated as the area of the bi-linear curve formed by the failure load. Where $\Delta_{\varepsilon=0.001}$, the deflection for service limit state corresponds to the strain 0.001 of marginal compression concrete fibre (mm). More information is shown in Figure 7 and Equation 9.

$$E_{tot} = \frac{1}{2}\left[P_{\varepsilon=0.001} \cdot \Delta_{\varepsilon=0.001} + (P_{\varepsilon=0.001} + P_u) \cdot (\Delta_u - \Delta_{\varepsilon=0.001})\right] \tag{9}$$

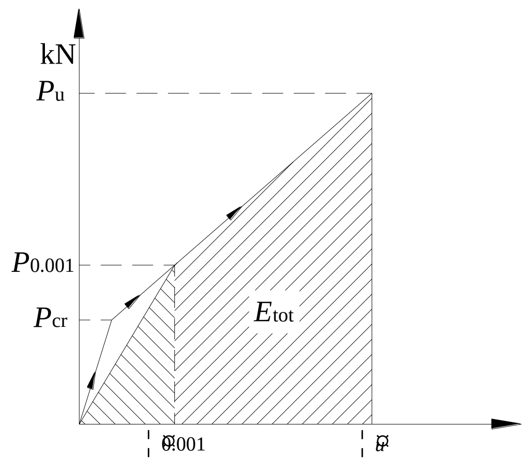

Fig. 7 - The graph of approximate formula on E_{tot}

In order to reduce crack width, deflection and mitigate contradiction between durability and workability of FRP reinforced flexural member, several engineering measures such as mixed reinforcement, pre-stressing technique were proposed by many scholars to improve the capacity of deformation and ductility on FRP reinforced concrete beams. Based on data gathered, the synthetic ductility index for FRP rebars reinforced flexural concrete member was communicated and analysed respectively. Detailed results were shown in Table 6.

*Tab. 6 - The synthetic ductility index for FRP rebars reinforced flexural concrete member**

Beam ID	$P_{\varepsilon=0.001}$ (kN)	P_u (kN)	$\Delta_{\varepsilon=0.001}$ (mm)*	Δ_u (mm)	μ_Δ	S	E_{tot} (kN.mm)	E_{ela} (kN.mm)	μ_e	μ_s	Failure model
	$\mu_\Delta=\Delta_u/\Delta_{\varepsilon=0.001}$; $\mu_e=E_{ela}/E_{tot}$; $\mu_s=\mu_\Delta\cdot\mu_e$										
GL-2-0[14]	22.4	66.1	8.9	50.0	5.62	1.56	1918.4	1404.1	0.73	4.11	CC
GL-3-0[14]	39.8	88.4	12.8	42.9	3.35	2.29	2184.1	1708.0	0.78	2.62	
GL-3-2[14]	31.4	72.0	12.3	45.0	3.66	1.81	1883.7	1429.3	0.76	2.78	
LGL-2-2[14]	29.0	67.5	7.4	35.7	4.82	2.46	1472.8	926.2	0.63	3.03	
LGL-2-4[14]	27.7	76.0	6.0	27.2	4.62	3.13	1182.3	922.5	0.78	3.60	
LGL-3-3[14]	41.5	79.2	11.6	39.1	3.37	2.53	1900.3	1241.0	0.65	2.20	
YRGL-1[15]	70	90	14.5	37.4	2.58	3.95	2339.5	1025.6	0.44	1.13	CC
YRGL-2[15]	90	110	13.3	28.7	2.16	5.77	2138.5	1048.0	0.49	1.06	FR
YRCL-1[15]	80	100	11.5	27.6	2.40	5.81	2125.0	860.0	0.40	0.97	CC
YRCL-2[15]	80	140	6.0	23.1	3.85	9.12	2121.0	1074.2	0.51	1.95	
CFRP+ GFRP[16]	70	120	20	63	3.15	2.53	6535.0	2850.2	0.44	1.37	CC

CC: concrete crushing, FR: FRP rupture.

GFRP bar reinforced beams [14] with failure model of concrete crushing have better ductility. More FRP bar and reinforcement embed in compressed area is contributed to the improvement of FRP structure on the synthetic ductility index, especially for continuous beam. By increasing the amount of steel at tensile zone and compression region simultaneously, the value of ductility index declined obviously.

Pre-stressed FRP reinforced flexural member [15] could remarkably increase the cracking load, reduce crack width and deflection at the service limit state. The more degree of pre-stressing force means better effect. The synthetic ductility index of pre-stressed FRP reinforced flexural member is closely related to the modulus and pre-stressing force degree of FRP. Pre-stressed CFRP reinforced beams have worse ductility. Fabricated FRP (different modulus) reinforced beams have better synthetic ductility [16] contrast with Pre-stressed FRP reinforced flexural member.

CONCLUSION

Mechanical behaviours of high-strength concrete beams reinforced with steel fibre and BFRP rebar are investigated in this study. By analysing working performance, ultimate bearing capacity and synthetic ductility index, the following conclusions may be drawn from the present work.

The compressive strength and splitting tensile strength of high-strength concrete improved with additions of steel fibre at various volume fractions. Increase steel fibre volume content from 0.5% to 1.5%. The compressive strength grows from 12.1% to 18.7% and 18.2% contrast with plain concrete. While, splitting tensile strength grows from 61.6% to 173.3% and 260% with the same steel fibre volume.

For high-strength concrete beams reinforced with BFRP rebar and steel fibre, there is an increase of 2.1%, 23.6% and 16.8% higher than beams without steel fibre was observed in flexural capacities when fibre content is increased from 0.5% to 1.5% by volume. Meanwhile, the serving load increase with range from 75%, 100% and 125% and the cracking load increase from 25% to 50%.

Reinforcement ratio of BFRP rebar is a key factor influence bearing capacity and failure mode of high-strength concrete beams reinforced with steel fibre. When keep the addition of 1% in volume steel fibre constant, increase reinforcement ratio of BFRP rebar 0.57%, 0.76% and 0.95%, the ultimate strength is improved by about 16.8, 55.7 and 85.6% and the servicing load is increased by 33.3%, 38.3% and 75% compared with contrast specimen.

Improving the property of concrete regarded as an effective measure to get the desired ductility capacity for flexural member. Under the condition of appropriate reinforcement ratio and steel fibre volume, the synthetic ductility indices of steel fibre reinforced concrete reinforced with FRP rebar are above the minimum requirement of $\mu_c \geq 4$. The synthetic ductility of double reinforced beam possess better capacity of deformation and ductility. Pre-stressed FRP bar reinforced concrete beam and hybrid FRP reinforced flexural member have poor synthetic ductility performance due to the deteriorate capacity of ultimate bearing.

Due to ignoring the factor of load types and insufficient data, the analysis of statistical and uncertainty are not done. Therefore, we need to conduct additional analytical, structural innovation and experimental research to optimize the deformability and ductility of FRP reinforced structure. Furthermore, based on the demand bearing capacity, deflection and crack width, we need to develop various types of FRP strengthening systems to ensure desired adequate ductility and deformability at different situation.

ACKNOWLEDGEMENTS

The investigation of this paper was supported by the National Natural Science Foundation of China (Grant No. 41572285 and No. 51178433).

REFERENCES

[1] Alsayed S H, Alhozaimy A M. Ductility of concrete beams reinforced with FRP bars and steel fibers. Journal of composite materials 1999; 33(19):1792-1806.

[2] Wang H, Belarbi A. Ductility characteristics of fiber-reinforced-concrete beams reinforced with FRP rebars. Construction and Building Materials 2011; 25(5): 2391-2401.

[3] Harris H G, Somboonsong W, Ko F K. New ductile hybrid FRP reinforcing bar for concrete structures. Journal of composites for construction 1998; 2(1): 28-37.

[4] Wierschem N, Andrawes B. Super-elastic SMA-FRP composite reinforcement for concrete structures. Smart Materials and Structures 2010; 19(2): 025011.

[5] Spadea，G.，Bencardino，F. And Swamy, R.N. Strengthening and upgrading structures with bonded CFRP sheets. Design Aspects for Structural Integrity，Proceeding of the 3rd International RILEM Non-Metallic (FRP) for Concrete Structures. Sapporo, Japan; 1997. p. 379-386.

[6] Naaman AE，Jeong SM. Structural ductility of concrete beams prestressed with FRP tendons. In：Proceedings of the second international RILEM symposium (FRPRCS-2): Non-metallic (FRP) for concrete structures. Ghent, Belgium; 1995. P. 379-86.

[7] Jaeger L G, Mufti A A, Tadros G. The concept of the overall performance factor in rectangular-section reinforced concrete members. Proceedings of the 3rd International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures, Sapporo, Japan; 1997. 2: 551-559.

[8] Oudah F, El-Hacha R. A new ductility model of reinforced concrete beams strengthened using fiber reinforced polymer reinforcement. Composites Part B: Engineering 2012; 43(8): 3338-3347.

[9] Cosenza. E, Manfredi. G. and Realfonzo. R. Behaviour and modeling of bond of FRP rebars to concrete, Compos. For Constr., ASCE, 1997; 1(2):40-51.

[10] Cosenza E, Manfredi G, Realfonzo R. Analytical modeling of bond between FRP reinforcing bars and concrete. Proc. 2nd Int. RILEM Symp. (FRPRCS-2), L. Taerwe, ed; 1995.

[11] Bi Q W. Experimental Research on the Micro-structure of Basalt Fiber Reinforced Concrete and the Oblique Section Bearing Capacity of the BFRP bars Reinforced fiber Concrete Beams. D.E. thesis, Dalian University, Dalian; 2012. (in chinese)

[12] Belarbi A, Wang H. Bond durability of FRP bars embedded in fiber-reinforced concrete. Journal of Composites for Construction 2011; 16(4): 371-380.

[13] Thniguchi. Grace. Response of continuous CFRP Pre-stressed concrete bridges under static and repeated loadings. PCI Journal 2000; 45(6): 84-102.

[14] Qi A, Weng C.G. Experimental Study on Ductility Behavior of Concrete Beams Reinforced with FRP rebars. Earthquake Resistant Engineering and Retrofitting, 2008, 29(5): 63-67. (in chinese)

[15] Yuan J F. Analysis on Flexural Behavior of Concrete Beam Reinforced with FRP bars. M.E. thesis, Southeast University, Nanjing; 2007. (in chinese)

[16] Yang J. Experimental Study and Theoretical Analysis on Concrete Beams Reinforced with Different FRP Bars Blended. M.E. thesis, Chongqing University, Chongqing; 2013. (in chinese)

DOI 10.14311/CEJ.2018.03.0030