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Fatigue Strength of Parallel Wire Strands in Anchorage

Résistance à la fatigue de câbles à fils parallèles à l'ancrage

Dauerfestigkeit von Paralleldrahtbündeln am Anker

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SUMMARY

This paper concerns the fatigue strength of a parallel wire strand (PWS) which uses galvanized wires with a breaking strength of 1765 MPa and zinc-poured-sockets at both ends. It has been indicated the PWS fatigue strength declines at the zinc-poured-sockets. The causes of this are investigated through a fatigue test using a 37 wire PWS and FEM analysis. Furthermore, a method that can improve the fatigue strength without changing the structure of the present socket is proposed. The effectiveness of this method is also verified through a fatigue test using a 37 wire PWS.

RÉSUMÉ

Ce rapport traite de la résistance à la fatigue de câbles à fils parallèles utilisant des fils galvanisés à contrainte de rupture de 1765 MPA et des douilles scellées au zinc aux deux extrémités. La résistance à la fatigue de câbles à fils parallèles diminue aux douilles scellées au zinc. Les causes de ce phénomène sont étudiées par l'intermédiaire d'un essai de fatigue sur des câbles à fils parallèles à 37 fils et d'une analyse par éléments finis. Une méthode permettant d'améliorer la résistance à la fatigue, sans modifier la structure de la douille actuelle, est proposée. Son efficacité est également vérifiée par un essai de fatigue sur de câbles à fils parallèles à 37 fils.

ZUSAMMEMFASSUNG

Die vorliegende Abhandlung befaßt sich mit der Dauerfestigkeit von Paralleldrahtbündeln unter der Verwendung von verzinktem Draht mit vergoßenen Zinksockeln and beiden Enden mit einer Bruchfestigkeit von 1765 MPa. Es gab Anzeichen dafür, daß die Dauerfestigkeit an den jeweiligen vergoßenen Zinksockeln abnimmt. Die Ursachen dafür wurden mit einem Dauertest mit 37-Draht-Bündeln und FEM-Analyse untersucht. Außerdem wird ein Verfahren vorgeschlagen, das die Dauerfestigkeit verbessert, ohne die Struktur der gegenwärtigen Sockel zu verändern. Die Wirksamkeit dieses Verfahrens wurde mit einem Dauertest unter Zuhilfenahme von 37-Draht-Bündeln bestätigt.

1. Introduction

It has been said that the endurance limit of PWS (prefabricated parallel wire strand) with zinc-poured-anchorage (including zinc-copper-alloy-poured anchorage) is about 150 MPa in terms of stress range when wires with a breaking strenth of 1 569 MPa are used[1]. In the fatigue tests carried out so far, almost all wire-failure occurs inside the anchorage and hardly occurs at the free length. Because the wires with a breaking stress of 1 569 MPa itself possesses the endurance limit about 400 MPa in terms of stress range[2], the wire fatigue strength in the anchorage reduces by about 70%. Opinion to attribute the cause to heat effect at the time of zinc-pouring or wire fretting has been predominant, and in order to preclude these effects, a different anchorage system has been proposed[3]. However, the causes that lower the PWS fatigue limit in zinc-poured-anchorage have not yet been completely elucidated.

The purposes of our study are to find out causes reducing the PWS fatigue strength through fatigue tests and FEM analysis performed on the zinc-poured-anchorage of PWS as well as to improve the PWS fatigue strength without providing any significantly large structural change to the current anchorage.

In our study, PWS was first fabricated in accordance with the standard specifications which have been followed to date (hereinafter called the "standard PWS"), then fatigue tests were performed, and poured portions were taken into pieces to investigate the wire-failure condition in the anchorage. Samples used were PWS-37 (37 wire bundle) with 1.0-meter length between sockets which uses 5.0 mm-ø wires with a breaking strength of 1 765 MPa. The fatigue limit of 1 765 MPa wire itself is about 500 MPa in terms of stress range[2].

Then, FEM analysis was carried out on the anchorage and the stress condition of wires in anchorage was investigated. Based on the calculation results, the causes of wire- failure in anchorage were inferred and at the same time a method to improve the PWS fatigue strength was proposed.

Lastly, in order to verify the adequacy of these investigations, PWS with the proposed improved anchorage (herein-after called the "improved PWS") was fabricated to carry out fatigue tests.

2. Fatigue Tests of Standard PWS

2.1. Standard PWS and specimen-size

Standard PWS is fabricated as follows:
(1) Bundle and form wires in a hexagon.
(2) After inserting the wire bundle into a socket, bend the wires and spray in a form of a broom.
(3) As shown in Fig.1, set and fix wires in such a manner that the wire-spray-initiation-point coincides with the taper-initiation-point on the socket-inner- wall. (Note 1.)
(4) Under pin-point temperature control, pour zinc.

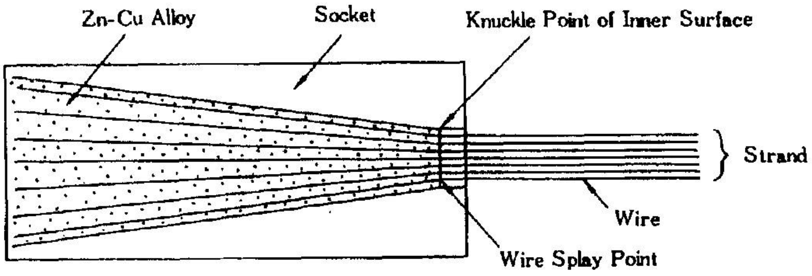

Fig.1 Rough sketch of standard PWS

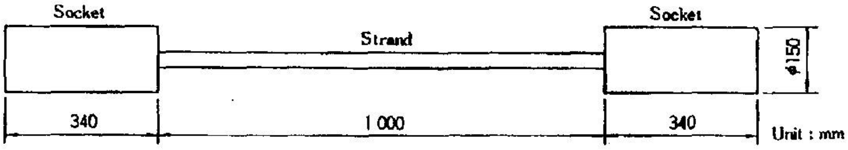

Fig.2 Dimension of specimen

(Note 1.) In order to complete the initial creep of poured metal, PWS has its poured-metal pressed from the rear side of the sockets, that is, so-called pre-compression is provided after pouring. It is the poured metal that is pressed and the wire is not pressed directly, but as a result, the wire bundle is pressed out several millimeters from the sockets. In strict sense, the setting referred to here is carried out with the displacement of wire bundle due to pre-compression taken into account so that the wire-spray-initiation-point coincides with the taper-initiation-point on the socket-inner-wall after pre-compression is achieved.

With the same procedure as specified above, eight pieces of test specimens (PWS-37) with the dimensions shown in Fig. 2 were newly prepared and fatigue tests were conducted. In preparing these specimens, special attention was given to the wire setting specified in Step (3) above. Zinc was poured in accordance with the Honshu-Shikoku Bridge Authority Standard, HBS G3503-1979 (zinc-copper-alloy instead of zinc: Zn 98%, Cu 2%; pouring temperature: 460 ± 10 °C).

In the fatigue tests, the maximum load was set to 579 kN for all the specimens and the minimum load was varied according to specimens to set the loading range. During the tests, so-called load control was performed to maintain this loading range constant. Consequently, with respect to the practical wire stress after the first wire failed, both maximum and minimum stresses varied and the stress range itself increased.

2.2. Test Results

Test results are shown in Table 1 and Fig. 3. The maximum and minimum stresses and stress range shown in Table 1 are values all calculated from the strand cross section before failure occurs. Fig. 3 arranges these values in terms of the number of cycles when the second wire-failure occurs and it corresponds to the 5% failure fatigue strength popularly referred.

The number of data is small but it is estimated that the fatigue limit of the standard PWS tested recently is about 150 MPa as well as the past test data used the 1 569 MPa wires. The test was characterized by appreciable scatter in the test results.

After the fatigue test, two of the standard PWS specimens (Specimen No.S-7 and S-8) were anatomized at the poured portion and wire-failure condition was investigated. All wire-failure occurred in the socket and primarily at the area 10 mm inside from the taper-initiation-point on the socket-inner-wall as shown in Table 2. The wire-fracture surface is divided into two sections as shown in Fig. 4, a fatigue fracture surface cracked at about 45° to the wire axis and a final fracture surface nearly normal to the wire axis.

Specimen	Maximum Stress (MPa)	Minimum Stress (MPa)	Stress Range (MPa)	Frequency (Hz)	Number of Cycles (x 10^4)		
					First Wire Failure	Second Wire Failure	Test Stop
S-1	796	649	147	4	No Failure		200.0
S-2	796	600	196	4	61.8	64.8	64.8
S-3	796	600	196	4	112.0	130.0	130.0
S-4	796	600	196	4	58.0	78.8	78.8
S-5	796	600	196	4	81.0	92.0	92.0
S-6	796	550	246	4	48.5	50.9	50.9
S-7	796	550	246	4	19.5	29.8	29.8
S-8	796	550	246	4	22.5	23.4	23.4

Table 1 Fatigue test result of standard PWS

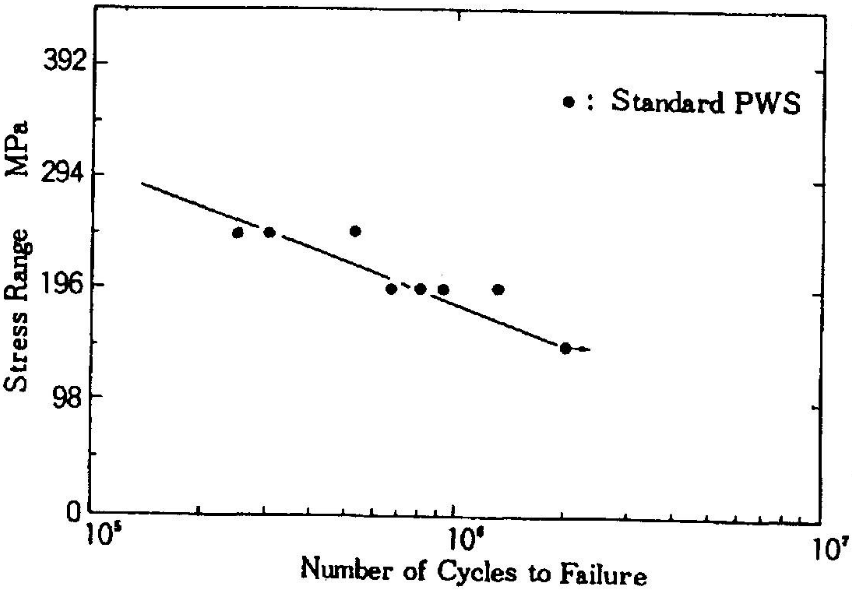

Fig.3 Fatigue test result of standard PWS

Specimen	Number of Broken Wires	Broken Wire	X mm
S-7	2	② ⑭	−8 −5
S-8	2	① ⑦	−9 −7

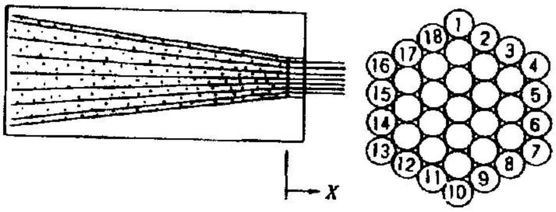

Table 2 Wire-failure location of standard PWS

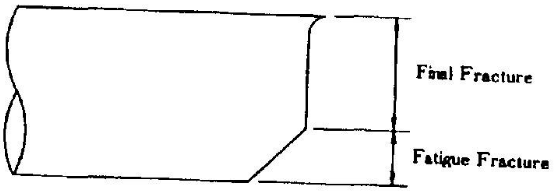

Fig.4 Rough sketch of wire fracture surface

3. FEM Analysis of Standard PWS Anchorage

In an attempt to attain relevance to the above fatigue tests, the model for anchorage of PWS-37 is assumed as shown later to carry out FEM analysis. The model used was a plane axisymmetric model, on which elastic analysis was conducted. The elastic modulus of socket, wire, and poured metal were 206 GPa, 196 GPa, and 20 GPa, respectively, and the Poison's ratio was all designated to 0.3. The slips between respective elements were not taken into account. In dividing meshes, the outermost-layer-wire was divided into four in the wire radial direction so that the stress distribution of the wire surface can be observed, and the inner-layer-wires were divided into two.

Fig. 5 shows the mesh divisions together with calculation results. For analysis, a general-purpose program PLASTO was used.

The calculation results shown in Fig. 5 represent the distribution of stress on the outermost-layer-wire surface, which is shown as a stress ratio when the principal stress of the free length is designated as 1.0. As clear from Fig. 5, the vicinity of the taper-initiation-point on the socket-inner-wall serves as a stress concentration area for the outermost-layer-wire surface. The principal stress shows the peak nearly at the taper-initiation-point on the socket-inner-wall and is about 40% greater than that at the general strand portion in terms of numerical value. On the other hand, the maximum shear stress shows the peak at about 5 mm inside from the taper-initiation-point on the socket-inner-wall and this is also 40% greater than that of the free length. As compared with the principal stress which shows the peak collectively at one point, the maximum shear stress shows comparatively smooth peak development. It is assumed that these stress concentrations are primarily attributed to the wedge effect of poured metal due to the taper provided on the socket-inner-wall.

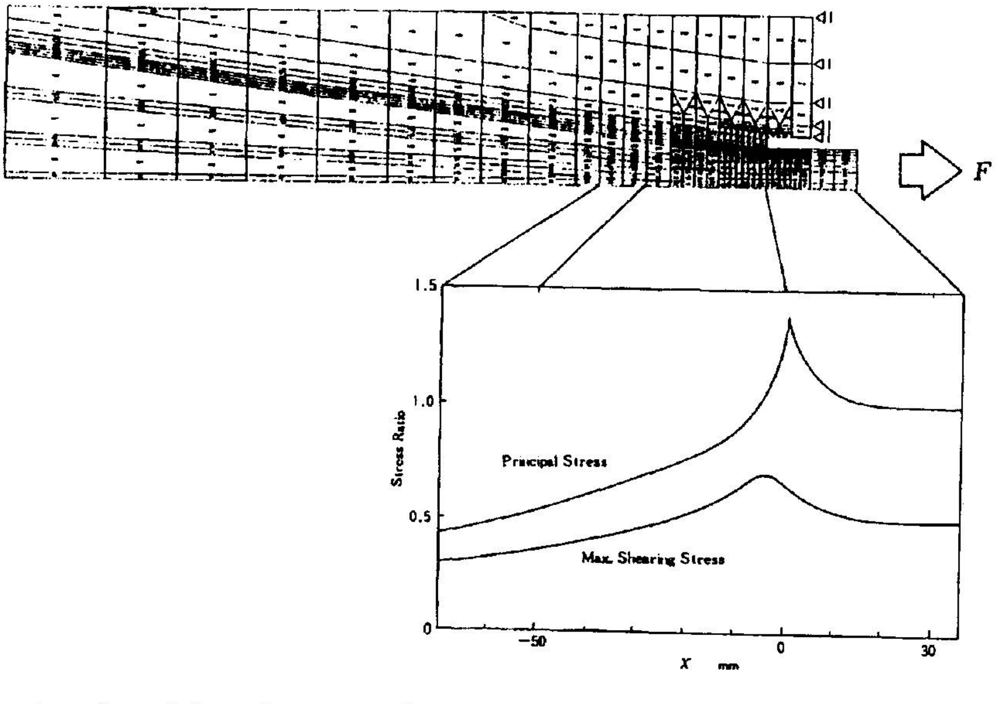

Fig.5 Structural model and stress distribution of outermost-layer-wire surface

4. Estimation of Causes Reducing Fatigue Strength of Standard PWS and investigation on its Improvement

4.1. Estimation of Causes Reducing Fatigue Strength

The results of fatigue tests and FEM analysis can be summarized as follows:
(1) The area about 20 mm inside from the taper-initiation-point on the socket-inner-wall serves as a stress concentration area for the outermost-layer-wire surface, and the peak values of both principal stress and maximum shear stress are increased by about 40% as compared with those of the free length.
(2) The wire-failure position is located at the area 10 mm inside from the taper-initiation-point on the socket-inner-wall and corresponds to the wire-bending affected zone.
(3) The fatigue crack of the failed wire initiates at about 45° with respect to the wire axis.

Putting these together, the causes reducing the fatigue strength of the standard PWS in anchorage can be inferred as follows. That is, the problem lies in the fact that the wire-spray-initiation-point subjected to the wire-bending effect was aligned to the taper-initiation-point on the socket-inner-wall, which is likely to become the stress concentration area. It is also estimated that the maximum shear stress is greatly responsible for fatigue initiation and propagation.

On the other hand, the appreciable scatter in fatigue test results of the standard PWS might be attributed to interactions between the following factors.
(1) Depending on the individual difference of workers' skill, scatter occurs in wire- bending degree and range.
(2) The relative position of wire-bending affected zone and stress concentration point subtly deviate according to specimens.

4.2. Investigation of Improvement in Anchorage

If the above inference is correct, the following can be suggested as the improvements of anchorage.
(1) Provide a gentle taper angle on the socket inner wall to reduce wire stress concentration.
(2) Avoid wire-bending.
(3) Displace the wire-spray-initiation-point from the stress concentration area.

Among them, in Suggestion (1) above, the setting rate of poured metal due to strand tension after installation becomes great, increasing the apparent creep as a cable unit. Suggestion (2) requires newly a device to elastically spray the wires during pouring and hold the wires until poured alloy solidifies; this creates another problem of disposing of wire terminals before the subsequent pre-compression.

The simplest improvement is Suggestion (3), and, in concrete, it can be achieved as follows. That is, the wire-spray-initiation-point is moved scores of millimeters toward the socket inside, displacing the wire-bending affected zone from the stress concentration area.

In the recent investigation, the wire-spray-initiation-point was moved by 50 millimeters toward the socket inside and located as shown in Fig. 6.

5. Fatigue Test of Improved PWS

Ten specimens of improved PWS were prepared and fatigue tests were performed. The specimens were prepared in the same size, by the same method, and by the same personnel as the specimens of the standard PWS, except that the wire-spray-initiation-point was shifted 50 millimeters backward.

Test results are shown in Table 3, and Fig. 7. Fig. 7 also shows the test results of the standard PWS. Judging from Fig. 7, the endurance limit of the improved PWS could be estimated to be about 340 MPa. Because the endurance limit of the 1765 MPa wire itself is about 490 MPa, the fatigue reduction rate in the improved anchorage has be suppressed to about 30%. [The fatigue reduction rate was 70% in the case of the standard PWS.]

Two of the improved PWS specimens (Specimen No.I-1 and I-2) were anatomized at the poured portion and investigation was made on the wire-failure condition as done for the standard PWS specimens. The wire failure positions were 2 millimeters and 15 millimeters inside, respectively, from taper-initiation-point on the socket-inner-wall. Same as the standard PWS, the fracture surface consisted of two sections: fatigue fracture surface cracked at about 45° to the wire axis and final fracture surface nearly normal to the wire axis.

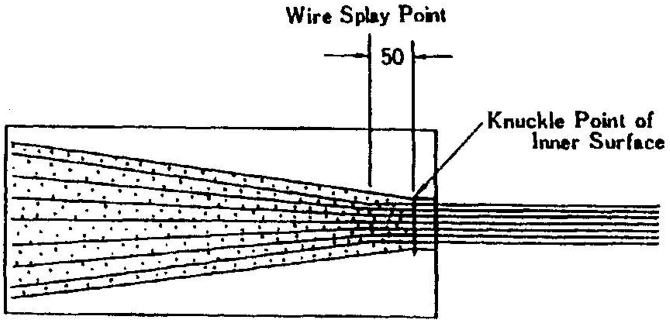

Fig.6 Rough sketch of improved PWS

Specimen	Number of Broken Wires	Broken Wire	x (mm)
I-1	1	⑭	− 2
I-2	1	⑨	−15

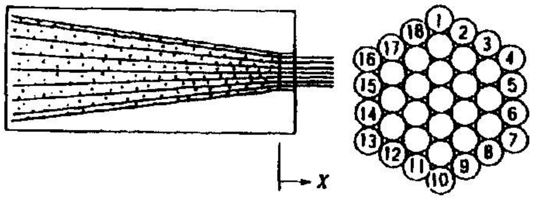

Table 4 Wire-failure location of improved PWS

Specimen	Maximum Stress (MPa)	Minimum Stress (MPa)	Stress Range (MPa)	Frequency (Hz)	Number of Cycles (x 10^4)		
					First Wire Failure	Second Wire Failure	Test Stop
I-1	796	550	246	4	174.0	No Failure	200.0
I-2	796	499	297	3	139.0	No Failure	200.0
I-3	796	452	344	3	No Failure		200.0
I-4	796	428	368	3	68.5	No Failure	200.0
I-5	796	418	378	3	62.3	64.8	64.8
I-6	796	404	392	3	40.6	56.2	56.2
I-7	796	379	417	3	50.5	52.0	52.0
I-8	796	355	441	3	26.2	29.8	29.8
I-9	796	306	490	3	23.9	28.5	28.5
I-10	796	282	514	3	11.8	14.1	14.1

Table 3 Fatigue test result of improved PWS

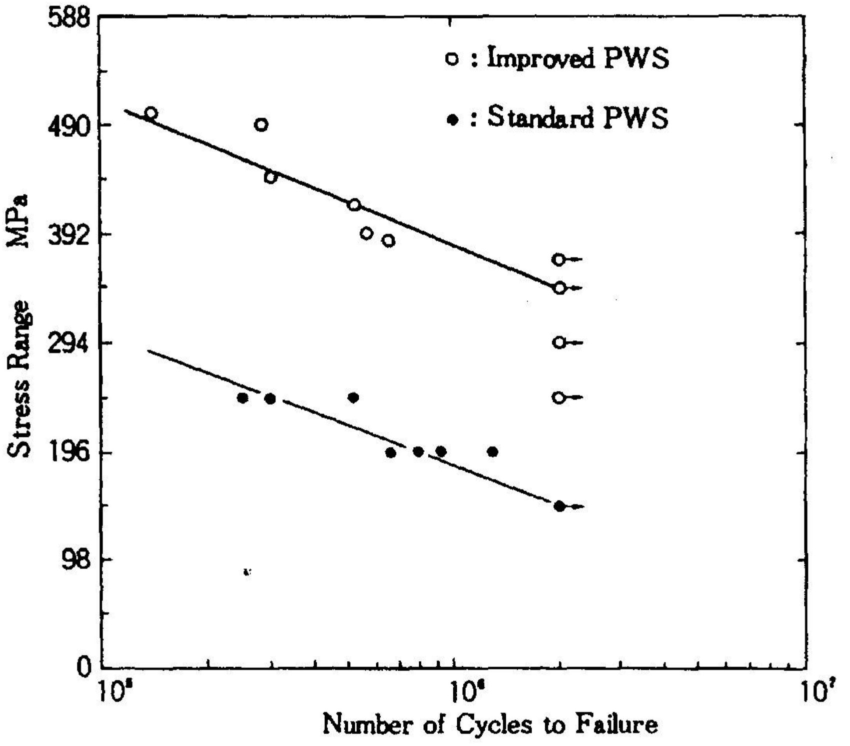

Fig.7 Fatigue test result of improved PWS

6. Discussion

With the foregoing description, it has been evidenced that the improved PWS in which the wire-spray-initiation-point is shifted only by 50 millimeters toward the socket inside as compared to that of the standard PWS has a great possibility to remarkably improve the fatigue strength of PWS with zinc-poured-anchorage.

Shinke et al. have already pointed out that slightly changing the anchorage fabrication method can generate a difference in fatigue strength of PWS with zinc-poured anchorage[4]. Shinke et al. fabricated PWS specimens with zinc-poured-anchorage using 1 569 MPa wire of the following two types:
(Type A) Wire spray was performed in the most popular conventional method like the the standard PWS in this paper.
(Type B) Wire-bending curvature of the wire spray portion is made slightly gentle.
and conducted fatigue tests. They further compared the fatigue test results with those[5] of single wire specimens with zinc-poured-anchorage (Type C) and summarized as follows:
(a) Fatigue limit at 2 million cycles of Type A and Type B is about 200 MPa and 250 MPa, respectively.
(b) That of Type C is about 340 MPa.

With these data taken into account, the recent investigation and test results are discussed as follows:
(1) The wire fatigue strength reduces in the zinc-poured-anchorage, and the reduction rate increases in order of single wire not subjected to bending, PWS with slightly smaller bending rate than that in current fabrication specifications, and PWS wire-sprayed in accordance with the current fabrication standard.
(2) In the zinc-poured-anchorage, even wire free from bending reduces fatigue strength. One of the principal causes could be attributed to the stress concentrated on the wire surface in the vicinity of the taper-initiation-point on the socket-inner-wall. According to the investigation results of the wire fracture surface, the maximum shearing stress arising from the wedge effect of poured metal seems to be greatly responsible for the initiation of fatigue crack.
(3) It would be appropriate to estimate that the bending magnitude of the wire spray portion is also responsible for the reduced fatigue strength in the regular PWS anchorage, to which wire spray is performed and zinc is poured. That is, the portion which is more greatly subjected to wire-bending and acts as a weak point with respect to the initiation of fatigue crack seems to be more likely to fail earlier due to fatigue.
(4) Same as the stress on the wire surface which is distributed in a certain area, the susceptibility of bent wire to fatigue crack would be also distributed in a certain area, and fatigue strength seems to vary according to the correlationship between respective distributions*. For example, the wire is most likely to fail due to fatigue when the stress concentration peak coincides with the weakest point of the wire, and when these deviate each other, either factor becomes critical and possibly causes fatigue failure.
Difference of wire bending technique of each individual worker or subtle difference in wire bundle extrusion rate due to pre-compression may tend to cause the correlationship between these distributions to vary in a unit of millimeter. It is estimated that appreciable scatter in fatigue test results generated in the standard PWS may be caused by the minor deviation of stress

concentration area and wire weak point.
(5) From the above estimation of causes, following improvements are proposed.
(a) The socket shape will be changed to the extent that would not cause any detrimental effect on the setting rate of poured alloy in order to alleviate stress concentration on the surface.
(b) The PWS fatigue limit can be improved by either relaxing the bending magnitude of the wire located at the stress concentration area or designing a method that does not need any bending at all. The method proposed in this paper is to locate the wire free from bending at the stress concentration point.

7. Conclusion and Future Subjects

In this study, fatigue tests and FEM analysis were carried out on zinc-poured PWS-37 used the wires with a breaking strength of 1 765 MPa and causes reducing fatigue strength of conventional standard PWS were estimated and improvements of anchorage were investigated. Our conclusions are summarized as follows:
(1) 5% failure fatigue strength of standard PWS is about 150 MPa in terms of stress range in the recent experiment using 1 765 MPa wire and appreciable scatter was found in experiment results.
(2) From the observation of wire fracture surface and FEM analysis results of anchorage, it was inferred that the fatigue failure in anchorage is attributed to the locational coincidence of the stress concentration area of the wire surface near the taper-initiation-point on the socket-inner-wall with the wire-bending affected zone.
(3) To improve the fatigue strength of PWS with-zinc-poured-anchorage, proposal was made to remove the wire bent portion from the stress concentration area and verification experiments were carried out. As a result, it has been confirmed that 5% failure fatigue strength of PWS using the 1 765 MPa wire can be increased from about 150 MPa before improvement to about 350 MPa in terms of stress range.
(4) Following items remain as future subjects:
- Increase the number of data to complete the S-N curve.
- Carry out fatigue tests with PWS of greater size.

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