

DESIGN, EXPERIMENTS AND MASS PRODUCTION OF UFC SLAB IN TOKYO INTERNATIONAL AIRPORT (HANEDA) D RUNWAY

Osamu MOCHIZUKI

General manager, Technology Center, Taisei Corporation, Tokyo, Japan

Hiroyuki MUSHA

Technical Manager, Technology Center, Taisei Corporation, Tokyo, Japan

Kenji YOKOI

Manager, Tokyo Branch, Taisei Corporation, Tokyo, Japan

Akio OHTAKE

Manager, Tokyo Branch, Taisei Corporation, Tokyo, Japan

Kouji SHIRATANI

Manager, Design Dept. Civil Engineering Div., Taisei Corporation, Tokyo, Japan

Norio WATANABE

Manager, Design Dept. Civil Engineering Div., Taisei Corporation, Tokyo, Japan

Takatoshi NOGUCHI

Manager, Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Tokyo, Japan

Masafumi MIYATA

Senior researcher, National Institute for Land and Infrastructure Management, Yokosuka, Japan

ABSTRACT:

Approximately 6,900 slabs, which made of Ultra-high strength Fiber reinforced Concrete (hereafter, UFC), will be erected in 192,000 m² of Tokyo International Airport (Haneda) Runway D. This UFC slab has dimensions of 7.82 m x 3.61 m, and is pre-tensioned in two directions. UFC has made 56% self-weight reduction possible comparing with conventional concrete. To confirm the load performance of the UFC slab, load tests of the full-scale slab were conducted. In this report, the outline of the design of the UFC slab is introduced, and the performance confirmation experiment is described.

Keywords: UFC, ultra-high strength, fiber reinforced concrete, slab, loading test, pre-tension, full scale, design

1. INTRODUCTION

The outside area (the area colored blue in Fig. 1) of the runway and taxiway of the pile-elevated platform of Runway D at Haneda Airport is made from precast slabs using ultra high strength fiber reinforced concrete (hereafter referred to as UFC). The area of this part is 192,000m², and about 6,900 UFC slabs (including irregular shaped slabs) with standard dimensions 7.82m×3.61m will be used.

Compared with conventional concrete, UFC has a significantly higher mechanical performance and durability. By using UFC slabs in the pier portion it is possible to make the deck lighter, and therefore to reduce the weight of the steel jacket and piles of the pier. Also, because the material has high durability, it is expected that the maintenance cost will be reduced.

In this paper, the fundamental performance of UFC, the slab design calculations, and a summary of load capacity confirmation tests using full size specimens are described. Also, the mass production under severe quality control in a dedicated UFC slab factory in

Chiba Prefecture is described.

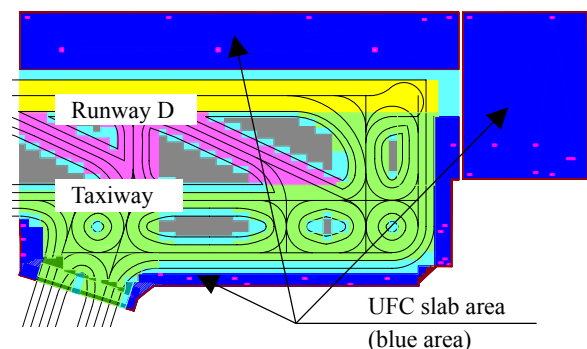


Figure 1 UFC slab allocation

2. SUMMARY OF UFC

2.1 Fundamental performance of UFC

UFC has an extremely high compressive strength, 200N/mm², and contains steel fibers and so has high

toughness. Also, because of the dense structure of the matrix, it has very high durability. In 2004, the Japan Society of Civil Engineers published Concrete Library 113 “Recommendation for Design and Construction of Reinforced Concrete using Ultra-high Strength Fiber (Draft)” [1] (hereafter referred to as “UFC Guideline”), which provides guidelines for design and construction. The following are the characteristics of UFC.

(1) High strength, high toughness

The UFC used in this project is a new cementitious material made from cement, silica fume, and silica sand powder, together with steel fibers for reinforcement (diameter 0.2mm, length 15mm, percentage by volume 2%) and a special plasticizer. The compressive strength is extremely high, about 200 N/mm², and crack extension and enlargement of crack widths is reduced by the steel fibers, so an extremely high toughness and bending strength of about 45 N/mm² are obtained.

Table 1 shows a comparison of the fundamental property values of UFC compared with normal concrete after undergoing standard curing (90°C, 48 hour steam curing).

Table 1 Comparison UFC with conventional concrete

Item	Units	UFC(*)	Conventional high strength concrete
Compressive strength	N/mm ²	180	40
Tensile strength	"	8.8	2.7
First cracking strength	"	8.0	1.3
Young's modulus	kN/mm ²	50	31
Mass per unit volume	kN/m ³	25.5	24.5
Shrinkage strain		50×10 ⁻⁶	130×10 ⁻⁶
Creep coefficient		0.4	2.6
Water permeability coefficient	cm/s	4×10 ⁻¹⁷	10 ⁻¹⁰
Chloride ion diffusion coefficient	cm ² /year	0.002	0.7

(*)after standard heat curing (90°C heat treatment for 48 hours)

(2) High durability

UFC contains powders with differing particle diameters based on the ideal of “maximum density filling,” and the water content is reduced to give a water cement ratio of about 22%. Also, reactive powder such as silica fume is contained, so the water binder ratio is very low at about 14%. As a result, the hardened concrete is extremely dense, so the permeability of chloride (depth of ingress of chloride ion) is about 1/10 that of normal concrete (W/C: 45%), so the durability performance is extremely high

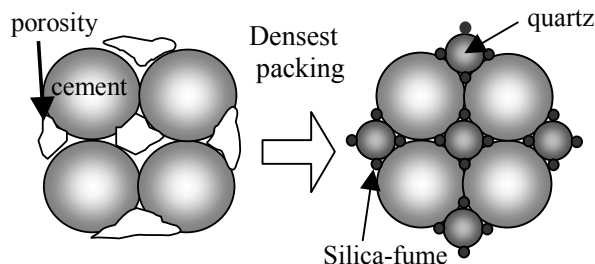


Figure 2 Image chart of “Maximum Density Filling”

Table 2 Mix proportion of UFC*

*Standard UFC Material described in UFC Guideline					
	Pre-mixed powder	Fine Aggregate	fibers	super-plasticizer	water
Unit Quantity kg/m ³	1,308	932	157	28 (liquid)	162
					Total Water : 180

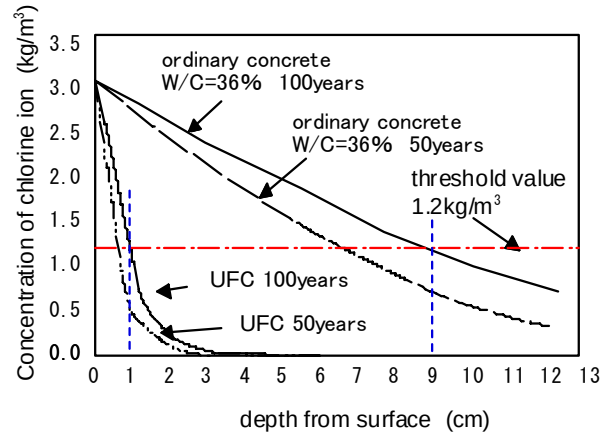


Figure 3 Comparison of chloride profiles

Figure 3 shows the results of a comparison of the resistance to chloride ingress of UFC and normal concrete. This figure shows the depth to which chloride ion will permeate after 50-100 years when the concrete is exposed to a very corrosive environment, as obtained by calculation. According to this figure, after 100 years the depth of ingress of chloride ion into UFC at threshold value will be about 1cm, a value almost an order of magnitude smaller than the 9cm for normal concrete.

Also, because of the dense matrix, UFC has very high wear resistance (about 6 times that of normal concrete), so it can be used in the spillways of dams or the linings of tunnels, etc.

This UFC with its excellent performance was developed in Europe and introduced into Japan in the year 2000. Thereafter various technical developments has been carried out in Japan, and in 2002 the 50 m long footbridge “Sakata Mirai Bridge” was constructed [2] [3], followed by several other footbridges [4], and at present UFC is being applied to road bridges [5]. However, this is the first time UFC has been applied to harbor or airport large-scale facilities.

2.2 Application of UFC to Runway D

The reasons for using UFC in the deck slab were as follows.

- ① It is possible to reduce the weight of the deck by using high strength UFC. That is 56% reduction in dead load. As a result, the weight of the steel jacket and the piles can be reduced, so the construction cost can be reduced.
- ② The durability is excellent, so the maintenance cost can be reduced.
- ③ In September 2004, the UFC Guideline was published by the Japan Society of Civil Engineers, so it became possible to carry out an objective check of the required performance.

3. OUTLINE AND DESIGN OF THE UFC SLABS

3.1 Structural outline of the UFC slabs

Figure 4 shows the structural outline of the UFC precast slabs. Pre-tensioning in two directions using prestressing steel in the slabs was adopted to reduce the cost of mass production of precast concrete slabs. There was no precedent for a precast slab structure pre-tensioned in two directions, but this structure is more advantageous from the cost point of view than pre-tensioning in one direction and post-tensioning in the other direction.

In this design, the average slab thickness was about 135mm, but if conventional concrete (design strength 50N/mm²) were used in the precast slabs, the average slab thickness would be about 320 mm.

The reduction in dead load (ratio of average dead loads) using UFC slabs compared with normal concrete slabs is about 56% (Table 3).

3.2 Design of UFC slabs

(1) Outline of design conditions

The loads that determined the cross-section of the UFC slabs were as follows.

- Serviceability limit state (normal conditions): Slab dead load + vehicle loading
- Ultimate limit state (emergency condition): Slab dead load + aircraft loading (aircraft deviating from the runway and taxiway)

The items checked at serviceability limit state and ultimate limit state are shown in Table 4.

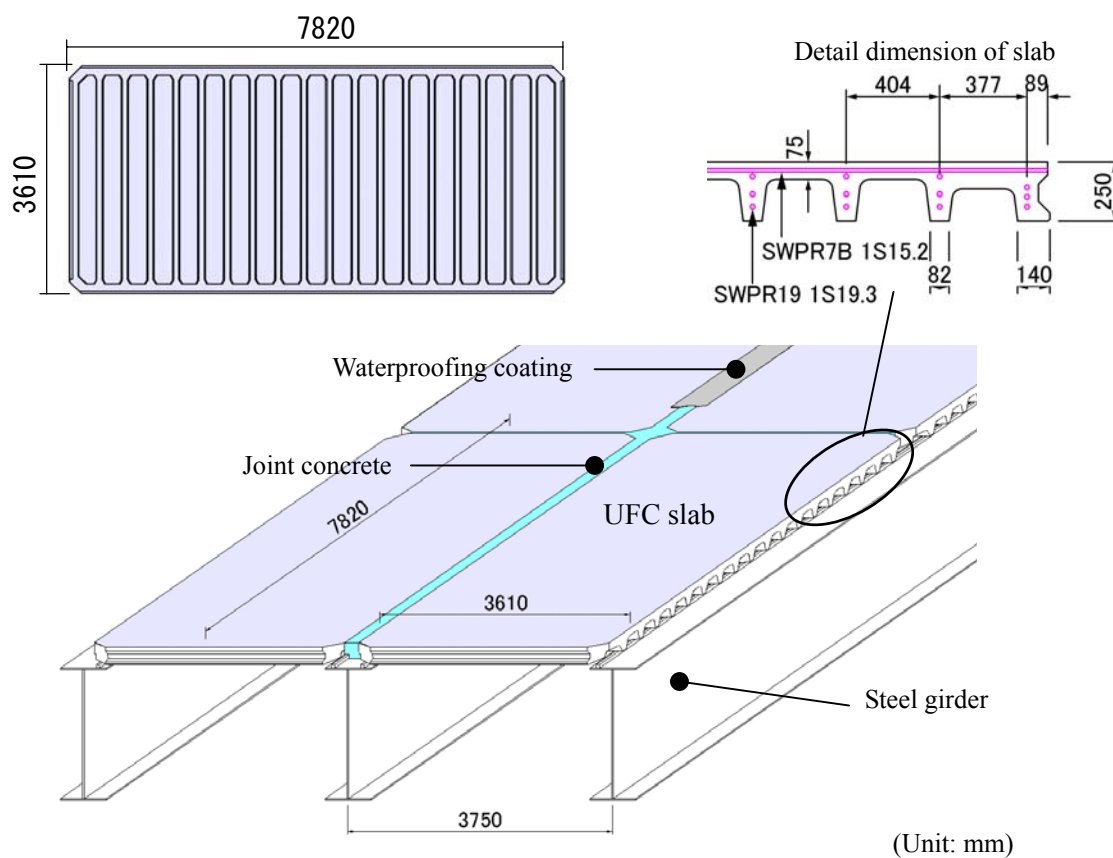


Figure 4 Structural outline of the UFC precast slabs

Table 3 Comparison of UFC slab and conventional concrete slab

	UFC Slab	Conventional Concrete Slab ($f_{cd} = 50\text{N/mm}^2$)
Structure	Thickness is 250 mm at a rib, 75 mm between ribs	Thickness is 320 mm; rectangular section
Average Thickness	135 mm	320 mm
Unit Dead Load	3.83 kN/m ²	7.84 kN/m ²

Table 4 Items checked in the UFC slabs

	Serviceability limit state	Ultimate limit state (during aircraft loading)
Required performance	· No cracking or damage in the UFC	· Damage that would require urgent replacement or repair shall not occur
Items checked	· Tensile stress < limiting value · Compressive stress < limiting value	· Factor of safety against collapse > 1.0 · Stress in prestressing steel < yield stress

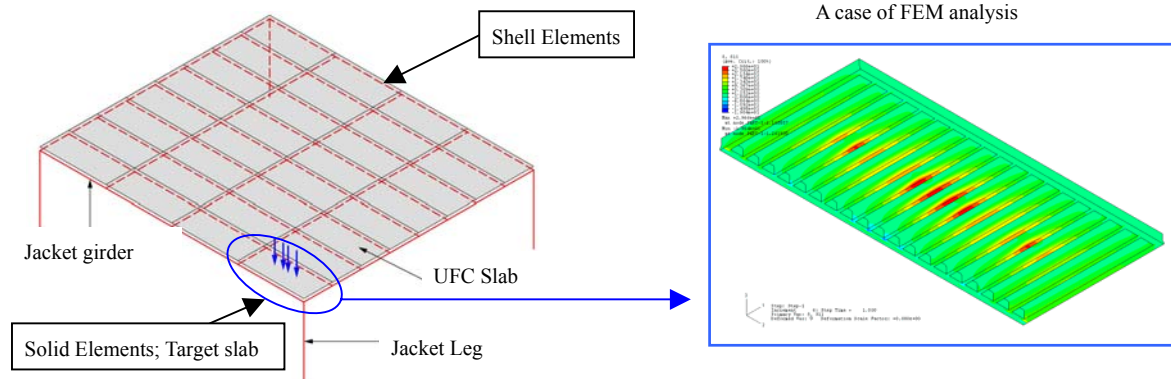


Figure 5 Outline of FEM Analysis model

The material properties and limiting stress values in the UFC design calculations were set in accordance with the UFC Guideline. The design strength of the UFC was 180 N/mm^2 .

At the ultimate limit state cracking in the slab is allowed, but it is required that the slab will not collapse. However, particularly in the case of aircraft running, it was required that there be limited damage so that urgent repair and replacement is not necessary, and that the slabs can be subsequently used. In order to satisfy these conditions, a limit was imposed that the stress in the prestressing steel shall be less than the yield stress when aircraft loading is applied.

(2) Calculation of cross-sectional forces

The cross-sectional forces and stresses in the UFC slabs were calculated from 3-dimensional elastic FEM analysis (Fig. 5). In the FEM analysis, the beams of the jacket were also modeled, and the legs were evaluated as vertical springs.

(3) Calculation results

As examples of the design calculations, Tables 5 to 6 show the results for bending in the standard slab for serviceability limit state and ultimate limit state.

The tensile stress arising under the serviceability limit state was less than the limiting value of 8 N/mm^2 , so it was confirmed that cracking would not occur.

It was also confirmed that the factor of safety against bending collapse was sufficiently high under aircraft loading, and that the prestressing steel did not reach the yield stress.

Checking against shear, etc., was also carried out in the design calculations, and it was confirmed that the required performance was satisfied.

Table 5 Results of checks on flexural stress at SLS

Unit : N/mm^2

	Flexural stress	Limit stress
Short direction (slab with rib section)	-6.9	-8.0
Long direction (slab section)	-7.5	

* : A positive value is compression.

** : the compressive stress was omitted because it is far smaller than the limit value.

Table 6 Results of check on flexural capacity at ULS (during aircraft loading) and check on stress of steel wire

	Safety factor against Flexural Collapse	Stress of steel wire (N/mm^2)
Short direction (slab with rib section)	$1.73 > 1.00$	$1070 < \sigma_y = 1562$
Long direction (slab section)	$1.86 > 1.00$	$920 < \sigma_y = 1562$

4. Load tests using full size UFC slabs

4.1 Objectives and outline of the tests

Load tests using full size slabs were carried out in order to confirm that the response and load resistance could be obtained in accordance with the UFC slab design calculations [6] [7].

Load tests were carried out on two specimens in order to verify the amount of variation due to the UFC material properties and due to manufacture.

The test specimens were basically the same as the actual structure shown in Fig. 4.

In the tests, first, vehicle loading was applied three times, then aircraft loading was applied twice. Then finally loading in excess of the aircraft loading was applied (Fig. 6).

The items checked for each loading were as follows.

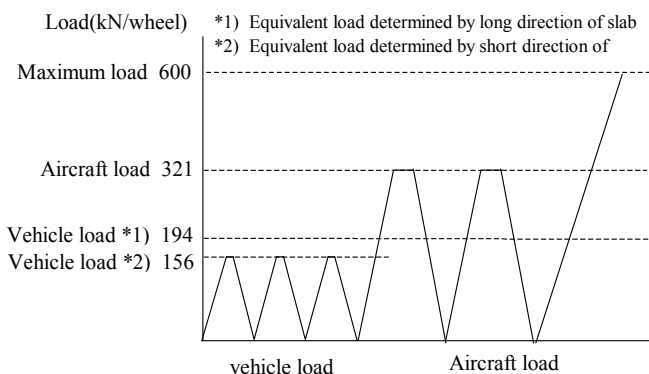


Figure 6 Loading steps

- 1) Items checked under three repetitions of vehicle loading
 - That cracking did not occur
 - That the response (displacement, strain) was linear with respect to the load, and was the same as the calculated value.
- 2) Items checked under two repetitions of aircraft loading
 - That the prestressing steel did not yield
 - That the relationship between load and displacement was uniformly increasing for loads up to the aircraft load, that the residual displacement when the aircraft load was removed was small, and that the displacement when the aircraft loading is applied the second and third times was not significantly greater than when it was applied the first time.
- 3) Items checked at maximum load
 - The margin of load resistance with respect to the aircraft loading was determined by loading in excess of the aircraft loading.

The position of application of the loads is shown in Figure 8. The wheel load pressure area and separation and layout are different for the vehicle loading and the aircraft loading, but in these tests the wheel loading arrangement for aircraft loading was used. The wheel loading layout was the wheel layout for the B777-200ER, for which the ultimate cross-sectional forces are highest.

Also, in the actual structure the support conditions are on the beams of the jacket, which can bend, but in the tests the test specimens were supported on rigid foundations and simply supported at the long sides (Fig. 7). To take the effect of the difference in the actual structure conditions and the test conditions into account, equivalent loads were set to reproduce the cross-sectional forces and stresses calculated during the design. There was sufficient safety with respect to fatigue, so no fatigue tests were carried out.

To predict the slab behavior, 3-dimensional elasto-plastic FEM analysis was carried out. Here, in order to confirm that the variation in the two test results were within the postulated range, the upper and lower limits on the variation in the material quality postulated for the production of the actual slabs were set based on the test results given in the guide, etc., and the analysis was carried out.

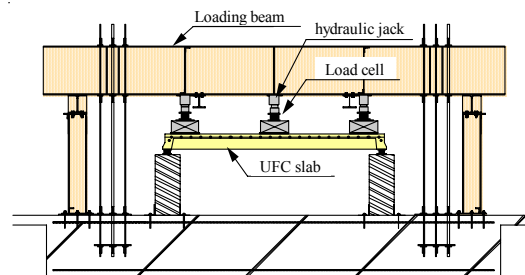


Figure 7 Load test equipment

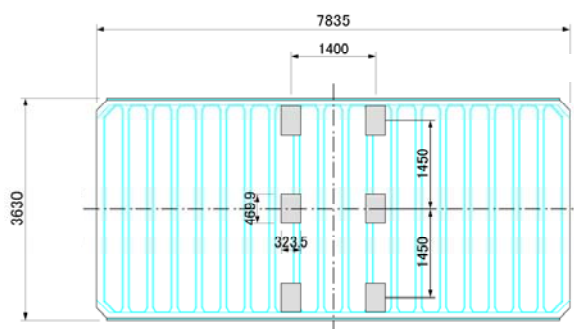


Figure 8 Position of wheel loads on UFC slab

Table 7 FEM analysis parameters

	UFC (N/mm ²)			Steel wire (N/mm ²)		
	compressive strength	Tensile strength	modulus of elasticity	Yield strength	Tensile strength	modulus of elasticity
Upper Limit value	207	13.8	53,200	1,870	1,980	191,000
Lower Limit value*	180	8.8	46,800	1,570	1,860	191,000

*: Lower limit is a value of UFC Guideline



Photo 1 Loading test



Photo 2 Measuring displacement of slab

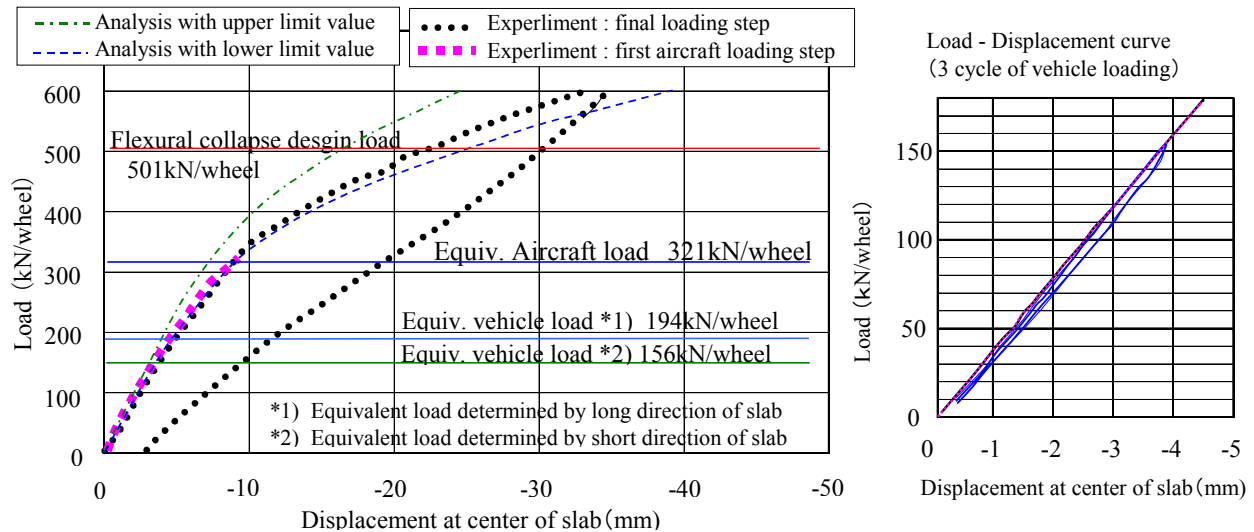


Figure 9 Load - displacement

4.2 Test results

(1) Load – displacement curve

Tests were carried out on two test specimens, and the load – displacement curve for one of these cases is shown in Fig. 9.

The results for the other case had a similar trace to that of the figure shown below.

i) Regarding the serviceability limit state

- Under the three repetitions of vehicle loading, the displacements were linear, and there was no significant residual displacement. Also, there was good agreement with the FEM analysis results.
- The first crack was found in the beam in the short direction, at the stage when the load slightly exceeded 200 kN. The load at which the tensile stress in the beam reached the limiting value (8N/mm²) was calculated to be 178 kN/wheel.

ii) Regarding the ultimate limit state

- There was no significant difference between the behavior under the 1st and 3rd loads at the equivalent aircraft load (321 kN/wheel) (the vertical displacement increased from 8.79 to 9.01 mm, a 2.5% increase).

- The crack width was only 0.1 mm or less under a load (600 kN/wheel) in excess of the bending collapse load (501 kN/wheel) based on the design calculations. It was inferred that the slab still had some margin of resistance (loading was stopped at this load because of restrictions on the loading equipment).
- Regarding punching shear in the 75 mm thick slab, there was no significant damage up to 600 kN/wheel, which exceeds the aircraft loading.

The test results for the other test specimen were generally the same, the difference in vertical displacement under aircraft loading was only 1.8%. Therefore, it can be concluded that the variation in the slabs is very small, and that they possess stable load performance.

(2) Summary of load test results

The conclusions regarding the design of the UFC slabs based on the results of the loading tests carried out using two full size test specimens of the UFC slabs are shown in Table 8. It has been confirmed from the tests that the UFC slabs satisfy the required performance.

Table 8 Summary of test results

Item	Judgment criterion	Test result	Conclusion
Serviceability limit state (vehicle)	Response is linear	Response was linear and displacements and strains agreed well with the FEM analysis results for 3 load repetitions.	Cracking does not occur at the serviceability limit state, and the required performance is satisfied. The validity of the design method based on the FEM analysis was confirmed.
	Cracking does not occur	The load at which cracking occurred exceeded the design value.	
Ultimate limit state (aircraft)	It shall not be necessary to carry out emergency replacement or repairs. (No yielding in the prestressing steel)	The increase in the vertical displacement on the 3rd repetition of the aircraft loading was about 2.5% that of the 1st repetition	Emergency replacement or repair will not be necessary (the prestressing steel will not yield).
Maximum load	The load resistance has an appropriate margin with respect to the aircraft loading.	The load – displacement relationship was uniformly increasing up to 600kN/wheel, a load 1.8 times the aircraft load, and crack widths were 0.1mm or less.	The load resistance has sufficient margin with respect to the aircraft loading.

5. PRODUCTION OF THE UFC SLABS

In November 2007 production started at a UFC slab production factory in Chiba Prefecture. The results of a production test [8] carried out at the same time as the loading tests were reflected in the planning of the factory. Figure 10 shows the layout plan of UFC slab factory. This factory is two direction pre-tension factory which can be not seen in the world, and the factory that produces UFC materials is the world's largest.

A dedicated UFC batching plant capable of mixing 15m^3 per hour was installed within the factory site (Photo 3), and can produce 70 m^3 of UFC (quantity of 20 slabs) in 5 hours.

The roofed area of the factory had a width of 45 m and a length of 200 m (Photo 4). There are two lines, A and B, and each line had its own production yard, secondary curing tank, prestressing steel end processing area, and inspection area (Fig. 10). In the production yard of each line, concrete abutments were provided for pre-tensioning, and 20 sets of formwork were provided within the abutments (Photo 5). The UFC mixed in the batching plant is transported to the production yards, where it is poured into the formwork with the pre-tensioning cables in two directions (Photo 6). On the following morning after it has been confirmed that the strength exceeded 45 N/mm^2 , the prestress is introduced, the prestressing steel is cut, and the slabs are transported to the secondary curing tank by a gantry crane.

Three secondary curing tanks were provided per line, based on considerations of the production cycle. The UFC slabs transported from the production yards are placed within one of the curing tanks, and steam curing is carried out at 90°C for 48 hours. As a result of the accelerated curing under this high temperature and moisture, a final strength of about 200 N/mm^2 can be obtained. After processing the ends of the prestressing steel, the slabs were stored in a stockyard within the site until shipment (Photo 6).

At present production is proceeding at the rate of 320 slabs per month (Photo 7).



Photo 3 UFC batching plant



Photo 4 UFC slab factory

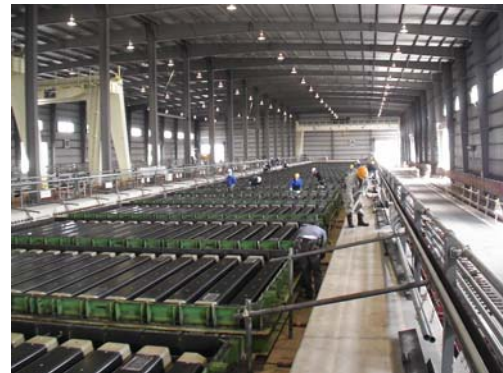


Photo 5 UFC slab production line

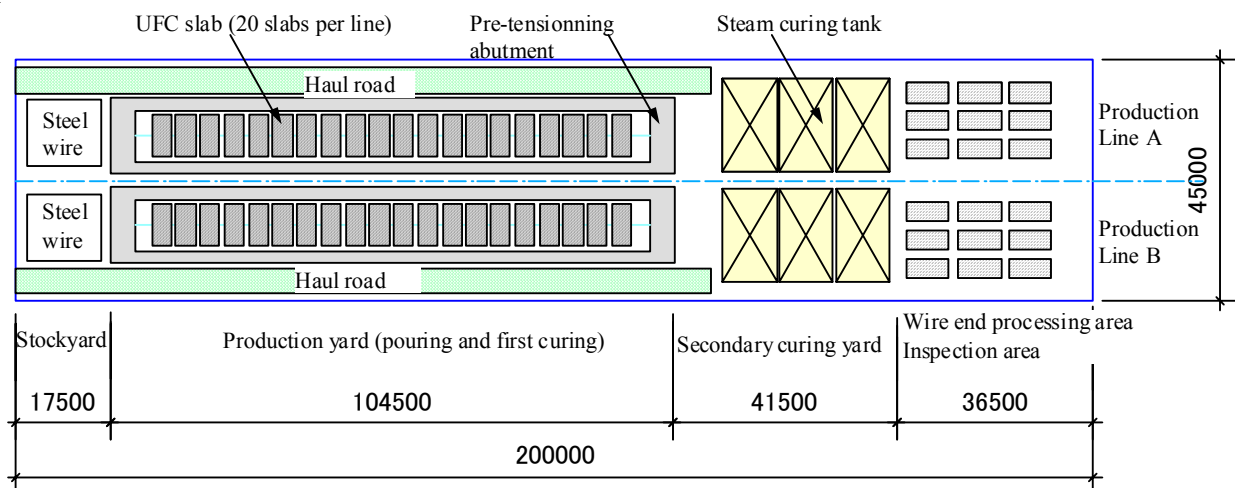


Figure 10 Layout plan of UFC slab factory



Photo 6 Pouring UFC to slab



Photo 7 Stock of UFC slab

6. CONCLUSIONS

UFC is a material with excellent mechanical and durability performance. UFC slabs have been selected as the ideal slab structure for Haneda Airport Runway D, utilizing these characteristics. As shown by the results of design analysis and loading tests, it is considered that UFC slabs satisfy the performance required for Haneda Airport Runway D.

Also, various investigations have been carried out for the mass production of UFC members, and the production system has been established. As a result, a dedicated UFC batching plant and production yard has been built, and about 6,900 large size slabs will be mass produced over about two years. There have been no precedents in the world for the application of fiber reinforced concrete without steel reinforcement, such as UFC, and mass production to large-scale structures. This material was developed in France, but it is no exaggeration that the technology obtained as a result of much research and development in Japan is at the forefront of technology in the world. We hope that this UFC slab technology will assist the future development of concrete technology.

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