Development of HEM Anchorage Having Large Capacity of 2500 kN with CFRP Strands*

2500 kN級CFRPより泉を用いたHEM定着具の開発

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1. INTRODUCTION

The authors have studied the anchorage using Highly Expansive Materials (HEM) for FRP [1],[2],[3],[4]. The HEM anchorage system of multi-cables with six CFRP strands (ϕ 12.5) has already been used as the "Ground Anchor System" in Japan. The prestressing capacity of "Ground Anchor System" is 600kN at present. Recently, the needs of CFRP tendon grips having larger prestressing capacity have been increased, because of higher durability for longevity is required for large scale structures such as "Cable Stayed Bridge". In the near future, the HEM tendon grips having the capacity of 5,000kN will be required.

At the first stage of the development of HEM tendon grips with large prestressing capacity, the HEM tendon grips having the capacity of 2,500kN has been examined. This tendon grip consist of twelve CFRP strands with ϕ 15.2mm diameter and steel sleeve. In order to design and produce the HEM multi-cables tendon grip for practical purpose, experimental and analytical studies were carried out.

2. PULL-OUT TEST RESULTS OF SINGLE STRAND

One of the important matter in the design of HEM anchorage using CFRP strand with ϕ 15.2mm diameter, is to clarify the relationship between the expansive pressure and the sleeve length. First, the characteristics of HEM anchorage with a single CFRP strand (ϕ 15.2) were examined by the pull-out tests in which the amount of expansive pressure and the sleeve length were treated as parameters. The required expansive pressure was changed at 10MPa, 30MPa and 50MPa, and the steel sleeve (outer diameter : 39.0mm, inner diameter : 23.7mm) was used, having 100mm, 165mm and 300mm lengths.

Fig.1 shows the relationship between "T/UL" and "p". "T" is the pull-out load, "U" is the circumferential length of CFRP strand and "L" is the anchorage length. From this figure, showing best-fit linear relationship the following equation (1) can be obtained.

$$T = UL(\tau_0 + \mu p) \qquad (1)$$

where, τ_0 : bond stress

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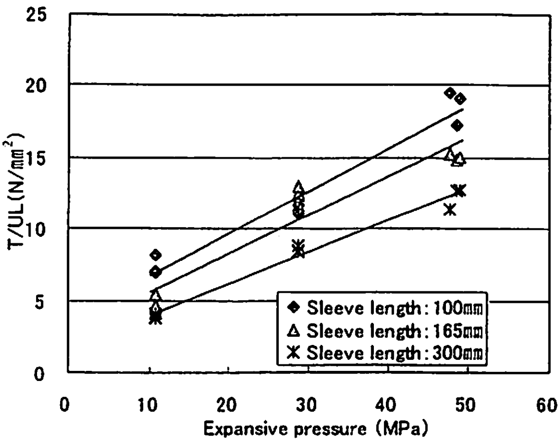

Fig. 1 Relations between "T/UL" and expansive pressure

Table 1 Calculated values of "τ" and "μ"

L (mm)	τ (N/mm^2)	μ —
100	3.767	0.297
165	2.914	0.269
300	1.771	0.221

μ : friction factor between CFRP strand and HEM

From Fig.1, it was found that the best-fit linear relationship shift to the lower lever level of *T/UL* values in proportion to the length of sleeve. This reason is considered that the configuration of unit shear "q" distribution from the loaded end to the free end of the sleeve at pulling-out is changed according to the sleeve length, however, the average bond stress *T/UL* is used to estimate for convenience. Table 1 shows the values of "τ_0" and "μ" are calculated by the least square method. The required expansive pressure for ultimate tensile force of 238kN is calculated as 47 MPa for 300 mm sleeve length. Also, the expansive pressure of 71MPa is required for 165mm long sleeve. Based on the above results, it was decided that the expansive pressure and sleeve length are 50MPa and 300 mm, respectively, to hold firmly up to failure.

3. OUTLINE OF TENDON GRIP WITH CAPACITY of 2500 kN

Usually, tendon grip having large capacity is made by multiple cables, since the tendon capacity can be arranged easily. Here, the required tensile strength of tendon grip is designed at 2500kN by using twelve CFRP strands with ϕ15.2 diameter. The tensile strength for design of single CFRP strand with ϕ15.2 diameter is 238kN.

Tendon grip itself should be compacted as much as possible to execute the prestressing and anchoring work easily. Twelve CFRP strands are arranged in the steel (outer diameter : 125mm, inner diameter : 86mm) as shown in Fig.2. The minimum space between CFRP strands is 2 mm. After setting CFRP strands in the steel sleeve, the slurry of HEM is poured into the small spaces between steel sleeve and CFRP strands. When the expansive pressure reaches 50MPa, the tendon grip which is connected to the tension rod, is tensioned by a center-hole jack up to the required prestressing level, and then, HEM tendon grip is fixed with a locking nut.

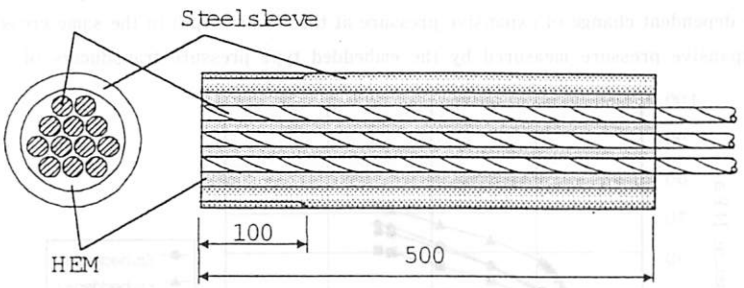

Fig.2 Anchoring system by HEM

The sleeve length under 50MPa pressure is 300mm long and can hold a single CFRP strand (ϕ 15.2) up to failure based on the pull-out tests. However, the length of steel sleeve is determined as 500mm considering the transmission length of expansive pressure at both free ends with a wide diameter of steel sleeve.

4. BEHAVIOR OF EXPANSIVE PRESSURE

4. 1 OUTLINE OF EXPERIMENT

It has already been confirmed that the expansive pressure was transmitted in the manner similar to that of fluid in a single strand HEM anchorage. However, for multi-cable HEM anchorage, it is important to grasp the behavior of expansive pressure. In order to examine the distributions of expansive pressure for longitudinal direction and in the same cross sectional plane, the experimental investigations were carried out.

The expansive pressure was measured by the embedded type pressure transducers and the diaphragm type pressure transducers as shown in Fig.3. The embedded type pressure transducer is cylindrical type having the same diameter of CFRP strand. Also, the strain gauges were installed at the surface of sleeve for longitudinal direction, and the expansive pressure was calculated by the thick-wall cylinder theory using measured strain values. Since the expansive pressure is affected by the ambient temperature, HEM anchorage after pouring HEM slurry was cured for ten hours at 20°C and after that, the accelerate curing at 50°C was done. Both curing at 20°C and 50°C were made in water.

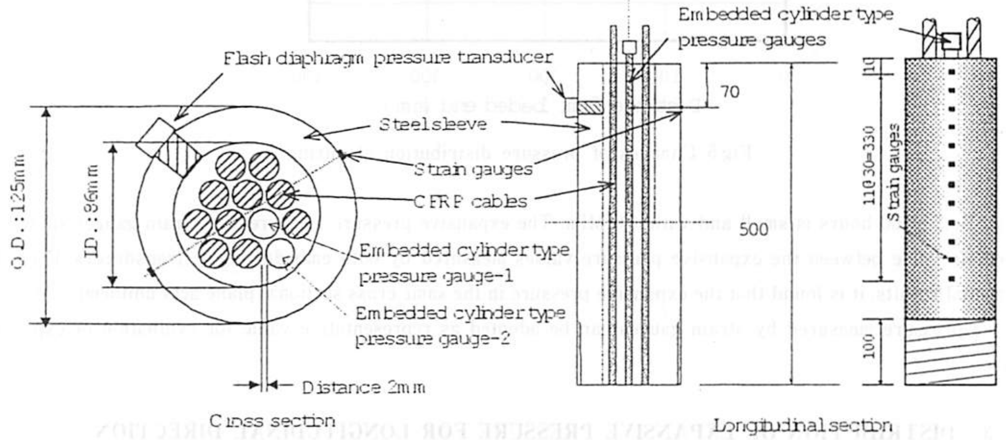

Fig.3 Anchoring sleeve assembly and gauge positions

4. 2 EXPANSIVE PRESSURE IN CROSS SECTIONAL PLANE

Fig.4 shows the time-dependent change of expansive pressure at the 70 mm depth in the same cross sectional plane. The difference of expansive pressure measured by the embedded type pressure transducers of

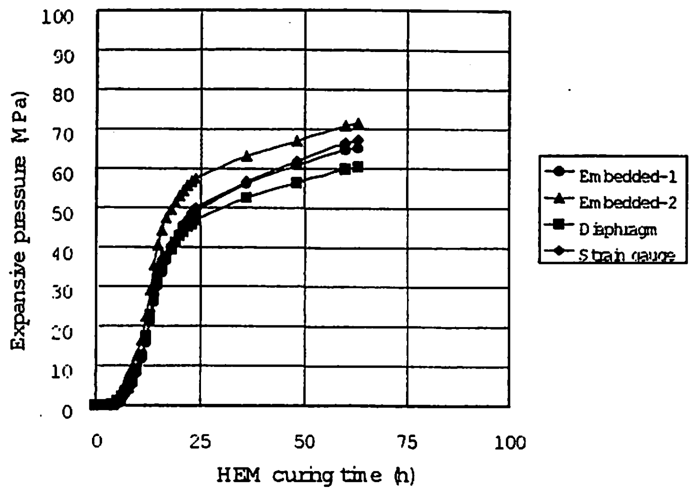

Fig.4 Pressure changes at 70mm position by various gauges

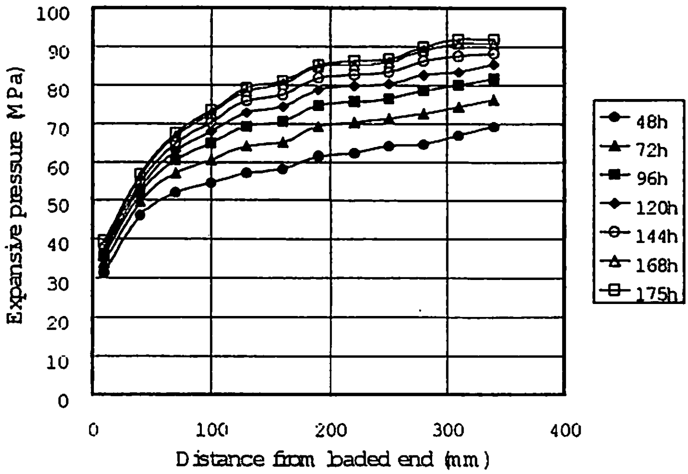

Fig.5 Changes of pressure distribution at curing

No.1 and No.2 at 60 hours is small and within 6 MPa. The expansive pressure measured by strain gauges shows the intermediate value between the expansive pressure values measured by both embedded type transducers. From the experimental results, it is found that the expansive pressure in the same cross sectional plane acts uniformly. Also, the expansive pressure measured by strain gauges can be adopted as representative value for evaluation of expansive pressure.

4. 3 DISTRIBUTION OF EXPANSIVE PRESSURE FOR LONGITUDINAL DIRECTION

Fig.5 shows the distribution of expansive pressure for longitudinal direction measured by the strain gauges at arbitrary time. The amount of expansive pressure increases according to the distance away from the free end of sleeve. However,

the increment of expansive pressure converges at the central region of sleeve. The expansive pressures located at 280mm, 310mm and 340mm were almost the same value of 90MPa at 175 hours after pouring the HEM slurry. The expansive pressure only at 10mm distance from the free end was 40MPa.
The high expansive pressure more than 40MPa can be obtained for the entire sleeve length when the curing was done sufficiently.

5. TENSILE TESTS

5. 1 OUTLINE OF EXPERIMENT

The specimen for tensile tests has two HEM tendon grips with 500mm long at both ends. Twelve CFRP strands (φ 15.2) of 3 m long were set in parallel to both ends. When the expansive pressure reached at 60MPa, the specimen was set at the tensile testing machine having capacity of 10MN horizontally and fixed with the locking nut at both ends as shown in Fig.6. Repeated loading ranged from 0kN to 2000kN was loaded ten times. After tenth repeated loading, the load was increased gradually up to the failure of CFRP strands. Strains gages installed at the both surfaces of sleeve, were used to measured at the interval of 200kN in each repeated loading.

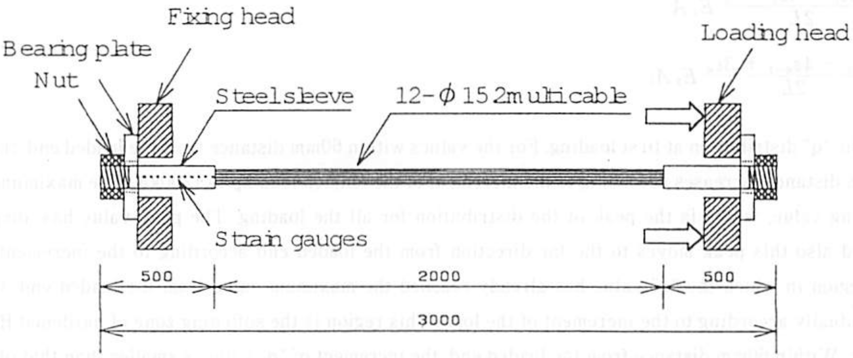

Fig.6 Tensile testing setup (capacity 10MN) for 12-φ 15.2HEM anchor system

5. 2 ULTIMATE TENSILE STRENGTH

Tensile test up to the failure of CFRP strands was carried out for two specimens. The ultimate loads at failure of CFRP strands were 2570kN and 2540kN as shown in Table.2. The ultimate load of both specimens are above the required the ultimate capacity. One strand was broken at No.1 specimen and three strands were broken at No.2 specimen. The pull-out from the sleeve was not observed. The failure of CFRP strands occurred at the point nearer to the sleeve for both specimens. In tensile test of multi-cable tendons, in usual, all tendons are not broken at the same time, but some tendons having high tension are broken at the ultimate strength, because the tension load distributed each tendons differ from each other due to the difference of tendon length.
The following considerations are based on the results of No.2 specimen.

Table.2 Tensile test results

No.	Breaking Load	Expected capacity	Ratio of breaking load and expceted capacity	Failure mode
1	2,570kN	2,500kN	103%	Breakage of strands
2	2,540kN	2,500kN	102%	Breakage of strands

5．3 DISTRIBUTIONS OF UNIT SHEAR "q"

The unit shear "q" acting between CFRP strand and HEM appears to resist the pull-out load, and distributes along the axial direction of the sleeve. The same amount of "q" is acting between the sleeve and HEM occurs at the same time. Here, it is assumed that twelve CFRP strands behave as a bundled unified strand. The unit shear "q" values can be calculated by Equation (2), using the measured strain values on the sleeve. The "q_i" is the value of unit shear at point "i" and the same point of installed "i th"strain gauge from loaded end.

$$q_i = \frac{\varepsilon_{i+1} - \varepsilon_{i-1}}{2L} E_s A_s \qquad (2)$$

where, ε_{i+1}, ε_{i-1} : measured strain values sleeve

L : interval between strain gauges

$E_s A_s$: Tension stiffness of steel sleeve

The unit shear "q" values at the initial and end points of strain gauges can be calculated by using the following Equations.

$$q_0 = \frac{-3\varepsilon_0 + 4\varepsilon_1 - \varepsilon_2}{2L} E_s A_s \qquad (3)$$

$$q_0 = \frac{\varepsilon_{n-2} - 4\varepsilon_{n-1} + 3\varepsilon_n}{2L} E_s A_s \qquad (4)$$

Fig.7 shows the "q" distribution at first loading. For the values within 60mm distance from the loaded end, the peak of "q" value at 60mm distance increases according to the increment of the tension load up to 1200kN. The maximum value of "q" has the limiting value, which is the peak of the distribution for all the loading. The peak value has almost the same magnitude and also this peak moves to the far direction from the loaded end according to the increment of the load. Within the region in which the "q" value has already reached the maximum value from the loaded end, the "q" value decreases gradually according to the increment of the load. This region is the softening zone of hardened HEM as shear transfer layer. Within 60mm distance from the loaded end, the increment of "q" value is smaller than that of far distance point from the loaded end, since the expansive pressure is lower due to the transmission length of expansive pressure. The integration of "q" value distribution at arbitrary load is equal to the tension load.

Fig.8 shows the "q" value distribution at secondary loading. From the same figure, the negative "q" values appear within 160mm distance from loaded end, when the load is small. The peak of "q" value at 2000kN can be observed at the point of

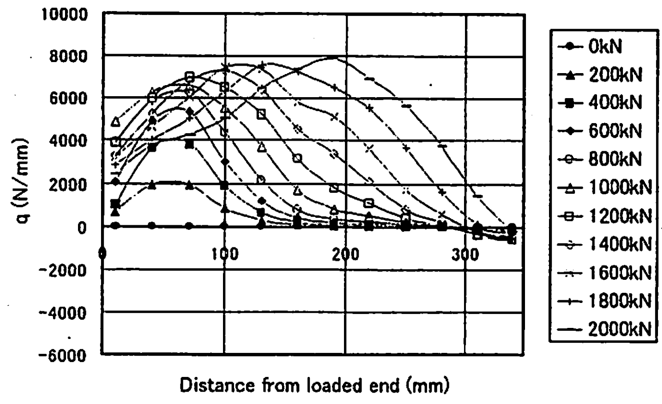

Fig.7 "q" distributions at 1st loading

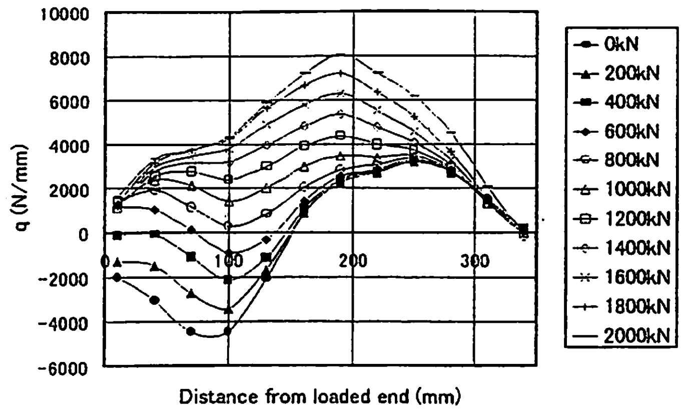

Fig.8 "q" distributions at 2nd loading

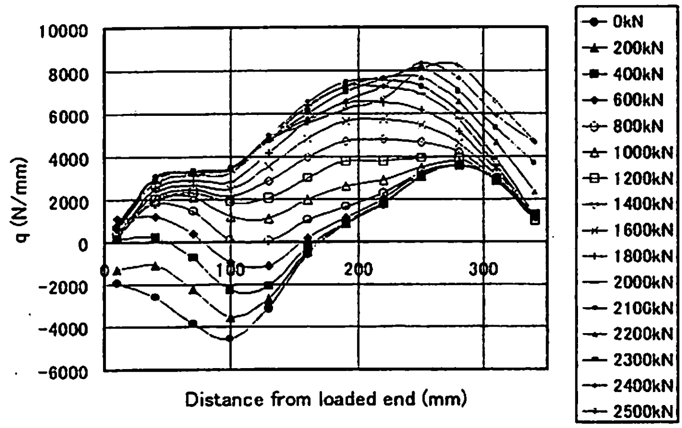

Fig.9 "q" distributions at 10th loading

190mm distance, same as the first loading.

The "q" value distribution at tenth loading as shown in Fig.9 show almost the same result as secondary loading except the loading level of 2000kN over. In the loading level of 2000kN over, the peak of "q" value increases slightly and moves to the far distance from loaded end. It is found that the progression of the softening zone of HEM caused by the repeated loading cannot be observed in comparison of Figures 8 and 9.

5．4 "Tp" DISTRIBUTIONS

Figures 10, 11 and 12 show distributions of "Tp", which is the tension load of total CFRP strands in the sleeve, calculated by using Equation (5) and with the measured strains "ε_s". Equation (5) carries the meaning that the summation of internal force for axial direction at any cross section should be in equilibrium to the pull-out load "P". Here, the steel sleeve and CFRP strands are assumed to be elastic up to the failure load of CFRP strand.

$$T_p = P - E_s A_s \varepsilon_s \qquad (5)$$

In the first loading as shown in Fig.10, "Tp" value decreases gradually according to the distance far from the loaded end. From Fig.11, the residual load of about 500kN is observed at around 160mm distance from loaded end, up to 600kN of

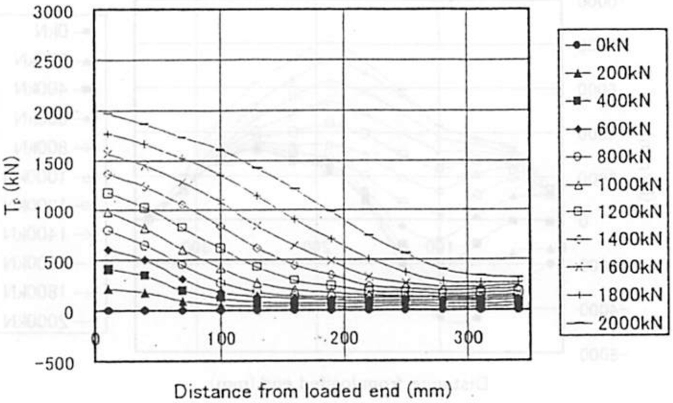

Fig.10 "T_p" distributions at 1st loading

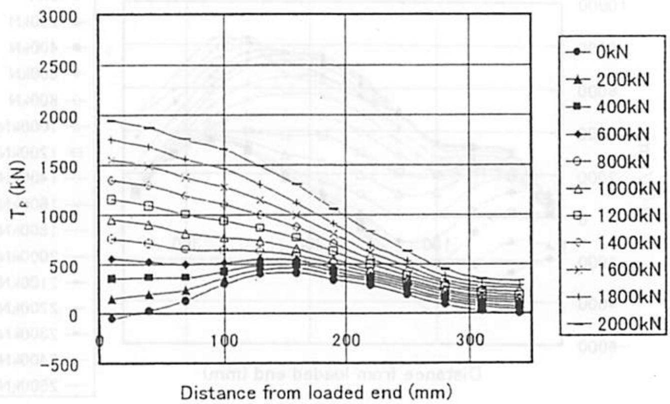

Fig.11 "T_p" distributions at 2nd loading

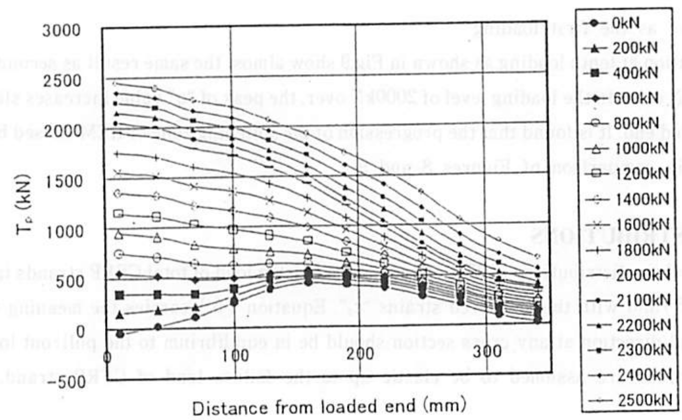

Fig.12 "T_p" distributions at 10th loading tension load. The 160mm distance from loaded end is the point that the sign of "q" value changes from negative to positive, because the following formula is made up.

$$q = \frac{dT_p}{dx} \qquad (6)$$

It is considered that the residual load is in action similar to the prestress and also this is caused by unit shear "q" under the process of unloading and the slippage between CFRP strands and HEM, since the action of expansive pressure is still active.

As shown in Fig.12, the configuration of "Tp" distributions are almost the same that of secondary loading within 2000kN.

From above results of "q" value and "Tp" distribution, the behavior of multi-cable HEM anchorage is quite similar to that a single strand HEM anchorage [3]. Therefore, the assumption that twelve CFRP strands behave as a bundled unified strand is valid.

5. 5 RELATIONSHIP BETWEEN "q" and "γ"

The relative shear strain "γ" as shown in Fig.13, can be calculated by Equation (7). Here, from the above assumption that twelve CFRP strands behave as a bundled unified strand was also applied.

$$\gamma = \frac{w_s - w_p}{h} \qquad (7)$$

where, w_s, w_p : the deformation of steel sleeve and CFRP strands at the arbitrary distance from the loaded end, respectively

h : the thickness of HEM layer (8mm)

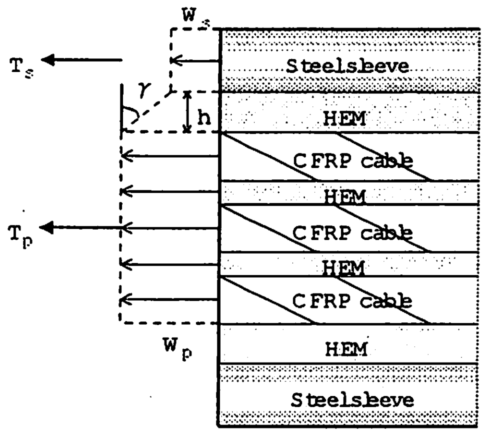

Fig.13 Defromations in HEM anchor

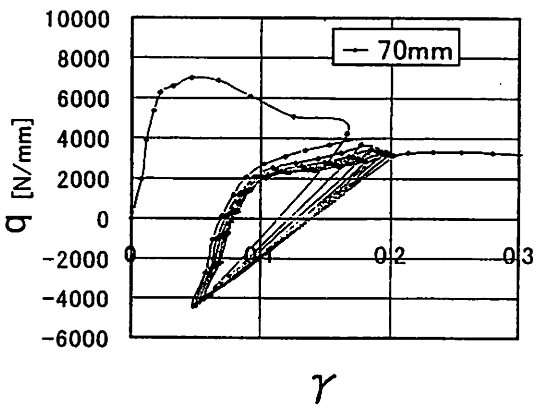

Fig.14 "q" - "γ" relation at 70mm position in 10 cycles

The values of "w_s", "w_p" were obtained by the integration of measured strains from the free end to the arbitrary point of steel sleeve. The relationship between "q" and "γ" express the characteristics of shear spring of HEM. This relation is very important because it should be used as constituive law of FEM analysis using shear spring model, in which the HEM layer assumed the shear spring Figures 14, 15 and 16 show the relationship between "q" and "γ", at 70mm, 130mm and 250mm distance from the loaded end, respectively. From all figures, the relationship between "q" and "γ" incerases almost linearly and the gradient of the straight curve is almost the same, when the "q" value is small. As shown in figures 14 and

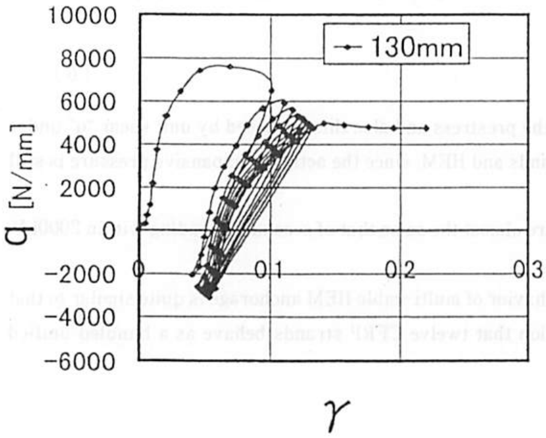

Fig.15 "q" - "γ" relation at 130mm position in 10 cycles

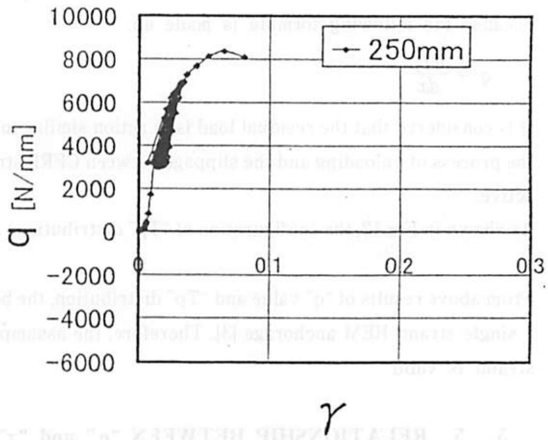

Fig.16 "q" - "γ" relation at 250mm position in 10 cycles

15, it can be observed the softening region of HEM, since the envelop curve after the peak decreases gradually. The configuration of the envelop in the softening region is almost the same in comparson of Fig.14 and Fig.15. However, the peak value of "q" slightly increases depending on the distance from the loaded end, because of the difference of the expansive pressure as shown Fig.5. In the softening, the hystresis loop under repeated loading does not change so largely.

At the point of 250mm distance as shown in Fig.16, the behavior of HEM is elastic, because there is no hystersis loop under repeated loading.

6. CONCLUSIONS

The results obtained in this study are summarized below.

(1) It is found that the expansive pressure in the same cross sectional plane acts uniformly. Also, the expansive pressure measured by strain gauges can be adopted as representative value for evaluation of expansive pressure.

(2) The amount of expansive pressure increases according to the distance far from the free end of sleeve. However, the increment of expansive pressure converges at the central region of sleeve and also the high expansive pressure up to 90MPa can be obtained if the curing is done sufficiently.

(3) The ultimate loads at failure of CFRP strands were 2570kN, 2540kN and exceeding the required ultimate capacity of 2500kN. Also, the pull-out from the sleeve was not observed.

(4) From the results of "q" value and "Tp" distribution, the behavior of multi-cable HEM anchorage is quite similar to that of a single strand HEM anchorage. The assumption that twelve CFRP strands behave as a bundled unified strand is useful for the design of multicable HEM anchorage.

(5) HEM as the shear transfer layer is considered to be a shear spring model having the characteristics of elastic softening and it should be used as constitutive law of FEM analysis.

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2500 kN 級 CFRP より泉を用いた HEM 定着具の開発

研究概要

著者らは、4本の FRP のアンカーに HEM（膨張材）を使用し研究した。HEM アンカーシステムには6本巻きの CFRP ストランドが、日本ではグランドアンカーシステムとしてすでに使われている。グランドアンカーシステムの現在の圧縮応力は600 kN である。近年、CFRP 膨張材グリップの大きな圧縮応力の増加を期待している。何故なら、斜長橋のような大規模な建造物には長期耐性が必要とするからだ。近い将来、HEM グリップは5000 kN に遷えうる能力を必要とされるであろう。

最初の段階では、HEM を用いた緊張材グリップの大きな圧縮応力の開発の為に、この直径15.2㎜ある12本の CFRP の CFRP を使用した緊張材のグリップと鉄のスリーブの2500 kN の引き抜き試験を行った。この考案をもとに実用的に HEM アンカーを用いた緊張材を作る為に、実験と解析研究を行なった。