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H01/6

Study on the tensile force redistribution of heated tendon

Kato A.(1), **Abe T.**(2), **Sono Y.**(3), **Yamaguchi T.**(4), **Yamamoto M.**(4)
(1) The Japan Atomic Power Company, Japan
(2) The Kansai Electric Power Company, Inc., Japan
(3) Kyushu Electric Power Company, Inc., Japan
(4) Obayashi Corporation, Japan

ABSTRACT

In Japan, PCCVs are adopting un-bonded PS system, and results of their ISI show that some of tensile force deviations of a hoop tendons differ at each end and that tensile force redistribution is apt to occur. To examine relationship between tensile force at both ends of a tendon and average tensile force along the tendon, an examination is carried out to heat and cool tendons with un-uniform tensile force being fixed at two apart points. In addition, these results are compared with a formulation of tendon friction theory to evaluate it.

1. FORWARD

The change of forces in tendon is measured at in-service inspections(ISI) as a change between lock-off forces (measured at the anchoring end of tendon right after prestressing) and lift-off forces (measured at in-service inspections) for prestressed concrete containment vessel (PCCV) of nuclear power plant. Basically the change of forces is influenced by losses due to elastic deformation of the structure, relaxation of tendon, creep and shrinkage of concrete. However, based on the results of measurement, the amount of the change of forces at both ends of a tendon sometimes shows obvious difference and they are not explicable by the losses mentioned above (in other words, an average change of forces along the tendon).

As the tensile force of tendons is apt to differ due to friction forces, a redistribution of the tensile force may be caused by temperature of the anticorrosive grease, deformation at the structural integrity test (SIT), change of temperature and so on. In order to evaluate relationships between the average deviation of tendons and that at the ends of the tendons, it is important to make the influence of the tensile force redistribution clear.

This study aims to evaluate experimentally the tensile force redistribution in a tendon, when a tendon which is fixed at both ends and has varying tensile force distribution during increasing or decreasing the temperature of a tendon.

2. METHOD OF THE EXPERIMENT

Figure 1 shows an outline of a test bed. The test bed is made of reinforced concrete, and consists of a filled cylinder whose diameter is 4.0 m with four cut off portions for measurement and a massive wall. The test bed has six anchoring portions.

The un-bonded tendons are modeled as 5mm diameter steel wire or 12.4mm diameter steel strand ; both types are rolled around the test bed, and are prestressed and heated. Table 1 and 2 show test specimens. As shown in these tables, studied parameters are length of rolled portion of tendon (totally rolled angle), length of the straight portion and extent of set-loss.

The tensile force is initiated by one-way loading. The extent of set-loss is adjusted by a screw type anchoring head. The tendon is heated up to 80 ℃ by electric conduct, then it is cooled down in natural condition. The tensile force in the tendons are measured by load cells at anchoring ends and by strain gauges in the middle of them. As a srtain gauge for the 12.4mm diameter un-bonded steel strand are set on an individual string, certain amount of measuring error must be torelated.

3. RESULTS OF THE EXPERIMENT

As a typical result, strain distributions of the 5mm wire H5.0-2.2 and H5.0-4.1 at the time of prestressing, before heating, at the time of maximum temperature and after cooling are shown in Figure 2 and 3. Relationship between temperature and tensile force at fixed end and prestressing end of the tendon is shown in Figure4, and relationship between temperature and strain in the middle of it is shown in Figure 5.

As seen in these figures, the tensile force redistribution is observed when a tendon between fixed two points with un-uniform tensile force is heated. There is a trend of redistribution that the loss of tensile force at the high tensile force side is large and the loss of tensile force at the low tensile force side is small during the heating, while the increase of tensile force at the high tensile force side is small and the increase of tensile force at the low tensile force side is large during the cooling. This trend is clearly observed in the relationship between temperature and tensile force at fixed end and prestressing end of the tendon and the relationship between temperature and strain at the middle of tendon. Figure 4 shows more precise condition of these phenomena; during heating, the tensile force at tensionning end of the tendon is reduced more than that at the fixed end, and during cooling, on the contrary, the tensile force at tensioning end of the tendon is gained less than that at the fixed end. This mechanism leads the phenomena stated above.

4. EVALUATION OF THE RESULTS OF THE EXPERIMENT

4.1 *Uniformity of tensile force of tendon*

A scattering chart of tensile force gradient (substitution of tensile forces at adjacent two points/ distance of two points) at the time of maximum temperature and after cooling for H5.0 series specimens is shown in figure 6 and 7.

The ratio of the tensile force gradient at the time of maximum temperature compared with that at the time of prestressing is 0.642, and the ratio of the tensile force gradient after cooling compared with that the time of maximum temperature is 0.931, showing that both heating and cooling of tendons make tensile force gradient gradually small and tensile force distribution uniform. The friction coefficients (μ) of the 5mm diameter steel wire and the 12.4mm diameter un-bonded steel strand are 0.322 and 0.027 respectively, showing that in case of small μ , the tensile force distribution becomes uniform faster (refer to Table 4).

4.2 *An average tensile force of tendon after cooling*

Table 3 shows average tensile forces of whole tendon in each condition.
Compared with the average tensile force of tendon after prestressing, smaller tensile force is observed at the time of maximum temperature, and almost same tensile force is observed after cooling. This result shows that the whole average tensile force of tendon may not differ at the same temperature even though after the history of several heatings and coolings. The ratio of average temparature after prestressing and that after cooling is 1.00 to 1.02; and good agreement of deviation of the average tensile force and the average temparature is observed.

4.3 *Relationship between average tensile force at ends and whole average tensile force*

The relationship between average tensile force at ends and whole average tensile force at each condition is shown in Table 4. In H5.0 series, the ratio is 1.00 to 1.06, and in H12.4 series, the ratio is 0.97 to 0.98; this shows that the average tensile force at ends and whole average tensile force are in good agreement.

5. EVALUATION BY THE FORMULATION OF TENDON FRICTION THEORY

For an evaluation method of the tensile force redistribution of heated tendon, a formulation of tendon friction theory is presented in a paper (1). In this study, the experiment results are compared with the presented theory; and due to a good agreement of experiment results and the presented theory, the theory is shown to be reasonably correct.

5.1 *Theoretical formulation of tendon friction theory*

The theoretical formulation presented in paper (1) is shown as follows.

Figure 8 shows a relationship between friction force distribution and tensile force of tendon during heating with a constant temperature gradient and cooling, after prestressing of tendon.

The tensile forces at both ends of tendons and friction coefficient before heating are T_A (high tensile force side), T_B (low tensile force side), and μ respectively. Similarly, the tensile forces at both ends of tendons are T_A* and T_B* after heating , and observed friction coefficient (considering friction force reduction by thermal deformation) as that after the tensile force redistribution is μ *. As shown in Fig 8, thermal stress let tendon move to reduce the friction force which is applied toward low tensile force side during prestressing, and as a result, the tensile force of the tendon changes. We call this phenomenon “the outlook friction force”.

Then T_B* takes the following form.

$$T_B * = T_A * \cdot e^{-\mu^* \alpha_B} \quad (1)$$

Using the heating temperature gradient (takes plus for heating and minus for cooling) as Δ T, coefficient of linear expansion as α_S, tendon strain for a tendon length deformation at point i during heating (or cooling) as ε_i* takes the following form.

$$\varepsilon_i^* = \varepsilon_{\sigma i}^* + \alpha_s \cdot \Delta T_T \quad (2)$$

Here, $\varepsilon_{\sigma i}^*$ is a strain due to tendon stress after the tensile force redistribution ($T_i^*/E_S A_S$), Es is young's modules of the tendon and As is a cross section of the tendon.

Length deformation of tendon before heating, Δ li, and after heating Δ li*, take the following forms respectively.

$$\begin{aligned}\Delta\ell_i &= \int_{\alpha_A}^{\alpha_i} \varepsilon_i a d\alpha_i \\ &= \int_{\alpha_A}^{\alpha_i} \left({T_i}/{E_S A_S} \right) a d\alpha_i\end{aligned} \qquad (3)$$

a is a radius of the cylinder where the tendon is rolled.

$$\begin{aligned}\Delta\ell_i^* &= \int_{\alpha_A}^{\alpha_i} \varepsilon_i^* a d\alpha_i \\ &= \int_{\alpha_A}^{\alpha_i} \left({T_i^*}/{E_S A_S} \right) a d\alpha_i + \int_{\alpha_A}^{\alpha_i} \alpha_S \Delta T_T a d\alpha_i\end{aligned} \qquad (4)$$

The tendon is heated after the prestressing and both ends A and B are fixed, therefore the total length of that tendon between the both ends are constant. Thus, Δ l_{AB} = Δ l_{AB}^* is true and that makes the following form.

$$\left({T_A}/{E_S A_S} \right) \int_{\alpha_A}^{\alpha_B} e^{-\mu\alpha_i} a d\alpha_i - \left({T_A^*}/{E_S A_S} \right) \int_{\alpha_A}^{\alpha_B} e^{-\mu^*\alpha_i} a d\alpha_i - \int_{\alpha_A}^{\alpha_B} \alpha_S \cdot \Delta T_T \cdot a d\alpha_i = 0 \quad (5)$$

Solving the form (1) and (5), the tensile forces at both ends of tendons T_A^* and T_B^* after heating are given.

5.2 *Calibration of the theoretical formulation with the experimental result*

The strain distribution of tendon in typical specimens are shown in Figure 2 and 3, and the relationship between temperature and tensile force at representative points are shown in figure 4 and 5.

Here, $E_S = 2.10 \times 10^6$ kg/cm^2 , $\mu = 0.36$ (Based on Test Result)
$A_S = 0.196$ cm^2 , $\mu^* = 0.32$ (At Max Temperature) (Based on Test Result)
$\alpha_S = 10 \times 10^{-5}$ 1/℃ , $\mu^* = 0.20$ (After Cooling) (Based on Test Result)

These figures indicate that the strain distribution of tendon and the relationship between temperature and tensile force show good agreement between the theoretical formulation and the experimental result, and implicitly show the theoretical formulation simulate the tensile force redistribution due to the tendon deformation. Thus the assumption used in the theoretical formulation is reasonable.

6. CONCLUDING REMARKS

A tensile force redistribution of heated tendon is observed, and cyclic redistribution makes the tensile force uniform; an average of tensile forces at both ends also converge to that of whole length of the tendon. Although the tendon experiments cyclic heating and cooling, the whole average tensile force of tendon may not differ at the same temperature, so there may be no tensile force change as a result. These tensile force redistribution characteristics can be mostly expressed by the formulation of tendon friction theory considering tendon deformation by heating and cooling.

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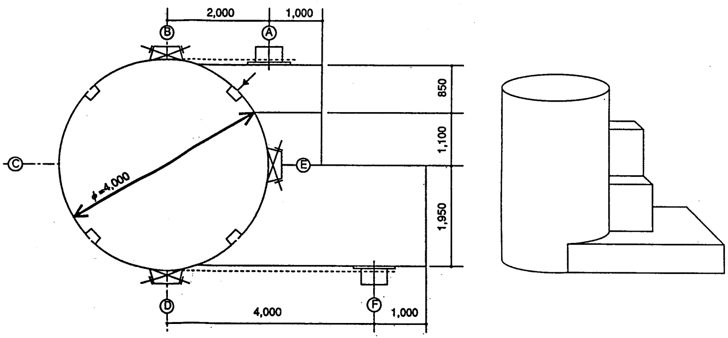

Fig.1 Test Specimen

Table 1 H5.0 Series Specimen
(ϕ5.0mm Steel Wire)

Specimen No.	Change of Angle (rad)	Fixed End	Tensionning End	Extent of Set Loss
H5.0-1.0	0	A	B	≒0
H5.0-2.1	5.4906	B	B	≒0
H5.0-2.2	5.4906	B	B	≒0
H5.0-3.1	2.7453	A	D	≒0
H5.0-3.2	2.7453	A	D	≒0
H5.0-4.1	5.4906	B	B	Exist
H5.0-4.2	5.4906	B	B	Exist
H5.0-5.1	2.7453	A	D	Exist
H5.0-5.2	2.7453	A	D	Exist

Table 2 HL12.4 Series Specimen
(ϕ 12.4mm Steel Strand)

Specimen No.	Change of Angle (rad)	Fixed End	Tensionning End	Extent of Set Loss
H12.4-1.0	0	A	B	≒0
H12.4-2.1	5.6107	B	B	≒0
H12.4-2.2	5.6057	B	B	≒0
H12.4-3.1	2.7891	A	D	≒0
H12.4-3.2	2.7916	A	D	≒0
H12.4-4.1	5.5932	B	B	Exist
H12.4-4.2	5.6057	B	B	Exist
H12.4-5.1	2.7941	A	D	Exist
H12.4-5.2	2.7916	A	D	Exist
H12.4-6.1	5.9202	B	D	Exist
H12.4-6.2	5.9202	B	D	Exist
H12.4-6.3	5.9202	B	D	Exist

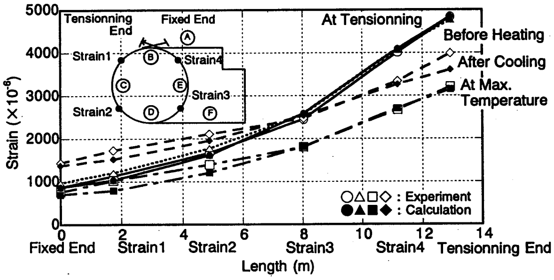

Fig.2 Strain Distribution of Tendon
(H5.0-2.2)

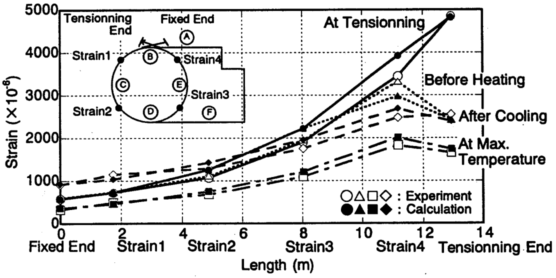

Fig.3 Strain Distribution of Tendon
(H5.0-4.1)

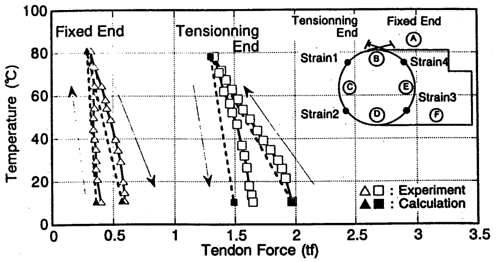

Fig.4 Relationship between Temperature
and Tendon Force at End (H5.0-2.2)

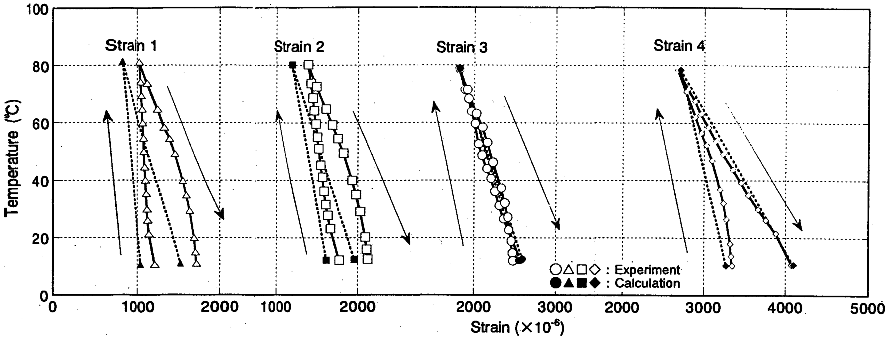

Fig.5 Relationship between Temperature and Strain in all Measurement Points (H5.0-2.2)

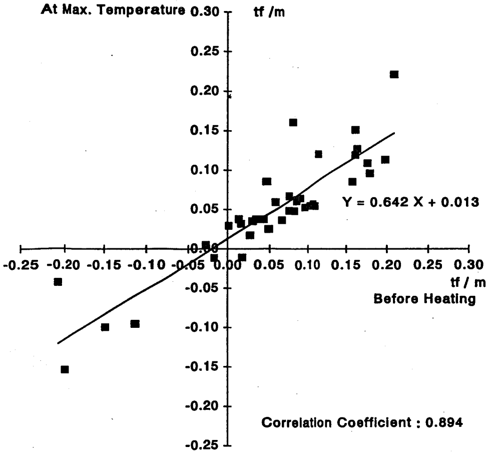

Fig.6 Force Gradient Scattergram of Before Heating and At Max. Temperature (H5.0)

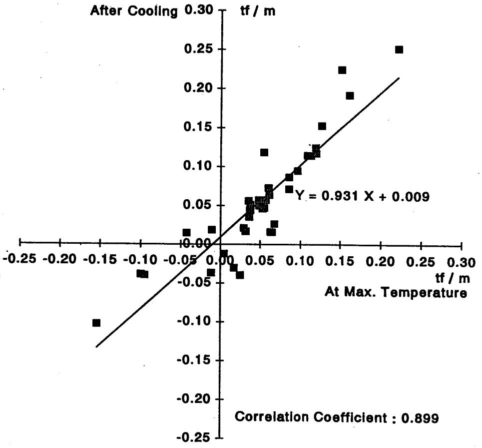

Fig.7 Force Gradient Scattergram of At Max. Temperature and After Cooling (H5.0)

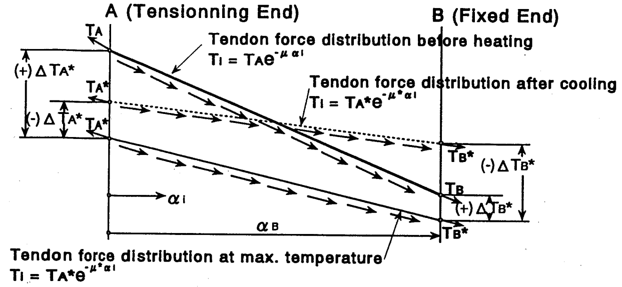

Fig.8 Friction Force Distribution and Tendon Force At Max. Temperature and After Cooling

Table 3 Average Tendon Force at Ends and Average Tendon Force in all Measurement Points

Specimen No.		At Tensionning			Before Heating			At Max. Temperature			After Cooling		
		A	B	A/B	A	B	A/B	A	B	A/B	A	B	A/B
H5.0	2.1,2.2	1.20	1.04	1.15	1.17	1.05	1.11	0.86	0.77	1.12	1.17	1.06	1.11
	3.1,3.2	1.42	1.27	1.12	1.37	1.27	1.09	1.04	0.95	1.10	1.42	1.29	1.10
	4.1,4.2	1.11	0.88	1.26	0.59	0.68	0.86	0.40	0.44	0.91	0.68	0.70	0.97
	5.1,5.2	1.45	1.25	1.17	0.95	1.01	0.94	0.65	0.71	0.92	1.04	1.05	0.99
HL12.4	2.1,2.2	9.22	9.31	0.99	8.95	9.17	0.98	7.80	8.06	0.97	8.83	9.05	0.98
	3.1,3.2	9.58	9.61	1.00	9.35	9.50	0.98	8.11	8.34	0.97	9.29	9.47	0.98
	4.1,4.2	9.23	9.34	0.99	8.57	8.75	0.98	7.39	7.53	0.98	8.46	8.60	0.99
	5.1,5.2	9.42	9.45	1.00	9.16	9.16	0.98	7.72	8.14	0.95	8.89	9.14	0.97
	6.1-6.3	1.91	1.89	1.01	1.77	1.77	0.99	0.73	0.76	0.96	1.67	1.70	0.99

Note A : Average Tendon Force at Tensionning End and Fixed End (Unit:tf)
B : Average Tendon Force in all Measurement Points (Unit:tf)

Table 4 Average Tendon Force in all Measurement Points For Each Condition

Specimen No. (H5.0)		A	B	C	Specimen No. (HL12.4)		A	B	C
1.0	Before Heating	2.05	0.81	1.00	1.0	Before Heating	9.86	0.83	0.94
	Max. Temperature	1.67				Max. Temperature	8.20		
	After Cooling	2.05				After Cooling	9.26		
2.1	Before Heating	1.03	0.73	1.00	2.1	Before Heating	9.18	0.89	0.99
	Max. Temperature	0.75				Max. Temperature	8.13		
	After Cooling	1.03				After Cooling	9.07		
2.2	Before Heating	1.01	0.72	1.00	2.2	Before Heating	9.31	0.88	0.99
	Max. Temperature	0.73				Max. Temperature	8.18		
	After Cooling	1.01				After Cooling	9.18		
3.1	Before Heating	1.14	0.73	1.00	3.1	Before Heating	9.59	0.88	1.00
	Max. Temperature	0.83				Max. Temperature	8.43		
	After Cooling	1.14				After Cooling	9.55		
3.2	Before Heating	1.35	0.79	1.03	3.2	Before Heating	9.54	0.88	1.00
	Max. Temperature	1.06				Max. Temperature	8.42		
	After Cooling	1.39				After Cooling	9.51		
4.1	Before Heating	0.71	0.59	0.97	4.1	Before Heating	8.76	0.86	0.97
	Max. Temperature	0.42				Max. Temperature	7.52		
	After Cooling	0.69				After Cooling	8.55		
4.2	Before Heating	0.70	0.68	1.03	4.2	Before Heating	8.89	0.86	0.98
	Max. Temperature	0.48				Max. Temperature	7.65		
	After Cooling	0.72				After Cooling	8.57		
5.1	Before Heating	0.99	0.71	1.01	5.1	Before Heating	8.94	0.89	1.00
	Max. Temperature	0.70				Max. Temperature	7.93		
	After Cooling	1.01				After Cooling	8.91		
5.2	Before Heating	1.09	0.70	1.00	5.2	Before Heating	9.52	0.90	1.00
	Max. Temperature	0.77				Max. Temperature	8.54		
	After Cooling	1.09				After Cooling	9.48		
Average			0.72	1.00	Average			0.87	0.98

Note A :Average Tendon Force in all Measurement Points (Unit:tf)
B : Ratio of Max. Temperature to Before Heating
C : Ratio of After Cooling to Before Heating