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# IMPACT RESISTANCE PERFORMANCE OF UHPFRC PANELS UNDER LOW VELOCITY IMPACT LOADING

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**Abstract**

In this research project, the impact resistance of ultra-high performance fiber-reinforced concrete (UHPFRC) panels is studied by conducting a series of impact tests using falling weights. A weight of mass 115 kg is freely dropped with an impact velocity that varies between 1.0 and 12 m/s. For reference, two types of RC panel designed to exhibit bending and shear failure modes are also tested. The effects of thickness and the addition of steel strand reinforcement and prestress on the impact resistance of the UHPFRC panels is evaluated. The failure mode of UHPFRC panels without reinforcement is found to be bending, while UHPFRC panels with added reinforcement and prestress exhibit punching shear failure. The UHPFRC panel without reinforcement has identical impact resistance to a standard RC panel of double the thickness. The UHPFRC panel with prestress has a superior impact resistance to a standard RC panel of triple the thickness.

**Résumé**

Dans ce projet, la résistance à l’impact de panneaux de béton fibre à ultra-hautes performances (BFUP) est étudiée grâce à une série d’essais d’impacts par masses tombantes. Un poids de 115 kg est lâché en chute libre avec une vitesse d’impact variant de 1,0 à 12 m/s. Deux panneaux en béton armé calculés pour présenter des ruptures en flexion et en cisaillement sont également testés en référence. L’effet de l’épaisseur, du ferraillage et de la présence de précontrainte sur la résistance à l’impact des panneaux en BFUP est évalué. Le mode de rupture des panneaux en BFUP non armés s’avère correspondre à une rupture en flexion, tandis que les panneaux en BFUP armé ou précontraint présentent une rupture par poinçonnement. Le panneau en BFUP non armé a une résistance à l’impact identique à celle d’un panneau en béton armé standard deux fois plus épais. Le panneau en BFUP précontraint a une résistance à l’impact supérieure à celle d’un panneau en béton armé standard trois fois plus épais.

# 1. INTRODUCTION

In recent years, researchers in the field of impact engineering have been looking into methods of improving the impact resistance of fiber-reinforced concrete (FRC). Ultra-high performance FRC (UHPFRC) is known to have good impact resistance, but widespread adoption of UHPFRC cannot be expected if it does not offer greatly superior performance as compared to conventional FRC because of its high cost. Therefore, focusing on thin UHPFRC panels, the authors have been carrying out three types of test to confirm their impact-resisting performance. The scope of these tests, in which the weight and velocity of the impacting object were varied, is illustrated in Fig. 1. In outline, the three types of test have the following characteristics.

- High-velocity impact tests: experiments based on the assumption that a small projectile (50-500 g, such as a bullet) impacts at high speed (100-500 m/s)
- Medium-velocity impact tests: experiments based on the assumption that some fragment of an object (4-8 kg, such as debris resulting from an exploding missile or a tornado) impacts at moderate speed (20-70 m/s)
- Low-velocity impact tests: experiments based on the assumption that a heavy object (around 100 kg, such as a rock ejected by a volcanic eruption) impacts at free-fall speed (1-15 m/s)

Of these tests, this paper describes the low-velocity impact tests, which were carried out by a falling mass method. A preliminary test was first carried out to determine a suitable specimen shape and the kind of reinforcement fiber to be tested, then the main tests were conducted to examine influence of adding steel strands and prestress reinforcement.

The UHPFRC material was fabricated using the standard powder mixture described in 'UFC Recommendations for Design and Construction' [1], using either high tensile strength steel fibers (tensile strength Pu = 2,800 MPa, diameter φ=0.2 mm, length L=15 mm) or organic fibers (PVA, tensile strength Pu = 1,050 MPa, diameter φ=0.3 mm, length L=15 mm). The UHPFRC mix proportions are shown in Table 1.

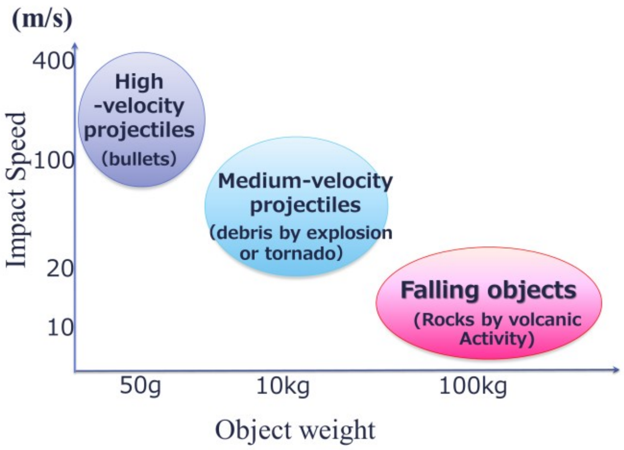



Figure 1: Scope of impact test

Table 1: Mix proportion

Unit : kg/m$^3$

| | Pre-blended powders | Fine aggregate | Fiber | Super plasticizer | Water |
|---|---|---|---|---|---|
| UHPFRC-FM (Steel fiber mixed) | 1,322 | 932 | 157 (2.0 vol%) | 28 | 162 |
| | | | | Unit water : 180 | |
| UHPFRC-FO (Organicl fiber mixed) | 1,309 | 922 | 39 (3.0 vol%) | 26 | 162 |
| | | | | Unit water : 178 | |

## 2. WEIGHT FALLING PRELIMINARY TEST

### 2.1 Outline of preliminary test

An outline of the preliminary test is given in Fig. 2. A RC or UHPFRC panel was mounted on a support frame and fixed with cramps along two edges. A flat-bottomed steel impact weight with a mass of 115 kg and a diameter of 15 cm was allowed to drop onto the center of the panel under free fall from a prescribed height. Pieces of 3 mm thick rubber sheeting were laid between the specimen and the support frame to ensure contact.

The preliminary test consisted of the cases shown in Table 2 with the aim of comparing the effect of specimen characteristics such as the fiber reinforcement material, cross-sectional shape, and the presence or absence of prestress. All panels measured 1,800 mm long by 1,040 mm wide. In prestressed specimens, steel strands (SWPR7B, diameter 12.7 mm) were spaced every 14 cm in the UHPFRC panels. The introduced effective prestress was 110 kN per strand, for a total prestress of 880 kN in the panel (the compressive stress was 17.7 N/mm2).

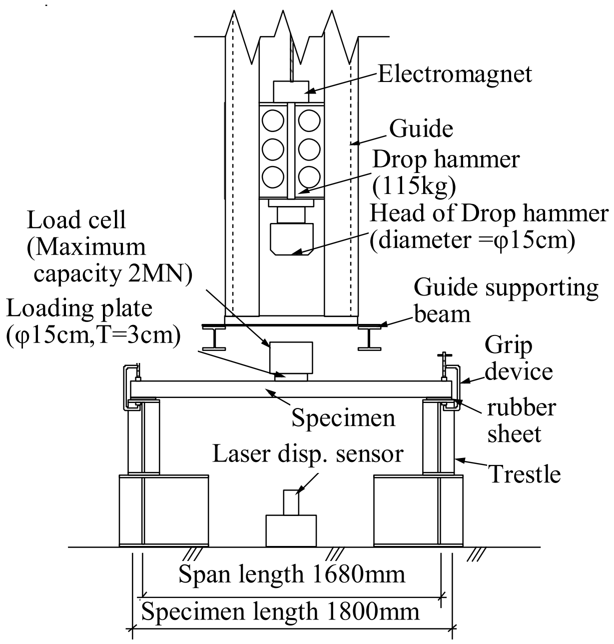



Figure 2: Drop hammer impact test setup

Table 2: Preliminary test cases

| Case | Materials | Design strength ($N/mm^2$) | Prestress | Section shape | Thickness (cm) | Aditional reinforcement |
|---|---|---|---|---|---|---|
| FM4/6 | UHPFRC FM | 180 | — | Rib | Slab : 4 Rib : 6 | — |
| PFM4/6 | UHPFRC FM | 180 | ○ | Rib | Slab : 4 Rib : 6 | Steel strands (longitudinal direction ) |
| PFM5 | UHPFRC FO | 180 | ○ | Flat | 5 | Steel strands (longitudinal direction ) |
| PFO4/6 | UHPFRC FO | 160 | ○ | Rib | Slab : 4 Rib : 6 | Steel strands (longitudinal direction ) |
| RC12D | RC | 50 | — | Flat | 12 | Rebar D10@ 150 Covering: 40mm |

Table 3: Material strengths in preliminary test

Unit: $N/mm^2$

| | Compressive | First cracking | Tensile |
|---|---|---|---|
| UHPFRC-FM (Steel fiber mixed) | 182 | 11.4 | 11.9 |
| UHPFRC-FO (Organicl fiber mixed) | 168 | 9.1 | 5.4 |
| RC | 51 | ——— | ——— |

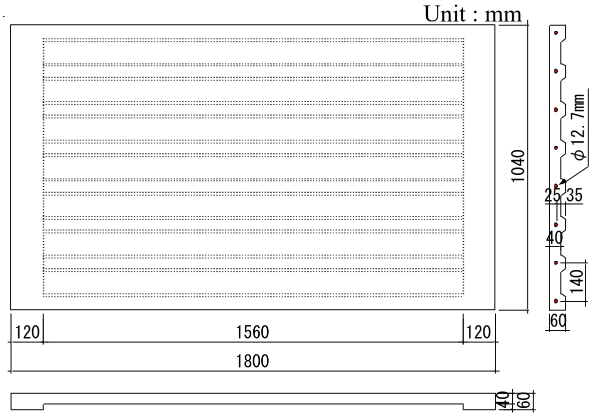



Figure 3: Basic specimen shape (PFM4/6)

The basic specimen (PFM4/6) is shown in Fig. 3. Case FM4/6 is introduced to compare the effect of steel strand reinforcement and prestress. Case PFM5 compares the effect of cross-sectional shape. Case PFO4/6 is to investigate the effect of organic fibers as compared with the basic specimen, PFM4/6. Finally, a RC panel 12 cm in thickness (RC12D) is used to provide a comparison with conventional rebar-reinforced concrete. The material strength of the specimens at the time of the tests is shown in Table 3.

Drop tests were conducted repeatedly on each specimen by increasing the impact speed (fall height) as shown in Table 4.

Table 4: Impact speed and drop height

| Impact speed (m/s) | Drop height (m) |
|---|---|
| 1.0 | 0.05 |
| 2.5 | 0.32 |
| 5.0 | 1.28 |
| 7.5 | 2.87 |
| 10.0 | 5.10 |
| 10.8 | 6.00 |

## 2.2 Results and consideration of preliminary test

The results of the preliminary test are given in Fig. 4 and Fig. 5.

In the case of FM4/6, which had no steel prestressing strands and therefore handled the impact load only through fiber bridging effects, the rebound height for a drop height of 287 cm was very small (around 90 mm), indicating that impact energy absorption due to deformation of the specimen was small. The fracture mode of FM4/6 was bending at the span center (the loading point).

In the case of PFM4/6, into which prestress had been introduced, the rebound height for a drop height of 510 cm was 945 mm, more than 10 times greater than for case FM4/6 (with no steel strands). This significant difference is thought to arise not only because of increased loading capacity brought about by the reinforcement but also because of significant energy absorption with associated restoring force brought about by the prestressing strands. As a result, specimen PFM4/6 was able to endure double the drop height of FM4/6. The fracture mode was punching shear. Longitudinal cracks initiated as a result of the first drop and occurred along at the corner of the rib. It may be caused by a shock wave of the impact.

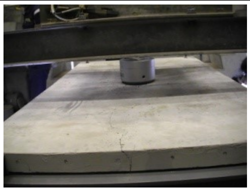
| Case | Drop height<br>Impact speed<br>Fracture mode | Impact side | Rear side | Fracture mode photo |
|---|---|---|---|---|
| FM4/6 | 287cm<br>7.5m/s<br>flexural failure |  |  |  |
| PFM4/6 | 600cm<br>10.8m/s<br>Punching shear failure<br>(Crack in longitudinal direction) |  |  |  |

Figure 4: Preliminary test result 1 (FM4/6, PFM4/6)

In the case of PFM5, which had a flat cross-sectional shape, the maximum impact speed was same as with PFM4/6. The fracture mode was combined punching shear and longitudinal cracking. The rebound height for a drop height of 510 cm was 855 mm, a little less than with PFM4/6.

In the case of PF04/6, which used organic fibers, the maximum impact speed was the same as for PFM4/6, but the rebound height for a drop height of 510 cm was 750 mm, less than in the case of PFM4/6 (945 mm). This indicates that less energy was absorbed than in the case of PFM4/6, and it can be assumed that a relatively greater impact force acted on the panel. The fracture mode was combined punching shear and diagonal cracking. Crack width in the diagonal direction was particularly large; the panel was close to collapse through brittle failure.

In the case of RC12D, which was a RC specimen with twice the thickness of the others, energy absorption was very low due to the high sectional stiffness. The rebound height for a drop height of 287 cm was so small as to be immeasurable. The maximum impact speed and the maximum drop height in the case of RC12D was 7.5 m/s and 287 cm respectively, and the fracture mode was large scale scabbing of the cover concrete.

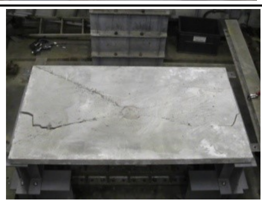
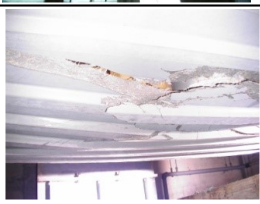
| Case | Drop height<br>Impact speed<br>Fracture mode | Impact side | Rear side | Fracture mode photo |
|---|---|---|---|---|
| PFM5 | 600cm<br>10.8m/s<br>Punching shear failure<br>(Crack in longitudinal direction) |  |  |  |
| PFO4/6 | 600cm<br>10.8m/s<br>Punching shear failure<br>(Large crack in diagonal) |  |  |  |
| RC12D | 510cm<br>10.0m/s<br>flexural failure<br>(Falling of large covering) |  |  |  |

Figure 5: Preliminary test results 2 (PFM5, PFO4/6, RC12D)

## 2.3 Findings from preliminary test

By the preliminary test, the various conditions to confirm the impact resistance of the thin UHPFRC panel in the main test were made clear. The outcome is as follows.

- The fracture mode of thin UHPFRC panels with reinforced steel strands and prestressing is not bending but punching shear, due to the fiber reinforcement effect and the absorption of impact energy.

- A longitudinal cracking phenomenon was observed in many cases, and it was presumed that this is a unique phenomenon in impact loading. Such cracks were particularly notable in the ribbed panel, where they occurred from the initial stage of loading. They initiated in the corner region of the rib. Therefore, it is concluded that a flat panel is the preferred geometry for an impact resistant panel.
- An UHPFRC panel less than half the thickness of a RC panel has superior impact resistance to the RC panel.
- In the case of the UHPFRC panel reinforced with organic fibers, the fracture mode was collapse as a result of well-developed diagonal cracks. Consequently, organic fibers may not be appropriate for use in impact-resistant panels.

These findings informed the selection of conditions for the main drop test.

## 3. WEIGHT DROP IMPACT TEST (MAIN TEST)

### 3.1 Experimental setup

The main impact test was set up the same as the preliminary test depicted in Fig. 2. Pieces of 1 mm thick rubber sheeting were laid between the specimen and the support to ensure contact. The thickness of rubber had been changed from 3mm to 1mm. Even though 3mm was thought thin enough at the pre-test, 1mm is better to avoid of affecting the result caused by the energy absorption and the bending of panels at supporting edges. Impact load and displacement were measured with a load cell and a laser-type displacement sensor at the center of the specimen. The load cell, which was capable of measuring up to 2 MN, was loading plate measuring 15 cm in diameter and 3 cm in thickness was placed at the center of the specimen and the load cell was set on the loading plate. The crack distribution on the rear face of the specimen was sketched after the test.

### 3.2 Test cases and specimens

Normal strength concrete was used in the RC panels and compressive strength was 56.4 MPa at a material age of 28 days. For the UHPFRC material, UHPFRC-FM as given in Table 1 was used. The average compressive strength was 205 MPa after standard heat curing for 48 hours and steam curing at 90 degrees, according to the recommendation [1].

Both the RC and UHPFRC panels were 1,800 mm long and 900 mm wide. The RC panels were 12 cm (RC-12) and 18 cm (RC-18) thick with 4 cm of cover concrete. The reinforcing bars, which were 10 mm and 13 mm in diameter in specimens RC-12 and RC-18, respectively, were spaced at 10 cm in two directions. The UHPFRC panels were much thinner than the RC panels, at 6 cm. The basic UHPFRC specimen (UFC-6) had no reinforcement, while panels with steel strand reinforcement in the longitudinal direction were also made (UFC-6-NP, UFC-6-P). In the reinforced panels, UFC-6-NP was without prestress and UFC-P had an introduced prestress of 80% of maximum capacity applied using steel wire strands (SWPR7B, diameter 12.7 mm) spaced every 9 cm. The reason for not

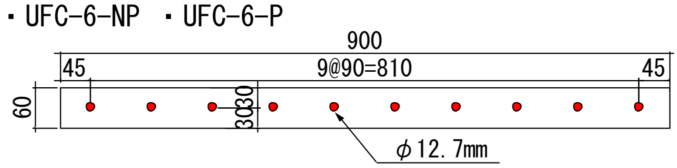



Figure 6 : Cross section of UHPFRC specimen

introducing full prestress is that there was a possibility of crack initiation because the panel was thin (6 cm) and the cover was thin (2 cm). A cross section of the UFC-6-NP and UFC-6-P panels is shown in Fig. 6.

The test cases are summarized in Table 5. Both RC panels and UHPFRC panels were loaded repeatedly at impact velocities increasing from 1 m/s until the specimen fractured. Since damage gradually accumulates in a specimen over repeated impacts, repeated tests using a higher initial impact velocity (11 m/s) were completed on a prestressed UHPFRC specimen (UFC-6-P).

Table 5: Main drop test cases

| Case | Thickness | Prestress | Impact velocity (m/s) |
|---|---|---|---|
| RC-12 | 12cm | — | 1.0, 2.5, 5.0, 7.5 |
| RC-18 | 18cm | — | 1.0, 2.5, 5.0, 7.5, 10.0, 11.0 |
| UFC-6 | 6cm | — | 1.0, 2.5, 5.0, 7.5, 8.0 |
| UFC-6-NP | 6cm | Non | 1.0, 2.5, 5.0, 7.5, 8.0, 9.0, 10.0, 11.0 |
| UFC-6-P | 6cm | 784kN (14.5N/mm$^2$) | ①1.0, 2.5, 5.0, 7.5, 10.0, 11.0, 12.0<br>②11.0, 12.0 |

### 3.3 Failure mode of RC panels

Figure 7 illustrates the failure mode of RC-12. At an impact velocity of 2.5 m/s, bending cracks appeared in the middle of the specimen and these cracks developed to become more widely distributed as impact velocity increased. The repeated impact test was terminated at 7.5 m/s because the bending crack opened wide, as shown in the photo in Fig. 7. The failure mode of RC-18 is illustrated in Fig. 8. In this case, bending cracks appeared at 5 m/s and they took on a distribution similar to those in RC-12. Ultimately, the specimen exhibited apparent punching shear failure with a punched diameter as large as 80 cm, as visible in the photo in Fig. 8.

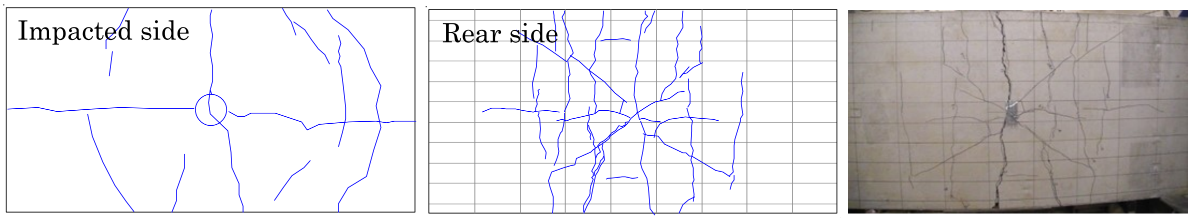



Figure 7 Fracture mode of RC-12 (7.5 m/s)

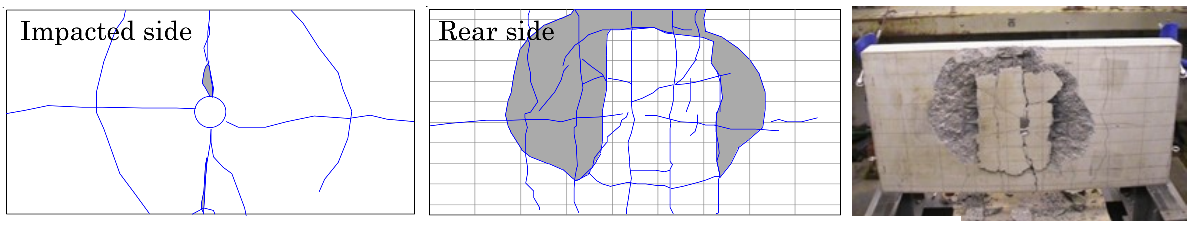



Figure 8 Fracture mode of RC-18 (11.0 m/s)

### 3.4 Failure mode of UHPFRC panel

Figure 9 shows the failure mode of UFC-6 (without steel strands and prestress). No damage was observed at an impact velocity of 2.5 m/s, in contrast with RC-12, which suffered bending cracks at this velocity, but radial cracks occurred from the center of the specimen at 5 m/s. The test was terminated at 8 m/s, because concentrated bending cracks were developing at the center of the panel rear side and several dispersed circular cracks occurred on the impact face, as seen in Fig. 9. The impact velocity at the ultimate limit state of the UHPFRC panel was 7.5 m/s, which means that a UHPFRC panel of 6 cm thickness without reinforcement has identical impact resistance to a RC panel of 12 cm thickness.

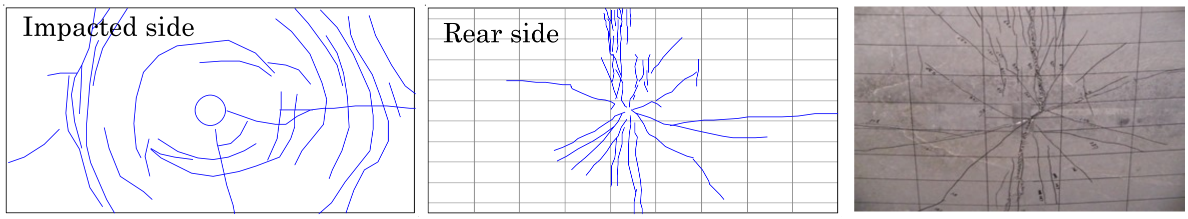



Figure 9 Fracture mode of UFC-6 (8.0m/s)

Test results for UFC-6-NP (with steel strand reinforcement, without prestress) are shown in Fig. 10. In this case, the bending cracks seen in UFC-6 were restrained because of the reinforcement by steel strands in the longitudinal direction. Longitudinal cracking initiated first at 5 m/s. As the impact velocity increased, bending cracking occurred, and the specimen ultimately exhibited combined bending and punching shear failure at 11 m/s. Assuming that the impact energy was absorbed through deformation of the specimen, it is determined that specimen UFC-6-NP possesses identical impact resistant to an RC panel of 18 cm thickness. Thus the reinforcement is very effective in enhancing the absorption capacity of a UHPFRC panel. Since the absorbed energies of UFC-6-NP and UFC-6 were 6.96 KJ and 3.68 KJ, respectively, the absorption capacity of UHPFRC panels was enhanced by 90% through the addition of the steel strands.

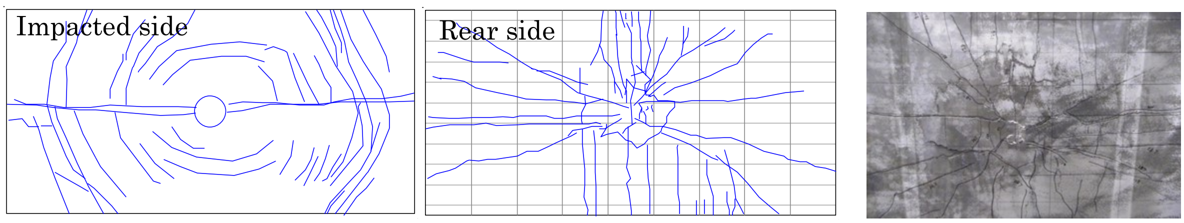



Figure 10 Fracture mode of UFC-6-NP (11.0m/s)

Figure 11 shows the test results for UFC-6-P, which reinforcing strands and prestress. The initiation of bending cracks was restrained and longitudinal cracks occurred similarly to those in UFC-6-NP. At the ultimate failure state, a clear punching shear line was formed. No circular cracks appeared on the impact face, indicating that punching shear failure was dominant in this case. The introduction of prestress enhanced energy absorption by 19% as compared to the case of without prestress (UFC-6-NP). The repeated impact test at the higher initial impact velocity (with impacts beginning at 11 m/s) showed the same result. Thus it was recognized that a single impact test and repeated impact tests give similar results under these test conditions. Figure 11 also demonstrates that the ultimate failure state of 6 cm UHPFRC panels varied from bending mode to punching shear mode as the amount of reinforcement increased. This test indicates that prestress is not very effective in enhancing impact resistance, though prestress has been shown to result in significant elongation and resistance in static loading cases [2]. The low shear strength in dynamic loading probably resulted in less ductile behaviour than under static loading.

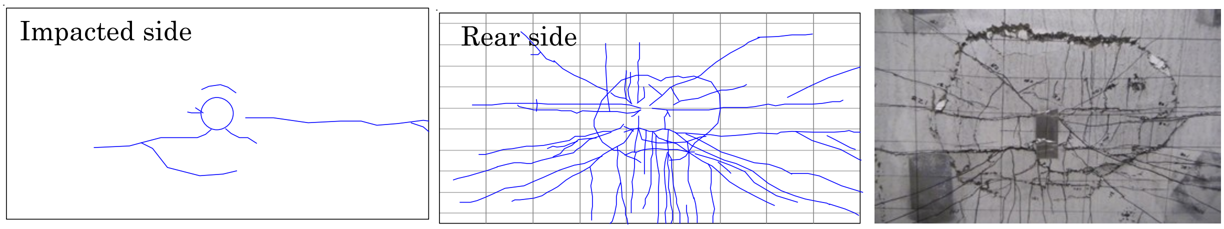
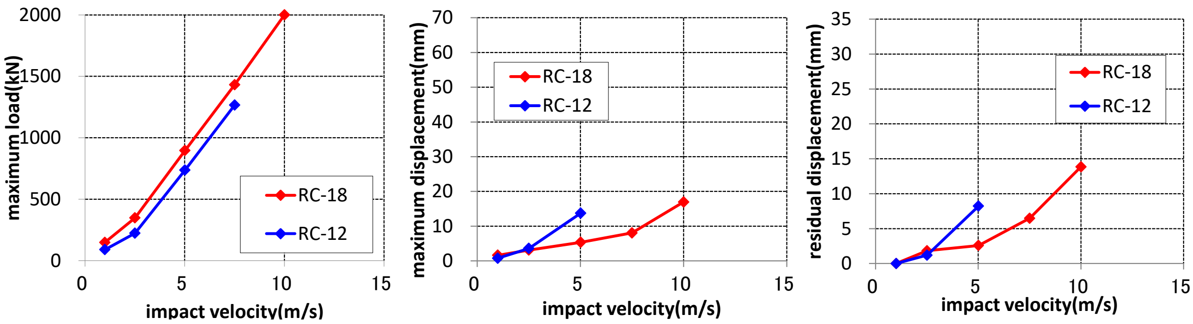



Figure 11 Fracture mode of UFC-6-P (11.0m/s)

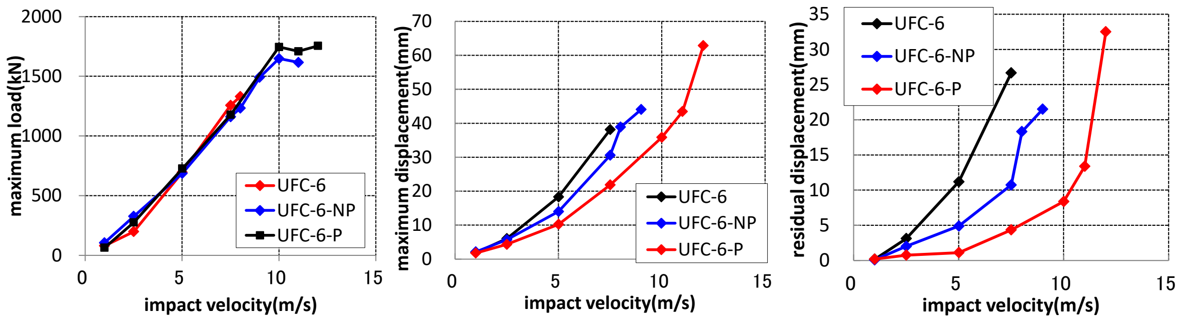
### 3.5 Maximum impact load and characteristics of maximum displacement

Fig. 12 and Fig. 13 show maximum impact load, maximum displacement and residual displacement, respectively. In the figures, some cases in which the impact load seemed to exceed the capacity of the load cell of 2 MN, or the displacement sensor seemed to be destroyed due to large failure did not measure impact load and displacement. The maximum and residual displacements show cumulative value at the rear face. Fig. 12 shows the case of RC panels.




(a) Maximum load (b) Maximum displacement (c) Residual displacement

Figure 12 Relation between maximum load, displacement and impact velocity (RC)




(a) Maximum load (b) Maximum displacement (c) Residual displacement

Figure 13 Relation between maximum load, displacement and impact velocity (UFC-6)

The maximum impact loads of both of panels increase linearly as the impact velocities increase. The maximum impact load of RC-18 is slightly larger than that of RC-12 in spite of its double stiffness of RC12, because RC-18 was fractured suddenly by punching shear. The maximum and residual displacements of RC-12 exhibit larger (faster failure) than those of RC-18 because of its bending deformation. In contrast, the displacements of RC-18 exhibited slowly progress because the panel showed the bending failure at the beginning of the impact loading even though it showed punching shear failure at the ultimate state.

Figure 13 shows the case of UHPFRC panels. It was found that the impact load increases similarly regardless of the reinforcement of strands and prestress. The impact load linearly increases as the increase of the impact velocity, and those in the case of UFC-6-NP and UFC-6-P showed constant loads between 1,600 kN and 1,700 kN due to the punching shear failure. The displacement shows more ductile behaviour as large as twice as compared to that of RC panels because of their significant large ductile nature. Also, UHPFRC panels with reinforcement and prestress shows smaller maximum and residual displacements, and apparently the effects of prestress more restrained the residual displacement rather than the maximum displacement.

## 4. CONCLUSIONS

This study has resulted in an understanding of the impact resistance of UHPFRC panels. The results can be summarized as follows.

- For a panel designed to resist impact, steel fiber reinforcement and a cross section that is as flat as possible are preferable.
- The fracture mode of thin UHPFRC panels is bending, while UHPFRC panels with prestress exhibit punching shear failure.
- A 6 cm UHPFRC panel has the same impact resistance as a 12 cm RC panel, while a 6 cm UHPFRC panel with prestress has superior impact resistance than an 18 cm RC panel.
- An UHPFRC panel with prestress can endure the same impact load as a UHPFRC panel without prestress, however it also has a remarkable ability to recovery from the displacement after impact.

By furthering these examinations and accumulating more experimental impact data for UHPFRC panels, the authors believe that we can contribute to practical use of UHPFRC's superior impact resistance in the near future.

## REFERENCES

[1] JSCE (Japan Society of Civil Engineers), 'Recommendations for the Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures (Draft)', 2004.

[2] Mochizuki, O., Musha, H., Yokoi, K., Ohtake, A., Shiratani, K., Watanabe, N. and Noguchi, T., 'Design, Experiments and Mass Production of UFC Slab in TOKYO International Airport (HANEDA) D Runway', 8th International Symposium on Utilization of High-strength and High-Performance Concrete, TOKYO, August, 2008, Volume 2, 901-908.