15th World Congress on Computational Mechanics (WCCM-XV)
8th Asian Pacific Congress on Computational Mechanics (APCOM-VIII)
Virtual Congress: 31 July – 5 August 2022
S. Koshizuka (Ed.)

Study on Reinforced Concrete Slabs Subjected to low velocity impact
- The method of preventing scattering debris by steel deck plates -

MASAKI GOHARA[1], YASUNORI MIZUSHIMA[2]

YUKI IDOSAKO[3] YASUTO YONEZAWA[4]

[1] University of Hyogo
1-1-12, Shinzaike-honcho, Himeji, Hyogo 670-0092, Japan
nd22y006@stshse.u-hyogo.ac.jp

[2] University of Hyogo
1-1-12, Shinzaike-honcho, Himeji, Hyogo 670-0092, Japan
mizushima@shse.u-hyogo.ac.jp

[3] Takenaka Corporation
1-5-1 Ohtsuka, Inzai-shi, Chiba 270-1395 Japan
idosako.yuuki@takenaka.co.jp

[4] JFE Metal Products Corporation
Shinagawa Season Terrace 11F Konan 1-2-70, Minato Ward, Tokyo 108-0075, Japan
y-yonazawa@jfe-kenzai.co.jp

Key words: Steal Deck, Steal Pipe, Reinforced Concrete Slab, Impact Test, Finite Element Analysis

Abstract. *In the building construction above public lines such as railroads, it is necessary to assume the accident by falling objects such as column members lifted by cranes. Even if RC slabs prevent perforation caused by falling objects during construction, scattering concrete debris may cause serious damage to the public space below the slabs. This study suggests an anchoring system to control the debris scattering by folding up the end of steel deck plates which are used as permanent formworks. Impact test was performed with specimens that have an anchoring system or not with changing the drop height as parameters. As a result, the anchoring system prevents debris from scattering in the case that the falling height was twice as high as the case without the anchoring system. In addition, finite element analysis was also performed to evaluate the result of the impact test. The result showed the analysis could evaluate the debris scattering of both the specimen which has the anchoring system or not.*

1 INTRODUCTION

During the building construction work, if a heavy object, which is suspended by a crane, falls and hits the reinforced concrete slab (RC slab), it causes significant damage to the space below the RC slab due to the perforated object and scattered concrete debris. When construction work is performed over public lines such as railroad tracks and roads, the damage is not only to the workers but also to third parties passing below the RC slabs. In order to prevent such damage, night-time construction may be required, which may increase construction costs and time. These factors may become an obstacle to the development of valuable space above the public lines. The risk of perforation and scattering of debris due to collision with heavy objects can be solved by improving the impact resistance of the RC slab that is subjected to the collision. Therefore, improving the impact resistance of RC slabs is considered to be important.

In a previous study, Mizushima et al. conducted full-scale impact tests assuming a suspended object being dropped on RC slabs [1], and confirmed that the perforation limit proposed by Degen [2], which is generally used as a concrete perforation limit, can predict the approximate failure mode of RC slabs. Specifically, it has been confirmed that for impacts exceeding the perforation limit, penetration occurs on the impact face, but does not lead to complete perforation. Finite element analysis has also shown that this prevention of perforation is due to energy absorption by the reinforcement bars in RC slabs. It was also observed that when the perforation limit of the Degen is exceeded, the steel deck plate that constitutes the RC slab drops out of the underside, causing the scattering of concrete debris.

Many studies related to the prevention of the debris scattering to the back side of RC slab have been conducted. Mikami et al. reported that the stiffness against static and cyclic loads is improved by applying the CFRP or AFRP sheets to the back surface of RC slabs [3]. Beppu et al. also conducted high-speed impact tests on concrete mixed with short organic fibers and reported that the crack dispersion effect of the fiber suppresses the penetration and debris scattering[4]. However, if these methods are adopted in a large area for rare events such as falling objects suspended by a crane, it may lead to increased workloads and the use of large quantities of new materials.

This study proposes an anchoring system between deck plate and concrete as a method to control debris scattering caused by the impact of heavy objects on RC slabs. This method can prevent the scattering of debris without increasing on-site work and using a large amount of new materials. Specifically, both ends of the steel deck plate are folded up toward the concrete, and the anchored deck ends to the concrete suppress the falling off of the steel deck plate. In this study, an impact test to confirm the performance of this anchoring system was conducted, using specimens with and without this system and drop height as test parameters. In addition, this study reports the results of a finite element analysis to evaluate this impact tests.

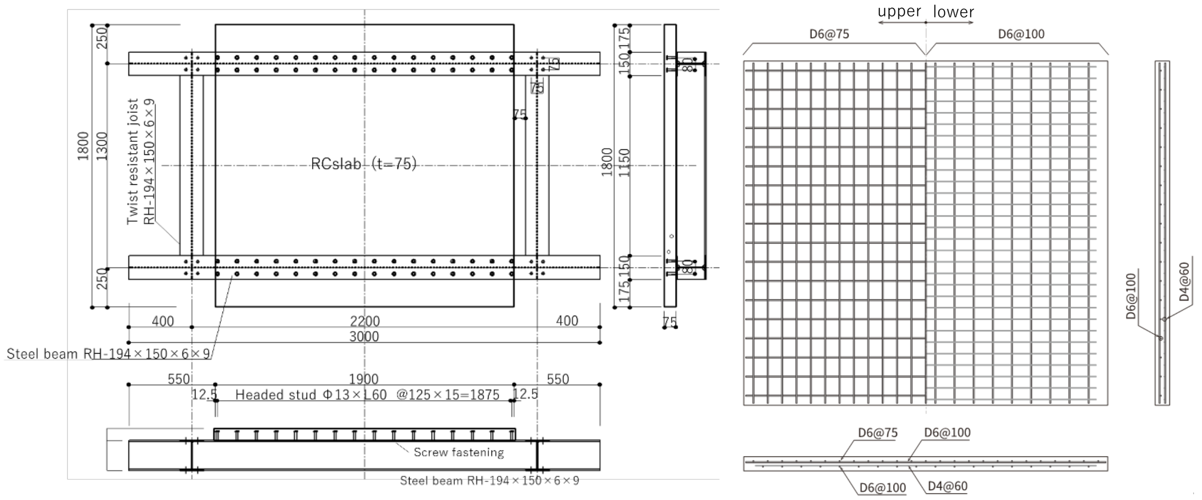
2 EXPERIMENT

2.1 Specimen

The test specimen and the arrangement of reinforcement are shown in Figure 1. The specimen was designed to simulate the specifications of RC slabs commonly used in steel-framed buildings in Japan. The specimen is half the size of the RC slab actually used in the building construction. The thickness of the RC slab of this specimen was 75 mm, and the support span was 1300 mm. The reinforcement bars were D6@75 main reinforcement and D6@100 reinforcement at the top, and D6@100 main reinforcement and D4@60 reinforcement at the bottom. A steel deck plate with a thickness of 0.6 mm was used as a permanent formwork at the bottom of the slab within the support span.

The steel beams were two 3 m long H-194 x 150 x 6 x 9 steel beams, joined by beams of the same cross-section as anti-torsion in the axial direction. RC slabs were made one-directional slabs and joined to the steel beams using headed studs. The specification of the headed studs was 2-13@125.

Three of the six specimens had an anchoring system. The height of the folded-up anchoring system was the same as the slab cover thickness to prevent interference with reinforcement bars in the RC slab. Tables 1 show the results of material tests. The tests were conducted over a period of three days. The material test results were conducted on the days of the experiment.



(a) Plan (b) Diagram

Figure 1: Specimen (reinforced concrete slab)

Table 1: Material test (concrete)

Specimen	Young's modulus (MPa)	Compressive strength (MPa)	Tensile strength (MPa)
N-7.5, N-9	2.64×10^4	34.5	2.23
N-13, F-13, F-14 F-15	3.18×10^4	39.7	2.62

2.2 Test setup

Figure 2, Figure 3, and Figure 4 show the experimental setup, a detailed view of the bearing section and steel pipe used as a projectile, respectively. The cross-section of this projectile was □-375×375×25 and the length was 1050 mm, and a lifting piece was installed at the top for lifting by a crane. The weight of the projectile was 310.8 kg including the lifting piece and jig. The test was conducted outdoors, and the projectile was dropped after being lifted to the predetermined height by a crane. The test stand was set on the steel plate laid on the ground surface and four load cells were installed on top of the test stand as shown in Figure 2. A ball seat was installed at the specimen support, and a PTFE sheet was inserted between the ball seat and the steel plate to allow for both rotation and horizontal sliding.

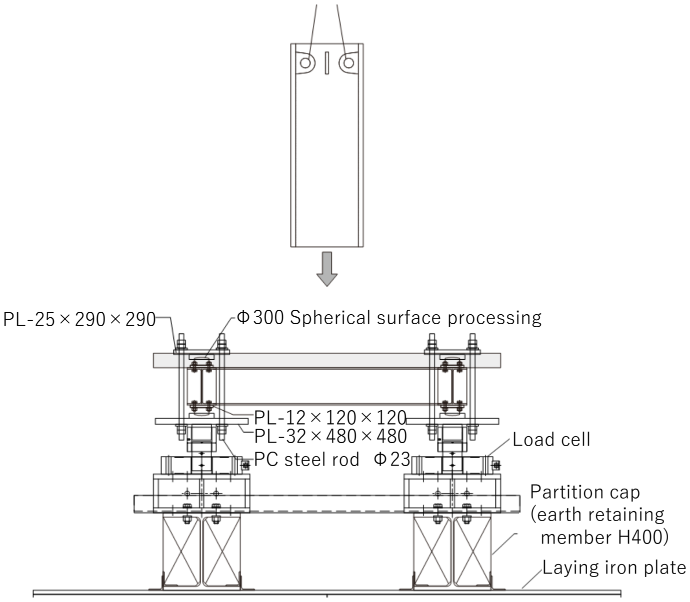


Figure 2: Setup of the test

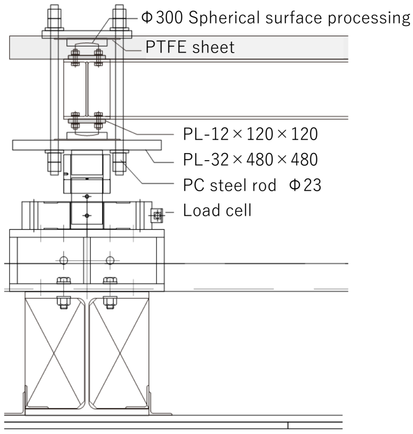


Figure 3: Bearing section

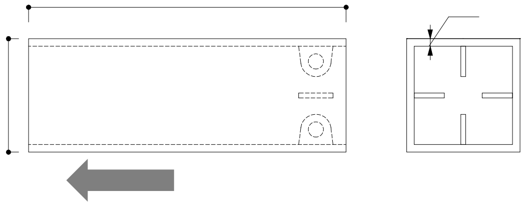


Figure 4: Projectile

The load acting on the RC slab at the time of impact was measured by four load cells in the support points. The displacement and velocity of the projectile were measured by capturing images of markers attached to the surface with a high-speed camera and tracking the markers using image analysis software. Markers were attached to all four surfaces at three points at a pitch of 150 mm from the lower edge of the falling impactor at 100 mm to avoid detection loss during the detection process. The camera was set to capture images at 1/4000 second per frame.

2.3 Parameter

The test parameters were to install the anchoring system or not and the drop height of the projectile. The test cases are listed in Table 2. In the cases without the anchoring system, target drop heights were 7.5, 9, and 13 m, and these cases were named N-7.5, N-9, and N-13, respectively (N-series). In the cases with the anchoring system, target drop heights were 13, 14, and 15 m, and these cases were named F-13, F-14, and F-15, respectively (F-series).

Table 2: Parameter

Height [m]	7.5	9	13	14	15
Not anchoring	N-7.5	N-9	N-13		
Anchoring			F-13	F-14	F-15

2.4 Results

Figure 5 and Figure 6 show the test result of N-13 and F-13. In N-series, deck plates fell off and debris of broken concrete scattered below the RC slab in all cases. In F-series, the deck plates did not fall off and debris scattering was prevented in the cases the drop height is 13m and 14 m. It was confirmed that this anchoring system can prevent debris scattering even when the projectile is dropped from about twice the height of that without it. Even when the anchoring system was installed at the end of the deck, the deck fell off and debris scattered to the backside of the RC slab in the case of F-15, where the drop height was 15 m.

(a) The moment of impact

(b) Close view of impact area

(c) Close view of deck end

Figure 5: Result of impact test (N-13)

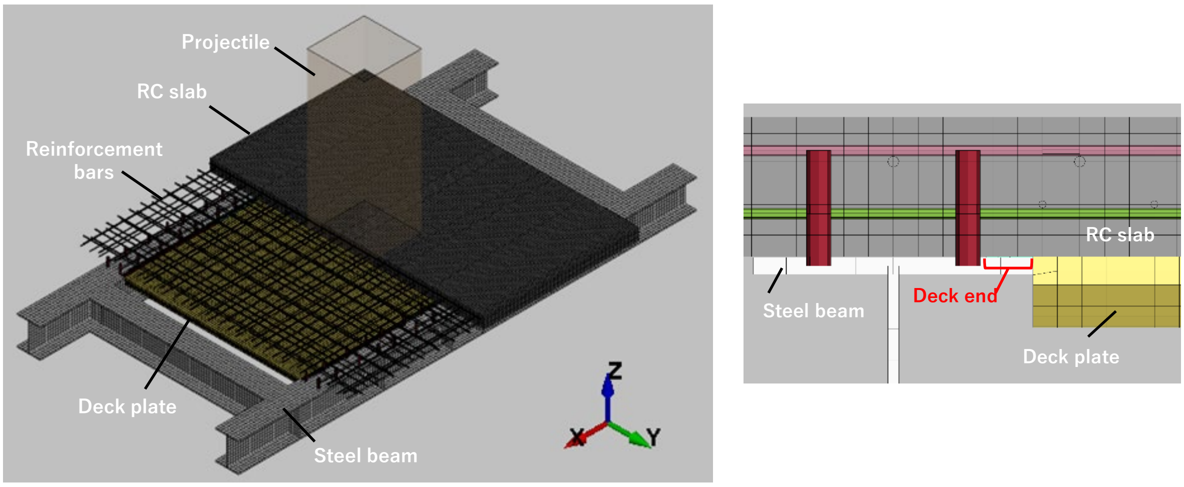
(a) The moment of impact (b) Close view of impact area (c) Close view of deck end

Figure 6: Result of impact test (F-13)

3 FINITE ELEMENT ANALYSIS

3.1 Analysis model

An overview of the analysis model is shown in Figure 7. Analysis models is modeled with the same size as the specimen in the impact test. Contact condition is applied based on the penalty method. This contact method is employed between deck-concrete and deck-steel beams, deck-projectile, concrete-steel beams, and concrete-projectile. The static and kinetic coefficients of friction of the contact surfaces are set to 0.3.



(a) Entire view (b) Close view of deck end

Figure 7: Analysis model

Concrete is modeled with 8-node hexahedral element. The elastoplastic material model considering cracking behavior by smeared crack was employed to concrete parts. The stress-strain relationship after cracking was modeled as linear softening [5]. The width of the crack, w, was determined using the criterion for the fracture energy, G_f given in the standard specification for concrete [6].

$$w = 2G_f/f_t \qquad G_f = 10f_c^{1/3}.d_{max}^{1/3} \tag{1}$$

where, d_{max} is the maximum diameter of aggregate in the concrete, f_c is the compressive strength, and f_t is the tensile strength.

To represent the damage of concrete, the limit of element deletion is set to the maximum principal strain and maximum shear strain. Based on the results of the parameter study, the maximum principal strain is 0.04 and the maximum shear strain is 0.045.

The reinforcement bars were modeled with beam elements, and a two-node Hughes-Liu element with integration in the cross-section was used to account for shear deformation. The reinforcement bars were assumed to be elastoplastic with strain-rate dependence based on the Cowper-Symonds equation [7], and the stress-strain relationship was approximated by a multilinear approximation based on the results of the material tests. In addition, as a method of expressing the failure of the reinforcement bars, the limit of element deletion is set to 0.2 of the equivalent plastic strain.

Deck plate and steel beam were modeled with shell elements. In the experiment, the decks are connected to each other by screws at regular intervals at the bottom of the ribs, but in this analysis, the decks are represented by sharing the nodes at the same line. The deck plate was modeled as bilinear elastoplastic materials, and Young's modulus and yield strength were set to 1.97×10^5 MPa and 296MPa, respectively, using material test results.

Figure 8 shows an overview of the modeling of the anchoring system. The folded-up shape of the deck end was not modeled but was assumed to be the same as that without the anchoring system. The deck end has a failure criterion due to shear stress acting between the concrete and the deck end to express the anchoring system. An overview of the detachment criterion is shown in Figure 9. Based on the parameter study, the shear stress at the start of detachment was set at 4.0 MPa. The distance at which the reaction force is zero was set to 30 mm, and the distance between the two was modeled linearly.

(a) Not anchoring – N series (b) Anchoring – F series

Figure 8: Modeling of deck plate end

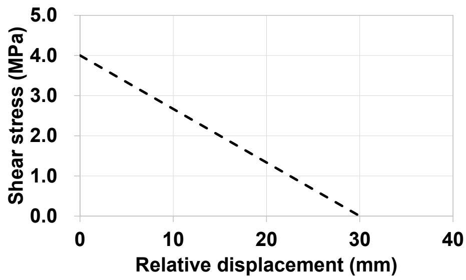
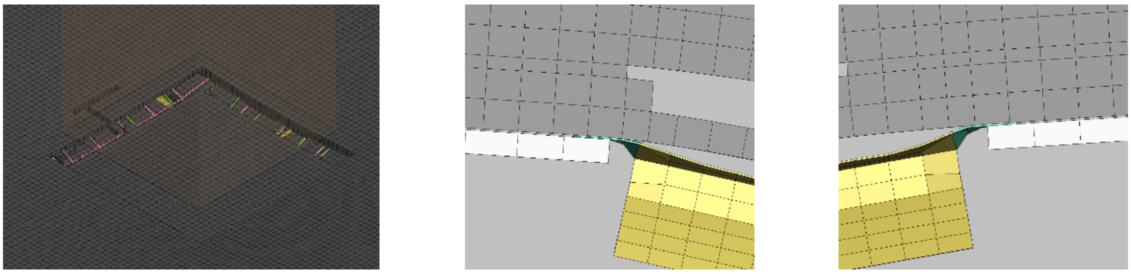


Figure 9: Failure model adopted as anchoring system

3.2 Results

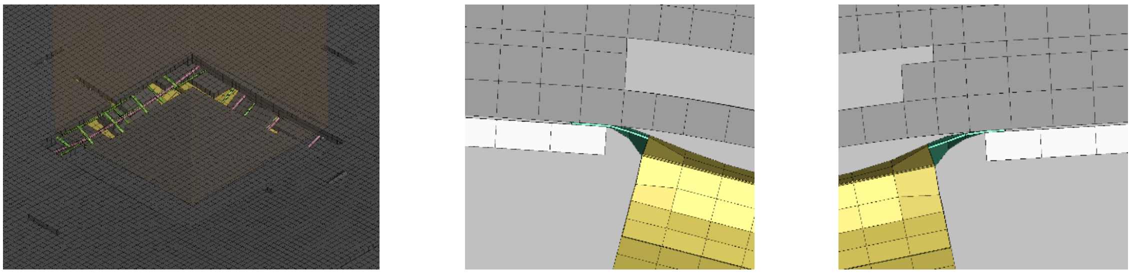
Figure 10 and Figure 11 show the failure state and the velocity time history of the projectile in the cases of N-series. In N-7.5, the concrete in the impacted area remained at the end of the analysis, reproducing the same fracture states in the experiment. No failure of the reinforcement bars was observed as in the experiment. The velocity time history of the projectile was almost the same as in the experiment. Both sides of deck ends were dislodged and about half length still remained. The analysis could not reproduce complete dislodging in the experiment, but both sides of deck ends were dislodged halfway to the edge of the deck. In N-9, the failure state of concrete at the end of the analysis was similar to that in the experiment, and the failure states was slightly larger than in N-7.5. In addition, two upper reinforcement bars failed. The velocity time history of the projectile was in close agreement with the experiment. More dislodging occurred at the deck ends than in N-7.5, but this did not lead to fall off completely. In N-13, the fractured state at the end of the analysis was similar to that in the experiment. The failure states were larger than in N-7.5 and N-9, and good reproduction of the experiment. Three upper reinforcement bars and one lower reinforcement bars failed. The velocity time history of the projectile was in close agreement with the experiment. One deck end was completely dislodged and the other also was, but about half length was still remained.

Figure 12 and Figure 13 show the failed state and the velocity time history of the projectile in the cases of F-series. In F-13, more concrete remained at the impact area at the end of the analysis than in N-13. One upper and one bottom reinforcement bars failed in this analysis. Although the actual drop height of F-13 was 40 cm higher than that of N-13, the number of failured reinforcement bars was less than N-13. The velocity time history of the projectile was in close agreement with the experiment. The deck was pushed down together with the slab, and not to be dislodged completely as in the experiment. In F-14, the projectile was dropped onto the RC slab at a slightly oblique angle in the experiment. Although no failed reinforcement bars were observed in the experiment, one upper reinforcement bars were failed in the analysis. The velocity time history of the projectile was in close agreement with the experiment. One deck ends was completely dislodged. In F-15, fracture propagated more widely around the impacted area of RC slab than the other cases. There was almost no concrete in the impacted area and a large fracture state was reproduced as in the experiment. However, only one upper reinforcement bars failed in the analysis. In the experiment, the number of failed reinforcement bars is 10. In the velocity time history of the projectile, the velocity reversal took about 0.15 seconds faster than in the experiment. This may be due to the fact that the reinforcement bars, which had a small number of breaks, absorbed the impact energy of the impacted object. The deck was completely dislodged as in the experiment.



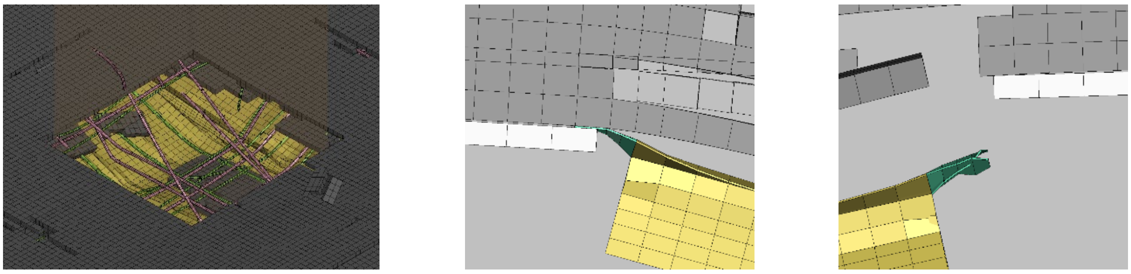
(i) Impacted area (ii) Close view of deck ends

(a) N-7.5



(i) Impacted area (ii) Close view of deck ends

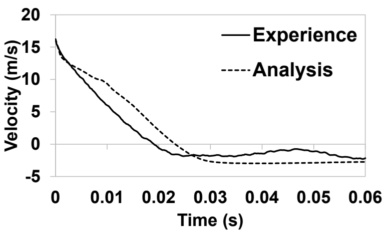
(b) N-9



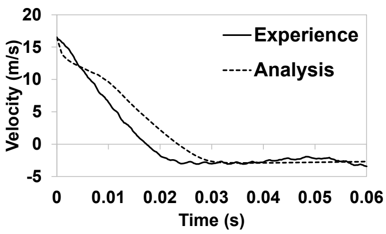
(i) Impacted area (ii) Close view of deck ends

(c) N-13

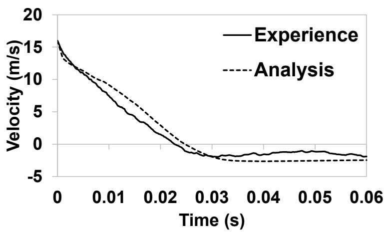
Figure 10: Failured model (not employed anchoring system)



(a) N-7.5

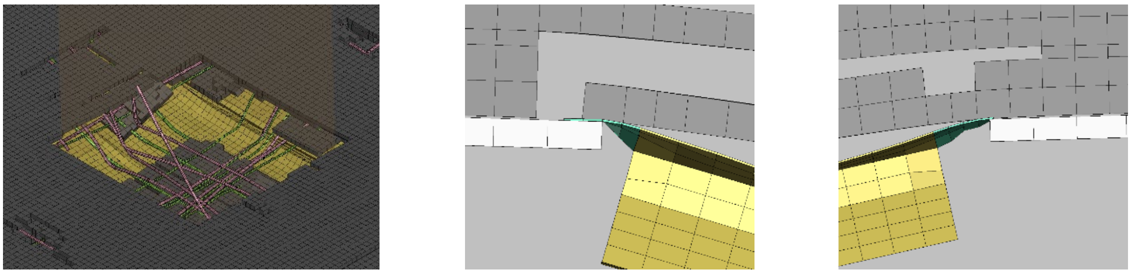


(b) N-9



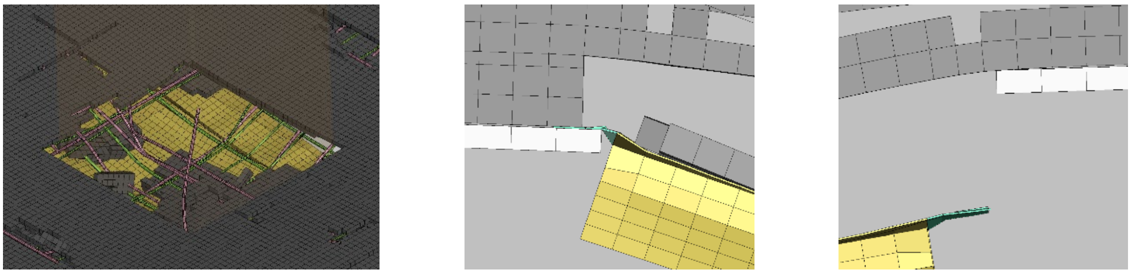
(c) N-13

Figure 11: Velocity time history of the projectile (N-Series)



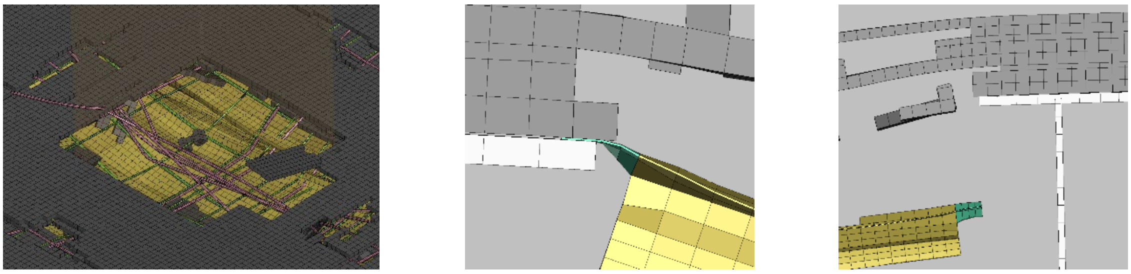
(i) Impacted area (ii) Close view of deck ends

(a) F-13



(i) Impacted area (ii) Close view of deck ends

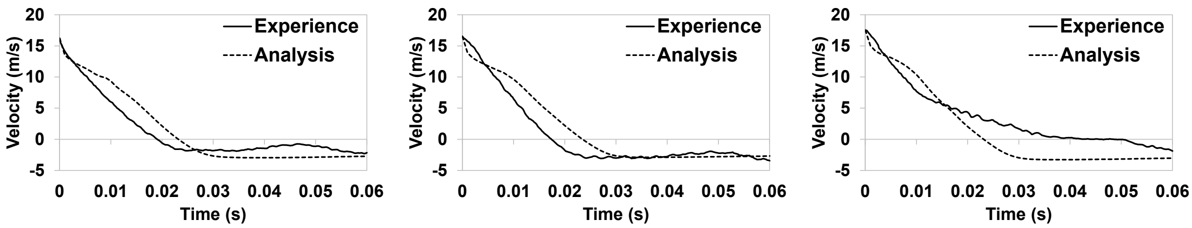
(b) F-14



(i) Impacted area (ii) Close view of deck ends

(c) F-15

Figure 12: Failured model (employed anchoring system)



(a) F-13 (b) F-14 (c) F-15

Figure 13: Velocity time history of the projectile (F-Series)

4 CONCULUSION

This study suggested an anchoring system which is folded up the end of steel deck plates to prevent debris scattering caused by falling objects assumed during construction. The impact test was performed with specimens which have the anchoring system or not and changing the drop height as parameters. In addition, finite element analysis was also performed to evaluate the result of the impact test. The following conclusions can be obtained from this study.

- In the case without the anchoring system, the deck plate fell off and debris scattered at a drop height of 7.5 m. In contrast, in the case with the anchoring system, the deck did not fall off and debris scattering was suppressed even at a drop height of 14 m. These results indicate that the anchoring system prevents debris from scattering in the case that the falling height was twice as high as the case without the anchoring system.
- In finite element analysis for the cases in which the drop heights were 13 m, the deck falling off was observed in the case without the anchoring system, but that was not observed in the case with the anchoring system. These results show that finite analysis can evaluate the falling of the deck plate and debris scattering in both cases of with and without the anchoring system. In F-14, which was shown oblique collision in the experiment, the deck plate fell off in the analysis. In contrast, the deck fell off as in the experiment and a large failure state of the impact area was able to be reproduced in F-15.
- Comparison of the velocity time history, the analysis showed good agreement with the test result in the case without the anchoring system. In the case with the anchoring system, F13 and F14 also reproduced the velocity of the projectile well. In the F-15, the velocity reversal time was about 0.15 seconds faster than that of the experiment. This may be since the failure of the reinforcement bars of the analysis was less than that of the experiment.

REFERENCE

[1] Mizushima, Y., Horiuchi, Y., Haraguchi, K., Hosokawa, I. and Oba, W. *Study on behavior of reinforce concrete slabs subjected to impact of accidentally falling objects during construction*. Journal of Structural and Construction Engineering (Transaction of AIJ). Vol.83, No.751, pp.1239-1249, 2018.9 (in Japanese).

[2] Degen, P.P. *Perforation of reinforced concrete slabs by rigid missiles*. J Struct Div, Proc ASCE 1980;106(ST2):6.

[3] Mikami, H., Kishi, T., Ando, T. and Kuribayashi, Y., *Experimental study on impact resistance of RC slabs strengthened with FRP sheet*. Journal of structural engineering. A. Vol.48, 2002-03 (in Japanese).

[4] Beppu, M., Ogawa, A. and Takahashi, J. *Impact resistant performance of fiber reinforced cementitious composite plates subjected to high velocity impact by a rigid projectile*. Journal of Society of Civil Engineers, Vol.70, No.2, pp.180-193, 2014 (in Japanese).

[5] Broadhouse, B.J. and Neilson, A.J. *Modeling Reinforced Concrete Structures in DYNA3D*. AEE Winfrith, 1987.10.

[6] Japan Society of Civil Engineering, *Standard Specifications for Concrete Structure -2012, Design*. JSCE, 2012 (in Japanese).

[7] Cowper, G.R. and Symonds, P.S. *Strain hardening and strain rate effects in the impact loading of cantilever beams*. Brown University, Applied Mathematics Report, 1958.