1. Introduction

Carbon fibre reinforced polymers (CFRP) have been increasingly used to strengthen reinforced concrete (RC) structures in recent decades due to their excellent characteristics, such as high strength-to-weight ratio and good corrosion resistance (Chen et al. 2003; Dai et al. 2005; Täljsten and Blanksvård 2007; Ueda et al. 2002; Ueda and Dai 2005; Varastehpour and Hamelin 1997; Wang et al. 2011; Zhang et al. 2018). Externally bonding a CFRP sheet or plate on the tension face of deficient RC beams or slabs can substantially improve their flexural behaviour (Aram et al. 2008; Chajes et al. 1995; Hawileh et al. 2013). Although this strengthening technique is easy to implement, premature debonding failure is a critical defect due to the brittle failure nature (Aram et al. 2008; Colombi et al. 2014; Chen and Teng 2001; Dror and Rabinovitch 2016; Oehlers and Moran 1990; Sebastian 2001). As a result of such debonding failures, the excellent mechanical properties of CFRPs are far from being fully utilized. More importantly, the safety of CFRP-strengthened RC members is limited by the poor reliability of the bonding (Degala et al. 2009; Hong and Harichandran 2005; Lee and Park 2012; Tahhan and Al-Mahaidi 2014).

An extensive number of studies have performed interfacial stress analyses of fibre reinforced polymer (FRP)-strengthened RC beams to reveal the debonding mechanism in such structures (Dai et al. 2007; He et al. 2020; Pan and Wu 2014; Täljsten 1996; Tounsi et al. 2009), in which the stress concentration at the ends of the FRP laminate due to stiffness imbalance was considered the main reason for end debonding (Chen et al. 2007; Deng et al. 2004; Teng et al. 2006; Teng and Yao 2007; Yao and Teng 2007; Yang and Wu 2007). Many attempts have been made to prevent debonding failure in FRP-strengthened RC structures. The debonding of the strengthened RC beams is commonly prevented by using U-shaped FRP sheets to improve the anchorage of externally bonded CFRP laminates. The effects are obvious when the U-sheets are sufficient and well arranged, which indicates the importance of a rational design (Fu et al. 2017). However, under hygrothermal or other harmful conditions, the bond between the CFRP sheet and the concrete may deteriorate, which poses a threat to the safety of the strengthened structures (Böer et al. 2014; Dong and Hu 2016; Ferrier et al. 2016; Karbhari and Ghosh 2009; Khan et al. 2010; Mahmoud et al. 2011; Pan et al. 2015; Sen 2015; Wu et al. 2005; Zhang et al. 2012; Zheng et al. 2015). Hence, it is necessary to explore alternative methods, including me-
mechanical anchorage (El Maaddawy and Soudki 2008; Kalfat et al. 2013; Skuturna and Valivonis 2016; Wang and Zhou 2017; Zhou et al. 2017).

FRP anchors are effective in preventing debonding (Kim and Smith 2010; Smith et al. 2011, 2017), but when these devices are applied through a CFRP sheet for strengthening, it must cut or modify a part of the fibre sheet, which will reduce the entire tensile capacity of the CFRP sheet. Lamanna et al. (2004) used fasteners to anchor a CFRP plate to strengthen RC beams. Despite being significantly effective, the CFRP plate must be specifically manufactured to prohibit the splitting of the CFRP plate. A pair of wave-shaped tooth devices was developed by Zhuo (2004) to enhance the end anchorage of the CFRP sheet or plate, which helped the beam achieve good flexural performance. In addition, Wu et al. (2010) proposed a strain localization plating system to anchor CFRP laminates, and it was very effective to avoid intermediate crack (IC) debonding. However, when the width of the section is limited for an RC beam, some of these methods are not applicable, such as the last two methods described above. To reduce the adverse effect of bonding deterioration due to fatigue loading or harsh environments, the authors developed an anchorage device that could achieve the self-locking of the CFRP sheet by wrapping the ends of the sheet around twin rods. When one drills the bolt holes used to install the device, the tensile rebars within the RC beam must be avoided. The anchorage device can be implemented on the bottom of the beam if there is sufficient width. However, for narrow beams, installing the anchorage device on the bottom of the beam does not leave sufficient width for the CFRP sheet; thus, an anchorage approach was proposed for the sides of the beam (see Fig. 1) (Zhou et al. 2012a, 2012b, 2018). First, the end of the CFRP sheet is wrapped around twin rods with a specific route and straightened to achieve self-locking while externally bonding to the RC beam. Then, the twin rods, which are connected to a pair of L-shaped brackets, can be bolted to the side of the RC beam. During loading, the tension face of the RC beam will elongate, and the CFRP sheet will be increasingly tightened under tensile stress because of self-locking. Thus, the mechanical anchorage device can work with the CFRP and the RC beam. This anchorage method is referred to as mixed anchorage or hybrid anchorage. In theory, unlike conventional bonding, this method does not have severe interfacial shear stress concentrations since the CFRP can bear large longitudinal tensile stress at the end. Therefore, the proposed method is beneficial to prevent CFRP end debonding and restrain the late development of IC debonding failure.

In this paper, four-point bending tests were performed to study the flexural performance of narrow RC beams strengthened with externally bonded CFRP sheets installed with the proposed end anchorage device. The effects of the concrete strength grade, CFRP width, and adhesive injection into the anchorage device were discussed. The adhesive injection means that the end of the CFRP sheet wrapped on the twin rods was soaked with adhesive to provide better end-anchorage effects. Then, the applicability of the existing methods for predicting the characteristic moments was examined based on the test results.

![End anchorage and Self-locking of strips](image)

Fig. 1 Anchorage device and the self-locking of strips by winding around twin rods.
2. Experimental programme

An experimental study was conducted to investigate the strengthening effect of the hybrid anchorage system. Three parameters were considered in the test: CFRP width, concrete strength grade and adhesive injection at the anchorage. Compared with the reference specimen (without CFRP strengthening), the four CFRP-strengthened specimens with the end-anchorage system can be divided into two types. The experimental flow chart is shown in Fig. 2, and the specimen arrangement is presented in Table 1.

In this study, the anchorage device is specially designed for the strengthening of narrow RC beams. Because the beam bottom lacks sufficient width, L-shaped brackets are designed for the side anchorage. As shown in Fig. 1, holes are produced in the anchor plate for the bolts and twin rods. Since the concrete in the compression zone is essential to the characteristic moments, damage should be avoided when drilling holes for anchorage device implementation. The height of the beam is 300 mm. To avoid damage to the concrete in the compression zone, the distance from the bolt centre to the boundary of the side plate is set to 100 mm, which is below the neutral axis. The diameters of the bolts and twin rods are 14 mm and 12 mm, respectively, which are determined to ensure that shear failure of the bolt or bending failure of the rods will not occur during loading. The CFRP sheets easily break when the rods are bent. However, the diameter of the twin rods in this study is sufficiently large to avoid immature breakage of the CFRP sheet under non-uniform tensile stresses. Additionally, it is worth mentioning that this is still a preliminary study, and the purpose is to confirm the feasibility of using this type of hybrid anchorage system. A parametric analysis could be carried out in the future to examine critical values for the strengthening design and to optimize the anchorage system.

2.1 Specimen design and preparation

Simply supported RC beams with rectangular sections were tested in this study, and the dimensions of the

| Specimen No. | CFRP width (mm) | Anchorage with adhesive | Cracking load $P_c$ (kN) | Yield load $P_y$ (kN) | Ultimate load $P_u$ (kN) | Ultimate crack width (mm) | Average flexural crack spacing (mm) | Failure mode* |
|--------------|-----------------|-------------------------|--------------------------|----------------------|-------------------------|--------------------------|----------------------------------|--------------|
| DM-C         | -               | -                       | 19                       | 80                   | 84                      | 3.00                     | 257                              | C            |
| DMJ-50       | 50              | Yes                     | 22                       | 86                   | 106                     | 2.55                     | 218                              | D>C          |
| DMJ-100      | 100             | Yes                     | 22                       | 91                   | 111                     | 2.63                     | 210                              | D>C          |
| DM-50        | 50              | No                      | 30                       | 95                   | 135                     | 1.95                     | 198                              | D>C          |
| DM-100       | 100             | No                      | 30                       | 96                   | 151                     | 1.80                     | 190                              | D>C          |

*Note: Failure modes are indicated by the following symbols.
C: concrete crushing; D>C: concrete crushing after CFRP debonding; D+C: concrete crushing during CFRP debonding.
CFRP sheet was Sikadur-330 (Sika Ltd.). Two CFRP widths (50 mm and 100 mm) were adopted. The mechanical properties of each material are presented in Table 2.

For the RC beams strengthened with the hybrid anchorage, the work procedure for specimen Type II involved surface treatment, wrapping the CFRP sheets on the twin rods, bonding the CFRP sheet to the concrete with adhesive, and anchoring the L-shaped brackets on the side of the RC beams. For specimen Type III, adhesive injection was applied in the second step. Without adhesive injection, the self-locking of the CFRP sheets was achieved completely through surface friction. There was no sliding between the strips and the twin rods when the outer layer of strips was under tension. In this study, to understand the effect of the self-locking anchorage, the case without adhesive injection was also studied. After adhesive injection, in addition to physical friction, the combination between the CFRP sheet and the anchorage device could be further enhanced due to chemical bonding. This could be an additional measure to ensure reliable anchorage, but whether it is necessary remains unclear and requires experimental verification.

The anchorage system is specially designed for narrow RC beams, and the application method has been described in detail in Section 1. By using a specific route, the end of the CFRP sheet was wrapped around the twin rods. While externally bonding the CFRP sheets to the RC beam, the CFRP sheet was straightened to achieve self-locking. As shown in Fig. 1, a pair of L-shaped brackets connected to the twin rods were bolted on the side of the RC beam.

As shown in Fig. 3, in the tested beams, strain gauges were attached at the centre of two longitudinal rebars under tension. In the compression area of the concrete, the strain gauges were attached at different heights in the mid-span. The strain gauges were also attached on the surface of the CFRP sheet in the longitudinal direction. All strain values were collected with data loggers, which were connected to a computer. To obtain the deformation at the mid-span of the tested beam during loading, linear variable differential transformers (LVDTs)

| Material   | Yield strength $f_y$ (MPa) | Ultimate strength $f_u$ (MPa) | Yield (ultimate) strain $e_y$ ($\times 10^6$) | Elastic modulus $E$ (GPa) |
|------------|-----------------------------|-------------------------------|-----------------------------------------------|---------------------------|
| Concrete   | 20.07                       | 29.6                          | 0.752                                        | 330                       |
| Steel rebar| 360                         | 544.3                         | 1800                                         | 200                       |
| CFRP sheet | 242.2                       | 356.7                         | 1153.3                                       | 210                       |

*Note: The the ultimate strength of concrete is the compressive strength of a standard cubic concrete sample.

specimens were shown in Fig. 3. The cross section dimensions were 150 mm × 300 mm (b × h), the beam length was 2000 mm, and the span was 1900 mm. The main tensile reinforcement was 2Φ14 (A = 308 mm² and $\rho_s = 0.752\%$) HRB335 rebars, the erection reinforcement was 2Φ12 HRB335 rebars, and the concrete cover was 20 mm thick. The stirrups were φ8@100 mm HPB235 rebars. Ordinary Portland cement (R32.5) was used for the concrete, and the target compressive strength values were 20 MPa (C20) and 30 MPa (C30), which were used in the Type-III and Type-II specimens, respectively, as shown in Fig. 2. Medium sand was used for the fine aggregate, and the maximum size for the coarse aggregate (gravel) was 20 mm. The mixture mass ratios for the concrete was cement: sand: gravel: water = 1: 1.67: 3.89: 0.5 (C20) or 1: 1.268: 3.105: 0.41 (C30).

In total, five RC beams were prepared as described. One beam without CFRP strengthening was set as the reference, and the other four beams adopted the mentioned strengthening technique. Among the beams strengthened with an anchorage, two beams had adhesive injected in the anchor, and the other two did not. The CFRP sheet and adhesive were produced by Sika. The nominal thickness of the CFRP sheet was 0.167 mm, and the length was 1600 mm. The type of adhesive was Sikadur-330 (Sika Ltd.). Two CFRP widths (50 mm and 100 mm) were adopted. The mechanical properties of each material are presented in Table 2.

For the RC beams strengthened with the hybrid anchorage, the work procedure for specimen Type II involved surface treatment, wrapping the CFRP sheets on the twin rods, bonding the CFRP sheet to the concrete with adhesive, and anchoring the L-shaped brackets on the side of the RC beams. For specimen Type III, adhesive injection was applied in the second step. Without adhesive injection, the self-locking of the CFRP sheets was achieved completely through surface friction. There was no sliding between the strips and the twin rods when the outer layer of strips was under tension. In this study, to understand the effect of the self-locking anchorage, the case without adhesive injection was also studied. After adhesive injection, in addition to physical friction, the combination between the CFRP sheet and the anchorage device could be further enhanced due to chemical bonding. This could be an additional measure to ensure reliable anchorage, but whether it is necessary remains unclear and requires experimental verification.

The anchorage system is specially designed for narrow RC beams, and the application method has been described in detail in Section 1. By using a specific route, the end of the CFRP sheet was wrapped around the twin rods. While externally bonding the CFRP sheets to the RC beam, the CFRP sheet was straightened to achieve self-locking. As shown in Fig. 1, a pair of L-shaped brackets connected to the twin rods were bolted on the side of the RC beam.

As shown in Fig. 3, in the tested beams, strain gauges were attached at the centre of two longitudinal rebars under tension. In the compression area of the concrete, the strain gauges were attached at different heights in the mid-span. The strain gauges were also attached on the surface of the CFRP sheet in the longitudinal direction. All strain values were collected with data loggers, which were connected to a computer. To obtain the deformation at the mid-span of the tested beam during loading, linear variable differential transformers (LVDTs)

Table 2 Properties of the selected materials.

| Material   | Yield strength $f_y$ (MPa) | Ultimate strength $f_u$ (MPa) | Yield (ultimate) strain $e_y$ ($\times 10^6$) | Elastic modulus $E$ (GPa) |
|------------|-----------------------------|-------------------------------|-----------------------------------------------|---------------------------|
| Concrete   | 20.07                       | 29.6                          | 0.752                                        | 330                       |
| Steel rebar| 360                         | 544.3                         | 1800                                         | 200                       |
| CFRP sheet | 242.2                       | 356.7                         | 1153.3                                       | 210                       |

*Note: The the ultimate strength of concrete is the compressive strength of a standard cubic concrete sample.
were placed on the supports and at the loading positions.

2.2 Four-point bending tests
The testing setup and loading control device are shown in Fig. 4. To better observe the cracking and debonding process, inverse four-point bending tests were conducted. The tension face of the RC beams was oriented to face upwards, and the supports were placed on the two sides with a distance of 1900 mm. The compression face was oriented to face downwards, and the supports were placed at the middle with a distance of 600 mm. A steel spreader beam, which had a high stiffness, was located above the upper supports for load transfer. A hydraulic jack with a capacity of 50 tons was placed at the mid-span of the steel spreader beam, and there was a load cell on top of the jack. By controlling the load cell, the loading will be stopped at different load levels. To better capture the cracking load, yielding load and ultimate load, the designed load level may be reasonably adjusted.

3. Test results and discussion

3.1 Failure modes
During loading, the crack development on the concrete surface was recorded with regard to the load of crack initiation. The crack pattern after loading is presented in Fig. 5. To better reveal the differences in the damage mechanisms among the samples, the failure mode of each specimen is shown in Fig. 6. For DM-C, when the load reached 19 kN, crack initiation was visually observed near the mid-span, which is under a pure moment. When the load increased, the cracks in the pure moment area continued to appear and propagate, and the crack space was even. When the load increased to 80 kN, the steel rebar strain, beam deflection and crack width began to rapidly increase, which indicates that the steel rebar yielded. Then, the load continued increasing to 84 kN. At this load level, the concrete was crushed in the pure moment region, which was approaching the inner side of the support (Fig. 6). The tested beam was in the ultimate flexural state. At failure, the cracks evenly developed in the pure moment area, which is the typical failure mode of this type of RC beam (see Fig. 5). The phenomenon of concrete crushing is shown in Fig. 6 (a).

For specimen DMJ-50, the cracks initiated in the mid-span when the load reached 22 kN. When the load was approximately 86 to 96 kN, the strain clearly increased, and the specimen entered the yield stage. When the load was 101 kN, a crack in the adhesive layer was observed. When the load increased to 106 kN, loud sounds emanated from the adhesive, and debonding initiation was noticed. When the load reached 111 kN, the CFRP sheet had clearly debonded from the RC beam, and the load suddenly dropped to 91 kN. Upon further loading, the load increased to 106 kN again. The concrete in the compression region was crushed, and the cracks dramatically propagated. The load decreased, and the beam completely failed. Specimen DMJ-100 had a similar failure process as specimen DMJ-50. The steel rebar yielded at a load of 91 kN, and the debonding began at 106 kN. When the load increased to 111 kN, the CFRP sheet clearly debonded from the RC beam, and the concrete in the compression region was crushed. The failure mode of concrete crushing during CFRP debonding is shown in Fig. 6 (b).
For specimen DM-50, the initial crack was observed in the mid-span within the pure moment area under a load of 30 kN. When the load increased, the cracks propagated, and the number of cracks increased; however, the crack spacing remained constant. When the load reached 65 kN, since the CFRP sheet began to experience stress, some sounds emanated from the adhesive layer of the CFRP ends. Next, when the load increased to 95 kN, the strain in the reinforcement suddenly increased. The steel rebar entered the yield stage, and the deflection significantly increased. When the load reached 130 kN, the CFRP sheet debonded from the RC beam at the mid-span. Finally, when the load increased to 135 kN, the beam completely failed due to concrete crushing in the compression area. As observed, for RC beams strengthened with the 50 mm wide CFRP sheet, the failure mode was concrete crushing after steel rebar yielding. Specimen DM-100 had a similar crack development process to specimen DM-50. The initial crack was also observed at a load of 30 kN. In the loading range of 96 to 106 kN, the strain in the steel rebar and CFRP sheet clearly increased, which indicates that the steel rebar was in the yielding stage. When the load increased to 136 kN, debonding began between the CFRP sheet and the RC beam. When the load reached 151 kN, the CFRP sheet completely debonded from the concrete. The failure mode of concrete crushing after CFRP debonding is shown in Fig. 6 (c).

Therefore, the proposed anchorage device can prevent CFRP end debonding failure due to self-locking; however, this device cannot stop intermediate debonding. Due to the reliable end anchorage, after the intermediate debonding occurs, the CFRP sheet can still bear substantial stress, so the specimen can be further loaded. Regardless of adhesive injection, sliding between the CFRP sheet and the anchorage device is not observed, which means that the self-locking provided by friction is sufficient for the anchorage device. Accordingly, the adhesive injection provides an insubstantial effect on the mechanical performance of the strengthened RC beams. After debonding, the load can be further increased until the beam exhibits flexural failure. In this sense, intermediate debonding is no longer a critical failure mode for the structures. Thus, the final failure mode of the strengthened RC beams can be divided into two types: flexural failure with CFRP bonding and flexural failure after CFRP debonding. The former occurs when debonding failure can be avoided. The distinction between the two failure modes is that the flexural failure with CFRP bonding bears a relatively higher tensile stress in the CFRP, and the stress can be calculated based on the plane cross sections assumption. In contrast, the latter bears less stress in the CFRP, and the negative effect of debonding should be considered in the stress calculation. Each mode of flexural failure can be further classified into two types: concrete crushing and CFRP sheet breakage. The definite mode of failure depends on parameters, such as the concrete strength grade, reinforcement ratio, and fibre ratio. Generally, failure occurs after the steel reinforcement yields unless the original reinforcement ratio is too high, in which case, the strengthening effect from externally bonding CFRP is not obvious and prestressing CFRP or other strengthening methods can be used to balance a part of the external load and achieve an increase in bearing capacity.

3.2 Maximum crack width

As shown in Fig. 7, for the CFRP-strengthened specimens, the development of the maximum crack width with respect to the load was analysed. The maximum crack widths were measured during loading after the cracks formed. The cracks developed as the loading increased, and the maximum crack width over the pure bending segment was determined from the measured crack width in each location (see Fig. 5). As observed, the crack width increased as the load increased and then significantly increased after the steel rebar yielded. For RC beams strengthened with narrower CFRP sheets, the crack width was much larger, especially for the anchorage without adhesive injection and the higher concrete strength grade. At the same load level, for the cases with

![Fig. 6 Failure modes of the tested specimens: (a) concrete crushing, (b) concrete crushing during CFRP debonding, and (c) concrete crushing after CFRP debonding.](image-url)
a CFRP width of 50 mm, the crack development processes were similar. However, for the cases with a CFRP width of 100 mm, the trends were different, and the beam with a lower concrete strength grade had a larger crack width at the same load level. Thus, the CFRP width plays a very important role in controlling the concrete crack width. In addition, when the CFRP is sufficiently wide, the concrete strength becomes a dominant factor in the crack development within the concrete.

3.3 Flexural behaviour and discussion

The test results are summarized in Table 1. After strengthening the beams with the CFRP sheets and the hybrid anchorage system, the cracking load, yield load, and ultimate load of the RC beams increased. Among these improvements, the ultimate load had the largest increase (e.g., the ultimate load of specimen DMJ-100 increased by 32%). The bearing capacity of the strengthened RC beams increased as the CFRP sheet width increased, but the degree of increase was related to the concrete strength grade. Although both the concrete strength grade and the use of adhesive injection changed, the adhesive injection provided no clear effect on the strengthening since the friction was sufficient for self-locking anchorage. For specimens with different concrete strengths, the increase in ultimate load was 5 kN and 16 kN, respectively. Hence, the strengthening effect can be enhanced if a higher concrete strength grade is used. The reinforcing effect is also related to the failure modes. Since the concrete strength grade was not high in this study, the dominant failure was basically concrete crushing in the pure moment region of the RC beam. The breakage of the CFRP sheet was not observed in the test. According to our previous study (Zhou et al. 2018), for the cases with and without adhesive injected on the anchorage part, the adhesive bonding in the anchorage part has an insignificant effect on the strengthening effect. Thus, self-locking can be completely achieved through simple friction. The results are of engineering application significance in both temporary and rapid strengthening.

The load-deflection relationships were obtained at the mid-span of the strengthened beams with different configurations, and these results are shown in Fig. 8. Before concrete cracking, the load-deflection curve was basically linear. For the cases with identical concrete strength grades, the difference between the cracking loads was marginal because the CFRP sheet had not been fully utilized. For the second stage, from concrete cracking to steel reinforcement yielding, the load-deflection curves remained nearly linear. For the reference beam, as observed in the failure condition, the deflection increased rapidly with increasing load after the reinforcement yielded, and the load increase was minimal due to concrete crushing in the compression zone. Compared with the reference beam, the strengthened beams exhibited a significantly higher yield load, and the increment depended on the strengthening type. For type II specimens, because of the higher concrete strength, the yield loads were higher and the difference between the two cases was due to the different CFRP widths. The yield load was almost the same for the type III specimens even though the width of the externally bonded CFRP sheet varied. After yielding, the increase rate of the load became very slow, whereas the deflection significantly increased. In addition, the ductility can be reduced with the increase in CFRP width because specimen DM-50 had the largest deflection. The higher concrete strength corresponds to a larger maximum deflection. Before concrete crushing occurred, intermediate debonding of the CFRP sheet was observed due to the higher deflection, but the load was sustained until the deflection reached a critical value. The results again verified the efficiency of the proposed strengthening method.

During the bending test, the strains in the concrete, CFRP sheet and steel rebar at the mid-span were measured. The obtained load-strain results from the CFRP sheet and steel rebar are shown in Fig. 9. Under identical load levels, the strains in the steel rebar of the strengthened beams were less than those of the reference beam, as seen in Fig. 9 (a), which implies that the
CFRP sheet can work well with the RC beam and bear part of the tension. For the cases with different CFRP widths, the strain difference in the steel rebar increases with increasing load. The cases with a CFRP width of 100 mm have lower strain in the steel rebar than the cases with a CFRP width of 50 mm. A similar trend was observed for the strains in the CFRP sheet, as shown in Fig. 9 (b), which indicates that the strains in both the steel rebar and the CFRP sheet are lower for wider CFRP sheets at the same load level due to the increase in stiffness. Before the steel rebar yielded, both strains increased linearly. However, after the steel rebar yielded, the strain in the CFRP sheet significantly increased, which implies that the CFRP sheet began to bear an increasing proportion of the load. The strengthening effect of the CFRP sheet was clear after the steel rebar yielded.

4. Examination of the formulas for the characteristic moment prediction

Based on the observed phenomena and results in the test, the existing formulas to calculate the cracking moment, yield moment and ultimate moment were assessed for the strengthened beams. The predicted results were also compared with the experimental values for validation. Although the formulas presented in this study are not new, they are the first formulas to be used in the calculation of this type of hybrid strengthened RC beam. The purpose of this section is to examine whether the existing formulas can be used to predict the mechanical performance of these particular strengthened beams. Without using these formulas, it is hard to ascertain how the bearing capacities of these beams are predicted and to determine areas that require improvement in future studies.

Based on the Chinese specifications “Technical specification for strengthening concrete structures with carbon fibre reinforced polymer laminate” (China CECS146 2003) and “Code for design of concrete structures” (China GB50010 2010), a theoretical analysis of CFRP-strengthened RC beams with an end-anchorage system was performed. The following assumptions were used in this study (Long 2005):

1) Plane cross sections
2) A stress-strain relationship of concrete under compression, which adopts a Rusch parabolic-linear curve and where the intercept strain is $\varepsilon_s = 0.002$ and the ultimate strain is $\varepsilon_{cu} = 0.0033$
3) Steel stress $\sigma_s = E_s \varepsilon_s \leq f_y$
4) CFRP sheet stress $\sigma_f = E_f \varepsilon_f \leq f_f$
5) No slip and,
6) after concrete cracking, the tensile stress in the section can be ignored.

Clearly, after CFRP debonding, assumptions 1 and 5 are not valid. In this case, the calculated ultimate moment can only be considered as the upper limit of the actual value.

4.1 Cracking moment

During loading, the concrete cracks gradually with increasing load. At initial cracking, the strengthened RC beam is not subjected to a high load. Under this condition, the concrete, steel rebar and CFRP sheet are bonded well and work collaboratively. Based on the elastic assumption of the materials, considering the plasticity of concrete approaching cracking, the cracking moment of the beam can be estimated as follows (Zhao 1999) [see Fig. 10 (a)]:

$$M_{cr} = \gamma \frac{f_L}{h - x_0}$$

$$x_0 = \frac{1}{2} bh^2 + (\alpha_e - 1) A_f h_0 + \alpha_f A_f h_f$$

$$A_0 = bh + (\alpha_e - 1) A_f + \alpha_e A_f$$

where $A_0$ is the area of the transformed section when the concrete approached the initial crack formation. Considering the effect of plastic deformation before concrete cracking, for the strengthened beam, the effective second moment of area ($I_e$) takes 0.85 times the second moment of area ($I_0$) of the original RC beam. The load-strain relationships at the mid-span of various strengthened beams: (a) steel rebar and (b) CFRP sheet.
moment of the area of the transformed section as follows (Zhao 1999):

\[
I = 0.85 \left\{ \frac{1}{3} b \left[ x_1^2 + (h - x_1)^2 \right] + (\alpha_c - 1) A_c (h_c - x_1)^2 + \alpha_f A_f (h - x_1)^2 \right\}
\]

(4)

where \(b\) and \(h\) are the width and depth of the beam cross section, respectively; \(A_s\) and \(A_f\) are the cross sectional area of the tensile reinforcement and CFRP sheet, respectively; \(h_0\) and \(h_f\) are the distances from the tensile reinforcement and CFRP sheet to the boundary of the compression area of the concrete, respectively; \(\alpha_E\) and \(\alpha_F\) are the elastic modulus ratio between the steel and concrete (\(E_S/E_c\)) and that between the CFRP sheet and concrete (\(E_F/E_c\)), respectively; and \(\gamma_m\) is the plastic effect parameter for the concrete in the tension zone, which can be set to 1.75 for a rectangular cross section.

### 4.2 Yield moment

For RC beams strengthened with CFRP, obvious IC debonding usually occurs after the yielding of the steel reinforcement. Although IC debonding could initiate before the yielding point, it can hardly be noticed. Thus, based on the above assumptions, by taking \(\sigma_s = f_y\) and \(\varepsilon_s = f_y/E_s\), we can estimate the moment \(M_y\) at steel yielding over the pure moment region as follows [see Fig. 10(b)]:

\[
M_y = C(h_f - y_0) + \sigma'_s A'_f (h_f - a') - f_y A_s (h_f - h_0)
\]

(5)

where

\[
C = f_y A_s + E_s A_f - \sigma'_s A'_f
\]

(6)

\[
\sigma'_s = E_s \varepsilon'_s \leq f_y
\]

(7)

According to whether the strain in the boundary of the concrete compression zone (\(\varepsilon_c\)) is larger than \(\varepsilon_{c0}\), \(C\) and \(y_c\) can be determined as follows:

\[
C = f_y b h_0 \frac{\varepsilon_{c0}}{E_c} (1 - \frac{\varepsilon_c}{\varepsilon_{c0}}), \quad y_c = \frac{1 - \frac{\varepsilon_c}{\varepsilon_{c0}}}{3 - \frac{\varepsilon_c}{\varepsilon_{c0}}} h_0 \quad (0 \leq \varepsilon_c \leq \varepsilon_{c0})
\]

(9a)

\[
C = f_y b h_0 (1 - \frac{\varepsilon_{c0}}{3\varepsilon_c}) y_c = \frac{1}{\frac{2}{3 \varepsilon_c} + 1 \left( \frac{\varepsilon_{c0}}{\varepsilon_c} \right)^2} h_0 \quad (\varepsilon_{c0} \leq \varepsilon_c \leq \varepsilon_{c0})
\]

(9b)

By combining Eqs. (7) to (9), Eq. (6) can be rewritten as follows,

\[
f_y b h_0 (3\varepsilon_{c0} + \varepsilon_c) x_0^2 + 3\varepsilon_{c0}^2 f_y A_f (h_f + h_0) \varepsilon_c + 2 f_y A_f h_0^2 x_0^2 - 3\varepsilon_{c0}^2 E_f A_f (h_0 + h_f) \varepsilon_c + 2 f_y A_f h_0 \] 0 \quad (0 \leq \varepsilon_c \leq \varepsilon_{c0})
\]

(10a)

or as:

\[
f_y b (3\varepsilon_{c0} + \varepsilon_c)^2 x_0^2 - 3\varepsilon_{c0} E_f A_f h_0 + 2 f_y b h_0 (2\varepsilon_{c0} + \varepsilon_c) + 3 E_f A_f \varepsilon_c^2 + 3 f_y A_f \varepsilon_c^2 x_0^2\]

(10b)

The height of the compression area (\(x_0\)) can be obtained by solving Eq. (10). \(C\) and \(y_c\) can then be solved.
This paper studied the flexural behaviour of narrow RC beams strengthened with externally bonded CFRP sheets that exhibited self-locking by wrapping the ends of the sheets around twin rods. Five RC beams were prepared and subjected to four point bending tests. Three parameters, the concrete strength grade, CFRP width, and anchorage type, were discussed. Existing formulas were used to calculate the characteristic moments of the specimens to examine the applicability of these formulas to the new type of strengthened beam. Based on the results and discussion, the following conclusions can be drawn:

1. The side anchorage and self-locking of the CFRP sheet can effectively prevent end-debonding failure. Even after intermediate debonding occurs, the load can increase further, which implies that the mechanical anchorage can work well after debonding.

2. The RC beams strengthened with the CFRP sheet and the proposed anchorage system exhibited a clearly higher ultimate load than the reference beam, whereas the cracking load was approximately unchanged by the strengthening.

3. When the concrete strength grade was high, the effect of the CFRP width on the flexural behaviour was clear. However, when the concrete strength grade was low, the CFRP width had less effect on the ultimate load of the strengthened beams since the final failure was governed by the concrete crushing in the compression zone.

4. There were no obvious mechanical differences between the specimens with and without adhesive injected in the anchorage part. Hence, friction was sufficient to achieve the self-locking effect, which means that the proposed method is significant for applications requiring temporary and fast strengthening.

5. Based on the existing formulas, the characteristic moments, including the cracking moment, yield moment and ultimate moment, were analysed. The validation of the existing formulas was examined for the prediction of the mechanical properties of RC beams strengthened with externally bonded CFRP sheets and the proposed hybrid anchorage system. The calculated results were basically consistent with the experimental values except for the ultimate moment, which indicated that the ultimate stress in the CFRP sheet after debonding requires further investigation.

**Acknowledgements**

This work was supported by the National Natural Sci-

---

### Table 3 Experimental and calculated values for the characteristic moment.

| Specimen No. | Compressive strength of concrete $f_{cu}$ (MPa) | Cracking moment $M_{cr}$ (kN·m) | Yield moment $M_y$ (kN·m) | Ultimate moment $M_u$ (kN·m) |
|--------------|---------------------------------|-------------------------------|---------------------|---------------------|
| DMJ-50       | 20.07                           | 7.15/7.34 = 0.97             | 27.95/27.64 = 1.05  | 34.45/37.83 = 0.91  |
| DMJ-100      | 20.07                           | 7.15/7.37 = 0.97             | 29.58/27.65 = 1.07  | 36.07/42.51 = 0.85  |
| DM-50        | 30.32                           | 9.75/9.51 = 1.02             | 30.80/27.89 = 1.1   | 34.88/42.03 = 1.04  |
| DM-100       | 30.32                           | 9.75/9.54 = 1.02             | 31.20/28.95 = 1.08  | 49.075/48.55 = 1.01 |

with Eq. (9). By substituting the relevant information into Eq. (5), we can calculate the yield moment of the strengthened beam ($M_y$).

**4.3 Ultimate moment**

When there is no interfacial debonding failure, the flexural failure has three failure modes: concrete crushing before steel rebar yielding, concrete crushing after steel rebar yielding and FRP rupture after steel rebar yielding. In our test results, all flexural failures are characterized by concrete crushing after the yielding of the steel rebar. In this case, $\varepsilon_s > f_y/E_s$, $\sigma_s = f_y$, and $\varepsilon_c = \varepsilon_{cm}$ [see Fig. 10 (e)]. By considering Eqs. (6), (8) and (9b), $x_0$ can be solved first; then, $C$ and $y_c$ can be obtained. Afterwards, using Eq. (5), the ultimate moment $M_u$ can be calculated. In addition, it is worth mentioning that sheet peeling fracture is also a premature failure mode for RC beams externally strengthened with bonded CFRP sheets (Lamanna et al. 2004). However, this phenomenon was not observed in this study. Therefore, the CFRP sheet peeling fracture is not considered in the calculation of the ultimate moment.

Based on the above equations, the cracking moment, yield moment and ultimate moment of the strengthened specimens were calculated. The experimental values and the calculated values are compared in Table 3. As shown, the experimental value of the cracking moment is generally consistent with the calculated value, and the ratio is very close to 1. The calculated yield moment is slightly lower than the experimental value, and the maximum deviation is approximately 10%. For the ultimate moment, while two specimens have satisfactory consistency, another two are obviously lower than expected, among which one of them reached a ratio of only 0.85. As previously described, although the failure mode of the strengthened beams was concrete crushing after steel rebar yielding, different degrees of debonding were observed before the final failure. Thus, it is reasonable that the ultimate stress in the FRP was less than the value calculated based on the plane cross sections assumption, and the experimental ultimate moment was less than the calculated ultimate moment for flexural failure with perfect bonding. Thus, the method used to predict the stress and moment at the ultimate load requires further investigation. New equations were not proposed in this study because the test data are still too limited. These data are insufficient to verify the reliability of the model, which should be performed after a sufficiently large database has been formed.

**5. Conclusions**
ence Foundation of China (project No. 51878664, 51708133, 50778176).

References

Aram, M. R., Czaderski, C. and Motavalli, M., (2008). “Debonding failure modes of flexural FRP-strengthened RC beams.” Composites Part B Engineering, 39, 826-841.

Böer, P., Holliday, L. and Kang, H. K., (2014). “Interaction of environmental factors on fiber-reinforced polymer composites and their inspection and maintenance: a review.” Construction and Building Materials, 50, 209-218.

Colombi, P., Fava, G. and Poggi, C., (2014). “End debonding of CFRP wraps and strips for the strengthening of concrete structures.” Composite Structures, 111, 510-521.

Chajes, M. J., Thomson, T. A. and Farschman, C. A., (1995). “Durability of concrete beams externally reinforced with composite fabrics.” Construction and Building Materials, 9, 141-148.

Chen, J. F., and Teng, J. G., (2001). “Anchorage strength models for FRP and steel plates bonded to concrete.” Journal of Structural Engineering, 127, 784-791.

Chen, J. F., Smith, S. T., Lam, L. and Teng, J. G., (2003). “Behaviour and strength of FRP-strengthened RC structures: a state-of-the-art review.” Structures and Buildings, 156, 51-62.

Chen, J. F., Yuan, H. and Teng, J. G., (2007). “Debonding failure along a softening FRP-to-concrete interface between two adjacent cracks in concrete members.” Engineering Structures, 29, 259-270.

China CECS146, (2003). “Technical specification for strengthened concrete structures with carbon fiber reinforced polymer laminate.” Beijing: China Association for Engineering Construction Standardization. (in Chinese)

China GB50010, (2010). “Code for design of concrete structures.” National Standard of the People’s Republic of China. Beijing: Standardization Administration of China. (in Chinese)

Dai, J., Ueda, T. and Sato, Y., (2005). “Development of the nonlinear bond stress-slip model of fiber reinforced plastics sheet-concrete interfaces with a simple method.” Journal of Composites for Construction, 9, 52-62.

Dai, J., Ueda, T. and Sato Y., (2007). “Bonding characteristics of fiber-reinforced polymer sheet-concrete interfaces under dowel load.” Journal of Composites for Construction, 11, 138-148.

Degala, S., Rizzo, P., Ramanathan, K. and Harries, K. A., (2009). “Acoustic emission monitoring of CFRP reinforced concrete slabs.” Construction and Building Materials, 23, 2016-2026.

Deng, J., Lee, M. M. and Moy, S. S., (2004). “Stress analysis of steel beams reinforced with a bonded CFRP plate.” Composite Structures, 65, 205-215.

Dong, K. and Hu, K., (2016). “Development of bond strength model for CFRP-to-concrete joints at high temperatures.” Composites Part B: Engineering, 95, 264-271.

Dror, E. B. and Rabinovitch, O., (2016). “Size effect in the debonding failure of FRP strengthened beams.” Engineering Fracture Mechanics, 156, 161-181.

El Maaddawy, T. and Soudki, K., (2008). “Strengthening of reinforced concrete slabs with mechanically-anchored unbonded FRP system.” Construction and Building Materials, 22, 444-455.

Ferrier, E., Rabinovitch, O. and Michel, L., (2016). “Mechanical behavior of concrete-resin/adhesive-FRP structural assemblies under low and high temperatures.” Construction and Building Materials, 127, 1017-1028.

Fu, B., Teng, J. G., Chen, J. F., Chen, G. M. and Guo, Y. C., (2017). “Concrete cover separation in FRP-plated RC beams: mitigation using FRP U-jackets.” Journal of Composites for Construction, 21, 1-13.

Hawileh, R. A., Naser, M. Z. and Abdalla, J. A., (2013). “Finite element simulation of reinforced concrete beams externally strengthened with a short-length CFRP plates.” Composites Part B: Engineering, 45, 1722-1730.

He, X. J., Zhou, C. Y. and Wang, Y., (2020). “Interfacial stresses in reinforced concrete cantilever members strengthened with fibre reinforced polymer laminates.” Advances in Structural Engineering, 23(2), 277-288.

Hong, S. and Harichandran, R. S., (2005). “Sensors to monitor CFRP/concrete bond in beams using electrochemical impedance spectroscopy.” Journal of Composites for Construction, 9, 515-523.

Sebastian, W. M., (2001). “Significance of midspan debonding failure in FRP-plated concrete beams.” Journal of Structural Engineering, 127, 792-798.

Kalfat, R., Al-Mahaidi, R. and Smith, S. T., (2013). “Anchorage devices used to improve the performance of reinforced concrete beams retrofitted with FRP composites: state-of-the-art review.” Journal of Composites for Construction, 17, 14-33.

Karbhari, V. M. and Ghosh, K., (2009). “Comparative durability evaluation of ambient temperature cured externally bonded CFRP and GFRP composite systems for repair of bridges.” Composites Part A, Applied Science and Manufacturing, 40, 1353-1363.

Khan, L. A., Nesbitt, A. and Day, R. J., (2010). “Hygrothermal degradation of 977-2A carbon/epoxy composite laminates cured in autoclave and Quickstep.” Composites Part A: Applied Science and Manufacturing, 41, 942-953.

Kim, S. J. and Smith, S. T., (2010). “Pullout strength models for FRP anchors in uncracked concrete.” Journal of Composites for Construction, 14, 406-414.

Lamanna, A. J., Bank, L. C. and Scott, D. W., (2004). “Flexural strengthening of reinforced concrete beams by mechanically attaching fiber-reinforced polymer strips.” Journal of Composites for Construction, 8, 203-210.
Lee, C. and Park, S., (2012). “De-bonding detection on a CFRP laminated concrete beam using self sensing-based multi-scale actuated sensing with statistical pattern recognition.” *Advances in Structural Engineering*, 15, 919-928.

Long, Z., (2005). “Experimental study on strength of RC beam strengthened by CFRP plate.” *Journal of Chongqing Jiaotong University*, 24, 30-34 (in Chinese).

Mahmoud, A. M., Ammar, H. H., Mukdadi, O. M., Ray, Imani, F., Chen, A. and Davlos, J. F., (2011). “Ultrasonic evaluation of CFRP-concrete interface for specimens under temperature and water-immersion aging effects.” In: L. Ye, P. Feng and Q. Yue Eds. *Advances in FRP Composites in Civil Engineering*. Heidelberg: Springer, 562-566.

Oehlerls, D. J. and Moran, J. P., (1990). “Premature failure of externally plated reinforced concrete beams.” *Journal of Structural Engineering*, 116, 978-995.

Pan, J. and Wu, Y. F., (2014). “Analytical modeling of bond behavior between FRP plate and concrete.” *Composites Part B: Engineering*, 61, 17-25.

Pan, Y., Xian, G. and Silva, M. A., (2015). “Effects of water immersion on the bond behavior between CFRP plates and concrete substrate.” *Construction and Building Materials*, 101, 326-337.

Sen, R., (2015). “Developments in the durability of FRP-concrete bond.” *Construction and Building Materials*, 78, 112-125.

Skuturna, T. and Valivonis, J., (2016). “Experimental study on the effect of anchorage systems on RC beams strengthened using FRP.” *Composites Part B: Engineering*, 91, 283-290.

Smith, S. T., Hu, S., Kim, S. J. and Seracino, R., (2011). “FRP-strengthened RC slabs anchored with FRP anchors.” *Engineering Structures*, 33, 1075-1087.

Smith, S. T., Rasheed, H. A. and Kim, S. J., (2017). “Full-range load-deflection response of FRP-strengthened RC flexural members anchored with FRP anchors.” *Composite Structures*, 167, 207-218.

Täljsten, B. and Blanksvär, T., (2007). “Mineral-based bonding of carbon FRP to strengthen concrete structures.” *Journal of Composites for Construction*, 11, 120-128.

Täljsten, B., (1996). “Strengthening of concrete prisms using the plate-bonding technique.” *International Journal of Fracture*, 82, 253-266.

Tashan, J. and Al-Mahaidi, R., (2014). “Bond defect detection using PTT IRT in concrete structures strengthened with different CFRP systems.” *Composite Structures*, 111, 13-19.

Teng, J. G., Yuan, H. and Chen, J. F., (2006). “FRP-to-concrete interfaces between two adjacent cracks: theoretical model for debonding failure.” *International Journal of Solids and Structures*, 43, 5750-5778.

Teng, J. G. and Yao, J., (2007). “Plate end debonding in FRP-plated RC beams - II: Strength model.” *Engineering Structures*, 29, 2472-2486.

Tounsi, A., Hassaine Daoudjii, T., Benyoucef, S. and Addabedia, E. A., (2009). “Interfacial stresses in FRP-plated RC beams: effect of adhered shear deformations.” *International Journal of Adhesion and Adhesives*, 29, 343-351.

Ueda, T. and Dai, J., (2005). “Interface bond between FRP sheets and concrete substrates: properties, numerical modeling and roles in member behaviour.” *Progress in Structural Engineering and Materials*, 7, 27-43.

Ueda, T., Yamaguchi, R., Shoji, K. and Sato, Y., (2002). “Study on behavior in tension of reinforced concrete members strengthened by carbon fiber sheet.” *Journal of Composites for Construction*, 6, 168-174.

Varastehpour, H. and Hamelin, P., (1997). “Strengthening of concrete beams using fiber-reinforced plastics.” *Material and Structures*, 30, 160-166.

Wang, W., Dai, J., Harries, K. A. and Bao, Q., (2011). “Prestress losses and flexural behavior of reinforced concrete beams strengthened with post tensioned CFRP sheets.” *Journal of Composites for Construction*, 16, 207-216.

Wang, Y. and Zhou, C., (2017). “Bond characteristics of CFRP/steel interface end-anchored with G-shaped clamps.” *Polymer and Polymer Composites*, 25, 661-667.

Wu, Z., Iwashita, K., Yagashiro, S., Ishikawa, T. and Hamaguchi, Y., (2005). “Temperature effect on bonding and debonding behavior between FRP sheets and concrete.” *Journal of the Society of Materials Science*, 54, 474-480.

Wu, Y. F., Yan, J. H., Zhou, Y. W. and Xiao, Y., (2010). “Ultimate strength of reinforced concrete beams retrofitted with hybrid bonded fiber-reinforced polymer.” *ACI Structural Journal*, 107(4), 451.

Yao, J. and Teng, J. G., (2007). “Plate end debonding in FRP-plated RC beams - I: Experiments.” *Engineering Structures*, 29, 2457-2471.

Yang, J. and Wu, Y. F., (2007). “Interfacial stresses of FRP strengthened concrete beams: Effect of shear deformation.” *Composite Structures*, 80, 343-351.

Zhao, G., (1999). “Advanced study on reinforced concrete structures.” Beijing: China Electric Power Press. (in Chinese)

Zhang, C., Wang, J. and Fridley, K., (2012). “Environment-assisted subcritical debonding of epoxy-concrete interface.” *Journal of Composites for Construction*, 16, 563-571.

Zhang, D., Shi, H., Zhu, J., Su, M. and Jin, W. L., (2018). “Cover separation of CFRP strengthened beam-type cantilevers with steel bolt anchorage.” *Engineering Structures*, 156, 224-234.

Zheng, X., Huang, P., Chen, G. and Tan, X., (2015). “Fatigue behavior of FRP-concrete bond under hygrothermal environment.” *Construction and Building Materials*, 95, 898-909.

Zhou, C., Ren, D. and Cheng, X., (2017). “Shear-
strengthening of RC continuous T-beams with spliced CFRP U-strips around bars against flange top.” Structural Engineering and Mechanics, 64, 135-143.
Zhou, C., Zhou, A. and Zhou, X., (2012a). “Method for self-locking flexible flaky material by turnstile.” Patent application no. ZL201010269384, Chinese National Intellectual Property Administration, People’s Republic of China. (in Chinese)
Zhou, C., Zhou, A. and Zhou, X., (2012b). “Device and method of anchorage with parallel rods for flexible sheet material.” Patent application ZL201010516838, Chinese National Intellectual Property Administration, People’s Republic of China. (in Chinese)
Zhuo, J., (2004). “Anchorage systems of high strength fiber reinforced polymer and the applications in strengthened structure.” Thesis (PhD). Chongqing University. (in Chinese)