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Recent innovative application of UFC bridges in Japan

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ABSTRACT: The design and construction technology of UFC bridges in Japan has been advancing in recent 5 years. This paper presents representative recent 3 projects of UFC structures that have been designed and constructed in Japan as well as the innovative technologies that have been applied step by step through the verification due to the fundamental experiments or accumulated construction know-how. First one is Toyota Footbridge that was applied for the first time the dry joint technology. Second one is a 40 m span monorail girder bridge that may be the longest span girder made of concrete. The last project is the mass production of UFC slabs in Haneda Runway D that must be the largest single project in the world in application of UFC.

1 INTRODUCTION

A 50 m span Sakata-Mirai Footbridge has been completed for the first time in Sakata City applying Ultra high strength Fibre reinforced Concrete (hereafter referred to as UFC), the brand name of Ductal® in October 2002. Based on this achieved design, construction technology, material test data and structural experiments, "Recommendation for Design and Construction of Ultra High Strength Fibre Reinforced Concrete Structures, -Draft" (JSCE, 2004) was published in 2004 by Japan Society of Civil Engineers.

The authors have been challenging the technical development of new design method, joint technology, efficient production methods of pre-cast segments and construction methods on site for various types of UFC structures. In this paper, the representative recent 3 projects of UFC structures are introduced featuring the innovated technologies. Furthermore, the advantages and disadvantages of UFC structures in Japan based on our experiences of the past projects are discussed.

2 TOYOTA CITY GYMNASIUM FOOTBRIDGE

2.1 *Structural features*

This footbridge is two-span continuous two-box girder with the dimension of 27.96m in length (span length is 22.5m), 4.72m in width and 0.55m in height (Photo. 1). The bottom and the top slab thickness is 6cm and the web thickness is 7cm (Fig. 1). A pre-cast segment method has been adopted account

Photograph 1. Completion of Toyota City Gymnasium Footbridge in 2007.

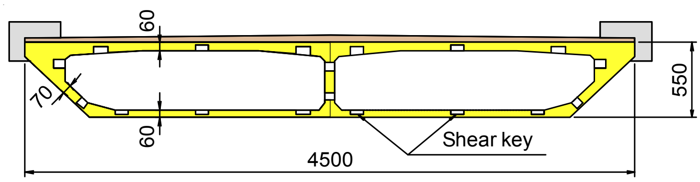


Figure 1. Match cast section and shear keys.

ing for newly developed dry joint method for the preparation of future large projects. The whole structure was divided into 12 pre-cast segments with the length of 1.9~2.5m. 1% parabolic curvature was required in the longitudinal direction. This means the match cast for dry joint should take this curvature into account when manufacturing. The pre-stressing cables were 4 sets of 19s15.2mm external tendons.

2.2 *Match cast method for dry joint*

The fundamental concept of our dry joint is same

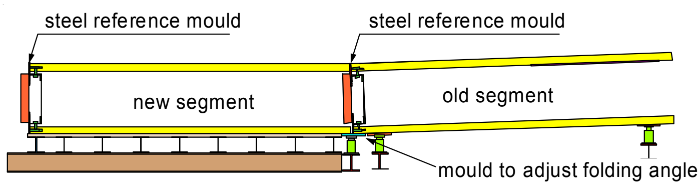


Figure 2. Match cast method for dry joint.

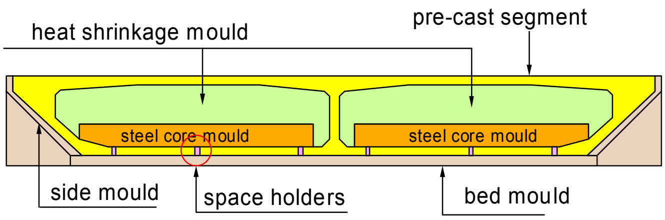


Figure 3. Manufacture of pre-cast segment.


Photograph 2. Erection of pre-cast segment.


Photograph 3. Dry joint for pre-cast segment.

as the conventional match cast method usually applied for PC bridges so called pre-cast segment method; i.e. the match cast face is glued by epoxy resin and each segment is connected together by prestressing. The different aspect from the conventional one is how to fabricate the match cast segment. The shrinkage of the UFC is primarily 400~500μm/m autogenous shrinkage that is much larger than the conventional concrete. The match cast face of the new segment is usually fabricated by arranging the match cast concrete face of the old segment as a mould. However, the match cast face of the old segment must already have had some autogenous shrinkage in case of the UFC and this sequentially causes unmatched segments. Our new fabrication method for the segments is that a steel end plate reference mould is set on the old segment to keep constant the sectional dimensions. The mould of the new segments is set on the old segment remaining the steel end plate reference mould on the old segment. As the steel end reference plate is constant thickness, the match cast faces result in the mirror image (Fig. 2).

Another unique point is that all shear keys on both sides of the matching face (Fig. 1), are couples of concave shapes. These UFC shear keys were manufactured in advance and were installed while dry-joint was proceeding. It is noted cracking risks usually generated around the shear keys for the case of the conventional match cast faces, will not happen for this case.

2.3 *Manufacturing and erection of pre-cast segments*

The height of two-box girder is too low to handle a conventional interior mould. New interior mould material was developed to easily relief the interior mould. The material for the interior mould acts as shrinking behaviour due to heat, therefore after the secondary heat curing the interior mould can be easily deleted (Fig. 3). The erection of the pre-cast segments was carried out by crane (Photo. 2). After giving a coat of epoxy resin on the matching surface, each pre-cast segment was pressed against the adjacent segments by traction equipment. The temporary contact pressure on the matching surface was $0.3N/mm^2$ (Photo. 3).


Photograph 4. Completion of 40m long monorail girder.

3 TOKYO MONORAIL GIRDER

3.1 *Structural features of long span girder*

Tokyo Monorail and Taisei corporations have been carrying out the corporative technical development of a 40m long monorail girder applying the UFC that must be the longest span in the world made of concrete material (Photo. 4). Because of the length re-

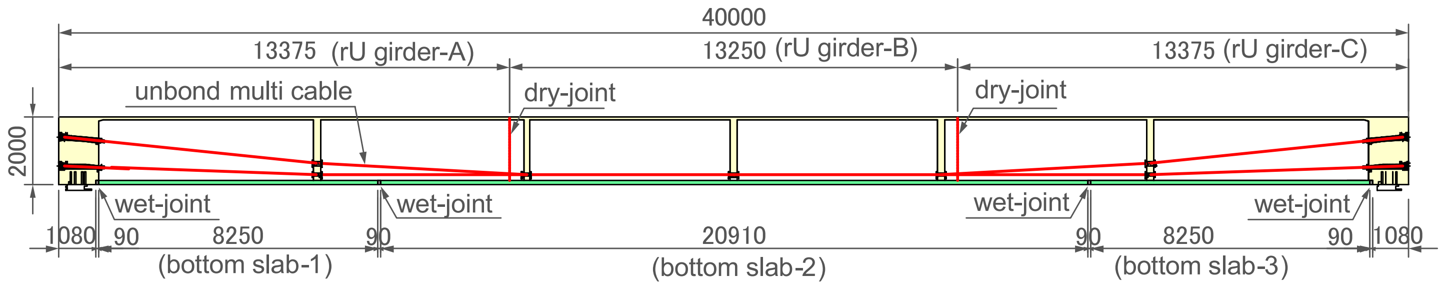


Figure 4. Structural composition of pre-cast segments; rU girder-A,B,C and bottom slab-1,2,3 combined with wet-joint and dry-joint.

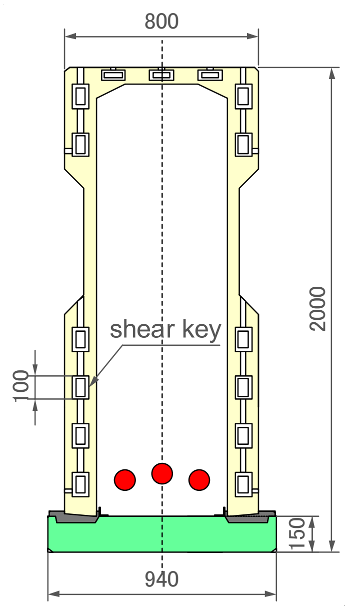


Figure 5. Dry-joint.

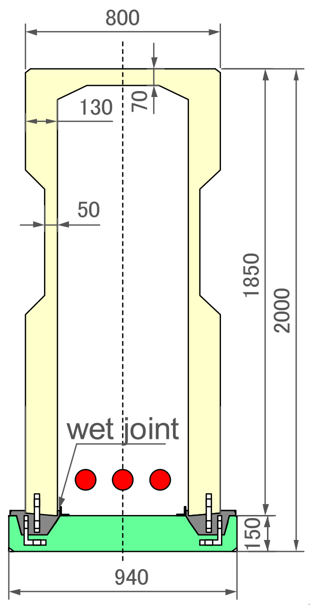


Figure 6. Wet-joint.

striction for the case of 40m long monorail girder, three reversed U-shaped girder (hereafter referred to as "rU girder") segments and three bottom slab segments were separately manufactured in the factory, conveyed to the construction site and jointed together by wet joint and dry joint. Three rU girder segments were connected by dry joint, on the other hand three bottom slab segments and rU girders were connected by wet joint. This wet joint for the connection between the bottom slab segments and rU girders has been originally developed through conducting the fundamental experiments applying the perfobond strips (abbreviated to PBL) with cast-in-situ UFC. It should be noted that the dry joints for rU girders are located in inner side of the span but the wet-joints for bottom slabs are located outside of the dry joint as shown in Figure 4. The tensile stress for the design load of service limit state (SLS) should be less than the first cracking strength (f_{cr}=8N/mm^2) except the joint section, however the tensile stress for SLS can not be allowed on both types of joint; i.e. it should be full pre-stressing for those joints. It is therefore possible to reduce the pre-stressing cables compared with the case that the locations of both joints coincide. The section of the dry joint and the wet joint is illustrated in Figure 5 and Figure 6, respectively.

3.2 *Experiment of a proto-type 10m long girder*

Most of the modelling parameters of the proto-type 10m long monorail girder such as girder width, combination of joints and pre-cast segments, surface finishing of top slab and sizes of PBL are identical with the 40m long girder except the total length and the height (Fig. 7). There are two main purposes for the proto-type monorail girder; i.e. one is to confirm the erection and fabrication method for the complex composition of the pre-cast segments, and another is to verify the structural safety including two kinds of joints. The sequential fabrication steps such as production of segments, match casting, dry joint and wet joint were implemented and evaluated how those effect on the final structural performance. The

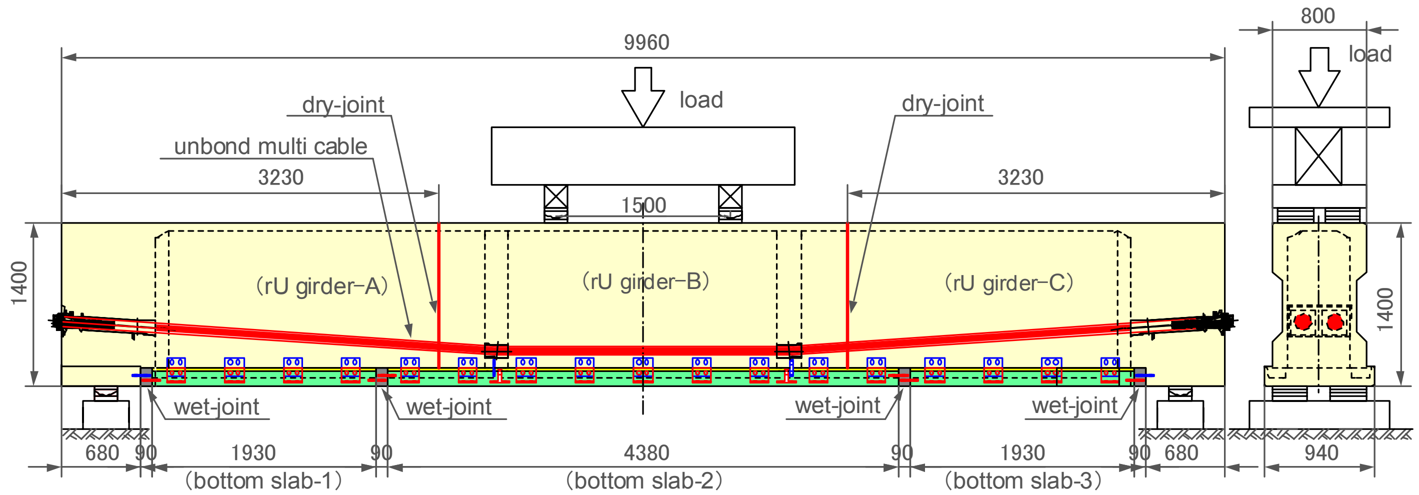
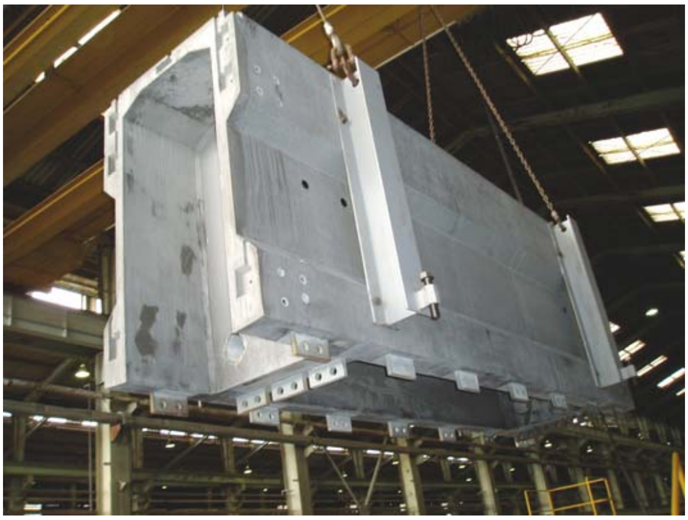


Figure 7. Structural composition of pre-cast segments and loading set up for proto-type girder.



Photograph 5. rU girder segment.

Photo. 6. Bottom slab. Photograph 7. r-U girder.

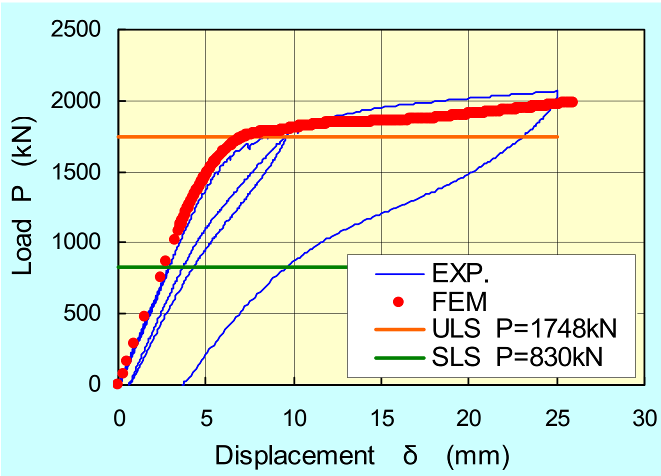


Figure 8. Comparison of loading experiment and FEM analysis.

rU girder segment is lifted to assemble with the rest of the segments as illustrated in Photograph 5 where the match cast face with concave shear keys and PBL inserted in the segment for wet joint with bottom slab are observed.

The loading set up for the completed proto-type girder was arranged so that both joints could have both bending moment and shear force (Fig. 7). The experimental result and a 3D-FEM analysis considered the modelling of material nonlinearity is indicated in Figure 8. Because a 10m long monorail girder instead of a 40m girder was to be tested to prove the structural safety, the equivalent loading values were calculated so as to have equivalent forces at joints for SLS and ULS. The loading value P for SLS and ULS became 830kN and 1748kN, respectively. It was proven that no initial cracking was observed for SLS and no serious damage for ULS. The first cracking was observed at the bottom slab of mid-span for the loading value P=1200~1300kN. At the same time, the first cracking at wet joint of bottom slab was found. For the loading value P=1700kN, the diagonal cracks were observed on web.

3.3 *Fabrication of a 40m long girder*

Three rU girder segments and three bottom slab segments were manufactured and conveyed to the construction site. Three bottom segments with PBL were settled on the levelled supporting beams (Photo. 6). Three rU girder segments with four adjustable legs were erected on the bottom segments at 10cm above the final level (Photo. 7). After giving a coat of epoxy resin on the matching surface, each rU girder segment was pressed against the adjacent segments by traction equipment. The temporary contact pressure on the matching surface was 0.3N/mm^2 and those dry jointed segments were set down about 10cm ready to the subsequent wet joint step. As a wet joint step, 1) cast-in-situ UFC was placed into the space between the web and the bottom slab as well as into the space between bottom slabs, 2) heat curing was carried out keeping the atmosphere temperature 60^{o}C for 48 hours. After the compressive strength of wet joint cast-in-situ UFC reaching up to at least 160 N/mm^2, the pre-stressing step has been progressed to supply the design stresses not only on the dry joint but also on the wet joint. It should be noted that the top slab surface and the side web surface of the dry joint were finished extremely smooth.

4 PLATFORM SLABS IN HANEDA RUNWAY D

4.1 *UFC slabs in Haneda Runway D*

The construction of Runway D is a national project of the extension of the Haneda International Airport, Tokyo. About one third of Runway D is composed of the pile-elevated platform and the rest of it is composed of the reclaimed land. The reason why such a complex structure was adopted is to avoid blocking the river flow of Tama River. The outside area (blue area in Fig. 9) of the pile-elevated platform is made from pre-cast slabs applying UFC. The area of this part is 192,000m^2 and about 6.900 pieces

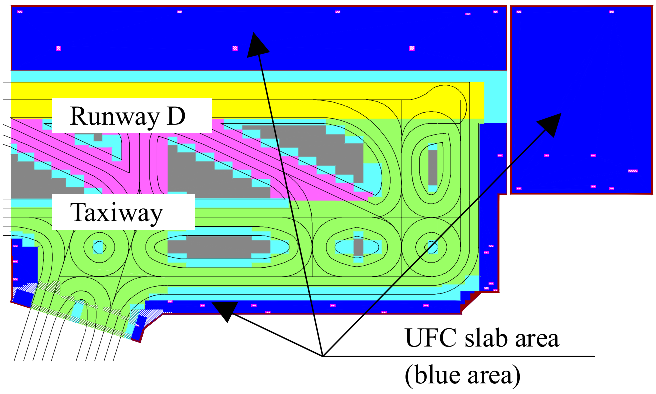


Figure 9. Allocation of UFC slabs on Haneda Runway D.

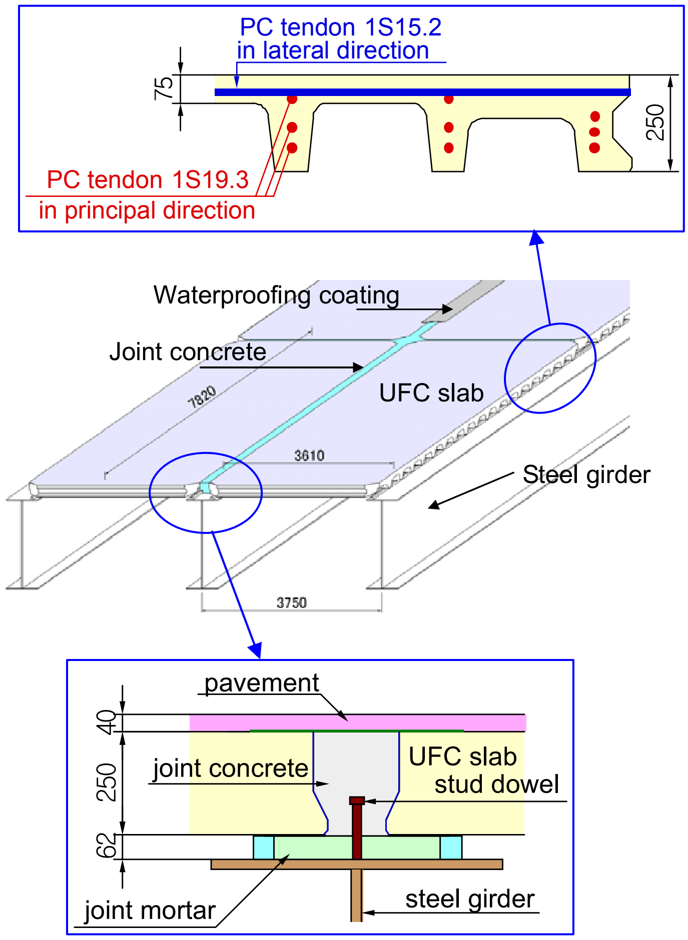


Figure 10. Structural detail of UFC slab and joint with steel girder.

of UFC slabs were applied. The reasons for applying UFC to the deck slabs were as follows; 1) Application of the UFC material to the deck slabs made it possible to realize the reduction in self weight of deck slabs by 56% compared to the ordinary concrete slabs. As a result, the weight of the steel jacket and the steel piles could be decreased so the construction cost could be reduced. 2) The UFC material is extremely durable so the maintenance cost must be reduced. 3) In September 2004, the UFC Recommendation (JSCE, 2004) was published by JSCE, so it became possible to conduct the objective check of the required performance.

4.2 *Structural features of UFC slabs*

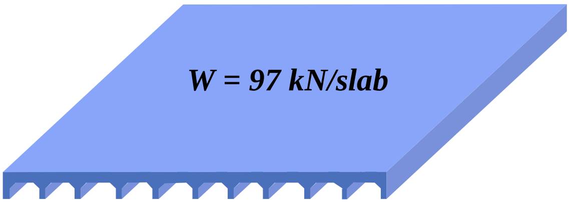
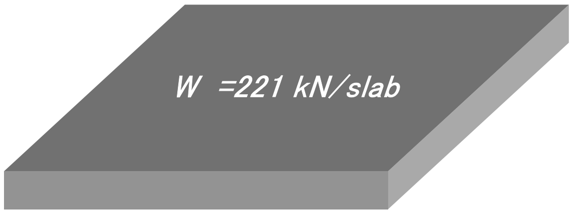
The principal direction of the slab coincides with the direction of the shorter side and the ribs are set along the principal direction (Fig. 10). The height including the ribs is 250mm and the thinnest thickness of the UFC slab is only 75mm. The averaged slab thickness is about 135mm on the other hand the ordinary concrete slab thickness with compressive strength 50N/mm^2 becomes 320mm. This means the reduction in dead load compared with the ordinary concrete slab is about 56% (Table 1). One of the featuring points of the UFC slabs is the adoption of the two-directional pre-tensioning newly developed technology in order to efficiently produce a huge amount of the UFC slabs. There was no precedent such a two-directional pre-tensioning method for manufacturing the slabs, however this method was more advantageous from the cost point of view than the usual method, i.e. pre-tensioning in one direction and post-tensioning in one direction.

The design load for each limit state is as follows; 1) SLS (normal condition) --slab dead load + vehicle loading, 2) ULS (emergency condition) --slab dead load + aircraft loading (aircraft deviating from the runway and taxiway). The items checked for SLS are the tensile and compressive stress should be less than -8.0N/mm^2 and 108N/mm^2, respectively. Those for ULS are factor of safety against collapse should be greater than one and the stress in pre-stressing steel should be less than yield stress. Particularly in the case of aircraft running, it was required that there would be limited damage so that the slabs could be subsequently used. In order to satisfy these conditions, the limiting state was imposed that the stress in the pre-stressing steel should be less than the yield stress when aircraft loading is applied. The UFC slabs are simply supported on the frame of the jacket platform. Three-dimensional FEM analyses including the jacket frame model was applied to calculate the stresses in the slabs and it resulted in that all stress responses and all final limiting states for SLS and ULS satisfied the design items.

4.3 *Loading tests using full scale UFC slabs*

The loading tests using full scale UFC slabs were conducted in order to confirm that 1) the response stresses and loading bearing capacity could be obtained in accordance with the UFC slab design calculations, 2) the production system such as material, formwork, casting, curing, pre-stressing, demoulding and fiber orientation to manufacture the UFC slabs could be stably under quality control. The loading tests were carried out on two specimens in order to clarify the variation due to the UFC material and due to manufacturing system. In the tests, the vehicle loading was firstly applied three repeated

Table 1. Comparison of UFC slab and conventional concrete slab.

UFC Slab	Conventional Concrete Slab
	
Average thickness=135 mm	Average thickness=320 mm
unit dead load=3.83 kN/m^2	unit dead load=7.84 kN/m^2

Photograph 8. Full scale loading experiment of UFC slab.

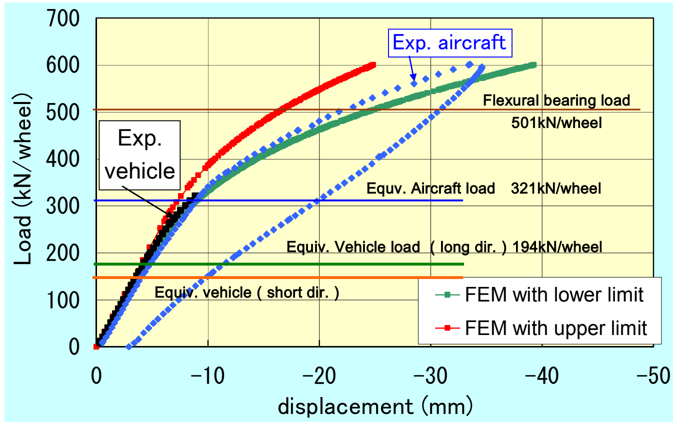


Figure 11. Comparison of experiment and FEM analysis.

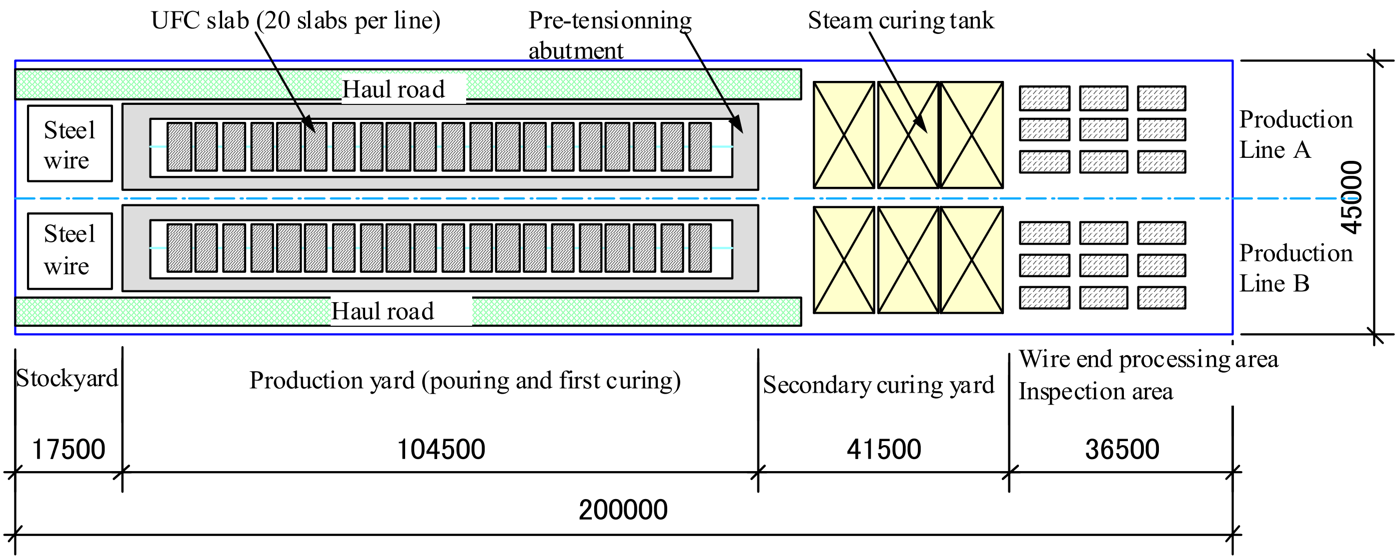


Figure 12. Layout plan of UFC slab factory.

times and then the aircraft loading was secondary applied two repeated times. Then finally the loading in excess of the aircraft loading was applied (Photo. 8). The wheel loading position (six wheels on one UFC slab) was determined in accordance with the wheel layout of the aircraft B777-200ER where the ultimate cross-sectional forces were most severe. The UFC slabs would be actually supported on the flexible steel frames of the steel jacket but the support condition of the loading tests was obliged to be rigid. Therefore the equivalent loads were set to reproduce the cross-sectional forces and stresses calculated during the design.

The loading test results of the load per wheel versus the displacement at the centre of the specimen and three-dimensional FEM analyses taking the UFC material nonlinearity into account are compared with each other in Figure 11. The displace

Photograph 9. UFC slab factory.

Photograph 10. UFC batching plant.

ments under the repetition of vehicle loading due to SLS demonstrated linearity and there were no significant residual displacement. The first crack was observed in the beam in the short direction at the stage when the load slightly exceeded 200kN. There was no significant difference between the behaviour under the 1^{st} and 3^{rd} loads at the equivalent aircraft load (321kN/wheel). The crack width was only 0.1mm or less under a load (600kN/wheel) in excess of the bending collapse load (501kN/wheel) based on the design calculation. In order to confirm that the variation in the two tests results were within the postulated range, the input data for FEM model were set to be upper and lower limits on the variation in the material quality postulated for the production of the actual slabs. The tests results were within the upper and lower limits FEM results. In addition two test results due to two specimens respectively were almost same therefore it can be concluded that the variation in the slabs is very small.

4.4 *Production of the UFC slabs*

The production factory for the UFC slabs was newly constructed in Footsu City in Chiba Prefecture. As shown in the factory layout plan of Figure 12, the factory is equipped with two-directional pre-tensioning abutments which can not be seen in the

Photograph 11. Slab production line.

Photograph 12. Casting UFC to mould.

world and this factory to produce the UFC material must be the world's largest. The roofed area of the factory had a width of 45m and a length of 200m (Photo. 9). There are two lines, A and B, and each line had its own production yard, secondary curing tank, pre-stressing steel end processing area, and inspection area. A dedicated UFC batching plant capable of mixing $15m^3$ per hour was installed within the factory site (Photo. 10), and can produce $70m^3$ of UFC (quantity of 20 slabs) in 5 hours. 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. 11). 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. 12).

On the following morning after it has been confirmed that the strength exceeded $45N/mm^2$, the pre-stressing is introduced, the pre-stressing tendons are 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.

5 CONCLUSIONS

Starting from Sakata-Mirai Footbridge in 2002, the authors have been developing the innovative design and construction technologies such as wet joint, dry joint, PBL joint, non-linear FEM analyses considering UFC tension softening and efficient manufacturing methods. In this paper, three typical innovative application projects of UFC bridges were introduced and the following conclusions are derived from those projects.

In the Toyota City Gymnasium Footbridge project, the match cast method for dry joint applying the UFC material was developed for the first time. Through applying a steel end plate reference mould to keep the sectional dimensions of the old segment, all pre-cast segments could be accurately manufactured and could be quickly jointed together only giving the a coat of epoxy resin on the matching surface. This joint method enabled the site construction time 1/3 compared with the conventional wet joint method. The wet joint method that the UFC material was poured into the 30mm gaps was developed in the Sakata-Mirai Footbridge project. Therefore, the accurate matching surface configuration of the segments is not required but the long construction period on site is required for the sake of the heat curing for the UFC joint material. In case of the Toyota project, 12 construction days for wet joint was reduced to 4 construction days for dry joint. This dry joint technology will be applied in the future for the large-scale pre-cast segments method for the construction of the long span highway bridges.

Tokyo Monorail girder was successfully completed as a result of structural verification of a series of experiments as well as the functional verification such as accurate configuration of the top slab surface for the rubber wheel running. It should be noted that the combination of the dry joint and the wet PBL joint was unique and effective, i.e. the different position between the dry joint for three rU girder segments and the wet PBL joint for the connection between the bottom slab segments must make reduce the pre-stressing cables. The three dimensional FEM analysis considering the modeling of material nonlinearity could well predict the loading experiments results of the proto-type 10m long monorail girder including the wet and dry joints. One of the key points of the modeling the material nonlinearity was the tension softening diagrams for the UFC material.

The most successful applications of the UFC material to the bridge structures is the construction of the UFC slabs for the pile-elevated platform in Haneda Runway D. The UFC pre-cast slabs were selected as the best cost-performance structures provided that the load tests using full sized UFC slabs could confirm that the response and load resistance could be obtained in accordance with the UFC slab design calculations. The conclusions regarding the design of the UFC slabs based on the results of the loading tests carried out using two full size specimens are 1) cracking does not occur at the SLS, 2) at the ULS (aircraft load) emergency replacement or repair will not be necessary, 3) the maximum load bearing capacity has sufficient margin with respect to the aircraft loading and 4) three-dimensional FEM analyses taking the UFC material nonlinearity into account can well predict the nonlinear behavior and are confirmed as a design tool. It should be noted that the key points of the success of the UFC slabs should be 1) total cost saving due to the enormous reduction of the slabs dead weight, 2) maintenance cost free even in the severe sea conditions due to extremely durable UFC material and 3) efficient and effective achievement of the mass production system due to assembly of standardized UFC members. We hope that this UFC technology would help the future development of concrete technology.

REFERENCE

JSCE 2004. Recommendation for Design and Construction Ultra High Strength Fiber Reinforced Concrete Structures-Draft. *Concrete Library No 113.*