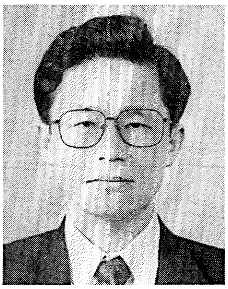
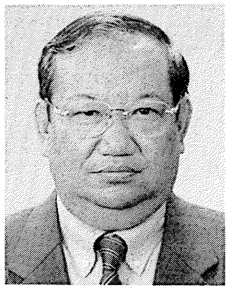
CONCRETE LIBRARY OF JSCE NO. 36, DECEMBER 2000

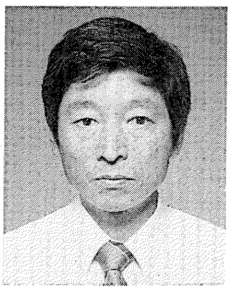
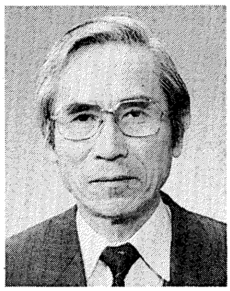
STUDIES OF ANCHORAGE METHOD FOR CONTINUOUS FIBER REINFORCING MATERIAL USING HIGHLY EXPANSIVE MATERIAL

(Translation from Proceedings of JSCE, No. 627/V-44, August 1999)





Tetsuo HARADA Takashi IDEMITSU Myo KHIN

Koichi SOEDA Akira WATANABE

When a continuous fiber reinforcing material (CFRM) is used as prestressing tendon or in tension tests, it is important to have an adequate method of securing it. The authors have developed a new anchoring method using a highly expansive material (HEM) in which the pressure of expansion can exceed 50 MPa and is transmitted in a manner similar to fluid pressure. In this paper, the relationship between anchorage length and expansive pressure for post-tensioning type anchors, their long-term stability, and their fatigue characteristics along with certain other properties are investigated. This is supplemented with an experimental study on the performance of multi-cable anchorages using the new material.

Key Words: *FRP tendon, highly expansive material, anchoring system, prestressed concrete*

Tetsuo Harada is a Professor in the Department of Structural Engineering at Nagasaki University, Nagasaki, Japan. He obtained his Dr. Eng. from the University of Tokyo in 1988. His research interests relate to the application of continuous fiber reinforcing materials to concrete structures. He is a member of the JSCE, JCI, and ACI.

Takashi Idemitsu is a Professor in the Department of Civil Engineering of Kyushu Institute of Technology, Kita-Kyushu, Japan. He obtained his Dr. Eng. from Kyushu Institute of Technology in 1992. His fields of research include analytical and experimental studies of PC composite structures and super-workable concrete. He is a member of the JSCE and JCI.

Myo Khin is an Associate Professor in the Civil Engineering Department of Dai-ichi Institute of Technology, Japan. He received his B.Eng. from the Rangoon Institute of Technology (Burma) and M.Eng. from Kyushu Institute of Technology. He is involved in research related to FRP bonding and anchorages. He is a member of the JSCE, JCI, and ACI.

Koichi Soeda is a deputy general manager in the Research and Development Laboratory of Onoda Corporation, Sakura, Japan. He obtained his Doctor of Engineering degree from Kyushu Institute of Technology in 1994. His research activities relate to the chemistry of cement, lime, and gypsum, and the development of new construction materials. He is a member of the JSCE and JCI.

Akira Watanabe is a Professor in the Department of Civil Engineering at Kyushu-Kyoritsu University and also emeritus professor at Kyushu Institute of Technology, Kita-Kyushu, Japan. He obtained his Doctor of Engineering degree from Kyushu University in 1965. His research interests cover design methods of concrete structures and the applications of new construction materials. He is a member of the JSCE, JCI, JSMS, and PCI.

1. INTRODUCTION

There has been active research in Japan on the application of continuous fiber reinforcing materials (CFRM), meaning continuous fibers such as carbon fiber and aramid fiber, to concrete structures. The document "RECOMMENDATION FOR DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES USING CONTINUOUS FIBER REINFORCING MATERIALS" was published by the JSCE as a result of this activity in 1997[1].

When CFRM in rod or strand form is used as a prestressing tendon, the most important issue is how to secure the CFRM. Since such fibers provide strength in a single direction, and are generally weak with respect to shear stress or local stress concentrations, ordinary PC anchorages cannot be used. As a result, several anchoring methods using various devices have been developed for use with CFRM. However, none can be considered a universal anchoring method that satisfies the multiple demands of excellent anchoring ability, ease of implementation, low cost, etc.

The authors have now developed a new simplified anchoring method for CFRM tendons using a highly expansive material (HEM). This characteristics of this material are such that the characteristics has of considerable expansive pressure up to 50 MPa is transmitted in a manner similar to fluid pressure[2].

In this paper, a fundamental study of anchoring using HEM is described. The HEM used has been developed from a material applied as an expansive demolition agent for demolishing concrete and rock without explosives. The material has been improved in areas such as workability during pouring, resistance to segregation, and degree of expansive pressure. The anchoring method is for application in the post-tensioning system or external cable system, so the relationship between anchorage length and expansive pressure, long-term stability, fatigue characteristics and other practical issues are investigated. Additionally, a multi-anchoring system using HEM is also described.

The experimental and analytical results have been presented in part at international conferences and other symposiums[3],[4],[5]. In this paper, however, new experimental and analytical results from all stages of the work, from initial development to application, are discussed systematically. The method has already been applied to the "Ground Anchoring Method"[6], and long-term tensioning tests have now exceeded seven years (as described in Section 4) so the stability of HEM anchorages can also be usefully discussed.

HEM can be considered to have a wide range of applications, and the authors hope that the basic results of this research, including certain problems that have been noted, will be widely used and that they will stimulate development in other areas of research.

This new anchorage method has found practical use as an "Intermediate Anchoring Method", in which ordinary PC tendons are held under tension[7]. Moreover, it can also be used to grip CFRM in tension tests. A manual for carrying out such tension tests using HEM has been published[1].

2. ORIGINAL CRITERIA AND OUTLINE OF HEM ANCHORAGE

2.1 The HEM Anchorage Concept

The authors have developed a special transducer that is used in the Inner Pipe Method [8] to measure expansive pressure directly within boreholes in concrete or rock. It is necessary to know the amount of expansive pressure needed to on internal cracks to induce failure when designing concrete or rock demolition methods employing an expansive demolition agent. The transducer consists of a steel pipe with orthogonal strain gauges attached to the inner surface. It is inserted into a borehole filled with an expansive demolition agent slurry, and the expansive pressure attained is calculated from the measured strains using thick-walled cylinder theory.

In order to calibrate the sensitivity of this sensor and to measure the exact expansive pressure acting on the inner surface of a borehole when using this sensor, double pipe tests were carried out, in which the expansive demolition agent was poured into the space between an outer and inner pipe. The main objective was to compare the relative expansive pressures acting on the outer pipe (p_o) and the inner one (p_i). The tests demonstrated that the time-dependent changes in p_o and p_i were equal as shown in Fig. 1; this was the case even when the transducer was made flat[8],[9]. It was also confirmed that expansive pressure in the axial direction was equal to that in the radial direction, because the sum of axial tensile force acting on the outer and inner pipes was equal to the product of the radial expansive pressure and the cross-sectional area of demolition agent ($p_i \cdot A_b$). These results showed that expansive pressure is transmitted in a manner similar to that of a fluid.

In implementing these tests, it proved quite difficult to remove the inner pipe once the demolition agent had hardened even slightly, as a result of the extreme expansive pressure acting on the two pipes. Initially, the authors did not grasp the significance of this interesting behavior of the expansive agent, or the possibility of applying it directly to FRP tendon anchorages. They did however consider its application to joining reinforcing bars. In later taking up research on the application of continuous fiber reinforcing materials to concrete structures, they discovered that the most difficult issue was securing the continuous fiber reinforcing materials (FRP tendons), particularly because the surface of the fibers has low resistance to shear stress and stress concentrations. The authors thought that the characteristics of expansive demolition agents might be usefully applied, and decided to try FRP tendons in place of the inner pipe in double pipe tests. This is how a study of demolition using an expansive demolition agent developed into a study of FRP tendon anchorages.

2.2 Outline of HEM Anchorages

The CFRM tendon is aligned in the center of a sleeve, made of steel or FRP, measuring about 200 mm in length and strong enough to contain the expansive pressure, as shown in Fig. 2. The expansive demolition agent or HEM, in the form of a water-based slurry, is poured into the space between sleeve and CFRM tendon. After several hours, the slurry hardens like concrete and gradually gives rise to expansive pressure. Finally, within 48 hours of pouring the slurry at normal air temperature, the sleeve and hardened HEM consolidate to form an anchorage under an expansive pressure of greater than 40 MPa. The consolidated HEM and steel sleeve are termed the "anchoring device" in this paper.

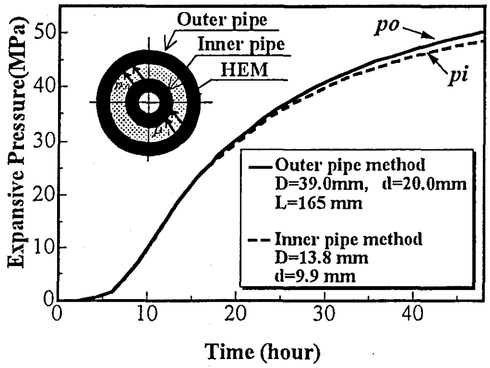


Fig.1 Expansive pressure behavior of HEM in double pipe test

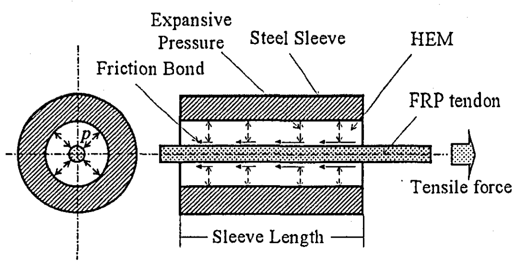


Fig.2 Anchorage using HEM

Table 1 Chemical composition and main mineral contents

	Chemical composition									Fineness (cm^2/g)
	Ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	total	f-CaO	
HEM A	1.5	8.0	1.9	0.9	83.5	0.6	3.4	99.8	56.1	3040
HEM B	1.6	8.8	2.3	1.3	81.5	0.4	3.8	99.7	52.2	2010
Expansive demolition agent	1.2	8.5	2.3	1.0	82.5	0.7	3.5	99.7	55.0	2380

It has already been confirmed that the distribution of expansive pressure along the sleeve is uniform, except near the two ends. The chemical compositions of the expansive demolition agent and the modified HEM are shown in Table 1. In both materials, the major expansion-inducing mineral content is CaO, and the characteristics of expansive pressure are almost the same fore the two compounds.

When a tensile force acts on the CFRM tendon, the anchorage — which is fixed with nuts and threads — is able to resist the force up until failure of the CFRM tendon. This is achieved because of the enormous friction-bonding capacity acting at the interface between the CFRM tendon and hardened HEM. Even if the CFRM tendon has an arbitrary non-circular cross section, it is firmly secured without stress concentrations because the expansive pressure acts uniformly. This makes the HEM anchorage suitable for all types of CFRM tendon regardless of configuration (round, strand, braided, plate, etc.) and the size and type of fiber used, provided that a suitable size of sleeve is chosen. Two prestressing and anchoring methods for HEM anchorages are considered in this paper, as shown in Fig. 3.

Method (I): The anchoring device at one end is fixed with a nut. Prestressing is achieved by tensioning the other anchor, which is connected to a tension rod and hydraulic jack. After prestressing, the anchor on the tensioning side is also anchored with a nut.

Method (II): The sleeves are set at both ends of the beam as permanent anchorages. After inserting a CFRM tendon through the sleeves, prestressing is executed using temporary anchorages, and the tendon fixed temporarily in place at both ends. The HEM slurry is poured into the sleeves to form a permanent anchorage. The sleeves, acting as permanent anchorages, take up the prestressing force when the nut at one temporary anchorage is released; this is done when the expansive pressure reaches the required level. One of the merits of

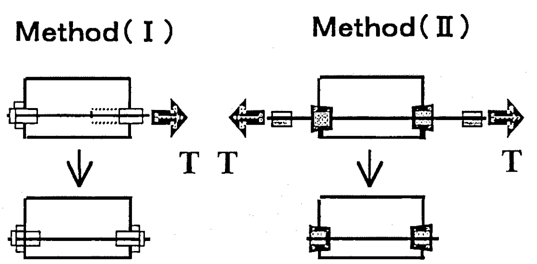


Fig.3 Prestressing and anchoring methods using HEM

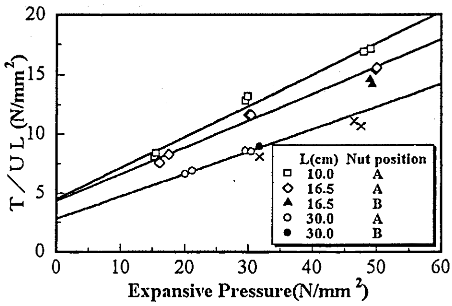


Fig.4 Pull-out test results

this method is that a firmer grip is achieved than with Method (I), since the HEM hardens against the CFRM tendon while it is under tension at both ends. In practice, Method (II) is used as an "Intermediate Anchoring Method" to hold conventional prestressing steel tendons. Method (II) was developed primarily to solve the problem that a long sleeve is necessary to take account of elongation of the CFRM tendon when Method (I) is used, because the Young's modulus of the CFRM tendon is generally smaller than that of a steel tendon.

3. PULL-OUT TEST

Figure 2 gives an outline of the anchorage itself. It is important to confirm that the anchorage does not fail at a load below the FRP tendon's tensile strength. This pull-out test is carried out in order to define the stability of the anchorage system, and to determine the relationship between expansive pressure and required length of steel sleeve.

3.1 Outline of Experiment

The pull-out test assembly consisted of FRP tendons terminated with anchors. The anchors consisted of a threaded steel sleeve and a fixing nut. The assembly was placed on the testing machine and pull-out tests were conducted up to the range of the machine. The steel sleeve was required to be sufficiently thick to prevent severe deformation as a result of the high pressure induced by the HEM. A 39mm outside diameter and 20mm inside diameter was chosen, and the sleeve was threaded internally throughout its length at M22 double pitch. This internal threading was designed to ensure consolidation between the HEM and the steel sleeve.

The anchor lengths tested in the experiments were 100 mm, 165 mm and 300 mm, at standard expansive pressures of 15 MPa, 30 MPa, and 50 MPa, respectively. Each anchorage's performance was measured at various pressures and strains were monitored using strain gauges affixed to the surface of the sleeve in both axial and tangential directions. Expansive pressure "p" was evaluated using equation (1) below. To ensure no pull-out at the other end of the beam, the length of the steel sleeve was made 300 mm. In the test, the expansive pressure rose above 60 MPa.

$$p = \frac{E_s\left(k^2 - 1\right)}{2\left(1 - \nu^2\right)}\left(\varepsilon_\theta + \nu\varepsilon_z\right) \qquad (1)$$

where, E_s: modulus of elasticity of the steel sleeve

k: ratio of outside to inside diameters (outside diameter/inside diameter)

ν : Poisson's ration for the sleeve

ε_θ: strain in circumferential direction
ε_z : strain in axial direction

In this experiment, the CFRP strand forming the CFRP tendon had a diameter of 12.5 mm. Regardless of anchoring sleeve length, all FRP tendons were 1.2 m long. A gradually increasing load was applied until the pull-out load was reached. The load-cell recorded the level of load, while a clip gauge with a sensitivity of 1/500 mm was used to measure the relative displacement of the CFRP strand and steel sleeve at the loaded end. A displacement transducer with a sensitivity of 1/1,000 mm was also used to measure CFRP strand displacement at the free end.

3.2 Results and Considerations

The relationship between T/UL and expansive pressure p is shown as a graph in Fig. 4, where T is the pull-out load, U is the circumference of the CFRP strand, and L is the anchorage length. From the graph, the best-fit linear relationship given by equation (2) can be obtained.

$$T = UL(\tau_0 + \mu p) \qquad (2)$$

where, τ_0: bond stress
μ : factor representing friction between CFRP and HEM

As indicated in Fig. 4, the anchorage system included two locking nut positions, one on the pull-out side and the other at the free end. Position "A" represents the case when the specimen was placed on the testing machine as shown in Fig. 2, with the locking nut at the free end side of the anchoring sleeve. When the locking rested against the redundant plate, this is position "B". Figure 4 shows that differences in locking nut position do not affect the pull-out load. The same figure also shows that the best-fit straight lines for specimens of length 100 mm and 165 mm are similar. However, the line for the 300 mm anchorage indicates lower T/UL values. This reason for this has been considered and is explained below.

Figure 5 shows the relationship between q (shear force per unit length of anchorage) for the pull-out loads analyzed and position along the sleeve from the loaded end. Here, the steel sleeve and the CFRP strand are taken to be elastic. The HEM for anchorage in the horizontal direction for transfer length is considered to be elastic-plastic shear spring element [10]. Using a finite element method (FEM) to analyze the relationship, the unit shear force integrated along the entire length of the sleeve is equal to the pull-out load. In analysis by incremental loading, the pull-out load T is the maximum value for integration of unit shear q, and sleeve length L is taken as parameters. The pull-out load T divided by the sleeve length L, T/L, is equal to the average value of q and this is shown in Fig. 5 by dotted lines. Moreover, when T/L is divided by the circumference U, the average bond strength along the sleeve in axial direction is obtained. This T/UL carries the same meaning as the average q value varying along the sleeve's length. Although the experimental results are treated as average bond stresses (T/UL) in Fig. 4, the distribution of q and the average q value are taken up in the following consideration. In this analysis, the expansive pressure is taken to be 50 MPa.

In Fig. 5, the x-axis is a non-dimensional value representing the ratio of distance from the loaded end to the point on the sleeve. For the shortest sleeve of 100 mm, the q distribution at the moment of pull-out has a mild slope and the relationship can be represented by the average value shown by the dotted line. Therefore, it can be concluded that for a shorter sleeve length, the average bond strength acting on the tendon can be represented by an overall bond strength that gradually reaches its limit value. On the other hand, for a sleeve length of 300 mm, the q distribution does not act evenly over the entire length of the steel sleeve, but rather a peak value can be

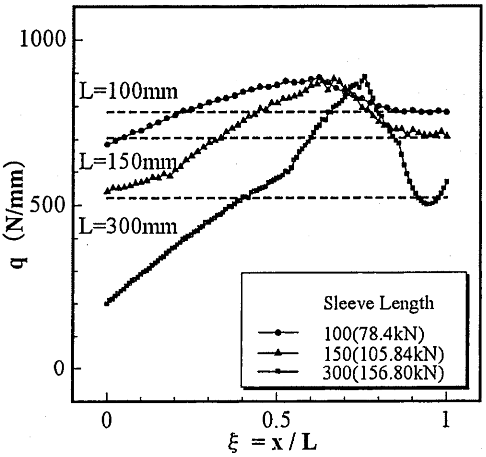


Fig.5 Distribution of "q "-value for pull-out load

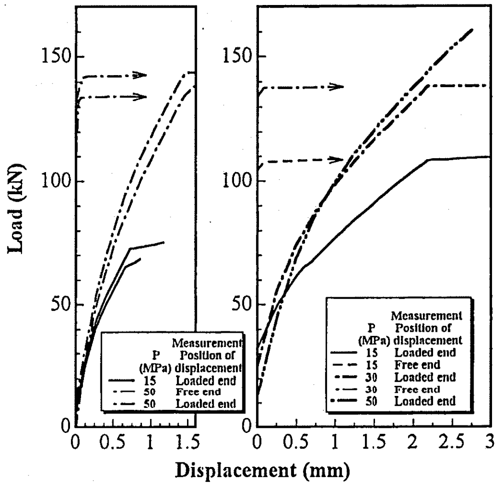


Fig.6 Pull-out displacement at loaded end and free end versus load

observed for one point on the sleeve, followed by a steeper fall. Thus the pull-out mechanism differs with respect to the length of the steel anchor. So when the steel sleeve is longer, there is no even distribution and average q values are normally lower .

The above analysis assumes an expansive pressure of 50 MPa. However, for lower expansive pressures, the average q value also decreases. Therefore, the linear relationship for the sleeve length as parameter and expansive pressure is maintained. As explained above, when the steel sleeve is made longer, the relationship shifts to lower values as shown in Fig. 4. This analysis does not aim to offer a constant quantitative evaluation but rather an example for a steel sleeve of 100 mm with an average q value of 800 N/mm, which is equivalent to a T/UL value of 15.3 MPa. Values from the analysis are somewhat lower than the experimental ones, but a fairly good relationship is obtained.

Equation 2 can be applied to determine the necessary anchorage length and expansive pressure for a CFRP strand of diameter 12.5 cm and tensile strength 165 kN. If the anchorage length is fixed, and using equation (2) for the T and p relationship, p can be determined by substituting T as 165 kN. For example, if L is 165 mm, then using the relationship shown by the solid lines in Fig. 4 as given by the method of least squares, the frictional coefficient μ (0.23) and the initial bond stress τ_0 (4.4 MPa) can be determined. Again, substituting μ and τ_0 values into equation (2) one obtains P as 64 MPa. For the anchor length of 300 mm, also, the corresponding values of μ and τ_0 are 0.19 and 2.8 MPa, respectively, and the expansive pressure will be 41 MPa. It is clear that a shorter sleeve length requires higher expansive pressure.

In order to apply equation (2) to other types of CFRM tendon, experimental values of μ and τ_0 will be necessary. As another example, in the case of an AFRP braided tendon 12 mm in diameter and with sleeve length 400 mm, the corresponding values of μ and τ_0 are 0.13 and 3.5 MPa, respectively. It can be expected that the varying surface properties of different FRP tendons will influence bonding and the frictional coefficient. Therefore, to estimate the expansive pressure required for FRP and steel tendons using equation (2), it will be necessary to know the values of steel length, μ and τ_0.

Table 2 Specimens for long -term tensioning test

Specimen	Type of expansive material	Steel sleeve length (mm) (Effective length)	Maximum tensioning force (kN) (for Method II)	Tensioning force when anchored with nut (kN) (for Method II)	Anchoring method
A	Expansive demolition agent B-100 W/B=25%	220(210)	113.0	110.0	I
B			112.4 (109.4)	111.5 (96.2)	II
C		300(290)	113.6	112.1	I
D	Expansive demolition agent A W/B=30%	220(210)	116.6	83.7	
E			117.4 (112.9)	115.4 (101.0)	II
F		300(290)	117.8	114.7	I
G		220(210)	83.6	77.5	
H		300(290)	116.3 (112.6)	112.0 (106.4)	II

Figure 6 show the relationship between pull-out load and pull-out displacement up to the moment of pull-out for anchoring sleeves measuring 165 mm and 300 mm in length. The relative displacement between the loaded end of the sleeve/CFRP strands and the free end is the pull-out displacement. At the loaded end of the anchorage, if the designated expansive pressure were low or at lower level, the pull-out displacement would be high at lower pull-out loads and pull-out would take place gradually. However, no pull-out displacement was observed at the free end until the last moment before pull-out. In fact, the strands withdrew accompanied by a loud noise, and this was followed immediately by total pull-out. The pull-out displacement at the free end was about 15 mm.

Tensile failure of the CFRP strand occurred at 70% of its tensile strength, and pull-out displacement at the loaded end was 1~2 mm. It is concluded that the stress concentration at the loaded end is released as pull-out displacement occurs.

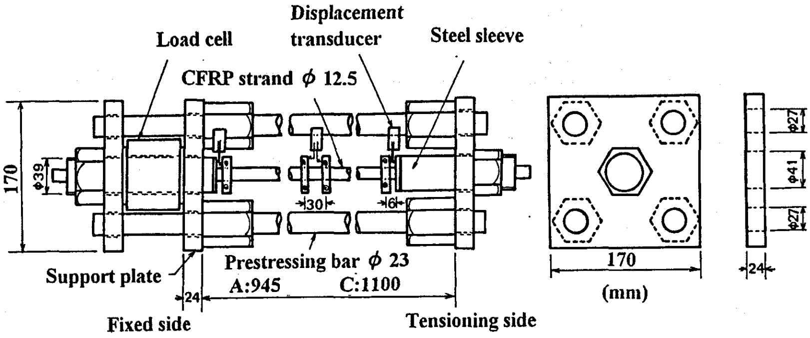
4. LONG-TERM CHARACTERISTICS OF HEM ANCHORAGE

A pull-out displacement of 1~2 mm at the loaded end of the HEM anchorage was observed at 70% of the failure load level in the case of a CFRP strand, even in a case where the CFRP strand did not fail as a result of pull-out. It can be deduced that the prestressing force might decrease gradually as this pull-out displacement increases. To check this, an investigation was carried out into the long-term characteristics of the HEM anchorage as a permanent post-tensioning anchoring method.

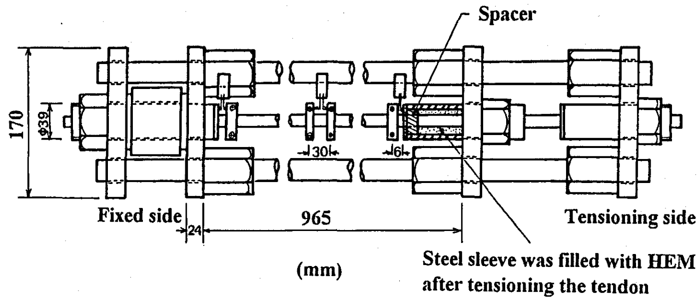
4.1 Specimens and Experimental Methods

The experimental parameters investigated were the type of expansive material, the anchoring method, the sleeve length, and the prestressing level. As shown in Table 2, eight specimens (A-H) were examined. The two previously discussed anchoring methods, Methods (I) and (II), were used.

Specimens using Method (I) were placed in the test apparatus as shown in Fig. 7(a) once the expansive pressure had reached the required value of 50 MPa. Prestressing was repeated for two cycles of loading and unloading up to the upper limit of the required prestressing level, and the tension was locked with a nut on the tensioning side at the third cycle of loading. The maximum tensioning force and the tensioning force at locking are shown in Table 2.



(a) Method (I)



(b) Method (II)

Fig.7 Long-term test apparatus

In the case of specimens using Method (II), the anchoring device on the tensioning side was first tensioned to the required level of prestress using a hydraulic-jack and locked temporarily with a nut, as shown in Fig. 7(b). A load-cell was attached to the fixed end of the specimen. Next, the HEM slurry was poured into the steel sleeve, which was positioned in the middle of the test apparatus. When the expansive pressure had reached 50 MPa, the locking nut forming the temporary anchorage on the tensioning side was loosened gradually to allow the anchoring device to gradually take up the prestressing force.

After completing the anchor with the locking nut, time-dependent changes in prestressing force and pull-out displacement at the loaded end were measured for all specimens. Pull-out displacement is the relative displacement between the steel sleeve end and the CFRP strand due to pull-out loading. Pull-out displacement at the loaded end was measured using clip gauges. Based on the pull-out results in Section 3, the standard sleeve length in this experiment was chosen to be 220 mm, including the length of the spacer at each end. "Effective length" as referred to in Table 2 is the length of sleeve completely filled with HEM slurry. The two prestressing levels were 70% and 50% of the ultimate tensile strength of the CFRP strand, respectively. The length of CFRP strand between the two anchoring devices for all specimens was 800 mm. Long-term experiments were carried out at a constant 25℃ in a temperature-controlled room.

4.2 Time-Dependent Change in Prestressing Force

Specimens anchored using method (II) exhibited a gradual decrease in initial prestressing force for the first 48 hours until the expansive pressure at the center of the steel sleeve reached 50 MPa. An additional loss of prestressing force by about 6-13 kN was observed when the anchoring device at the middle portion took up the prestressing force as the locking nut of temporary anchorage was loosened. This prestressing loss was caused by the small clearance between the anchor plate and the locking nut and by elastic deformation of the anchor plate; the effective length of 800 mm is relatively short, so even a small deformation or clearance affects the prestressing force.

Figure 8 shows the time-dependent decreases in prestressing force from the point at which the anchorage is formed with the locking nut. Experimental data were are collected until 4,500 hours for specimens A, B, and C, while other specimens were followed until 65,000 hours (7.4 years). These long-term observations are still on-going.

With Method (I), no influence of sleeve length is observed, with the loss of prestressing force measured at 6-11% for a sleeve length of 220 mm and 6-8% for a sleeve length of 300 mm, respectively. The loss of prestressing force for specimens B, E, and H using Method (II) is less than that for specimens using Method (I). Particularly notable is that the loss of prestressing force for specimen H is only 3%. It is considered that this firmer grip resulted from the addition of the Poisson's effect on CFRP strand to the expansive pressure under tension of CFRP strand.

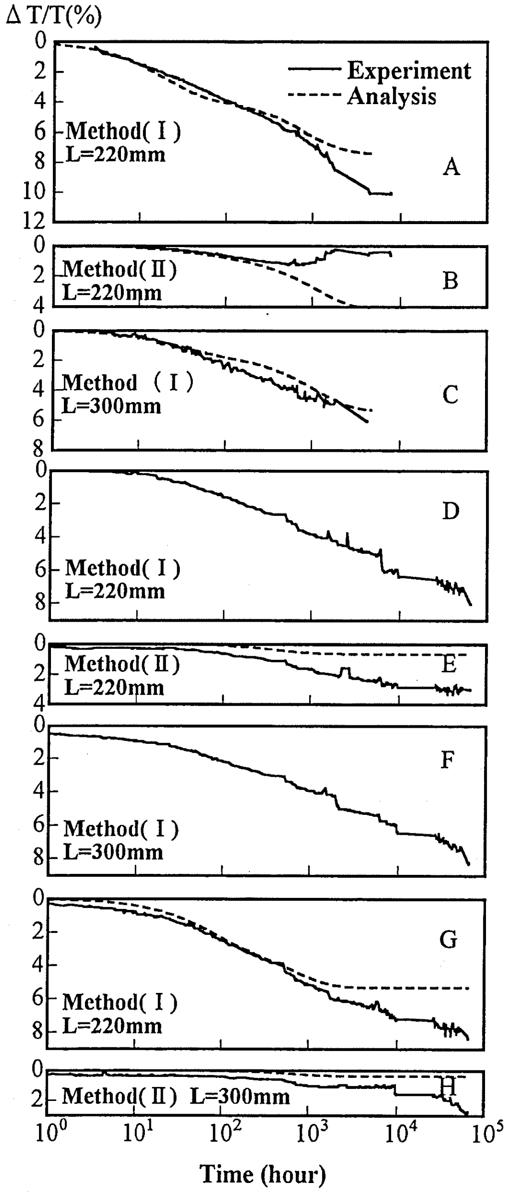


Fig.8 Time-dependent loss of prestressing force

4.3 Relationship Between the Decrease in Prestressing Force And Pull-out displacement at Loaded End

Assuming that the observed loss of prestressing force resulted mainly from pull-out displacement at the loaded end, the following argument is pursued. Typical curves of pull-out displacement at the loaded end over the long term are shown in Fig.9.

The pull-out displacement regression curve can be expressed as equation (3).

$$u(t) = \beta_1(1-\exp(-t/k_1)) + \beta_2(1-\exp(-t/k_2)) \qquad (3)$$

where, β_1, β_2, k_1, and k_2 are experimental constants determined by the least squares method.

Now, assuming that pull-out displacement is a form of creep strain, and ΔT is the loss in prestressing force up to an arbitrary time t, from the force equilibrium and the compatibility condition of strain in the steel frame and the HEM anchorage over differential time dt, then the following differential equation for ΔT may be introduced:

$$\frac{d\Delta T}{d\phi_t} + \alpha \Delta T - \alpha T_0 = 0 \qquad (4)$$

where, $\phi_t(t) = (u_1(t) + u_2(t))(T_0 L / E_p A_p)$

$u_1(t), u_2(t)$: pull-out displacement at fixed side and tensioning side, respectively

T_0 : initial prestressing force locked in with nut

L : length of CFRP strand anchoring devices

$E_p A_p$: tension stiffness of CFRP strand

α : ratio of stiffness of anchor frame to that of CFRP strand

In the initial condition, which is defined as $\Delta T = 0$ and $\phi_t = 0$ at $t = 0$, the solution to equation (4) is given by the following equation (5):

$$\Delta T / T_0 = 1 - \exp(-\alpha \phi_t) \qquad (5)$$

With Specimen D, pulling-out of the prestressing tendon occurred at 119 kN on the tensioning side of the sleeve during the third loading, immediately after it was locked with the nut, and the changes in prestressing force and pull-out displacement were measured. The results for the first 12 hours are shown in Figs. 10 (a) and (b), respectively. The pull-out displacement data were fitted to equation (3) and the time-dependent change in prestressing force was calculated using equation (5). The calculated curve agrees well with the experimental results. This demonstrates that the pull-out displacement behavior correlates with the loss of prestressing force. The initial prestressing force of specimen D, as shown in Fig. 8, was adopted as the stable value of 84 kN for the of 12 hour point.

In a similar fashion, long-term loss in prestressing force is considered to result from time-dependent changes in pull-out displacement. Changes in pull-out displacement up to 4,800 hours are shown in Fig. 9; pull-out displacement was also fitted using equation (3) and the decrease in prestressing force was calculated using equation (5). The calculated curve is shown in Fig, 8 which was adopted by the dotted line. The time dependent change of prestressing force at the measured point of pull-out displacement agreed well with simulated curves.

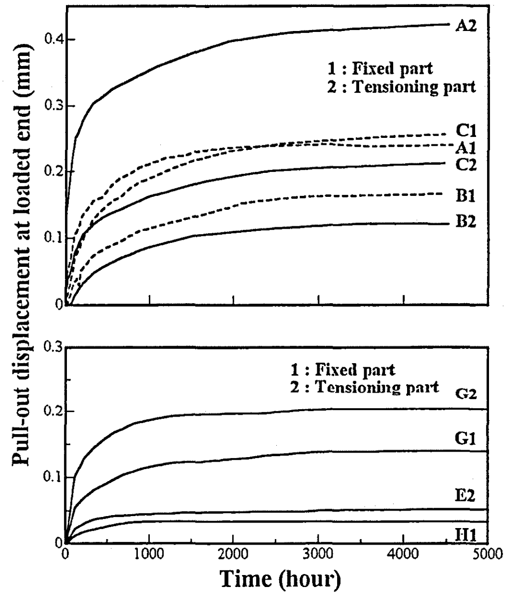


Fig.9 Time-dependent change in pull-out displacement at loaded end

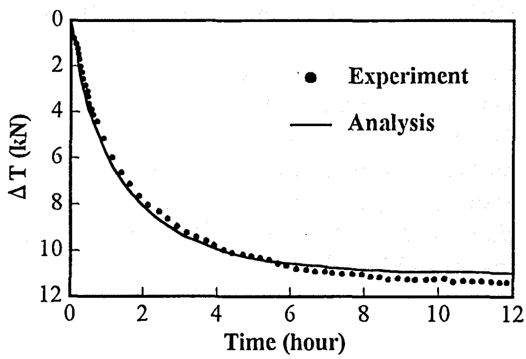


Fig.10(a) Time-dependent loss in prestressing force of specimen " D "

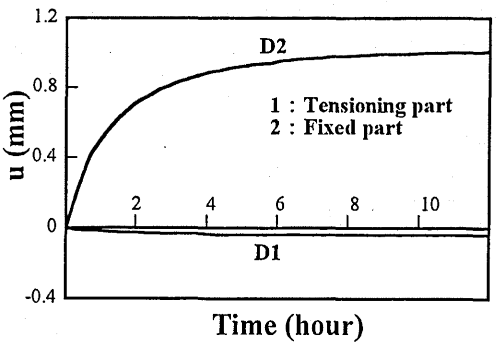


Fig.10(b) Time-dependent change in pull-out displacement at loaded end of specimen " D "

Simulation curves of prestressing force tend to converge to a constant value at around 1,000 hours, because equation (3) is a convergence function. The main factor resulting in loss of prestressing force is pull-out displacement, but the simulation curve of prestressing force can be made more accurate by introducing the influence of CFRP strand relaxation.

Simulations were not possible for specimens D and F, because of a lack of accurate pull-out displacement data in the long-term measurements.

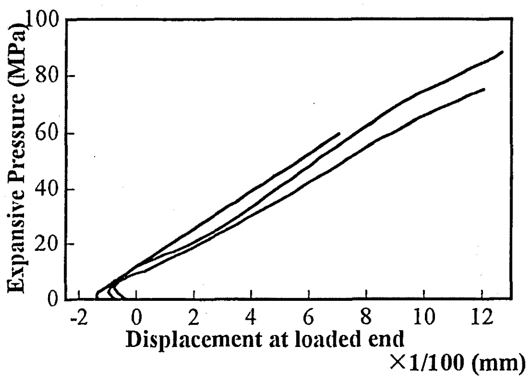


Fig.11 Relationship between expansive pressure and displacement at loaded end

4.4 Influence of Expansive Pressure on Loss of Prestressing Force

It was demonstrated above that the decrease in prestressing force was influenced mainly by time-dependent changes in pull-out displacement. The progress of pull-out displacement, in turn, was thought to be affected by expansion of the HEM in the sleeve longitudinal direction.

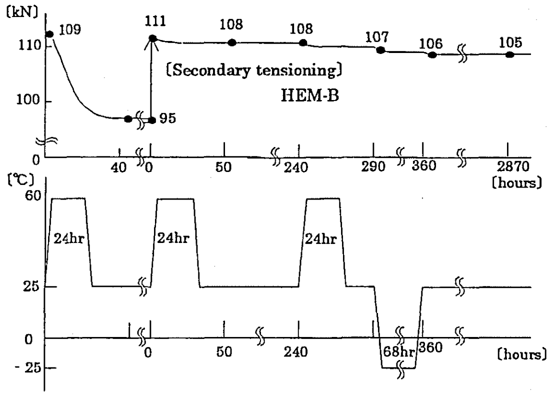


Fig.12 (a) Time-dependent change in tension at air temperature of 60℃

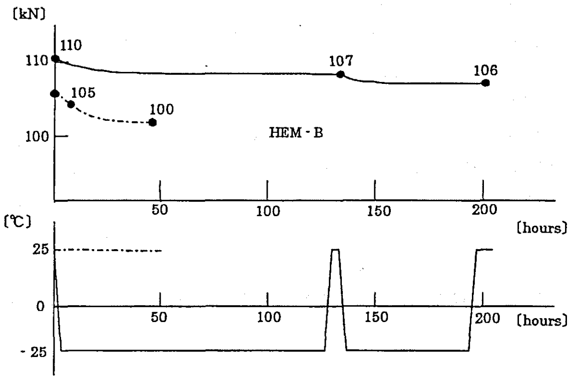


Fig.12 (b) Time-dependent change in tensioning force at air temperature of −20℃

The relationship between expansive pressure and pull-out displacement at the free end of the 220 mm sleeve is shown in Fig. 11 for a case in which the HEM slurry was poured with the sleeve in the vertical position. While the slurry state prevailed, displacement became negative due to the self-weight of the CFRP strand. However, as expansive pressure rose, the displacement also increased without tension being applied. This result indicates that the prestressing force will continue to decrease as pull-out displacement progresses under increasing expansive pressure. In contrast, if the expansive pressure stopped rising, the prestressing force would stabilize.

Expansive pressure is caused by hydration of the HEM, and high expansive pressures can be obtained at high temperatures. Since hardened HEM is itself subjected to the expansive pressure it exerts, and creep deformation in the axial direction under tension is quite large, this will have a great effect on the long-term behavior of

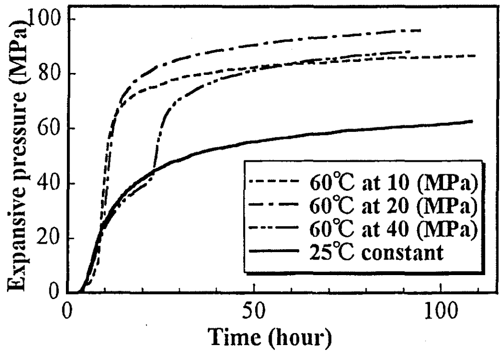


Fig.13 Influence of ambient temperature on expansive pressure

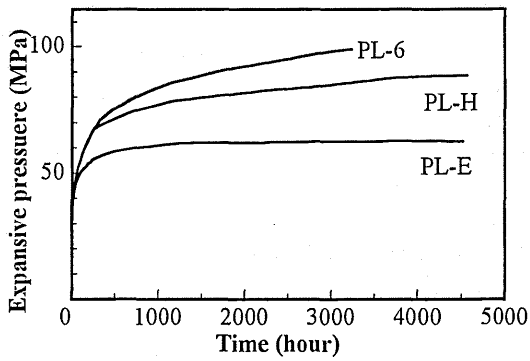


Fig.14 Time-dependent change in expansive pressure until 4,500 hours

prestressing force. To investigate this, two experiments with very different hydration levels of HEM were carried out.

The length of the CFRP was 300 mm to ensure that the influence of pull-out deformation was clear and a prestressing force of 115 kN was induced using the same apparatus as shown in Fig. 7(a). The prestressing force was measured at a constant temperature of 25℃. In Figs. 12(a) and (b), the time-dependent changes in prestressing force and air temperature are shown as compared with each figures on above two cases. The experimental results are summarized below.

1) The loss of prestressing force was 12.7% after 24 hours at an air temperature of 60℃, as shown in Fig. 12(a). Even if the relaxation loss of 2.5% of CFRP strand[11] at 60℃ was reduced, the value of loss was 10.2%. After the second stage of prestressing and twice heating hysterisis at 60℃ for 24 hours was given, an extreme loss of prestressing force as 2.4%, 0.6%, because hydration of HEM was apparently complete. The loss of prestressing at the first stage was very large, because the expansive pressure increased remarkably at 60℃. However, since the increment in expansive pressure almost ceased after the second stage of heating hysterisis, the loss of prestressing force then became very small.

2) Subjecting a specimen to freezing temperatures (-20℃) almost stops the hydration of HEM. The loss of prestressing force in this case was less than 2%, less even than that at 25℃.

From these results, it is concluded that the progress of HEM hydration is related closely to loss of prestressing force. Once the expansive pressure saturates, the loss of prestressing force stabilizes. The reason for this loss of prestressing force with increasing expansive pressure could not be examined, but this evaluation indicates that it is very difficult to measure the expansive pressure of a specimen under variable temperature and high load by means of strain gauges or other measurement tools.

Figure 13 shows an example of expansive pressure behavior at various air temperatures corresponding to the results in Fig. 12(a). The HEM slurry was poured into all steel sleeves at 25℃, and the air temperature was raised to 60℃ after the expansive pressure had attained values of 10 MPa, 20 MPa, and 40 MPa, respectively. The expansive pressure increased considerably in all cases, but the greatest increase was obtained in the case of 20 MPa. In the case of 40 MPa, the increase in expansive pressure is the smallest because hydration of the HEM is the most progressed of all the specimens. In the case of 10 MPa, the increment in expansive pressure at the initial stage was very notable, but over the long-term it was small. These results indicate that there is an ideal period in which the expansive pressure may be increased by heating.

Table 3 long-term expansive pressure

Specimen	Expansive pressure (MPa)	Time after HEM slurry was poured (Days)
B-100	95.4	800
HEM-B-1	90.8	1174
HEM-B-2	91.8	1174
B-150	110.7	1050

Even though the examined length of CFRP strand was short, at 300 mm and 800 mm in the above examples, the greatest loss of prestressing force was about 10%. To extrapolate this, assuming an initial prestressing force of 110 kN as in the above experiments, and also assuming total pull-out displacement at both sleeves of around 3 mm (which is more than in the experimental results), the calculated loss in prestressing force for a 10 m CFRP strand is only 2.8%. Even if a non-converging function is adopted as a creep function, the decrease in prestressing force of an HEM anchorage will be negligible in practice.

4.5 Long-term Expansive Pressure and Durability of HEM

If this method is to be used as a permanent anchor, it is important to investigate the amount by which expansive pressure will decrease and how chemical deterioration will affect HEM over the long term. Results indicate that the loss of prestressing force was less than 10% over the 7.4 years of these experiments, so there should be no problem as regards the long-term characteristics of the HEM anchorage. However, the long-term characteristics of expansive pressure and the influence of carbonation at the free ends are examined here.

Figure 14 shows an example of changes in expansive pressure with time up to 4,500 hours, where the HEM slurry was poured into the same steel sleeves as used in the long-term experiments. No decrease in expansive pressure was observed, and in fact a gradual rise, or at least a constant value, can been seen in this figure.
Table 3 shows some values of expansive pressure as calculated by thick-walled cylinder theory, using measured strains obtained when the expansive pressure acting on the steel sleeve was released with a core-drill. The expansive pressure was 90-100 MPa at 1,000 days after pouring the HEM slurry.

Now, the relationship between expansive pressure p and degree of hydration h of a demolition agent, of which the main mineral content is the same as HEM, is known and has been expressed by the following equation by the authors [9]:

$$p = 129(h/100 - 0.14)^{1.68} \qquad (6)$$

The estimated value of expansive pressure at 100% hydration as calculated by equation (6) is about 100 MPa, and the experimental results shown in Table 3 are also for nearly perfect hydration as compared with the calculated values. Hardened HEM is a solid material just like concrete, because it includes the same hardening minerals as cement, and expansion of HEM as a solid body will continue until hydration has finished. It is assumed that the hardened matrix of HEM changes minutely as expansive pressure rises based on the continuous expansion to resist the reaction. Furthermore, the hardened HEM itself has been always subjected to the high pressure, as the reaction against the steel sleeve [9],[12]. Since the hydration of HEM will continue, similar to that of cement, for a long period and the hardened and minute matrix of HEM based on the time dependent change of expansion, can be maintained under the restrained of steel sleeve. The creep deformation of HEM caused by its own expansive pressure at high degrees of hydration is quite small, therefore, it is considered that the decrease of expansive pressure cannot proceed for long-term.

Next, some experimental results on the carbonation of hardened HEM are described, as this is one of the durability issues facing HEM. Since both free ends of an HEM anchorage are exposed to the atmosphere and are free from restraint by the expansive pressure, it is considered that a decrease in expansive pressure and a matrix weakening will result from deterioration of HEM due to carbonation over the long term. (Carbonation is the process by which $Ca(OH)_2$ is produced through hydration of CaO in cement and similar materials.) To examine the influence of carbonation at the free ends of the HEM anchorage, accelerated carbonation tests were carried out with a 5% concentration of CO_2, an air temperature of 20 ± 1℃, and a the humidity of 60%. The steel sleeve had a 20 mm inner diameter and was 200 mm long, and HEM slurry (W/B = 27%) was into the tube. Two specimens were examined one week after placing in air at 20℃. One specimen type had the expansion-weakened portion down to about 5 mm deep removed. This was the unsealed specimen. The other specimen was sealed with epoxy resin paste at both ends. From the experimental results at an accelerated carbonation age of 12 months, no carbonation was observed in the specimen with epoxy resin paste sealing, and the average carbonation depth was only 2.2 mm in the unsealed specimen. Carbonation at the free ends of an HEM anchorage can thus be prevented by sealing the ends with epoxy resin paste.

5. FATIGUE CHARACTERISTICS

5.1 Outline of Experiment

In this section, the fatigue characteristics of HEM anchors are investigated by carrying out tensile fatigue tests. All steel sleeves were 220 mm long and had an effective length of 210 mm. The CFRP strand was 12.5 mm in diameter. The total length of the tendon was 720mm. Specimens HEM-B-4 and HEM-B-5 were exceptional, in having a length of 1,000 mm.

The repeated tensile loading ranged from 2.5 to 4 Hz. The lower limit of loading was fixed at above 60% of the guarantee load of 142kN. The minimum-to-maximum load range was determined based on the fatigue-durability of CFRP strands as reported by Enomoto and Shiratori [13], in order to undertake even larger load as much as possible with HEM anchorage without fatigue failure of CFRP strand.

In a strand-type tendon, as the tensile load increases, a twisting moment arises as the strands react to retain their initial shape. This twisting moment affects the actuator and early failure took place. In this experiment, in order to prevent this behavior, the actuator was fixed with a non-rotating device.

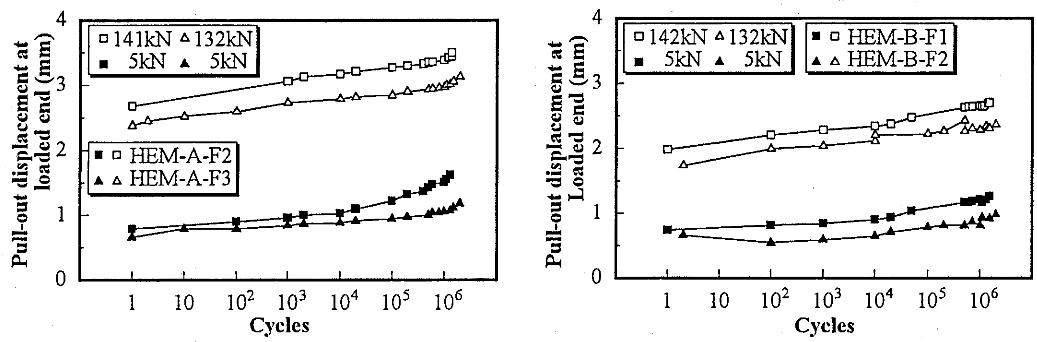
At the end of each two million cycles, a static loading test was applied from 4.9 kN to the upper limit load used in the cyclic test. Pull-out displacement between the loaded ends of the specimen, " δ " was measured. Here, the 4.9 kN load is the initially fixed load. The fatigue testing machine was started when the standardized expansive pressure of HEM reached 50MPa, and in addition, specimens with an expansive pressure of 100 MPa were also examined. When the expansive pressure finally reaches its peak of 100 MPa, concern may be felt regarding failure of the material at the loaded end.

5.2 Experimental Results And Consideration

A summary of the experimental results is shown in Table 4. Fatigue failure occurred with two specimens; one which failed before two million cycles and the other one before 2.05 million cycles. However, no failure took place at the loaded end of the anchorage in these cases. CFRP strands fail under tension by splintering, so it is

Table 4 Fatigue test results

Specimen	Type of expansive material	Expansive pressure (MPa)	Upper limit load (kN)	Lower limit load (kN)	Cycles	Ultimate tensile force after fatigue test (kN)
B-F1	Expansive demolition agent W/B=25%	50	117.7	88.3	200×10^4	154.0
B-F2			132.4	98.1	200×10^4	162.8
HEM-A-F1	HEM-A W/B=30%		132.4	98.1	200×10^4	162.8
HEM-A-F2			141.2	127.5	205×10^4	Fatigue failure
HEM-A-F3			132.4	117.7	500×10^4	141.2
HEM-B-F1	HEM-B W/B=27.5 (%)	100	132.4	98.1	210×10^4	168.7
HEM-B-F2			142.2	122.6	210×10^4	162.8
HEM-B-F3			117.7	78.5	150×10^4	Fatigue failure
HEM-B-F4		50	142.2	121.6	200×10^4	166.7
HEM-B-F5			133.4	85.3	200×10^4	163.8



(a) At expansive pressure of 50MPa (b) At expansive pressure of 100MPa

Fig.15 Change in pull-out displacement at loaded end under repeated load

hard to pinpoint the exact location of failure, but a fair estimate would be that failure took place in the brooming part of the fibers.

Figures 15 (a) and (b) show the pull-out displacement of the CFRP strand from the loaded end of the anchorage at upper and lower limit loads (the sum of pull-out displacement at bot ends) for each set of two million cycles. The pull-out displacement is greater at the loaded end for the higher load. There is also a gradual increment in pull-out displacement as the number of cycles rises. Pull-out displacement of 0.8 mm was found after two million cycles with an upper limit load of 141 kN, as shown in Fig. 15(a). Again, when the expansive pressure was set at 100 MPa, pull-out displacement was lower than at 50 MPa.

With the aim of determining the durability (endurance limit) of the HEM anchoring material under severe conditions, fatigue tests were conducted. Initially, the HEM specimen was placed in an oven for 46 hours at 60°C, and the temperature was then raised to 110°C for 24 hours. Finally, the specimen was gradually cooled down in the oven over a period of 96 hours. After removing the specimen from the oven and placing it in a freezer at -20°C for 160 hours, it was again replaced in the oven at 110°C for 48 hours and finally cooled down over 18 hours. These variations were designed to be much more severe than an HEM anchorage will encounter in practice. Even at five million cycles of repeated loading, no abnormalities in the CFRP strand or anchorage were found. After undergoing these severe conditions and then being subjected to five million cycles of repeated loading, specimen HEM-A-F3 was subjected to a pull-out test. The static failure load of this specimen was around 141 kN, about the same as the guarantee load. As for the other specimens, no clear difference in tensile strength was observed before and after the fatigue test. Failure always occurs at a position other than the loaded end or the anchorage. Based on the fatigue test results given in Table 4, the relationship between stress-amplitude and average-stress is shown in Fig. 16. In anchors used for prototype structures, such as external cables and unbonded cable systems, 60% of the guarantee load (1,100 N/mm^2) plus a supplemental varying stress (25 N/mm^2) due to the live load is normally anticipated. However, the combined action of both stresses at the same time is not considered. Therefore, in practice, this combined action does not have a bearing on fatigue behavior.

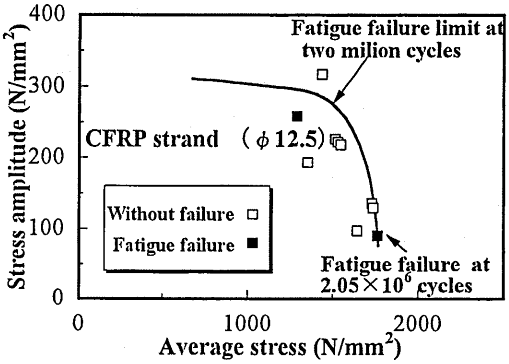
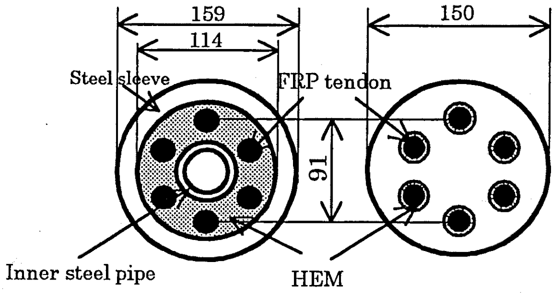


Fig.16 Fatigue test results of CFRP strand(ϕ 12.5)

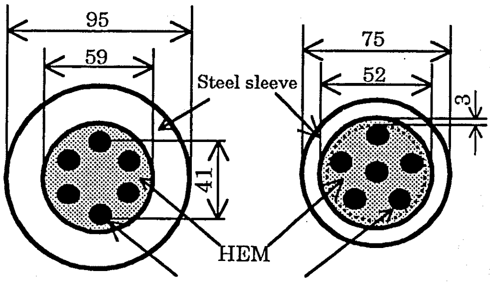
Here, though, in order to apply the HEM anchorage to external cable and unbonded cable systems, an investigation of fatigue safety is necessary. The above results related to fatigue also indicate that the HEM anchorage may be used in carrying out tensile-fatigue tests on CFRM tendons. Tensile fatigue tests on CFRP strands (ϕ 12.5 mm) using HEM anchors have been carried out at certain research institutions, and a great deal of data have been accumulated.



(a) Doughnut-hole type (b) Multi-hole type

Fig.17 Arrangement of multiple cables (Type A)

On the other hand, CFRP strand manufacturers conduct their own tensile-fatigue tests using epoxy-filled steel-sleeve anchors. At the free end of the steel sleeve, the CFRP strands are relieved from turning. In Fig. 16, the fatigue durability of CFRP strands (ϕ 12.5 mm) with epoxy resin anchors are indicated by solid lines [13]. The upper portion of the graph above the solid line represents fatigue failure within two million cycles. It is confirmed that the fatigue characteristics of CFRP strands (ϕ 12.5 mm) anchored using HEM anchorage are superior to those using an epoxy resin anchorage [10], in spite of the fact that they indicate the same strength in static tensile tests. Here, fatigue characteristics are expressed as the relationship between average stress and stress amplitude, as shown in Fig. 16. The CFRP strands with HEM anchorages are obviously superior in fatigue characteristics. The HEM anchorage is found to be stable even under the combined loading of average stress and stress amplitude, in which fatigue failure is reached came within two millions cycles of repeated loading for the epoxy resin anchors. In terms of Fig. 16, the solid line would be shifted upwards. This finding has not been confirmed with other CFRP tendons, but the influence of the anchorage on fatigue characteristics is very interesting and further investigations are necessary.



(a) Compact type I (b) Compact type II

Fig.18 Arrangement of multiple cables (Type B)

Table 5 Ultimate tensile force of CFRP (multi-strand)

Specimen	Tensile force at failure (kN)	Arrangement of multiple cables	Sleeve length (Effect length) (mm)
A-1	939	A-(a)	300(250)
A-2	916	A-(a)	300(250)
B-1	905	B-(a)	350
B-2	908	B-(a)	250
NM-1	900	B-(b)	400
NM-2	953	B-(b)	400
NM-3	952	B-(b)	400

6. MULTI-CABLE ANCHORAGE

In implementing the normal PC method, multi-cable tendons are used in stay-girder bridges where tensile forces are high and also as ground anchors. One of the merits of using the HEM anchorage method is the ease of installation. Here, in this chapter, a bundle of six CFRP strands (ϕ 12.5 mm) with a total tensile capacity of 600 kN is investigated and the results are explained.

6.1 Arrangement of Multiple Cables

The arrangement of tendons is shown in Figs. 17 (a) and (b). Figure 17 (a) is a cross section through a multi-cable anchor with a center-bore for a tension bar. This configuration, with an enlarged HEM cross section, is designed to prevent sudden rises in temperature. Figure 17 (b) is a single cable provided with a surround for independent HEM filling. Both sections are made with due consideration of the practical work of inserting the HEM from the side.

Figures 18(a) and (b) show an arrangement of tendons designed for compactness. The layout shown in Fig. 18(b) is the one presently used in the ground anchor method [6].

Generally, in designing multi-cable anchors using HEM and steel sleeves, the HEM must fully occupy the space between the steel sleeve and tendon. By ensuring this, the overall anchor system will exhibit a unified behavior. From past experience, an opening of 3 mm is thought adequate for filling with HEM, but where the sleeve's inner circumference is less than the summed circumference of the tendons, it is necessary to form grooves on the inside of the steel sleeve. For compact type II (see Fig. 18 (b)), grooves were formed on the inner face of the steel sleeve. It is important to note that the quality and dimensions of the steel sleeve should be such that no yielding or failure will occur under the expansive pressure and prestressing force.

6.2 Results of Tensile Tests and Consideration

The static failure loads of these multiple-strand tendons are shown in Table 5. The "A" in this table marks tendons shown in Fig. 17(a), while B represents those shown in Figs. 18(a) and (b). The total length of specimens A and B including the sleeve is 2 m, but non-metallic(NM) specimen are 2.5 m. The total failure load of these multi-strand tendons is somewhat lower than the sum of their individual failure loads. For instance, each CFRP tendon (ϕ 12.5 mm) has a tensile strength of 162 kN, but the actual failure load of the multiple cable is somewhat lower than the six times this value. Normally, in multi-cable anchors, slightly different cable lengths will lead to correspondingly different tensile forces. The first cable to fail will be the one taking most of the load. This explains why the total load-carrying capacity is lower than the sum of individual strengths, except

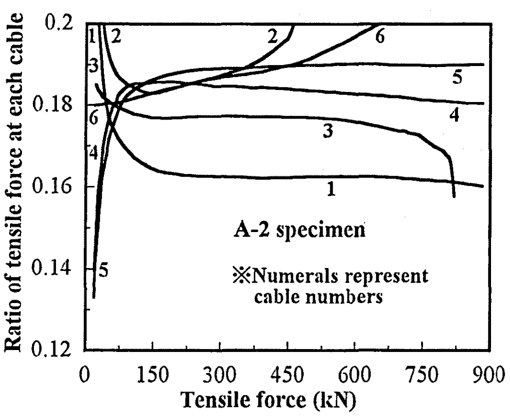


Fig.19 Relation between ratio of tensile force at each cable and total tensile force

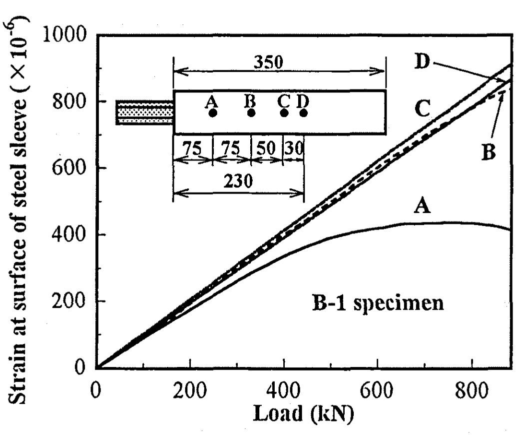


Fig.20 Behavior of strains at surface of steel sleeve

if the cables are short, when they often coincide. The reason for the capacity of multi-cable having the same as cable times their capacity is thought to be the equal load distribution in each cable in HEM anchorage.

Figure 19 shows the relationship between load distribution ratio of each cable versus the actual tensile load in specimen A-2. The overall length of this cable specimen, including the anchorage sleeves, is a relatively short 2 m. This is thought to be the unbalance nature of load distribution ratio. Here, the tensile load for load distribution ratio of each cable is calculated from the strain gauge fixed on the cable.. Using this method, the individual load on each cable can be determined independently, regardless of the other cables. Although it depends on the precision of the strain gauge readings, relative values of load distribution ratio can be obtained. Also from Figure 19, it is found that when the acting load increases, the load distribution ratio among cables converges and aggregated character is found.

Figure 6 showed that at a load level of 70% of the maximum load, pull-out displacement at the loaded end was 1-2 mm. In the case of the multiple-cable anchor, however, a greater tensile force can be absorbed by the anchorage system as a whole. Therefore, the individual cables will carry an average load that can be considered the sum of load taken by each cable is the one for the multi-cable anchor.

Figure 20 clarified that slip at the loaded end does not extend throughout the sleeve. The sleeve strain at a position 75 cm from the loaded end diverged from a straight line and a peak tensile load of 700 kN was observed. This is thought to be because the initial slip occurred at the interface between the CFRP strand and the steel sleeve. But at other gauge points on the sleeve, the strain readings fall on a straight line and this demonstrates the existence of secure bonding between the CFRP strand and the HEM. This can also be interpreted as meaning that the load acting on the CFRP strands is fully transferred to the steel sleeve by the HEM.

Figure 20 also shows that the strain readings on the steel sleeve are consistent with the multiple cables acting as a single tendon, and thus forming a multi-cable anchor. That is as noted above, each cable of the of multi-cable anchor shares the load uniformly.

7. CONCLUSIONS

The authors have developed a new anchoring method for CFRM tendons using HEM. They have studied fundamental characteristics with the aim of applying the HEM anchorage to post-tensioning systems as a permanent anchorage. The important conclusions reached in this study are summarized below.

(1) From pull-out tests, it was determined that the relationship between pull-out load (T) and expansive pressure (p) can be described by the following equation, which makes it easy to calculate the steel sleeve length or amount of expansive pressure required to hold a CFRM tendon of particular length:
$T = UL(\tau_0 + \mu p)$
(2) Two methods of prestressing and anchoring using HEM were developed. The long-term loss of prestressing force in Method (II), in which the tendon is anchored under tension, is smaller than that in Method (I).
(3) It was found that the loss of prestressing force was related to the pull-out displacement at the loaded end, and the pull-out displacement was proportional to the rise in expansive pressure. Once the expansive pressure has settled, the decrease in prestressing force is reduced and ultimately becomes stable.
(4) From long-term test results over a period of 65,000 hours (7.4 years), it was observed that a loss of prestressing force of 3-11% occurs for specimens with 800 mm CFRP strands. However, this loss is negligible in practical terms for a CFRP strand that is 10 meters long.
(5) If the stiffness of the steel sleeve, which acts as the restraining body, is maintained, the expansive pressure increases gradually up to 100 MPa and there is no decrease in expansive pressure over the long term. Further, carbonation of the hardened HEM can be prevented by proper sealing with an epoxy resin paste at the free ends of the sleeve.
(6) In the fatigue tests, the stress amplitude and the average stress of CFRP strand were set, at the changing values larger than that of the practical stress in design, no discrepancies were observed in HEM anchorage. On the basis of these results, the authors recommend the use of HEM anchorages in fatigue tests on all CFRM tendons.
(7) The arrangement of multiple cables in an HEM anchorage can be freely designed. The ultimate tensile strength of a CFRP multiple- strand cable is almost the same as the sum of the individual strengths of the cables because the tensile forces in each cable balanced each other automatically by way of pull-out displacement at the loaded end.

Acknowledgements

This research was partially supported by Grant-in-Aid for Scientific Research (C) (Grant No. 05650437 and Grant No. 10650452; Principal Investigator: Prof. Tetsuo Harada, Nagasaki University) from the Ministry of Education, Science, Sports and Culture of Japan. The authors would also like to thank Onoda Corporation and Tokyo Rope Mfg. Co. Ltd., who cooperated by providing materials for the experiments.

References

[1] JSCE, "RECOMMENDATION FOR DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES USING CONTINUOUS FIBER REINFORCING MATERIALS", Concrete Engineering Series 23, 1997
[2] Tetsuo Harada, Takashi Idemitsu, Akira Watanabe, and Shun-ichi Takayama, "Anchoring Method for FRP Tendons Using Expansive Demolition Agent", Proceedings of The First Symposium on Developments in Prestressed Concrete, pp.251-256, 1990 (in Japanese)
[3] Tetsuo Harada, Takehiro Yamasaki, and Takashi Idemitsu, " Long-term and Fatigue Characteristics of Anchorage for FRP Using Highly Expansive Material", Proceedings of the Symposium on Applications of

Continuous Fiber Reinforcing Materials to Concrete Structures, JSCE, pp.223-228, 1992 (in Japanese)

[4] Tetsuo Harada, Takashi Idemitsu, Akira Watanabe, Myo Khin, and Koichi Soeda, New FRP Tendon Anchorage System Using Highly Expansive Material for Anchoring, *Proceedings of FIP Symposium '93, Kyoto*, Vol. II, pp.711-718, 1993

[5] Tetsuo Harada, Myo Khin, Katsumi Hino, and Suguru Tokumitsu, "New FRP Multi-Cable Anchorage System Using Highly Expansive Material for Anchoring", Proceedings of The Third Symposium on Developments in Prestressed Concrete, pp.285-290, 1992 (in Japanese)

[6] Public Works Research Center, "NM (New Material) Ground Anchoring Method", 1994 (in Japanese)

[7] Yasuyuki Watanabe, et al., "Development of Intermediate Anchoring Method and its Execution", Prestressed Concrete, Vol. 40, No.3, pp.26-30, 1998 (in Japanese)

[8] Tetsuo Harada, Takashi Idemitsu, and Akira Watanabe, "Demolition of Concrete with Expansive Demolition Agent", Concrete Library of JSCE, No.8, pp.63-81, 1986

[9] Tetsuo Harada, Koichi Soeda, Takashi Idemitsu, and Akira Watanabe, "Characteristics of Expansive Pressure of an Expansive Demolition Agent and the Development of New Pressure Transducers", Concrete Library of JSCE, No.24, pp.95-109, 1994

[10] Tetsuo Harada, Masashi Soeda, Tsuyoshi Enomoto, Suguru Tokumitsu, Myo Khin, and Takashi Idemitsu, "Behavior of anchorage for FRP Tendons Using Highly Expansive Material Under Cyclic Loading", *Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third International Symposium*, JCI, Vol. 2, pp.719-726, 1997

[11] Y. Ito, T. Maruyama, N. Shiratori, and T. Enomoto, "Characteristics of Relaxation of CFRP Strand", Proceedings of the 45th Annual Conference of JSCE, Vol. 5, JSCE, pp.322-323, 1990 (in Japanese)

[12] Koichi Soeda and Tetsuo Harada, "The Mechanics of Expansive Pressure Generation with Expansive Demolition Agents", Concrete Library of JSCE, No.23, pp.121-135, 1994

[13] T. Enomoto and N. Shiratori, "Tensile Fatigue Characteristics of Carbon Fiber Composite Cable (CFCC)", Proceedings of the 45th Annual Conference of JSCE, Vol. 5, JSCE, pp.324-325, 1990 (in Japanese)