RAPID REPAIR WITH PRECAST PRESTRESSED CONCRETE SLAB PAVEMENTS USING COMPRESSION JOINT SYSTEM

Yoshitaka Hachiya, Port and Harbor Research Institute, Ministry of Transport,
1-1, Nagase 3, Yokosuka 239-0826, Japan

Fumishige Akamine, PS Corporation,
13-17, Kitaotsuka 1, Toshima, Tokyo, 170-0004, Japan

Osamu Takahashi, Port and Harbor Research Institute, Ministry of Transport,
1-1, Nagase 3, Yokosuka 239-0826, Japan

Yutaka Miyaji, Second Port Construction Bureau, Ministry of Transport,
4-6, Meigetsu 1, Tagajo, 985-0843, Japan

ABSTRACT

A compression joint system was developed to connect precast prestressed concrete (PPC) slabs. In this system, prestressing tendons are inserted through the joint, and compressive force is applied using the tendons to interconnect the slabs. The tendons are installed by fixing only both their ends to the slabs, so only damaged slabs need to be replaced, and sound slabs can be reused. The load transfer mechanism of the compression joint system was investigated, and the associated structural design method was then developed through laboratory studies. This system was used to construct 800 m^2 of PPC slab pavement in the Sendai Airport taxiway.

INTRODUCTION

Maintenance and rehabilitation of airport pavements are inevitable to maintain their functionality. Extensive rehabilitation measures for in-service concrete pavement is, however, practically impossible because the pavement cannot be closed for long periods of time.

Although concrete overlay is a typical rehabilitation measure for concrete pavement, the method is not a fully reliable construction procedure, particularly when the overlay is thin. Thus, reconstruction with precast prestressed concrete (PPC) slab pavement that has a relatively small slab size (e.g., 10m long, 2.5m wide by 240mm thick) has been adopted in Japan. In this procedure, PPC slabs are manufactured in the factory, transported to the construction site, placed on the reformed subbase, and finally interconnected using a horn joint system. At each horn joint unit, as shown in Figure 1, the arc-shaped steel bar is inserted into the horn-shaped plastic tube that is cast into the PPC slab. Cement paste is then injected into the void around the bar [1)]. This arc-shaped bar can be easily removed and reinstalled to replace damaged slabs if necessary in the future.

However, some distress has often occurred at the horn joint units of PPC slab pavements. A new

joint system that transfers bending moments in addition to shear forces was developed because the horn joint unit itself is difficult to improve. In the new joint system, which is a compression joint system, stressing tendons are installed through the joint, tensioned to a pre-determined force, and fixed only at both of its ends to the slabs, as shown in Figure 2. Thus, two adjacent slabs are joined by the compressive force applied by the tendons. When changing damaged slabs, sound slabs could be reused because the tendons were installed without bonding to the slab.

A survey of existing PCC slab pavements was made before starting to develop a reliable joint system. The load transfer mechanism of the joint was then modeled to contribute to the structural design of the PPC slab pavement. The validity of the method was verified through experimental pavements. Finally, a new compression joint system for PPC slabs was proposed.

FIELD SURVEY

PPC slab pavements with the horn joint system have been used at several airports in Japan. Some distress, such as pumping and faulting, has been observed several years after construction, even though these problems were not observed after accelerated repetitive loading tests in past experimental pavements[1)]. In the tests, the horn joint system demonstrated nearly the same load transfer efficiency as that of a conventional straight dowel bar joint system.

The condition of existing PPC slab pavements that were surveyed at five airports show that the damage was highly severe. The damage influences the structural condition of the pavement, as shown in Figure 3. The figure shows the transverse distribution of the PRI (Pavement Rehabilitation Index), which indicates the need for pavement rehabilitation. A PRI of A indicates that rehabilitation is not necessary, while B means that it will be necessary in the near future, and C indicates that immediate rehabilitation is necessary. The observed distress was mainly caused along the landing gear passage route, and its severity was sufficiently serious to need immediate rehabilitation[2)].

MODELING OF LOAD TRANSFER MECHANISM AT COMPRESSION JOINT

Small Scale Experiment Pavement

In a small scale experiment, two PPC slabs of 4.5m width, 2.4m length and 240mm thickness were placed on a subbase with hard styrene foam on the rigid foundation and connected by the compression joint system, as shown in Figure 4. The elastic modulus of the PPC slab and subbase was 23.6kN/mm^2 and 22.5N/mm^2, while Poisson's ratio was 0.21 and 0.1, respectively. Compressive force was introduced at the joint after cement milk was injected between the two slabs and sufficiently hardened. The tendons were set at three different intervals (0.5, 1 and 1.5m), and a tensile force up to 200kN was applied to each tendon.

In loading tests, loads up to 300kN were applied to the pavement using a 450mm diameter, hard rubber bonded steel loading plate. Both the deflections and strains of the PPC slabs were measured as the response of the pavement against the applied load.

Load Transfer Model

Results of the loading tests show that the compression joint system can transfer bending moment in addition to shear force, unlike a dowel bar joint system. Therefore, this must be considered in modeling the load transfer mechanism. A three-dimensional finite element method (3-D FEM) was used to facilitate data processing and further analysis.

In the dowel bar joint system, shear force transfer is generally modeled by a spring element located at the dowel bar position [3), 4)]. In contrast, multiple springs distributed along the joint are introduced in the compression joint system model because the shear forces are transferred through the contact plane at the PPC slab edge. The compressive force from the tendon is distributed within a certain width of the joint, so two kinds of springs were used: one in the vicinity of tendon and another between tendons.

The transfer of bending moment can be modeled by two horizontal springs: one at the top of the PPC slab and the other at the tendon depth. The former models the compressive force of the concrete, while the latter represents the tensile force of the tendon. Figure 5 shows the load transfer model of the compression joint system introduced in this study.

Spring Constant Identification in Shear Force Transfer Model

Transfer of the shear force around the compression joint unit is modeled by two kinds of shear springs, as shown in Figure 6, where k_{s1}, k_{s2} denotes a spring constant for the compressive force working range, for the area outside of this range, respectively. First, the extent of the joint around the tendon where shear force can be primarily transferred must be determined. The shear spring constant in the model must then be fixed. In addition, the spring constant between the tendons, which is not influenced by the compressive force, must also be determined.

To determine the shear force transferable extent *B*, the strain on the PPC slab surface perpendicular to the joint is considered. Figure 7 shows the measured strains at the tensile force of 100, 200 and 300kN when the tendons are installed at 1m intervals. From the figure, the extent is estimated at almost 800mm, which coincides with that calculated by Equation (1) assuming a compressive force distribution angle β of 45 degrees [5)].

$$B = w + 2h\tan\beta \qquad (1)$$

where, B : shear force transferable extent (mm),
w : pressing plate width (mm),
h : distance between plate and joint (mm),
β : compressive force distribution angle.

A relationship between the load transfer efficiency E_{st} and the shear spring constant k_s is calculated as shown in Figure 8, when the compression joint units are installed at a sufficiently small interval. The load transfer efficiency is defined by Equation (2), focusing on the strains on

the surface of the PPC slab parallel to the joint.

$$E_{st}(\%) = \frac{2\varepsilon_2}{\varepsilon_1 + \varepsilon_2} \times 100 \quad (2)$$

where, ε_1 : the maximum strain at loaded side,
ε_2 : the maximum strain at unloaded side.

Figure 9 shows the relationship between the average compressive stress and the load transfer efficiency. The average compressive stress is calculated by dividing the compressive force introduced in each tendon by the corresponding area (PPC slab thickness multiplied by tendon spacing).

A relationship between the average compressive stress and spring constant is derived from Figures 8 and 9, as shown in Figure 10. The straight line in the figure, expressed as Equation (3), is obtained by regression analysis with a correlation coefficient of 0.98. A spring constant is obtained by using this equation for the given average compressive stress. The shear spring constant per unit length k_s obtained in the equation corresponds to the k_{s2} in Figure 6, and k_{s1} is 59.6N/mm^2 when the average compressive stress σ_0 is equal to zero.

$$k_s = 59.6 \times 10^{\sigma_0} \quad (3)$$

where, k_s : shear spring constant per unit length (N/mm^2),
σ_0 : average compressive stress (N/mm^2).

Spring Constant Identification in Bending Moment Transfer Model

The horizontal spring constants at the top and the tendon position must be determined to consider the transfer of bending moment. Figure 11 shows that the strain on the unloaded PPC slab perpendicular to the joint varies with the average compressive stress (at 200kN load). As the strain merely decreases when the average compressive stress increases, the spring constant is considered to be a constant value regardless of the compressive stress from the viewpoint of structural design.

Since the horizontal spring at the top is introduced to restrict the horizontal displacement of the joint, its spring constant is assumed as 10^6N/mm^2. The horizontal spring constant at the tendon position k_p is calculated with Equation (4), which is derived from equilibrium of the tendon axial tensile forces.

$$k_p = \frac{E \cdot A}{h} \quad (4)$$

where, k_p : horizontal spring constant at the tendon position (N/mm^2),

E : elastic modulus of tendon (N/mm^2),
A : cross section of tendon (mm^2),
h : distance between pressing plate and joint (mm).

Confirmation of Shear Force Transfer Model

Strains on the PPC slab parallel to the joint were measured to confirm the shear force transfer model. Figure 12 shows the measured and calculated strains on the unloaded PPC slab parallel to the joint at 200kN load. Both observed and calculated strains increase with the average compressive stress, and they show the good correspondence, with a correlation coefficient of 0.88. This confirms the procedure described above for developing the shear force transfer model and calculating the spring constants.

Confirmation of Bending Moment Transfer Model

Strains on the PPC slabs perpendicular to the joint are considered to demonstrate the bending moment transfer model. Figure 13 shows the measured and calculated strains at 200kN load when five tendons are installed at 1m intervals and the tensile force in each tendon is 200kN. A negative strain is not caused on the unloaded side when the conventional shear spring model is considered. On the contrary, negative strains are calculated on the unloaded side using the new model. This corresponds to the measured value with a correlation coefficient of 0.93. These results confirm the procedure for developing the bending moment transfer model and calculating the spring constant.

VERIFICATION OF COMPRESSION JOINT SYSTEM

Arrangement of Compression Joint Units

The interval between the joint units is restricted to integral multiples of 500mm because cables for prestressing the PPC slab itself are installed at an interval of 500mm. However, shear force can be transferred within 800mm of the compression joint unit tendons, as described above. Therefore, instead of installing the tendons at an interval of 500mm, alternate installation of the tendons and arc shaped bars was used here to reduce installation costs.

The loads transferred through an arc shaped bar were calculated from numerical analysis of the previous small scale experiment, as shown in Figure 14 for an ESWL (Equivalent Single Wheel Load) of a B-747-400. In the figure, A designates an arc shaped bar, while T indicates a tendon. The figure describes the transferred shear force distributions for installing arc shaped bars at an interval of 1,000mm and for bars and tendons (with compressive force of 300kN) placed alternately at an interval of 500mm. The maximum shear force transferred through the arc shaped bar decreases from 12.1kN to 1.9kN by introducing the compression joint unit tendons, greatly reducing the risk of failure of the joint system.

Full Scale Experimental Pavement and Loading Test

Several types of joint systems were constructed in the full scale test pavement, and their behavior against load was observed. Two joint systems, namely horn joint system and compression joint system, are mainly described below.

The full scale test pavement consists of 240mm thick PPC slabs, 40mm thick asphalt treated subbase and 240 mm thick granular subbase on a sand subgrade. This pavement was designed for B-747-400 aircraft in accordance with the current design procedure[6]. The modulus of elasticity of the concrete is 33.1kN/mm^2, while Poisson's ratio is 0.22. The coefficient of foundation reaction on the asphalt treated subbase is 430MN/m^3 with the 300mm diameter loading plate. In plan, eight slabs with a width of 2.4m and length of 6m were connected to each other using various joint systems. In both horn joint system and compression joint system, joint units were installed at 500mm intervals. In the compression joint system, arc shaped bars and tendons with tensile force of 100kN are used alternately.

In the loading test, the design loads were applied repeatedly up to 10,000 cycles along each joint. During the test, the ground water table was kept above the subbase in consideration of the worst drainage conditions.

Test Results

The maximum deflection at joint, which was measured by an FWD with 200kN load, increased with the number of load repetitions for both joint systems. However, this tendency was pronounced for the horn joint system, and the deflection itself was larger for the horn joint system than for the compression joint system. Figure 15 shows the corner deflections, which are larger than those at the joints. The deflection increased significantly with the number of load repetitions for the case of the horn joint system compared to that of the compression joint system. At the end of the repetitive loading test, the deflection for the horn joints was more than three times as large as that for the compression joints.

The load transfer efficiency at corners, as calculated with Equation (2), is greatly influenced by repetitive loading, as shown in Figure 16. The horn joint system in particular decreases from 90% to less than 50% after 10,000 cycles of load. Figure 17, which shows the strains on the arc shaped bars measured during the loading test, reveals that the strains increased as the loading test proceeded and were much larger at horn joints than at compression joints.

These resulted from the failure of the horn joint system itself, which was confirmed by the careful observation of the PPC slab after the loading test. On the contrary, no substantial damage was observed for the compression joint system, even after 10,000 load cycles. Therefore, the compression joint system used in the full scale test pavement can be applied to actual projects.

IMPLEMENTATION OF COMPRESSION JOINT

Design Consideration

To determine the tensile force of the tendon, which is one of critical issues in the compression joint system, both the load transfer efficiency at the joint and the stress condition of the concrete in the vicinity of joint unit must be evaluated.

A relationship between faulting, which is defined by the difference in deflections between loaded and unloaded slabs, and the load amplitude was studied to evaluate the load transfer efficiency at the joint. The relationship obtained in the small scale experiment is shown in Figure 18 for a 200kN tensile force of the tendon. This shows that a tensile force of 100kN or more is required to keep faulting sufficiently small.

To study the stress condition at the joint, the strains in the concrete around the pressing plate of compression joint unit were calculated with 3-D FEM and compared to those measured during the loading test of the small scale experimental pavement. These correlate well, and the maximum tensile strain reaches 70×10^{-6} for a 300kN tensile force. This suggests that the tensile force should be restricted to less than 300kN to prevent the failure of concrete due to stress concentration around the pressing plate.

In addition, the fact that the compressive force applied by the tendons decreases substantially with a temperature drop of the concrete should be considered in the design. This effect results from the restriction for contraction of the PPC slab due to temperature drop by friction between the concrete slab and subbase. This force due to a temperature drop of the PPC slab is calculated by Equation (5).

$$P_t = f \cdot W \cdot L/2 \cdot t \cdot B \qquad (5)$$

where, P_t : temperature related force per tendon,
f : friction coefficient between slab and subbase,
W : unit weight of PPC slab,
L : length of PPC slab,
t : thickness of PPC slab,
B : spacing of tendon.

Application

An apron-taxiway of the Sendai Airport that was comprised of asphalt pavement was severely deteriorated due to heavy aircraft operations. In its rehabilitation project, PPC slab pavements, together with the compression joint system, were partly applied (in an area of 800m^2) to shorten the duration of facility closure.

Twenty-four PPC slabs, which are mostly 2.49m wide and 14.49m long, were fabricated. The pavement structure, which is almost same as the full scale test pavement, consists of 240mm

thick PPC slabs resting on a foundation with a reaction coefficient of 100MN/m^3. The composition of the PPC slabs were designed for B-747-400 aircraft and 10,000 load cycles in accordance with the current design manual for airport pavements. The slabs are connected using compression joint units and horn joint units installed alternately at 500mm intervals.

The amount of force for each tendon in the compression joint units was determined considering both load transfer though the joint and temperature variations of the PPC slab, as mentioned above. The amount of force required for the former was determined in accordance with the current design method for dowel bar joint systems, in which 40% of the applied load was assumed to be transferred through joint. Figure 9 was used by assuming a suitable load transfer efficiency. For the latter, as the largest distance between the joint and PPC slab edge was 14.49m, the effect of temperature variations was calculated with Equation (5). These calculations indicated that 200kN of force was required for each tendon.

Construction on site was conducted in February, 2000. All of the work - from the removal of existing pavements to the interconnection of slabs - was executed between 9PM and 7AM without disturbing aircraft operations. Figure 19 shows a plan view of the constructed PPC slab pavement.

In comparison with the conventional horn joint system, both the repair time and cost are increased in some degree. The amount of ten percent is roughly estimated in the latter.

CONCLUSION

The compression joint system was developed as a new connection system for PPC slabs. The validity of the joint system was verified through experimental pavements, and actual PPC slab pavements have been successfully constructed with this joint system and are in service. New findings obtained in this study are summarized as follows.

1. The compression joint system can efficiently transfer load from one slab to the opposite slab. Both shear force and bending moment are transferred through this joint system.
2. The transfer of shear force can be modeled by shear springs distributed within 800mm around the tendon. The spring constant varies with the average compressive stress.
3. The transfer of bending moment can be modeled by two kinds of horizontal springs installed at the top and at the tendon position. The spring constants do not vary, regardless of the average compressive stress.
4. In the compression joint system, the compression joint units and the horn joint units are installed alternately at 500mm intervals to decrease the construction cost.
5. The amount of tensile force of each tendon in a compression joint unit is determined by adding the force necessary to transfer the load to that necessary to prevent the joint from opening due to a temperature drop.

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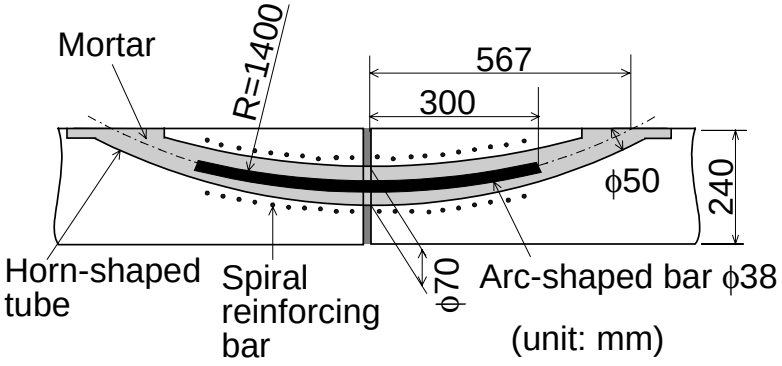


Figure 1 Horn joint unit

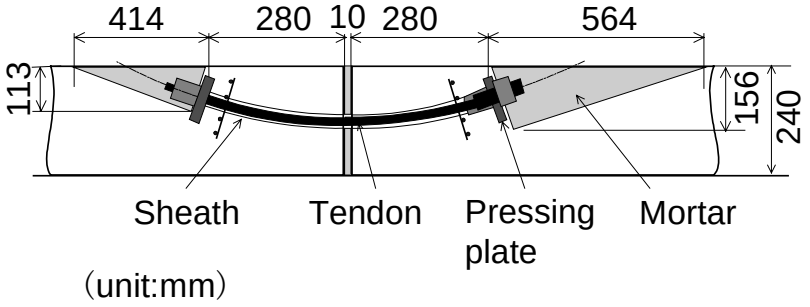


Figure 2 Compression joint unit

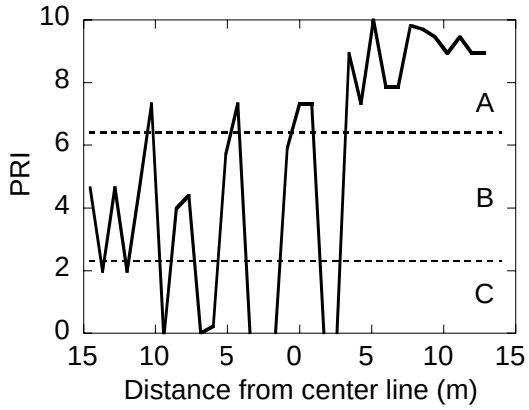


Figure 3 Transverse distribution of PRI

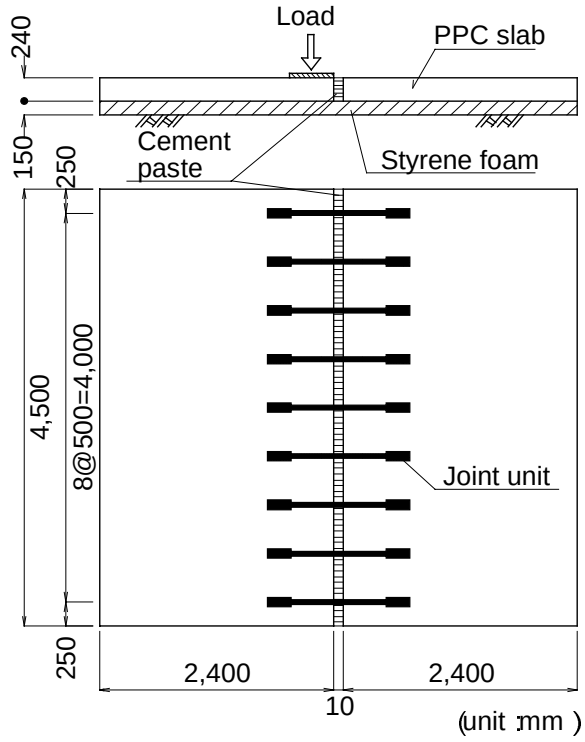


Figure 4 Small scale experimental pavement

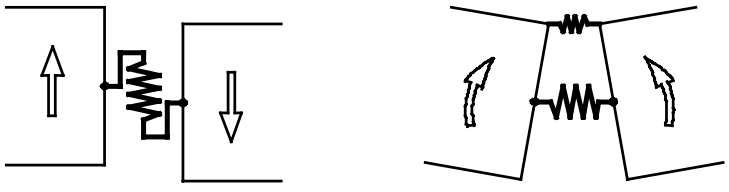

a) Shear force transfer b) Bending moment transfer

Figure 5 Load transfer model of compression joint system

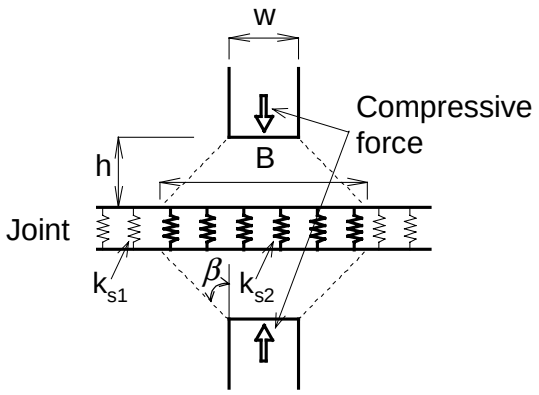


Figure 6 Compressive force distribution

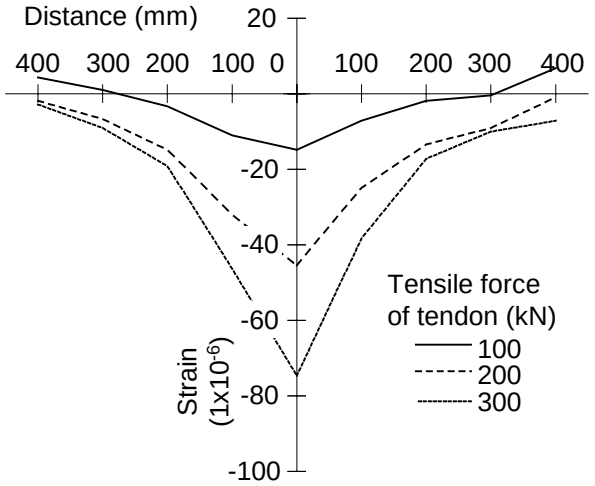


Figure 7 Strains on PPC slab perpendicular to joint

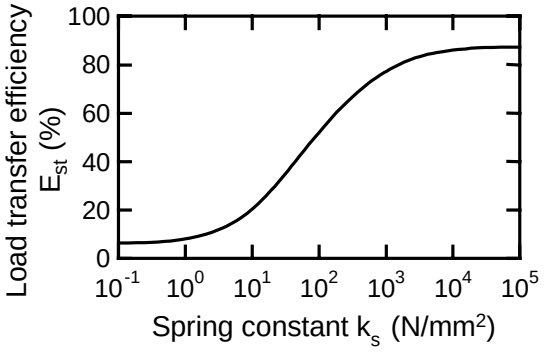


Figure 8 Shear spring constant and load transfer efficiency

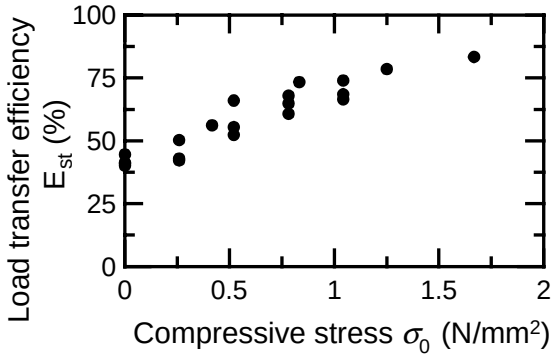


Figure 9 Average compressive stress and load transfer efficiency

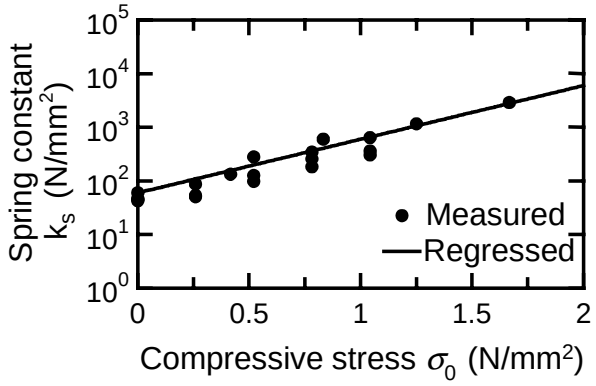


Figure 10 Average compressive stress and shear spring constant

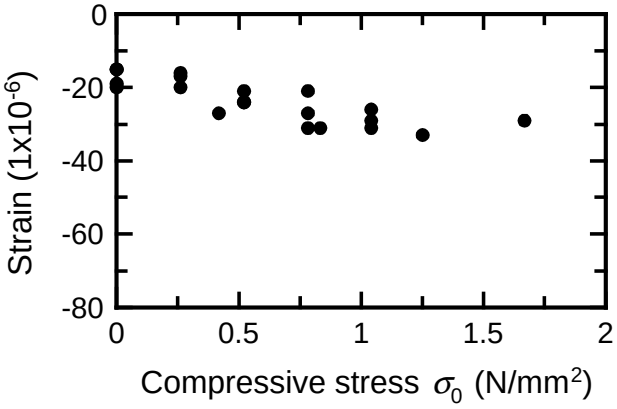


Figure 11 Average compressive stress and strain perpendicular to joint

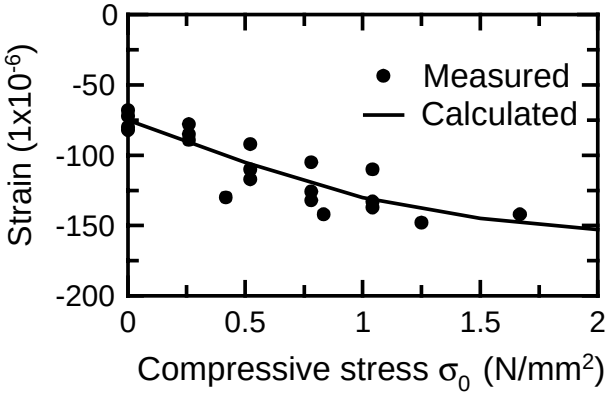


Figure 12 Comparison of PPC slab strain parallel to joint

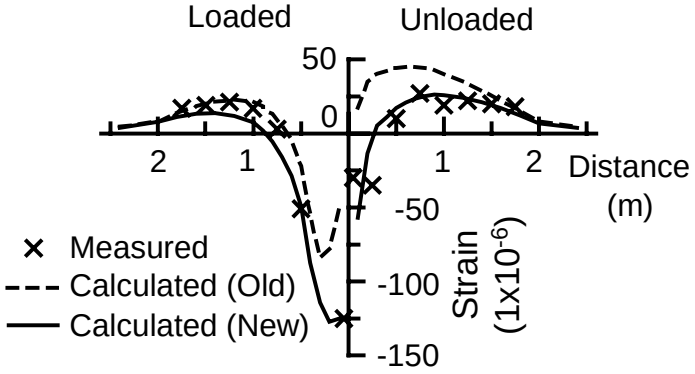
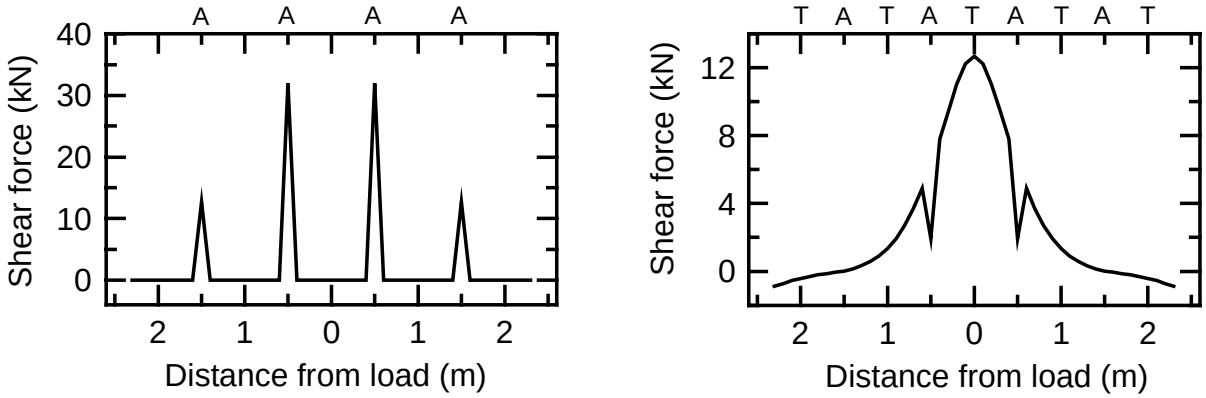


Figure 13 Comparison of PPC slab strains perpendicular to joint



a) Arc-shaped bar installation b) Alternate installation of bars and tendons

Figure 14 Distribution of load transferred through joint

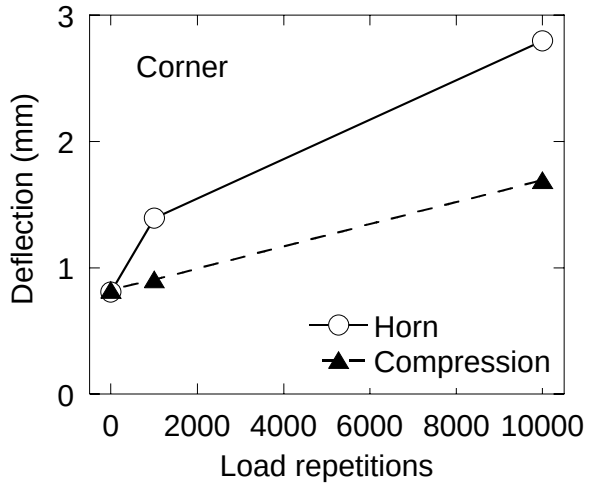


Figure 15 Changes of deflections at corners

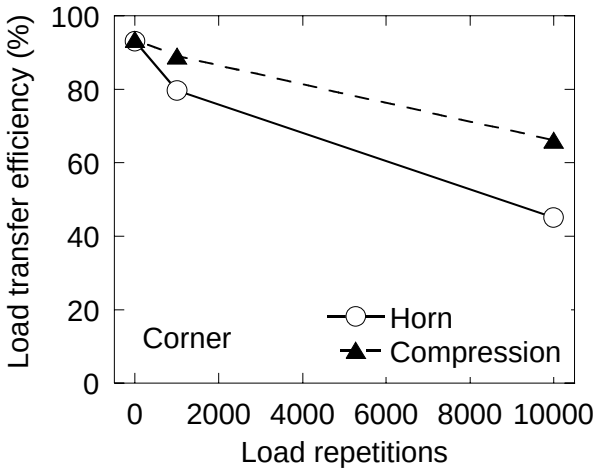


Figure 16 Changes of load transfer efficiency in repetitive loading

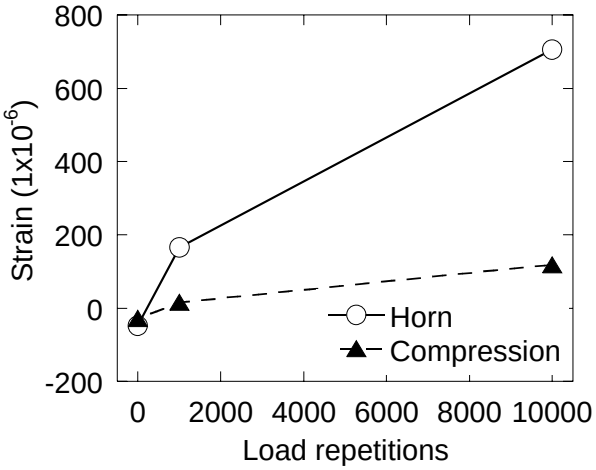


Figure 17 Maximum strain of arc shaped bar

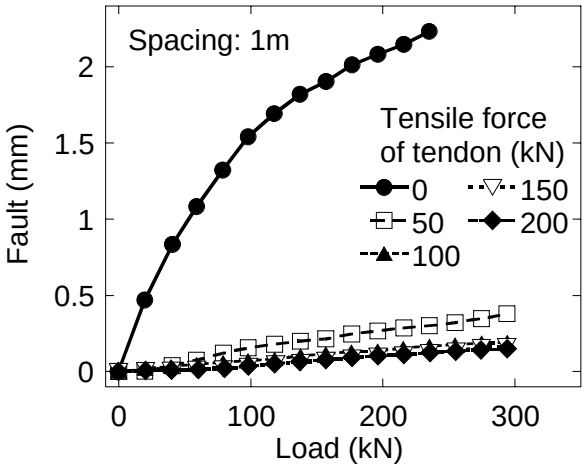


Figure 18 Relationship between load and faulting


Figure 19 Constructed PPC slab pavement at Sendai Airport

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