# Development and evaluation of mechanical anchorage rebar for joints between precast concrete slabs

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**Abstract.** The increasing deterioration of ageing reinforced concrete road bridge slabs in Japan has necessitated their replacement to ensure user safety. Currently, various rationalized joints using mechanical anchorage rebars have been developed, but most rely on rebar with post-installed anchorage, with few utilizing integrally formed anchorage zones for higher fatigue durability. In this study, a mechanical anchorage rebar with an anchorage zone integrally formed by high-frequency induction heating was developed. To verify its applicability to the joints between precast concrete slabs, the mechanical anchorage rebar underwent rebar tensile, static bending, wheel-load running, and water leakage tests. The results confirmed the developed rebar fractured at the base material. In addition, a static bending test of the joint confirmed that the load-carrying capacity of the slab joint using the rebar was maintained even after the member yielded. The wheel load running test using a full-scale specimen showed no failure under loading conditions. No water leakage from the underside of the slab was observed in the water leakage test on the upper surface of the slab. Furthermore, no punching shear failure occurred after accelerated fatigue loading, confirming that the slab joints with the developed mechanical anchorage rebars exhibited high fatigue durability.

## 1 Introduction

In recent years, the ageing of social infrastructure facilities that were intensively developed after the period of rapid economic growth in the 1960s has become a serious social problem in Japan. By 2031, approximately 57 % of bridges will be 50 years old [1]. The deterioration of reinforced concrete (RC) road bridge slabs is particularly severe in bridge structures. The main causes include the progression of fatigue damage due to an increase in heavy vehicles and environmental factors, such as the application of de-icing agents. Against this backdrop, large-scale replacement of ageing road slabs is currently underway throughout Japan under the leadership of three leading expressway companies [2]. In many road bridge slab replacement projects, highly durable precast prestressed concrete (PCaPC) slabs are used to reduce construction labour by shortening the construction period, reduce the burden on surrounding traffic, and extend the service life of the slabs. In the past, 'lap splices' and 'loop joints' have been used at the joints between PCaPC slabs to ensure slab integrity. However, the lap-splices require a large joint width to secure the necessary lap-splice length; and the loop joints limit the minimum slab thickness to the inner radius of bending, which depends on the rebar diameter. Thus, the slab cannot be made thinner. Therefore, methods have been proposed to 1) integrate road bridge slabs using a noncontact lap splices by attaching mechanical anchorage devices to the ends of the joint reinforcement [3] and 2) reduce the joint width using high-strength fibre-reinforced concrete in the joint concrete [4,5]. However, when post-installed anchorages are provided at the ends of the reinforcing bars in the joints, they are not fully integrated with the base reinforcing bars, which may lead to potential deterioration due to repeated stress. In addition, when fibre-reinforced concrete is used for padding, use of a mobile plant to cast the concrete onsite is necessary, which raises issues regarding the ease of material procurement and workability. In this study, a mechanical anchorage rebar was developed for slab joints by integrating an expanded diameter using high-frequency induction heating. In this paper, we report the results of various experiments conducted to verify the mechanical performance of slab joints by combining the developed mechanical anchorage rebars and high-strength concrete without fibres. This paper adds a discussion to the experimental results of a previously published study [6].

## 2 Mechanical anchorage rebar

In this study, a mechanical anchorage rebar with an expanded diameter (Figure 1) was developed for the slab joints. This rebar was integrally formed by high-frequency induction heating, which is an existing technology, with an expanded diameter in the shape of an arrowhead. Unlike conventional rebars, the outer

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diameter and length of the expanded section was ~1.5 times and twice the rebar diameter, respectively. The mechanical anchorage rebar, which was used as a reference technology, has been widely applied to field applications in shear and intermediate-zone reinforcements for structures, such as bridge piers, footings, tank base slabs, and sidewalls [7]. It allows for processing without the need to select specific rebar manufacturers or cross-sectional shapes and is also applicable to components subjected to high-cycle fatigue. The developed mechanical anchorage rebars resist external forces at the slab joint through the bond forces generated between the nodes of the base steel bars and concrete and the bearing resistance generated between the expanded section and concrete (Figure 2). Figure 3 shows the manufacturing process flow of the mechanical anchorage rebars developed in this study [8]. The details of steps (1)–(4) are as follows:

(1) A coil was used for induction heating at the end of the rebar.
(2) The end of the rebar was heated using high-frequency induction heating.
(3) The forming die was pressed against the heated rebar end.
(4) The integrated moulding process was completed.

An expanded diameter was formed at the end of the bar of the developed mechanical anchorage rebars using the same process as that used for conventional mechanical anchorage rebars.

In this study, tensile tests were conducted on the developed mechanical anchorage rebars. In this test, the expanded diameter of the specimen was fitted to a test jig fixed to the testing machine and the base metal was fixed to the chuck of the testing machine for tensile testing. The specimens were 400 mm long and were chucked 150 mm away from the edge of the base metal. The rebar used was D19 SD345. The results of a single tensile test are listed in Table 1, and the conditions of the rebar after the tensile test are shown in Figure 4. Evidently, the developed mechanical anchorage rebar broke on the side of the base metal rebar at the time of fracture and exhibited the same or higher strength than the base metal rebar. In addition, the interface between the expanded diameter and base metal rebar was not a weak point.

## 3 Static bending test

### 3.1 Specimen

In this study, static bending tests were conducted on slab joints using the developed mechanical anchorage rebars to confirm their load-bearing capacities. Two specimens were used in the tests: a 'one-piece' specimen without a joint for comparison as No. 1 and a 'specimen with a joint' with a joint length of 15D (D: rebar diameter) as No. 2. Figure 5 shows the shapes and dimensions of the test specimens. The reinforcement arrangement of the specimen was similar to that of the actual PCaPC slab, with 150 mm spacing between bars in the direction of the bridge axis (75 mm in the joint) and 125 mm spacing between bars perpendicular to the bridge axis. The thickness of the specimens was 220 mm, which is similar to that of actual PCaPC slabs. A D19 SD345 was used as the bridge axial rebar, a D13 SD345 threaded rebar was used as that perpendicular to the bridge axis, and a D19 SD345 threaded rebar was used as the reinforcement bar at the joints. A threaded rebar was used in the transverse direction of the bridge to simulate the lateral confinement force resulting from the continuous presence of an actual prestressed concrete (PC) deck slab along the side direction of the specimen. Locknuts were connected to the transverse rebar on both sides of the specimen to restrict lateral deformation. In this test, as in the actual PC slab, the steel bars interfering with the joints, that is, 500-mm section from the tip of the expanded diameter of the axial rebars and the reinforcement bars at the joints, were epoxy coated. Considering that the actual PCaPC road bridge slab was

**Fig. 1.** Mechanical anchorage rebar for slab joint

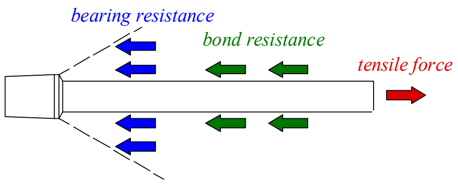

**Fig. 2.** Principle of the rebar anchorage

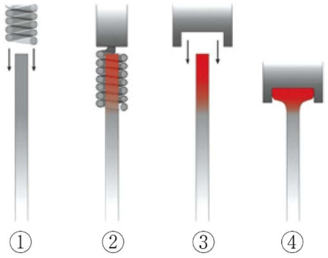

**Fig. 3.** Manufacturing process flow of anchorage rebar

**Table 1**. Result of the rebar tensile test

| Nominal diameter | Rebar grade | No. | Yield strength (N/mm$^2$) | Tensile strength (N/mm$^2$) |
|---|---|---|---|---|
| D19 | SD345 | 1 | 373 | 571 |
| | | 2 | 375 | 581 |
| | | 3 | 373 | 579 |

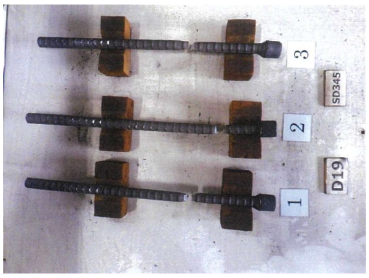

**Fig. 4.** Test specimen after testing

designed with a specified strength of 50 N/mm², high-early-strength concrete with a nominal strength of 36 N/mm² (28-day) was used for both the filling and PCa sections. This ensured that the actual strength at the time of the test was ~50 N/mm². The compressive strengths at the test age were 52.1, 52.6, and 51.4 N/mm² for the one-piece specimen (14-day), PCa section of the specimen with a joint (15-day), and filling section (14-day), respectively. Their static elastic moduli were 38.6, 39.2, and 38.5 kN/mm², respectively.

The load was applied by four-point bending using two jacks of 1 MN capacity, with loading and shear spans of 600 and 800 mm, respectively. Pin roller bearings were used as loading points and fulcrums, and the horizontal movement and rotation were not restrained. A 100 mm wide steel plate was inserted between the loading point and fulcrum, and the space between the plate and specimen was filled with plaster to ensure that the load acted uniformly on the installation surface. The measurement parameters were the load and specimen deflection (at the centre of the span, immediately below the loading point, and at the centre of the shear span). The deflection measurements in this test were performed using a displacement transducer installed in a channel connected to the side of the member to eliminate the effect of sinking of the specimen at the fulcrum owing to loading.

### 3.2 Experiment result

Figure 6 shows the load-deflection relationship. The deflection on the horizontal axis of the graph is the vertical displacement of the specimen measured at the centre of the span, and the load is the total load of the two jacks. Additionally, the figure shows the ultimate bending strength of specimen No. 1 calculated based on the Specifications for Highway Bridges [9]. The one-piece specimen reached its ultimate state owing to crushing of the compression edge after the member yielded. The specimen with the developed mechanical anchorage rebar joint exhibited a stiffness equivalent to that of a one-piece specimen from the onset of the bending cracks to member yielding. Although cracks near the joint became predominant, and the load decreased, the specimen maintained its load-bearing capacity even after yielding, similar to the monolithic specimen. Thus, the specimen was confirmed to have a bending strength exceeding the design value.

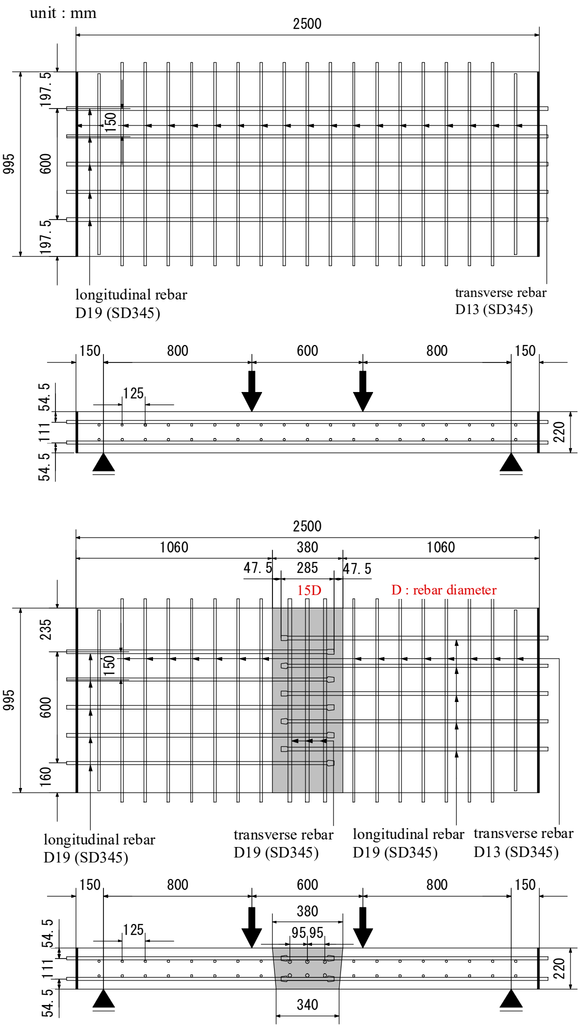

**Fig. 5.** Test specimen for static bending test

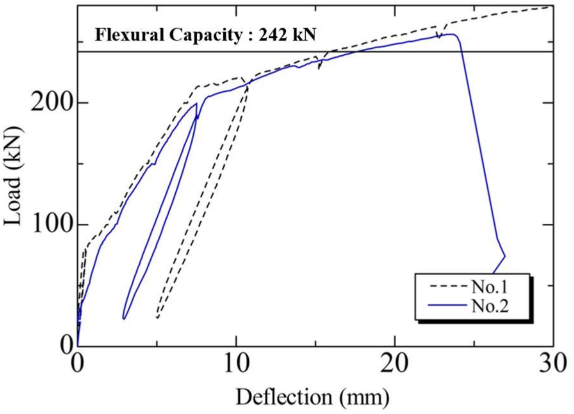

**Fig. 6.** Load- deflection relationship

## 4 Wheel load running test

To verify the fatigue durability of slab joints using the developed mechanical anchorage rebars, full-scale PCaPC slabs were fabricated and subjected to wheel-load running tests. This test focused on the longitudinal joints of the deck slab as they appear in actual bridge decks. The details of this process are described below.

### 4.1 Specimen

Figure 7 shows a drawing of the specimen. Figure 8 shows a cross-sectional view of the joint. Figure 9 shows the reinforcement arrangement of the joint. The dimensions of the specimen, rebar, and PC steel were determined according to the NEXCO Test Method 442 [10]. The overall length and width of the specimen were 4,500 and 2,800 mm, respectively, and the slab thickness was 220 mm. The deck slab was designed as a PC structure perpendicular to the bridge axis. Seven φ23 SBPR Type B prestressing steel bars were used per panel, and a post-tensioning force of 312 kN was applied per prestressing steel bar. The longitudinal direction was designed as an RC structure, and the joints were incorporated into the mechanical anchorage rebars

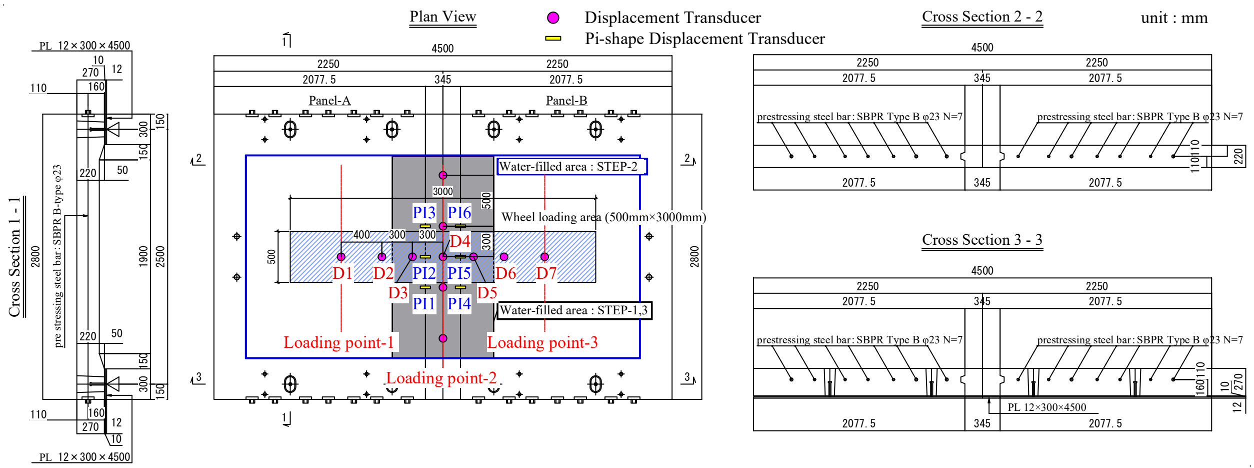

**Fig. 7.** Test specimen for wheel load running test

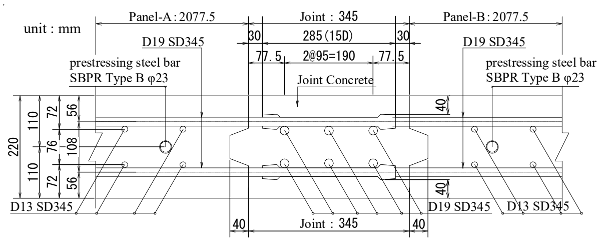

**Fig. 8.** Details of the joint

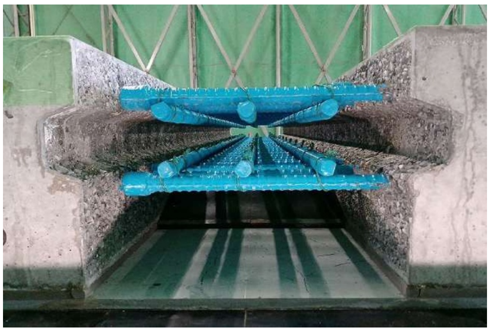

**Fig. 9.** Reinforcement arrangement of the joint

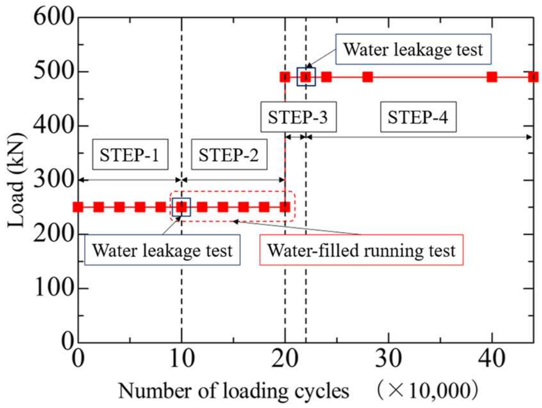

**Fig. 10.** Loading steps of wheel road running test

developed in this study. The joint length was set as 15D. For the PCa section, high-early-strength concrete with specified compressive strength of 50 N/mm$^2$ was used. Shrinkage-compensating concrete with an expanding agent was used for the joints and stud dowel holes. The results of material tests of concrete are listed in Table 2.

**Table 2.** Material test results

| | | At the beginning of STEP-1 | At the end of the STEP-4 |
|---|---|---|---|
| Panel | $f'_c$ ※1(N/mm$^2$) | 74.9 | 77.7 |
| | $E$ ※2(kN/mm$^2$) | 44.6 | 44.3 |
| Joint | $f'_c$ ※1(N/mm$^2$) | 73.7 | 77.5 |
| | $E$ ※2(kN/mm$^2$) | 42.4 | 44.7 |

※1 $f'_c$ :Compressive Strength ※2 $E$ :Elastic Modulus

**Table 3.** Specification items of the testing machine

| Items | | Specifications |
|---|---|---|
| Shape Dimensions | Testing machine frame | Height : approx. 6.5 m<br>Length : approx. 10.1 m |
| | Flywheel | Radius : 2.3 m |
| | Type of wheel | Steel wheel |
| Drive system | Travel range | 3.0 m or 4.6 m |
| | Flywheel rpm | Up to 15 rpm |
| Loading system | Load capacity | 120–490 kN |
| | Cylinder stroke | 295 mm |

## 4.2 Loading condition

Figure 10 shows the loading steps. In this test, STEP-1 corresponds to the test item of NEXCO Test Method 442 [10]. To evaluate the fatigue durability of the slab over 100 years of service, a water leakage test was conducted after 100,000 cycles of 250 kN loading. In STEP-2, a load of 250 kN was applied during the water-filled running. In STEP-3, a load of 490 kN was applied, and a leakage test was conducted after the specified cyclic loading was completed. In STEP-4, the same load of 490 kN was applied, and efforts were made to accelerate the fatigue as much as possible during the test period. In the leakage tests conducted after STEP-1 and STEP-3, a sponge frame was created within the area marked in grey in Figure 7, and the enclosed area was filled with ~5 mm of water. After leaving it for 6 h, the presence or absence of leakage from the deck slab underside was assessed. In the water-filled running test in STEP-2, the area marked with a blue frame in Figure 7 was similarly filled with ~5 mm of water, and the wheel-load running test was performed while maintaining the water depth. The specimen was simply supported with a slab span of

2,500 mm. The specimen was also elastically supported in the longitudinal direction by a transverse beam of H-section steel with the same stiffness as that of the floor slab and a length that could be considered infinitely long. The specimen was fixed to a support girder without any rotational restraints to prevent it from floating. The specifications of the test machine are listed in Table 3. A wheel-load running tester (G&U Technical Research Centre Co., Ltd.) was used as the testing machine. On the slab specimen, a row of 500 mm × 200 mm loading blocks were placed, and 500 mm wide steel wheels were moved back and forth in a range of 3,000 mm to apply the wheel load. Figure 11 shows the test in progress.

### 4.3 Measurement items

In this test, the load, specimen deflection, and crack width at the PCa–joint interface were measured. The cracks at the bottom and sides of the specimens were visually examined. Each displacement transducer and the pi-shape displacement transducer were installed at the bottom of the specimen at the locations shown in Figure 7. The load and crack width were measured at the 0th, 25,000th, 50,000th, 75,000th, and 100,000th cycles of each loading step in STEP-1 and STEP-2, before and after loading in STEP-3, and at 20, 000, 60,000, 180,000, and 220,000 loading cycles in STEP-4. At each measurement point, static loading was applied to each of the three loading points (1–3) as shown in Figure 7.

### 4.4 Experimental results

#### *4.4.1 Deflection transition*

Figure 12 shows the deflection measured during static loading at loading point 2 at D4 in the centre of the specimen. From STEP-1, in which a service life of 100 years was assumed, to STEP-2, in which a water-filled condition was assumed, no significant change was observed in the deflection, and the total deflection remained stable at ~1 mm. After STEP-3, when the applied load was 490 kN, the deflection gradually increased; however, no discontinuous deflection fluctuations were observed owing to the failure of the specimen, and a continuous increase in deflection with repeated loading was confirmed. Figure 13 shows the deflection distribution along the bridge axis measured during static loading at a loading point 2. As shown in the figure, no deformation localisation was observed at the joints in STEP-4, and the deflection was continuously distributed in the bridge axis direction. This confirmed the high integrity of the joints and PCa sections.

#### *4.4.2 Crack width transition*

Figure 14 shows the crack width at the joint–PCa interface, as measured by a pi-shape displacement transducer during static loading at loading point 2. The maximum crack width at the end of STEP-1 under cyclic loading (assuming a service life of 100 years) was ~0.10 mm, and no bond breakage of >0.20 mm was observed.

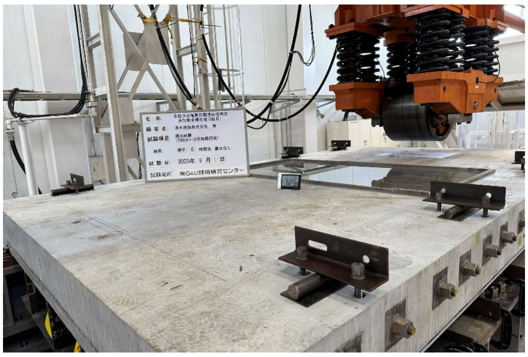

**Fig. 11.** Testing status (water leakage test at STEP-1)

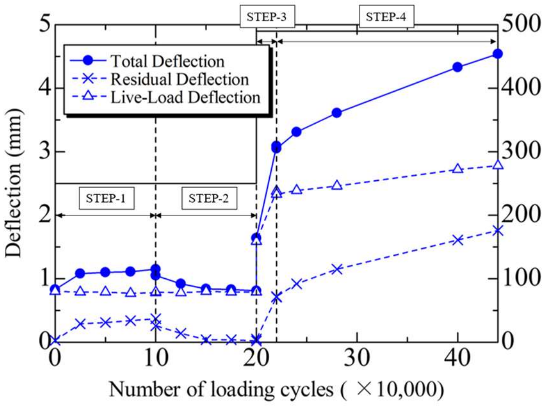

**Fig. 12.** Relationship between the deflection at D4 and the number of loading cycles

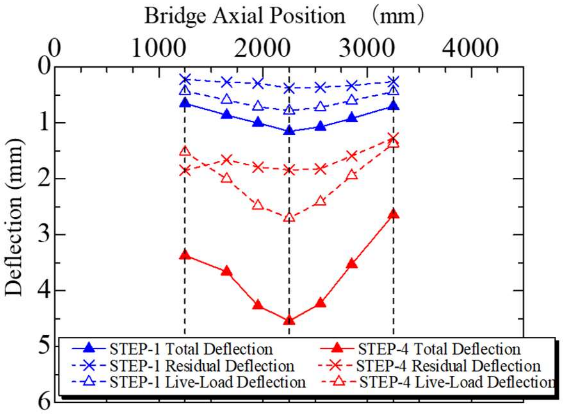

**Fig. 13.** Progression of deflection distribution in the bridge axis direction

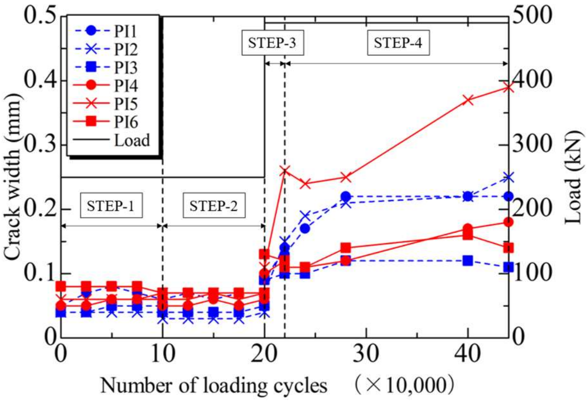

**Fig. 14.** Relationship between crack width at the joint interface and the number of loading cycles

These results indicated that the crack inspection by close-up visual inspection determined no need for repair. This confirmed the high fatigue durability of the joint–PCa interface. No fracture was observed at the interface at the end of STEP-4, and the integral behaviour of the joint and PCa sections was confirmed.

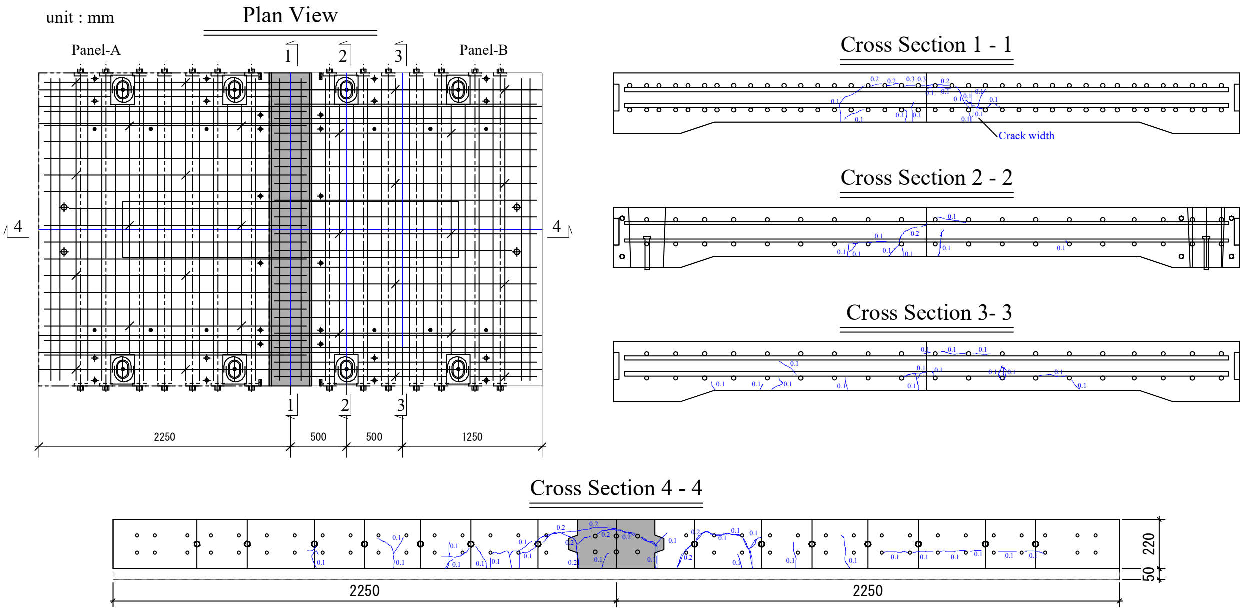

**Fig. 15.** Crack distribution on the cross section of the slab after the experiment

### 4.4.3 Crack behaviour and water leakage test

Figure 15 presents the crack patterns observed in the cross section after cutting the specimen at the end of the test. Even in the sections that included joints, no through-cracks and puncing shear failure were observed. Additionally, the leakage tests conducted after STEP-1 and STEP-3 showed no water leakage from the underside of the specimen. These results confirmed that the joint structure exhibited high fatigue durability.

## 5 Conclusion

In this study, various experiments were conducted to verify the mechanical performance of a joint method using a mechanical anchorage rebar with an expanded diameter formed integrally via high-frequency induction heating at the joint between precast PC slabs. The conclusions of this study can be summarised as follows:

1. The mechanical anchorage rebars for slab joints formed in one piece by high-frequency induction heating were confirmed to have a tensile strength equal to or greater than that of the base rebars, based on rebar tensile tests.
2. Static bending tests of the slab joints using the developed mechanical anchorage rebars in the slab joints confirmed that this joint structure had the same load-bearing capacity after yielding as a one-piece specimen.
3. The PC slab joint structure was confirmed to have high fatigue durability with no leakage observed in the wheel-load running test, which was conducted assuming a service life of 100 years.
4. According to the wheel load running test, it was confirmed that the PCaPC slab with this joint structure did not fail even after accelerated fatigue loading after STEP-2, indicating that the joint and precast parts have high integrity and high fatigue durability.

## References

1. Ministry of Land, Infrastructure, Transport and Tourism, *Roads in Japan 2024,* https://www.mlit.go.jp/road/road_e/pdf/ROAD2024web.pdf (Accessed February 3rd, 2025).
2. East Nippon Expressway Co., Ltd., https://www.e-nexco.co.jp/en/renewal/about/ (Accessed February 3rd, 2025).
3. H. Yoshimatsu, S. Matsui, K. Osawa, Y. Nakayama, H. Mizuno, S. Omote, Essential study on a rationalized connection of precast PC slab for slab replacement. J. Struct. Eng, **60A**, 1159-1168 (2014) (in Japanese).
4. K. Sasaki, T. Nomura, N. Oda, T. Iwaki, T. Tominaga, Experimental Study on Precast Deck Connection “Slim Fastener”, Report of Obayashi Corporation Technology Research Institute 82, (2018) (in Japanese).
5. T. Takeyama, Y. Nonami, H. Shinozaki, T. Matsuda, Splice Joint of Precast Deck Slab Using Ultra-Low Shrinkage and High Strength Fiber-Reinforced Cementitious Composites. Proceedings of the 76th JSCE Annual Meeting, (2021) (in Japanese).

6. K. Hara, K. Yoshitake, T. Ohta, E. Takashima, Development of PCa slab joints with enlarged-diameter part integrally molded by high-frequency induction heating, Proceedings of the Japan Concrete Institute, Vol.46, No.2, 511-516 (2024) (in Japanese).
7. General Incorporated Foundation, Public Works Research Center, Mechanical anchorage rebar with enlarged diameter “T-head rebar”, Report on Construction Technology Review and Certification, (2024) (in Japanese).
8. T. Ishibashi, Mechanical Fixing Rebar. Concrete. J. **54**(5), 453-457 (2016) (in Japanese).
9. Japan Road Association, Specifications for highway bridges, Part III Concrete Bridges, (2012) (in Japanese).
10. NEXCO-RI (Nippon Expressway Research Institute Company Limited), NEXCO Testing Methods, 4 Structure Tests. 91-94, (2019) (in Japanese).