(5)衝撃荷重を受けるCFRP補強RC梁の抵抗性

Resistance of CFRP strengthened RC beams under impact loadings

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Key Words: CFRP, flexural strengthening, impact loading, maximum midspan deflection

1. Introduction

Impact loading can be induced on reinforced concrete (RC) structures on various instances in their service life. They include crashing vehicles, ships, airplanes, rocks, explosions and even avalanches to name a few. As seismic strengthening should be applied to RC structures without sufficient earthquake resistance, RC structures without proper impact resistance should be strengthened to improve their impact performance. Carbon fiber reinforced polymer (CFRP) materials are being increasingly used to repair and strengthen bridges and buildings for major advantages of CFRP including high strength, high fatigue strength, high stiffness, high resistant to corrosion, light in weight, ease of application and high durability. However, little is known about the effect of impact loads on RC structures strengthened with the CFRP materials [1)-3)].

The behavior of a RC member under impact loading may consist of two response phases; one is the local response mainly due to the stress wave that occurs at the loading point during a very short period after impact, and the other is the overall response with a free vibration effect due to the elastic-plastic deformation that occurs in the whole structure member over a long period after impact. The overall response strongly depends on the quasi-static behavior with loading rate effect of the RC member. Overall failure tends to be a major issue concerning RC beams subjected to impact loading. In contrast, local failure such as penetration, scabbing, perforation and/or punching shear tends to be the predominant mode of failure for RC plates subjected to impact loading.

Therefore, the aim of this study was to experimentally examine the overall impact responses of RC beams strengthened with CFRP materials and to present a developed analytical model which predicts the maximum midspan deflection as an important damage index to evaluate the damage levels of CFRP strengthened RC beams subjected to impact loadings.

2. Experimental Program

2.1. Specimen preparation

Twenty RC beams with cross-sectional dimensions of 160×170 mm and lengths of 1,700 mm as illustrated in Fig. 1 were cast using the ready-mixed concrete. The RC beams were reinforced with two 10mm deformed bars with a yield strength of 382 MPa in both tension and compression. The stirrups were provided with 6mm deformed bar with yield strength of 295 MPa and spaced 60 mm apart. The maximum aggregate size was 10mm, taking into account the minimum clearance of rebar. The concrete compressive strength at the time of testing was 41.9 MPa. The design shear resistance of the RC beam was more than 47.5 kN. Therefore, the RC beams strengthened with CFRP reinforcement would be weaker in flexure.

To strengthen the RC beams in flexure, two kinds of CFRP reinforcement, i.e., unidirectional tow sheets and unidirectional pultruded laminates, were employed. The CFRP sheets had a maximum tensile strength of 3,400 MPa and an elastic modulus of 245 GPa, while the CFRP laminates had a maximum tensile strength of 2,400 MPa and an elastic modulus of 156 GPa. Of the twenty RC beams, four RC beams were not strengthened as Control specimens, and sixteen RC beams were strengthened with the CFRP reinforcement. Four

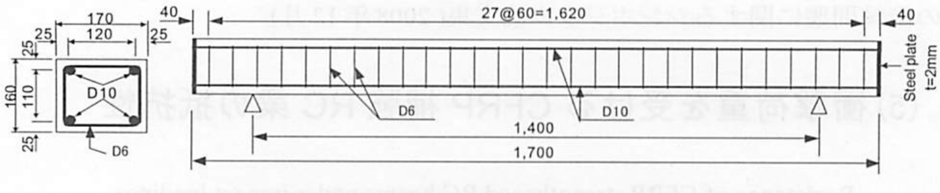
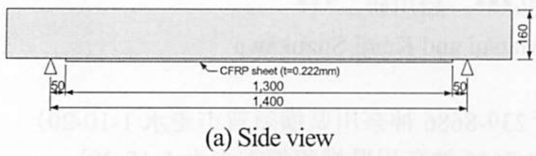
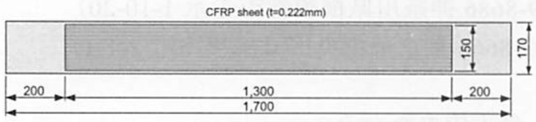


Figure 1 RC beam detail

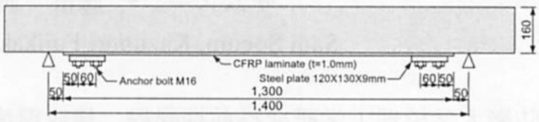


(a) Side view

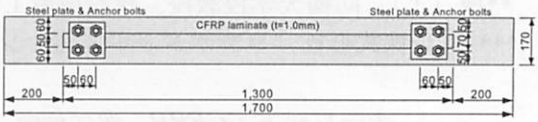


(b) Bottom view

Figure 2 TCN beam specimen

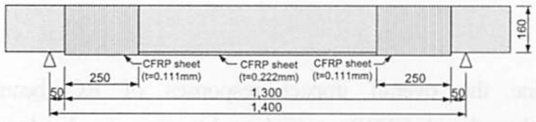


(a) Side view

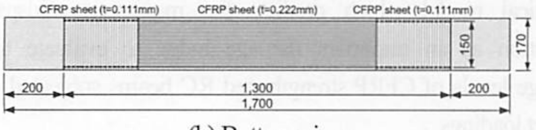


(b) Bottom view

Figure 4 TLB beam specimen

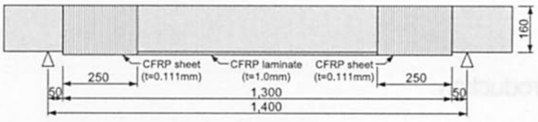


(a) Side view

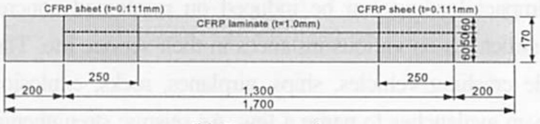


(b) Bottom view

Figure 3 TCC beam specimen



(a) Side view



(b) Bottom view

Figure 5 TLC beam specimen

different types of CFRP strengthening schemes, TCN, TCC, TLB and TLC were applied to the RC beams as shown in Figs. 2 to 5, for each of which four specimens were prepared. For TCN and TCC, CFRP sheets with a thickness of 0.222mm and a width of 150mm were bonded to the soffit of the RC beams as shown in Figs. 2 and 3. For TCC, a CFRP sheet with a thickness of 0.111mm and a width of 250mm was installed at the ends of the soffit CFRP sheet with the direction of the fibers perpendicular to the longitudinal beam axis to improve the anchorage of the CFRP strengthening system, while no end anchors were used for TCN. For TLB and TLC, CFRP laminates with a thickness of 1.0mm and a width of 50mm were bonded to the soffit of the RC beams as shown in Figs. 4 and 5. To improve the anchorage of the CFRP laminates at the both ends, steel anchor bolts with a diameter of 16 mm and steel cover plates with a thickness of 9 mm were provided for TLB, while CFRP U-wrap sheets with a thickness of 0.111mm and a width of 250mm were bonded for TLC. The CFRP sheets and laminates bonded to the soffit of the RC beams were designed to have approximately the same tensile rupture load. After the proper surface preparation applied to the RC beams, the CFRP sheets were impregnated with epoxy resin on site by a wet lay-up method, and the CFRP laminates were bonded to the soffit of the RC beams with an epoxy-based adhesive.

2.2. Impact loading test

For impact loading, a drop hammer impact loading machine was used, as shown in Fig. 6. A drop hammer with a mass of 300kg was dropped freely onto the top surface of the RC beam at midspan from specified heights. The striking tup had a hemispherical tip with a radius of 90mm. The beam specimen was supported over a span of 1400mm with specially designed devices allowing it to freely rotate to prevent the beam specimen from bouncing out.

In this study, two types of impact test were performed. One was a single impact test; the other was a repeated impact test. In the single impact test, the drop hammer was freely dropped from a height of 100, 200 or 400 mm only once. In the repeated impact test, the drop hammer was repeatedly dropped to the same specimen. The initial drop height was 50 mm, then the drop height was doubled after every two hundreds drops as shown in Fig. 7.

Two accelerometers were installed to the drop hammer to measure the contact force developed between the hammer and the RC beam. The midspan deflection response of the RC beam was measured using a laser displacement sensor as well.

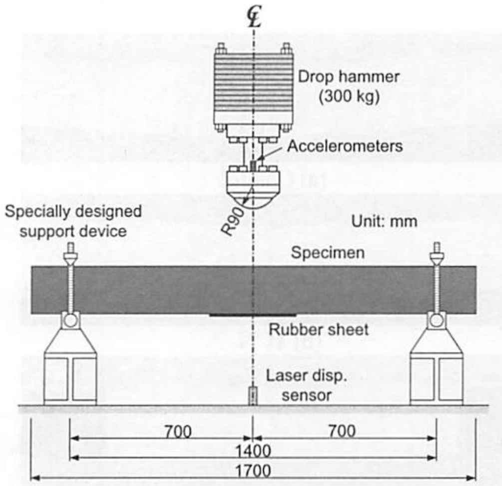


Figure 6 Impact loading test

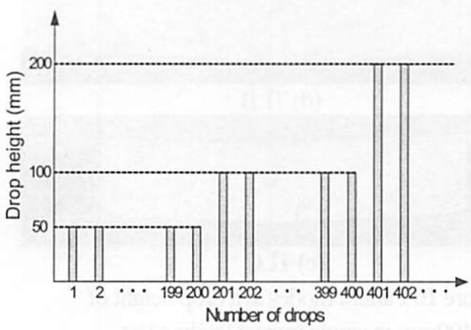


Figure 7 Repeated impact loading program

The PC-based data acquisition system recorded the data at a sampling rate of 100 kHz.

3. Experimental results

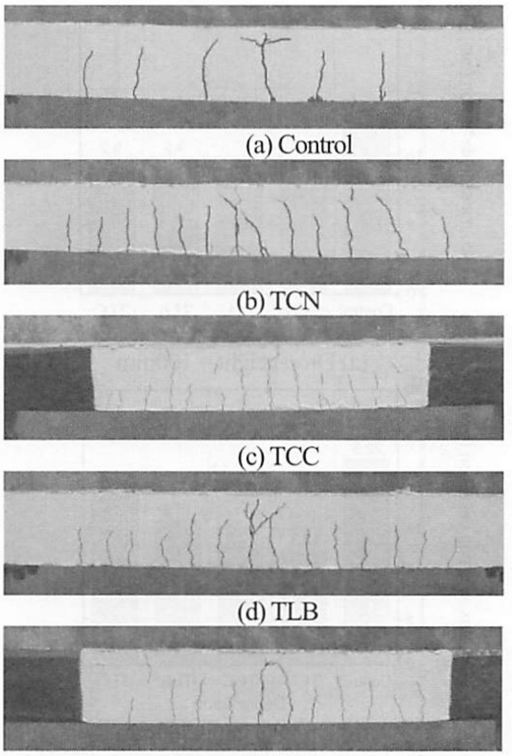
3.1. Single impact loading test results

(1) Drop height of 100 mm

Neither debonding of CFRP nor compression crushing of concrete was observed on each specimen at a drop height of 100mm, while only flexural cracks were formed as shown in Fig. 8. Control had a maximum crack width of 3mm with a crack spacing of approximately 100mm, whereas the CFRP strengthened RC beams had only hairline cracks with a crack spacing of approximately 60mm. Thus, by strengthening RC beams with CFRP in flexure, the crack spacing was decreased by 60%; the crack width was significantly decreased by less than 10% compared to the unstrengthened RC beam. With a drop height of 100 mm, as shown in Fig. 9(a), the maximum deflections of CFRP strengthened RC beams, TCN, TCC, TLB and TLC, decreased by 24 to 35% compared to Control, of which TCC had the smallest maximum midspan deflection of 8.2 mm.

(2) Drop height of 200 mm

With a drop height of 200 mm, the maximum midspan


(a) Control

(b) TCN

(c) TCC

(d) TLB

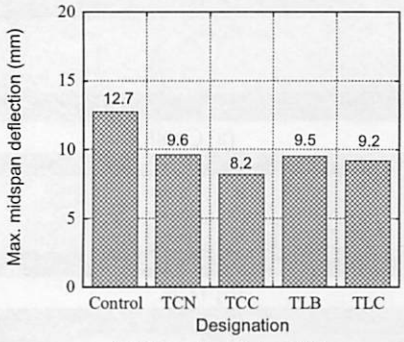
(e) TLC

Figure 8 Failure modes at a drop height of 100mm in single impact loading test

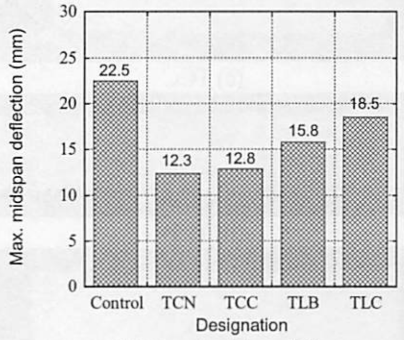
deflections of the CFRP strengthened RC beams are 18 to 45% smaller than that of the unstrengthened RC beam as shown in Fig. 9(b). Little compression crushing of concrete was observed for Control and TLC. In addition, TLC developed a CFRP laminate slip of 5 mm at one end anchorage. On the other hand, neither debonding of CFRP nor compression crushing of concrete was observed for TCN, TCC and TLB. Control had a maximum crack width of 5mm, while TCN and TCC had only hairline cracks with a width less than 0.3mm; TLB and TLC had maximum crack widths of 1.7 and 3.0mm, respectively. Therefore, it can be said that flexural crack widths can be reduced by strengthening the RC beam with CFRP, and the CFRP sheet rather than the CFRP laminate can make flexural crack widths smaller because of its high elastic modulus.

(3) Drop height of 400 mm

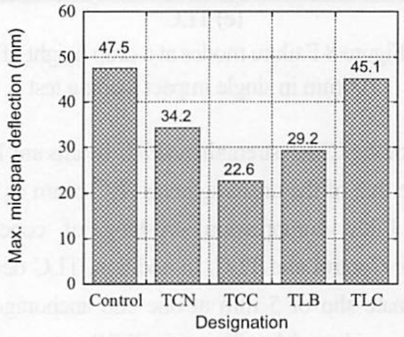
The failure modes obtained at a drop height of 400 mm are shown in Fig. 10 and the maximum midspan deflections measured are shown in Fig. 9(c). The strengthening schemes applied to the specimens significantly affect the maximum midspan deflections as shown in Fig. 9(c). The maximum midspan deflection of Control with the compression crushing of concrete and a maximum residual crack width of 15mm was 47.5mm. For TCN with a maximum midspan deflection of 34.2mm, the CFRP sheet was completely debonded, the compression concrete was crushed, and the cover concrete at



(a) Drop height = 100mm



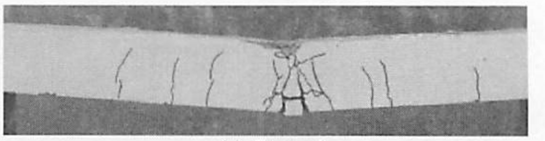
(b) Drop height = 200mm



(c) Drop height = 400mm

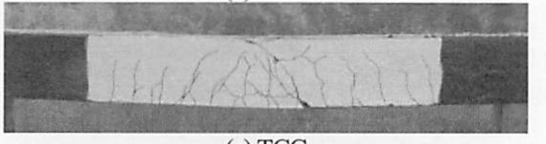
Figure 9 Maximum midspan deflections in single impact loading test

midspan was spalled, as shown in Fig. 10(b). TCC had the smallest midspan deflection of 22.6 mm, which was 54 % of the maximum midspan deflection of Control. For TCC, the compression crushing of concrete was observed and the CFRP sheet was partially debonded due to intermediate flexural shear cracks as shown in Fig. 10(c). The integrity as a strengthening system, however, was still maintained owing to the anchorages applied at the both ends of the CFRP sheet. In addition, the maximum crack width of 2.4mm was significantly small. Thus, one can say that, as strengthening RC beams with CFRP sheets, end anchorages applied at the both ends of the CFRP sheets help to prevent the CFRP sheets from debonding so that the CFRP strengthened RC beams with the end anchorages can resist comparatively large impact loads. On the other hand, the maximum midspan deflections of TLB and TLC strengthened with CFRP laminates are 29.2 and 45.1mm, respectively. TLB and TLC had the compression crushing of concrete and CFRP laminate slips of 8 and 15mm, respectively, at one end

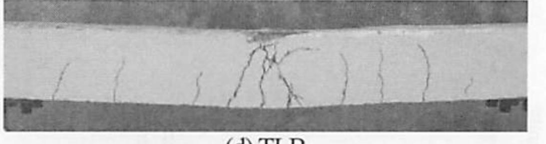


(a) Control

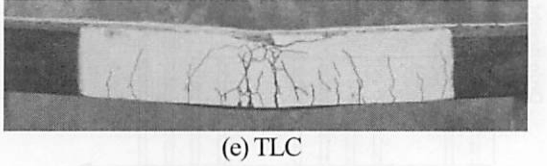
(b) TCN



(c) TCC



(d) TLB



(e) TLC

Figure 10 Failure modes at a drop height of 400mm in single impact loading test

anchorage. In addition, the maximum residual crack widths of TLB and TLC were 5.4 and 10mm, respectively. Thus, it can be said that, for strengthening RC beams with pultruded CFRP laminates, the end anchorages with steel plates and anchor bolts are highly effective against comparatively large impact loads compared to those with CFRP sheets.

A drop height of 200mm caused Control beam an ultimate state with a maximum midspan deflection of 22.5mm, while twice the drop height is required to lead CFRP strengthened RC beams, such as TCC and TLB, ultimate states. Thus, RC beams properly strengthened with CFRP materials can withstand twice the drop height necessary to cause unstrengthened RC beams ultimate failure.

3.2. Repeated impact loading test results

(1) Control Beam

Fig.11 shows the relationships between the maximum midspan deflection and the number of blows obtained in the repeated impact loading test. The maximum midspan deflection for Control specimen was 7.6 mm at the first drop from 50 mm height as shown in Fig. 11(a). After the first drop, the maximum midspan deflection was linearly increased with a rate of 3.2 mm per blow. Flexural cracks were generated with a crack spacing of approximately 100 mm, the widths of those cracks were increased with an increase in number of blows.

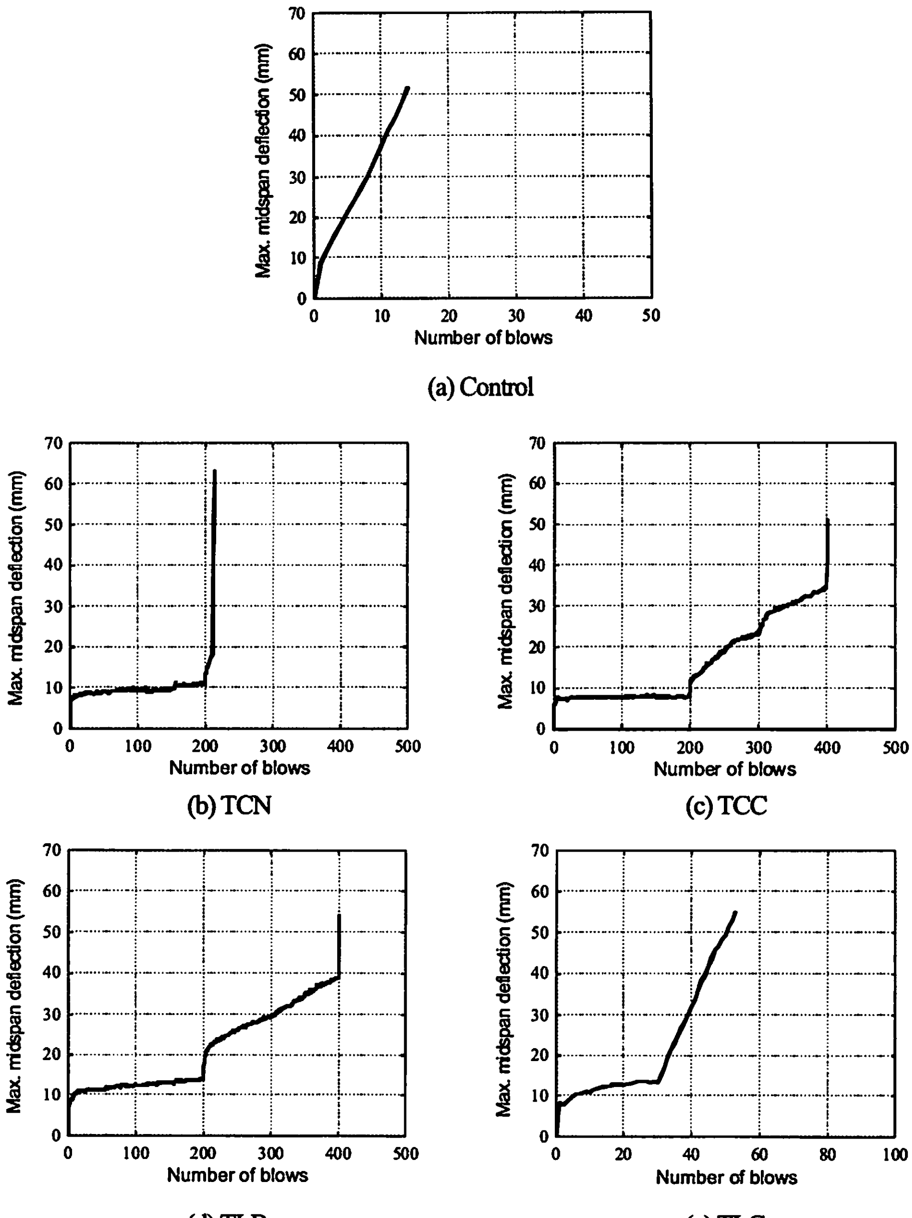


Figure 11 Relationships between maximum midspan deflection and number of blows in repeated impact loading test

At the 7th blow, the compression crushing of concrete was formed, and the maximum midspan deflection was 25 mm. When continuing the repeated impact loading, the maximum midspan deflection at the 14th blow was 48.7 mm. In the failure mode, no difference between the repeated impact loading test and the single impact loading test was observed.

(2) TCN Beam

The unstrengthened RC beam, Control, was led an ultimate state at the seventh drop from a height of 50 mm, while TCN strengthened in flexure with a CFRP sheet, had a maximum midspan deflection of 10.8 mm at the 200th drop as shown in Fig. 11(b), and was intact except that a crater with a diameter of 90 mm and a depth of 15 mm was formed at the contact point of the drop hammer on the RC beam because of abrasion and erosion as shown in Fig. 12. After the maximum midspan deflection was 13.6 mm at the 201st from a drop height of 100mm, the maximum midspan deflection increased with a rate of approximately 0.5 mm per blow. Finally, the CFRP sheet was debonded at the 212th drop due to intermediate flexural shear induced-cracks.

(3) TCC Beam

TCN failed by the debonding of a CFRP sheet at the 212th drop. TCN, however, could withstand further repeated drops owing to the end anchorages at both ends. The slight compression crushing of concrete as well as the partial debonding of the CFRP sheet due to intermediate flexural shear

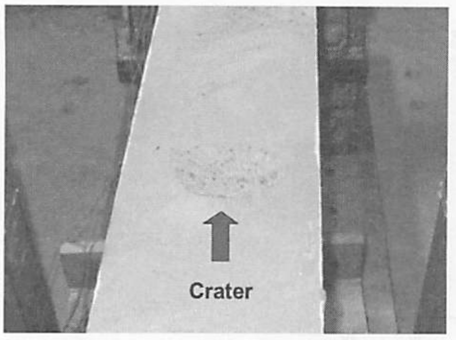


Figure 12 Crater formed on TCN

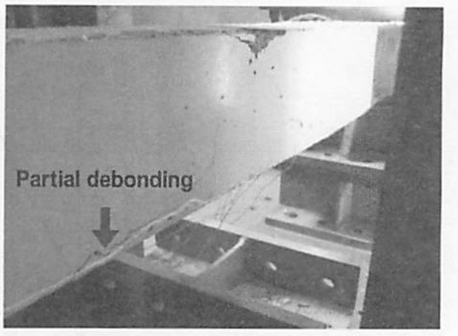


Figure 13 Partial debonding of TCC

cracks were observed at the 242nd drop as shown in Fig. 13. As subsequently continuing the repeated impact loadings, the midspan deflections increasing with a rate of approximately 0.1mm per blow were 34.6mm at the 400th drop from a 100mm drop height and 41.1mm at the 401st drop from a 200mm drop height as shown in Fig. 11(c). Finally, the complete debonding of the CFRP sheet with the rupture of the end anchorage at one end was observed at the 402nd impact.

(4) TLB Beam

TLB strengthened with a CFRP laminate could resist over 200 drops from 50mm height just like TCN and TCC, and had a maximum midspan deflection of 14.0mm without any damage between the CFRP laminate and concrete as shown in Fig. 11(d). Little abrasion was observed at the impact loading point by the 200th drop, while the big crater was observed for TCN and TCC by the 200th drop. Thus, the extent of local abrasion under repeated impact loads appears to be related to the flexural rigidity of the strengthened RC beam, because the flexural rigidity of TLB is smaller than those of TCN and TCC. The maximum midspan deflection that was 26.8 mm at the 201st drop from 100 mm height increased with a rate of approximately 0.1 mm per drop. At the 238th drop, the compression crushing of concrete was observed, when the midspan deflection was 25.2 mm. As subsequently continuing the repeated impact loadings, the maximum midspan deflections were 38.9 mm at the 400th drop from a height of 100 mm and 54.1 mm at the 401st drop from a height 200 mm.

(5) TLC Beam

Of all the CFRP strengthened RC beams, TLC failed with the least repeated blows as shown in Fig. 11(e). The maximum midspan deflection was 8.4 mm at the first drop and increased with a rate of 0.16 mm per drop. After a CFRP laminate slip of 3 mm was observed at one end anchorage at the 31st drop, the maximum midspan deflection was increased with a rate of 2 mm per drop. At the 37th drop, the compression concrete crushed and the maximum midspan deflection was 26.6 mm. As subsequently continuing the repeated impact loadings, the maximum midspan deflection was 55 mm at the 53rd drop.

4. Conclusions

Based on the results presented in this paper, the following conclusions were drawn.

1. By strengthening RC beams with CFRP in flexure, crack width is significantly decreased by less than 10% compared to unstrengthened RC beams.
2. End anchorages applied at the both ends of the CFRP sheets bonded to the soffit of the RC beams help to prevent the soffit CFRP sheets from debonding so that the CFRP strengthened RC beams with the end anchorages can resist comparatively large impact loads.
3. For strengthening RC beams with pultruded CFRP laminates, the end anchorages with anchor bolts and steel cover plates are highly effective against comparatively large impact loads.
4. RC beams properly strengthened with CFRP can withstand twice the drop height necessary to cause unstrengthened RC beams failure.

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