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Strengthening system using post-tension tendon with an internal anchorage of concrete members

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ABSTRACT

The present study aims to develop a strengthening system using prestressing tendons embedded into an internal anchorage of concrete member. The internal anchorage, a wedge-shaped hole, is made by using a special drilling machine. The tip of the hole is filled with high strength mortar to anchor firmly the prestressing tendon. The strengthening system is acceptable even in relatively narrow workspaces, and also applicable for joints between existing and additional concrete members. The experimental study conducted a pull-out test of the prestressing tendon to examine the load-bearing capacity. A finite element simulation was also performed to confirm the bonding and unbonding effects of the prestressing tendon. The test result confirms adequate load-bearing capacity of the anchorage for the prestressing tendon. In addition, the FE simulation shows that the strengthening system can provide a constant prestress even if the prestressing tendon is not bound to the mortar in the anchorage.

1. Introduction

Numerous civil infrastructures, including bridges, have been constructed over the past few decades in Japan. Civil engineers are tasked with maintaining and appropriately retrofitting these structures to sustain modern infrastructure. Various strengthening materials and methods have been developed and applied to concrete members. One of the more effective and reliable strengthening methods for concrete is an application of the prestressing system.

Conventional prestressing systems using metallic bars have been employed to strengthen existing concrete structures. In addition, fiber-reinforced polymer (FRP) laminates have been used for prestressing systems in recent decades. The strengthening system has been investigated for structural applications and has been discussed in previous studies. Kim et al. [1] examined the effects of prestressing levels of carbon fiber-reinforced polymer (CFRP) laminate. They also performed a three-dimensional finite element (FE) simulation to quantify the flexural behavior of the strengthened beam. Based on these investigations, they recommended a prestress level of 20–30% of the ultimate strain of the CFRP laminate to strengthen concrete beams. Michels et al. [2] developed an anchorage system for prestressing CFRP strips to strengthen concrete members. This system has some advantages, including faster installation and higher durability than conventional techniques. Schmidt et al. [3] summarized a state-of-the-art mechanical anchorage system for FRP tendons and discussed investigations using several anchorages such as spikes, wedges and clamping. Several directions for future research were also proposed. You et al. [4] studied a prestressed CFRP system using a new anchorage. According to their study, the prestressed CFRP system improved first-cracking and steel-yielding strengths by 133–235% and 77–186%, respectively. Wang et al. [5] focused on a prestressing tendon of basalt fiber reinforced polymer (BFRP), and investigated the structural performance of RC beam strengthened externally with this BFRP prestressing tendon. The paper presented appropriate prestressing level based on creep rupture limit. Faria et al. [6] studied flat slabs strengthened by a new post-tensioning system with anchorage using an epoxy adhesive. Their experimental investigation shows that deflection and cracks of the strengthened slab were reduced, and the punching shear strength was increased as compared with unstrengthened slabs. In addition, Faria et al. [7] reported the post-punching behavior of flat slabs strengthened with the post-tensioning system. Koppitz et al. [8] also examined punching shear behaviors of RC slabs strengthened with non-laminated prestressed CFRP straps. Their experimental investigation developed and used a modified mechanical anchoring system of CFRP straps for the strengthened slabs.

Several post-tension anchor systems were also investigated using pull-out tests or FE modeling. Kim et al. [9] conducted a large number of experimental tests for post-installed anchorage

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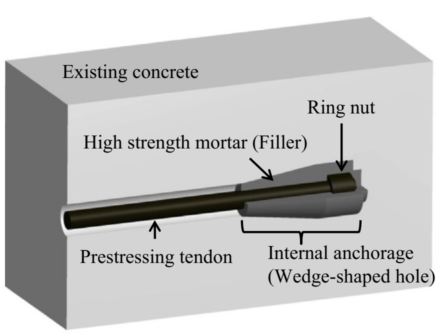
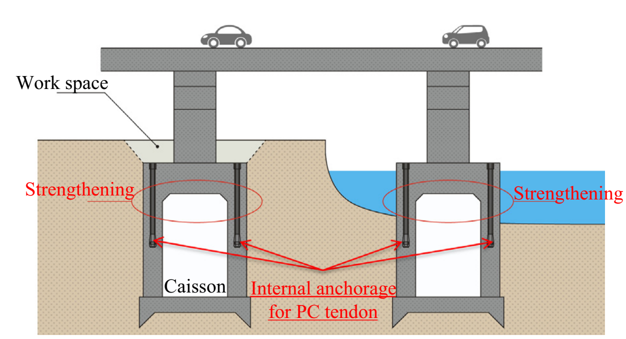
systems. The pull-out strength of the anchorage system was found to be affected by three parameters: torque ratio, embedment depth and diameter of embedded bars. The shear strength, however, was unaffected by torque ratio. They also carried out three-dimensional FE modeling of the anchor systems using ABAQUS to confirm the experimental test results. Yang et al. [10] analyzed pull-out tests of the anchor from the anchor–mortar–concrete anchorage system. Two different boundary conditions were used. The study presented variations in shear stresses along the thickness of the mortar layer and interfacial shear stress along the embedment length. Martí-Vargas et al. [11–13] investigated the transmission and anchor length of pre-tensioned prestressed concrete members. Test specimens were made with seven-wire prestressing steel strands of 13 mm diameter. They investigated the influence of concrete strength on transmission and anchorage lengths, and analyzed the bond behavior after bond failure. In addition, they developed an analytical model to predict strand slips. Obata et al. [14] reported on the structural behavior of a bond-type anchorage and found that the stress cone strength is proportional to the bond depth raised to the power of 1.5. Akisanya and Ivanović [15] carried out pull-out tests to examine debonding effects on the load-bearing capacity of the model anchor and discussed the interaction between the toughness of interface crack development and consequent reduction in load-bearing capacity. Yilmaz et al. [16] discussed tensile behavior of post-installed chemical anchors embedded in low-strength concrete blocks. They recommended that a free-edge distance and embedment depth of at least 15 times the anchor diameter should be chosen for an economical and efficient anchor design.

Reinforcing materials such as FRP rods and steel bar/cable are generally arranged outside of existing concrete members. Adequate workspace is often required for this strengthening work. New and old concrete joint members are often constructed as reinforced concrete structures, so steel corrosion may occur at the joint. Conventional strengthening systems are influenced by environmental conditions.



(a) Internal anchorage system



(b) Typical application-concrete foundations-

Fig. 1. Schematics of the developed strengthening system.

To mitigate the environmental impact and workspace issues, the authors have developed a new strengthening method for existing concrete members where a post-tension prestressing tendon is embedded into a wedge-shaped internal anchorage. Fig. 1(a) and (b) shows a schematic of the developed system and a typical application of the strengthening system, respectively. The machinery used in the strengthening work is compact and it can locally strengthen concrete members by embedding prestressing tendons at various points. Hence, the system can be used in relatively narrow work spaces such as the foundations shown in Fig. 1(b). In addition, FRP tendons are applicable as well as a conventional prestressing tendon when ring-nut or similar are attached to the FRP tendon. A previous study [17] reported a push-out test using full-scale concrete specimens embedding the wedge-shaped anchorage. The fundamental test was conducted to evaluate the anchor performance and determine the dimensions of the anchorage for a pull-out test using full-scale concrete specimens. To examine the load-bearing capacity of the embedded anchorage, a pull-out test of prestressing tendons was also performed using full-scale concrete specimens. In addition, a finite element simulation was performed to examine the bonding and unbonding effects of the prestressing tendon in the anchorage. This paper presents experimental and numerical investigations of the developed strengthening system.

2. Anchorage system

Fig. 2 shows the strengthening process of the post-installed anchorage system. The tip of the hole in the existing concrete is enlarged using a special drilling device as shown in Fig. 3. The anchorage that is filled with mortar acts as an internal wedge-shaped hole to resist the tensile force. The strengthening system is implemented as follows:

Step 1: Core-drill into existing concrete and enlarge the hole tip (wedge-shaped anchorage).
Step 2: Install a prestressing tendon and grout a filler (high-strength mortar) into the wedge-shaped hole.

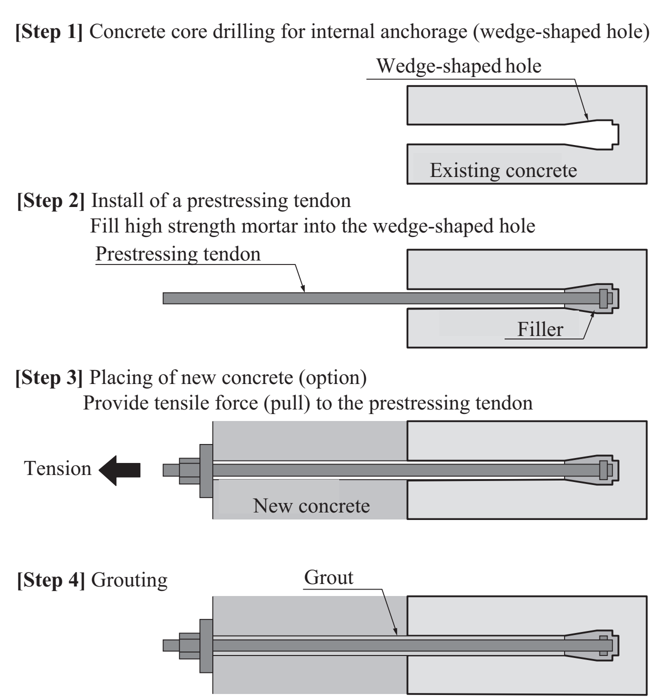
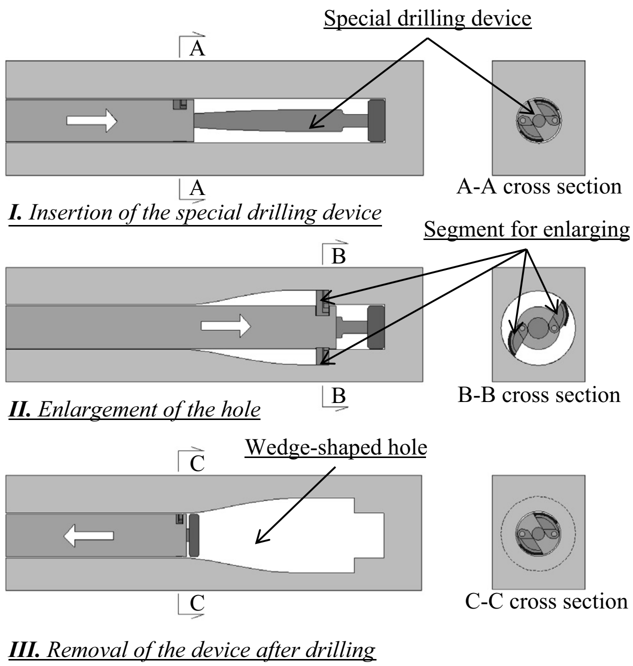
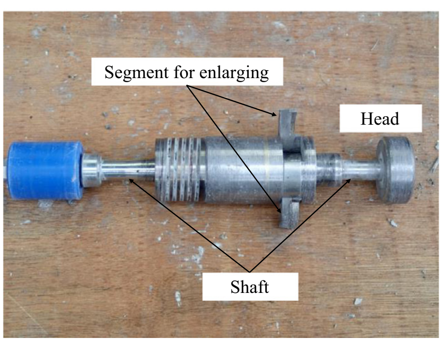


Fig. 2. Strengthening system process using a prestressing tendon fixed in the internal anchorage.



(a) Drilling process



(b) Special drilling device

Fig. 3. Wedge-shaped hole in concrete.

Step 3: Place new concrete if necessary. Provide tensile force (pull the prestressing tendon with a hydraulic jack).
Step 4: Grout mortar into the hole.

Mimoto et al. [17] conducted a fundamental test for the internal anchorage system. They reported that concrete member of 400 × 400 mm or greater and a specified cylinder strength of 24 MPa or higher (in compression) are preferable to decrease the possibility of splitting cracks at the internal anchorage. It is noted that the strengthening system is rarely applicable for thin structures having a lot of reinforcement such as flat slabs and walls.

3. Methodology

3.1. Materials

Table 1 gives the concrete and reinforcing materials used in this experimental investigation. Prestressing tendons of high yield strength (1080 MPa) were used to examine the ultimate load-bearing capacity of the internal anchorage with embedded a standard tendon. In addition, reinforcing bars (13 mm in diameter) were mainly used in reinforced concrete (RC) specimens.

Table 1
Materials.

Concrete materials	Type	Density
Water (W)		1.00 g/cm^3
Cement (C)	Ordinary Portland cement	3.16 g/cm^3
Fine aggregate (S)	Crashed sand	2.64 g/cm^3
Coarse aggregate (G)	Crashed stone	2.68 g/cm^3
Admixture (AD)	Superplasticizer	1.04 g/cm^3
Materials	**Properties**	
Reinforcing bar	JIS G-3112; Nominal diameter: 13 mm (D13) and 10 mm (D10) Yield strength: 345 MPa; Young's modulus: 206 GPa	
Prestressing tendon	JIS G-3109; Nominal diameter: 23 mm; Type B-1 Yield strength: 1080 MPa; Young's modulus: 202 GPa	
Ring nut	JIS G-3101; Nominal diameter: 38 mm; Yield strength: 235 MPa; Young's modulus: 206 GPa	
Bearing plate with a hole	JIS G-3101; Dimensions: 120 × 120 × 25 mm Yield strength: 235 MPa; Young's modulus: 206 GPa	
Filling material	High-strength mortar (see Tables 2 and 3)	

Table 2 summarizes the mixture proportions of the concrete and high strength mortar. The fresh concrete had a slump value of 12 cm (JIS A 1101) [18], and the fresh mortar had a flow value of 18.5–28.5 cm (JIS R 5201) [19]. Note is that the parentheses show the Japanese standard tests. The primary material of mortar is a commercial pre-mixed type used in sleeve joints of rebars. The high strength mortar was used to achieve sufficient strength, workability, non-shrinking and non-bleeding performance.

Conventional compression, splitting tension, Young's modulus and Poisson's ratio tests were conducted to determine the mechanical properties needed for a FE simulation. The Young's modulus is determined from the compression test, and the modulus is defined as a secant modulus under one-third of the maximum stress. Three concrete cylinders 100 mm in diameter × 200 mm in height were used in each test. Table 3 gives the mechanical properties of the concrete and the high strength mortar.

3.2. Test specimen

Fig. 4(a) and (b) shows the pull-out test, and Fig. 4(c) presents the dimensions of the test specimen. Three specimens of 400 × 400 × 1300 mm were prepared to investigate the behavior of the experimental members tensioned with a prestressing tendon. Fig. 4(d) shows the prestressing tendon used in the study. The tendon was installed to a wedge-shaped hole in the concrete according to the procedure described above (Fig. 2). Dimensions of the wedge-shaped hole are 66–42 mm diameter × 95 mm long.

Fig. 4(c) shows the arrangement of strain gages. Wire strain gages (120 Ω) were placed on the concrete surfaces to examine

Table 2
Mixture proportions.

	w/cm[a]	W	C	S	G	AD	Air
Concrete	0.53	175 kg/m^3	330 kg/m^3	887 kg/m^3	978 kg/m^3	1.16 kg/m^3	4.5%
Mortar[b]	0.12	3 kg/mix	25 kg/mix		N/A	N/A	N/A

[a] Water-cementitious material ratio.
[b] Premix mortar (filler).

Table 3
Mechanical properties of the materials used.

	Concrete	Mortar
Compressive strength (MPa)	41.4, 42.8, 42.9 <u>Av. 42.4</u>	90.1, 96.3, 94.7 <u>Av. 93.7</u>
Splitting tensile strength (MPa)	2.6, 2.8, 2.6 <u>Av. 2.7</u>	4.5, 4.7, 3.8 <u>Av. 4.3</u>
Young's modulus (GPa)	31.1, 30.8, 34.1 <u>Av. 32.0</u>	35.9, 38.9, 38.7 <u>Av. 37.8</u>
Poisson's ratio	0.19, 0.19, 0.20 <u>Av. 0.19</u>	0.21, 0.24, 0.23 <u>Av. 0.23</u>

the strain (stress) distribution. Embedded strain gages (350 Ω) [20] were also set into the concrete members to confirm the inner stress. Linear variable differential transformers (LVDTs) were placed on the top and bottom surfaces of the concrete to monitor the deformation. In addition, a center-hole type compression load cell (capacity: 1 MN) was used to measure the force of the prestressing tendon.

Fig. 4(e) and (f) shows cross sectional views including the arrangement of the rebars.

3.3. Pull-out test

The pull-out test was conducted using the prismatic specimen to examine the fundamental behavior of full-scale concrete members strengthened with the post-tensioning prestress system. The prestressing tendon was pulled out axially to determine the performance of the anchorage system and to investigate the behavior of a concrete member subjected to a longitudinal compression force. The pull-out test was conducted at a mortar-age of 28 days or later. Table 4 shows the load step in the pull-out test. High-strength prestressing tendons (SBPR930/1080: Type B-1) were used to confirm the anchorage effect under ultimate loading. According to Japanese industrial standards (JIS G 3109) [21], the yield strength (***Py***) and ultimate load-bearing capacity are 386.4 and 448.7 kN, respectively. In the pull-out test (Fig. 4(a)), the "slip" of a prestressing tendon is determined by subtracting the LVDT measurement (D) from the measurement (C). In addition, the "elongation" of a tendon is obtained by subtracting the LVDT measurement (C) from the measurement (A).

Table 4
Load steps for pull-out test.

Load step	Load (kN)	Load
0	0	Initial
0.60 ***Pu***	269.2	Design load
0.70 ***Pu***	314.1	Allowable load for design
0.90 ***Py***	347.8	Allowable load for prestressing
Py	386.4	Load at yielding
Pu	448.7	Ultimate tensile load
Pmax	See Table 6	Maximum load

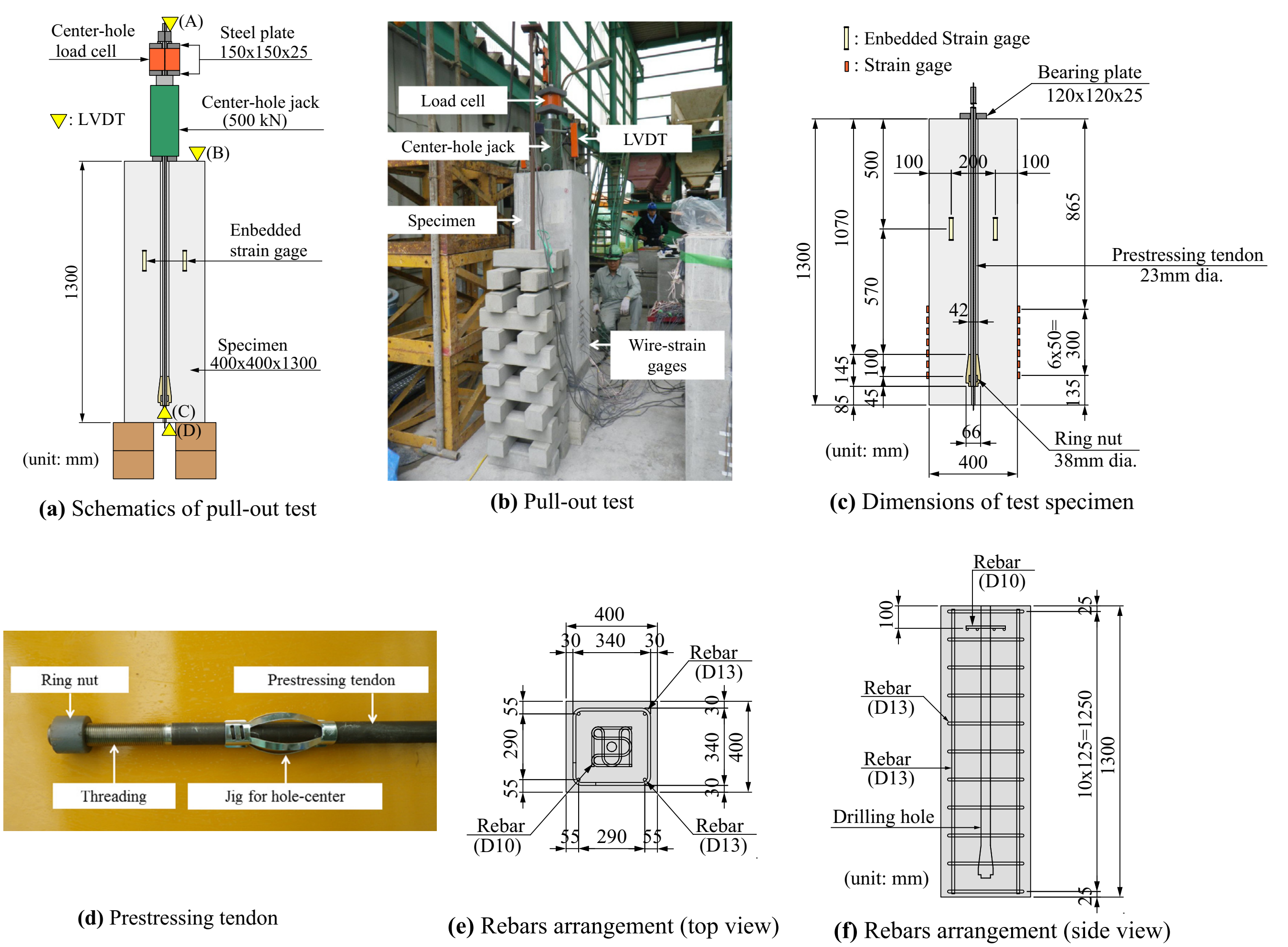


Fig. 4. Detail of specimen for pull-out test.

3.4. FE simulations

Numerical simulation using a linear FE program [22] was performed to examine the anchorage effect of a tendon under a designed prestressing force. Fig. 5 shows an FE model of the pull-out test. A half-dimensional model is used in the FE simulation. The FE simulation uses different bond conditions for the PC bar (Types A and B). Type A is a full-bond model in which the prestressing tendon interface is glued firmly to the mortar filler. The model addresses the idealized condition for anchorage of the tendon. Type B is a model that includes an unbonded interface shown in Fig. 5. The model is used to investigate the mechanical resistance of the ring nut without mortar bonding. Mechanical properties used in the simulation are given in Table 5. The concrete and filling material properties were determined according to the test results in Table 3.

4. Results and discussion

4.1. Load-bearing capacity

Table 6 gives the maximum load-bearing capacity of the prestressing tendon in the pull-out test. All test specimens achieved the ultimate tensile force (448.7 kN) required in JIS G 3109 [21]. Concrete cracking did not occur at ultimate load. The load-bearing capacity is sufficient using the internal anchorage up to the ultimate limit state. This result confirms that the prestressing tendon is firmly restricted by the filling material in the wedge anchor.

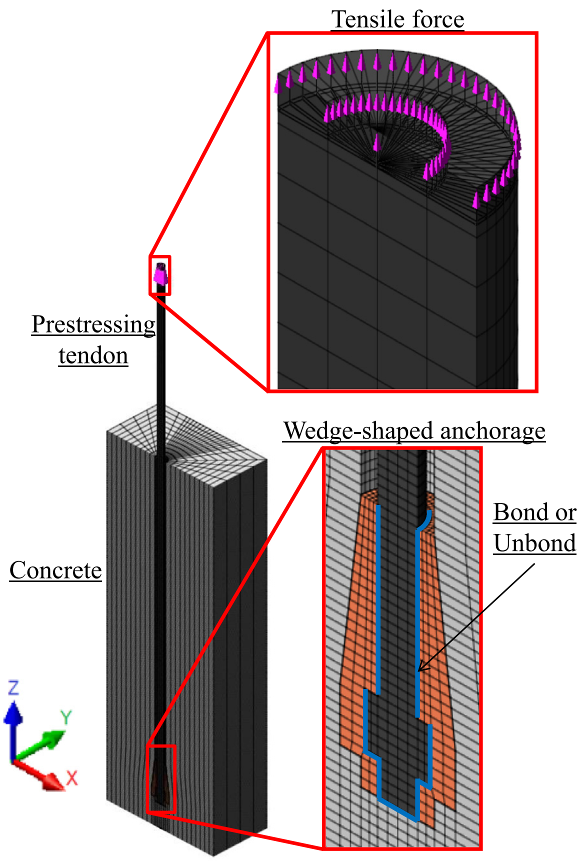


Fig. 5. FE simulation model (1/2 model).

Table 5
Mechanical properties for FE simulation.

Materials	Young's modulus (GPa)	Poisson's ratio
Concrete	32	0.19
Prestressing tendon	200	0.30
Filling material (mortar)	37.8	0.23

Table 6
Maximum loads in pull-out test.

Pmax	No. 1	No. 2	No. 3
Maximum load (kN)	489.6	490.9	490.5

4.2. Deformation

Fig. 6 shows load–slip responses (dash lines) and elongation behaviors (solid lines) of the prestressing tendon. A slight slip was observed at a load of 300 kN or higher. The (maximum) slip reached 0.24 mm at 0.90 ***Py***. This observation confirms that the negligible slip of the tendon hardly affects the internal anchorage under the allowable prestressing force. The dashed line indicates the calculation value estimated using the Young's modulus. The test results confirmed the elastic behavior under a 400 kN load. The prestressing tendon indicated plastic behavior after the load at yielding (***Py***). Plastic behavior after yielding is not required for the actual strengthening system because the load is significantly higher than the design load (269.2 kN). The most important observation is that the tendon can be anchored without slip deformation until the design load. This result implies that the developed strengthening method can be appropriately designed using the elastic behavior of the prestressing tendon.

4.3. Strains

Fig. 7 shows the load–axial strain responses of the prestressing tendon (specimen No. 1). A dashed line indicates elastic strain by using the Young's modulus of the tendon. The strain at 135 mm indicates a linear behavior at a load of approximately 250 kN. The linear strain behavior is almost equal to the elastic response of the tendon. Except for the strain at 135 mm, strains were lower than the elastic strain of the tendon.

Fig. 8 shows the axial strains measured in test specimens subjected to a design load of 269.2 kN. In addition, strain distributions estimated from the FE simulation are presented on the graph for comparison. Strains in the load–transition zone of the FE simulation agree relatively well with the experimental data. The FE sim-

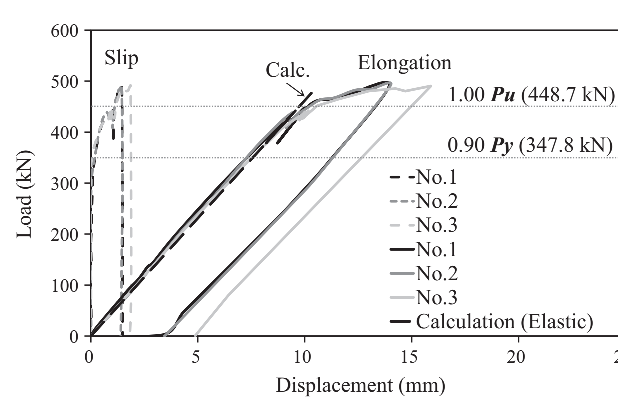


Fig. 6. Slip distance and elongation of prestressing tendon.

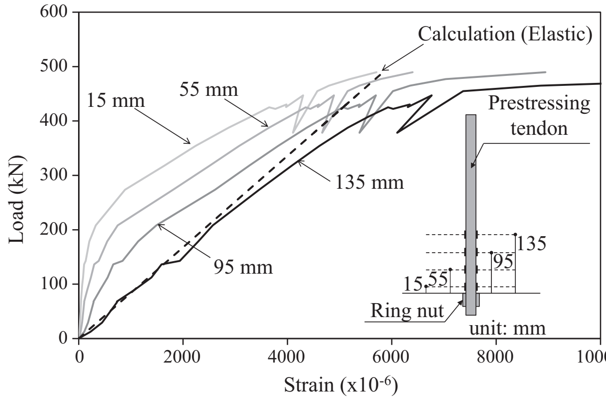


Fig. 7. Load–strain responses of prestressing tendon (specimen No. 1).

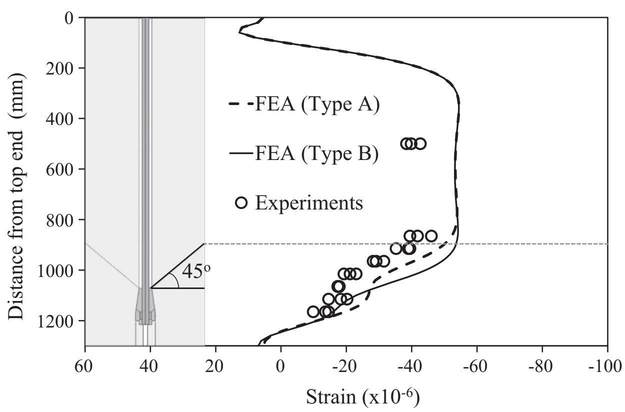


Fig. 8. Distribution of axial strain and FE simulation (269.2 kN).

ulation indicates a stable strain from 300 to 900 mm. The result confirms a constant prestress applied to the concrete. Both distributions of axial strains vary in the area below 800 mm because of the different source and friction surface on the prestressing load. The filling material and ring nut contribute to the load transfer. However, each effect is different in the type A or B model. Of interest is that the strain distributions are equal for a constant prestress. The strengthening system can provide a constant concrete prestress even if the prestressing tendon is unbonded to the anchor as given in the simulation for Type B.

Fig. 9 shows the horizontal strain distributions for the 269.2 kN load. The graph indicates the distributions of experimental and analytical results. Both distributions of horizontal strains vary below 600 mm because of the different boundary conditions. The comparative result confirms that the FE simulation (Type A) agrees well with the experimental results.

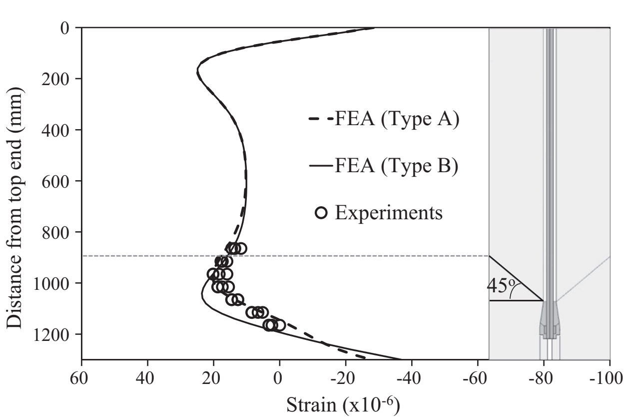


Fig. 9. Distribution of horizontal strain and FE simulation (269.2 kN).

5. Conclusions

The foci of this study were the load-bearing capacity of internal anchorage for the strengthening system, and the structural responses of the strengthened member. In this study, a pull-out test using a full-size specimen and a FE simulation were conducted. The conclusions of this investigation are summarized as follows:

- A new strengthening method is proposed for existing concrete members. In the strengthening system, a prestressing tendon can be anchored firmly in an internal wedge hole filled with high-strength mortar.
- Experimental results confirmed that the load-bearing capacity of the internal anchorage was sufficient to comply with the ultimate load defined by the Japanese criterion (JIS G 3109).
- The developed strengthening method can be designed using the elastic behavior of the prestressing tendon, as the tendon was anchored without slip deformation until the design load.
- The slip was 0.24 mm at 0.90 P_y in the pull-out test. Negligible slip resulted with the tendon subjected to an allowable load for strengthening.
- The FE simulation confirmed that the developed system can provide a constant prestress even if the prestressing tendon is not bound to the mortar in the anchorage.

While fundamental structural performance was confirmed in the study, further investigations are warranted before any practical applications. In particular, extensive experimental and analytical studies on the properties of the anchorage system and existing concrete members etc., in addition to research on the environmental conditions necessary for the strengthening work, are highly desirable.

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