Fatigue Problems of Bridge Cables in Japan

Fatigue dans les câbles de ponts au Japon

Ermüdungsprobleme bei Brückenkabeln in Japan

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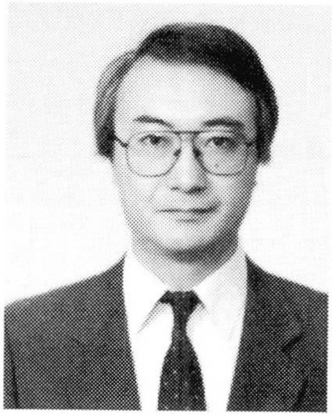

SUMMARY
Several long cable-stayed bridges and also the world´s longest suspension bridge have been built in recent years in Japan. This paper gives recent information on fatigue problems of bridge cables and indicates better solutions of cable system and the future developments from viewpoint of durabilty as well as fatigue strength and other mechanical properties.

RÉSUMÉ
Plusieurs ponts à aubans de grande portée ainsi que le pont suspendu le plus long du monde ont été tout récemment construits au Japon. Cette communication présente quelques informations récentes sur les problèmes relatifs à la fatigue des câbles de ponts et, par ailleurs, propose de meilleurs solutions pour les systèmes de câbles. Elle esquisse enfin leur développement futur, sous l'aspect de durabilité, de résistance à la fatigue et d'autres propriétés mécaniques.

ZUSAMMEMFASSUNG
In der letzten Zeit sind mehrere lange abgespannte Brücken sowie die weltlängste Hängebrücke in Japan gebaut worden. In der vorliegenden Arbeit werden gegenwärtige Auskunft über Ermüdungsprobleme an den Brückenkabeln erteilt, und bessere Lösungen für das Kabelsystem vorgeschlagen. Zuletzt wird die voraussichtliche Entwicklung hinsichtlich der Dauerhaftigkeit, der Ermüdungsbeanspruchung und anderen mechanischen Eigenschaften skizziert.

INTRODUCTION

Figure 1 shows how the cables of cable-stayed bridges in Japan have changed in recent years. As the size of cable-stayed bridge has become larger, cables have become longer and their diameter bigger even though multi-cable systems have been employed. The following points should thus be considered in the study based on these requirements.

(a) higher strength and modulus of elasticity

(b) higher fatigue strength both for tension and bending

(c) adequate corrosion protection

(d) easier installation and maintenance

The following describes the recent trends in the manufacture of bridge cables in consideration of the above points and additional matter which should be studied in the future.

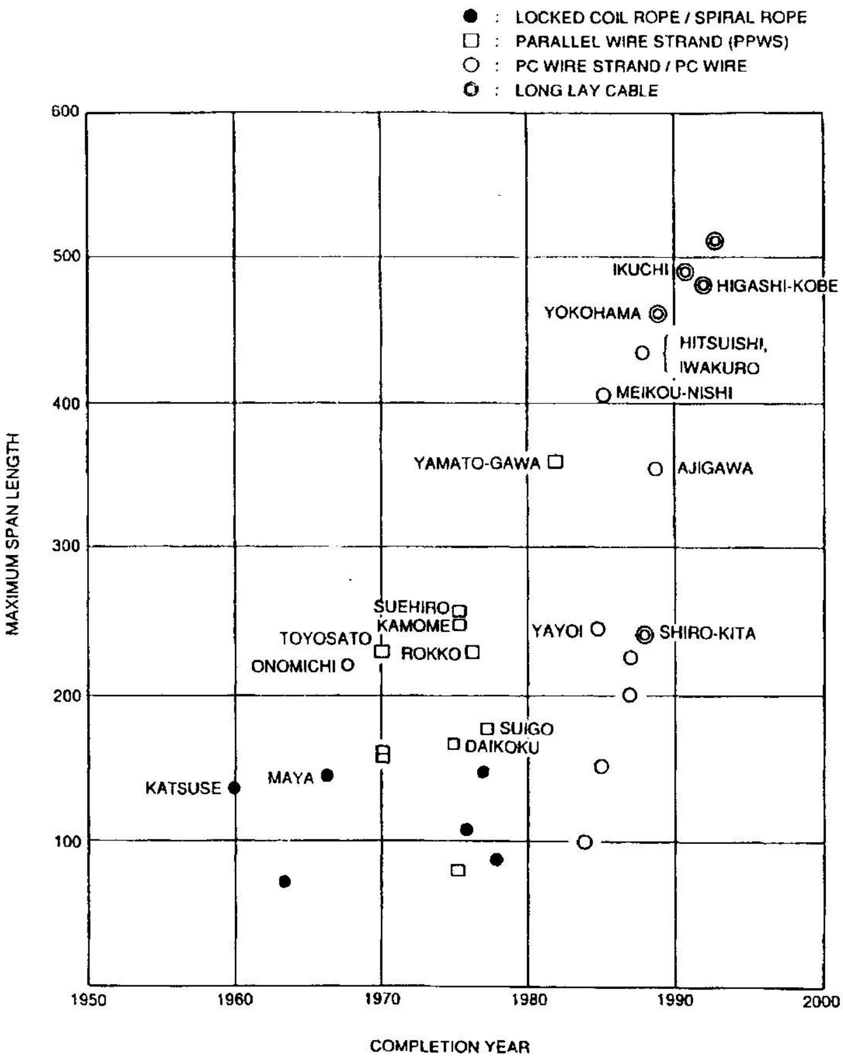

Fig.1 Historloal Change of Cable Type of Cable-Stayed Bridge in Japan

CABLE WIRE

1. Wire Rod

Cable wire is produced by two major processes : either by manufacturing wire rod or by wire producing processes like drawing and galvanizing.
The following factors influencing the fatigue strength arise mainly in wire rod stage.

(a) de-carbonization layer on the surface
(b) surface flaw
(c) non-metalic inclusion
(d) inappropriate chemical composition

In a study of factors which may influence the initiation of fatigue fracture, T.Yokobori et al achieved some good experimental results, they showed that in the case of drawn wire made from patented material, non-metallic inclusions are much more likely to initiate fatigue cracks than sureface conditions and the initiation of these micro-cracks will occur only during 5 ~ 20% of the total life [1].

These factors are essential items in the quality control of wire rod. Table 1 shows the new specifications of wire rod for the Akashi Kaikyo Bridge (suspension bridge, mid span = 1,990m)[2]. Although it is basical considering

Table 1 Specification on Wire Rod for Cable Wire in HBS (G 3507)

		REQUIREMENT
SIZE	DIAMETER	LESS THAN ±0.40 mm
	ROUNDNESS	LESS THAN ±0.40 mm
NON-METALLIC INCLUSION	RATIO	LESS THAN 0.07 %
DE-CARBONIZATION LAYER	DEPTH OF LAYER	LESS THAN 0.07 mm
SURFACE FLAW	DEPTH OF FLAW	LESS THAN 0.07 mm

whether the probability of failure is proportional to the degree of the factors mentioned above, it would be better to have the more stringent quality control requirements. However, it would also be important to improve both the manufacturing method and the QA programme to ensure the degree of manufacturing error (even 3 σ) would satisfy the requirements, and also to recognize that any such consideration should be based upon the kind of material, manufacturing method and specifications/standards used.

2. Galvanized Wire

The drawing and galvanizing processes also affect the fatigue strength. The important factors in this are assumed to be as follows.

(a) reduction ratio in the drawing process
(b) heat applied in the galvanizing process
(c) thickness of the Fe-Zn alloy layer

These factors basically relate to the processes used by individual wire makers and their degree of expertise. However, it has been reported in the recent studies [3][4] that :

(a) When the reduction ratio in the drawing process goes up, the fatigue strength first goes down but goes up later on. However, there comes a peak soon. So, it could be said that it would be better to raise the fatigue strength not through the drawing process but through chemical means and the heating process.

(b) For high carbon steel, when temperature of 450°C is maintained for a certain period of time. Though the tensile strength drops, the fatigue strength does not go down much. However, of 480°C, the fatigue strength drops significantly. So, care must be taken in choosing the temperature and the time it is maintained for, which should both be strictly controlled.

(c) As the Fe-Zn alloy layer gets thicker, the fatigue strength goes down. However, if the Fe-Zn layer becomes too thin, the amount of heat required would be less so that pre-heating would necessary before galvanizing.

The above could be said to apply to the high carbon steel wire with a ultimate strength of 160 kgf/mm^2 used in most of the suspension bridges and the cable-stayed bridges in Japan. Recently, a stronger wire (σ_{ut}=180 kgf/mm^2) has been developed and has been used for the main cables of the Akashi Kaikyo Bridge. The features of this steel wire are as follows :

(a) Higher strength achieved using silicon.

(b) The effect of heat on the tensile strength is less than for conventional wire.

(c) The fatigue strength of this wire is equal to or more than that of conventional wire.

As mentioned above, steel wire can be strengthened mainly by drawing alone but there would be restrictions on ductility and fatigue strength. So, it would be better to strengthen it by chemical means and the heating process. It is known that, in addition to carbon, slicon manganese and chromium are good for strengthening wire in the heating process and that silicon raises the strength of patented materials without changing the lamellar spacing. The tensile strength increases by approximately 15 kgf/mm^2 when the silicon is increased to 1%. Also, silicon can control the cementaite, so for 1% silicon, the tensile strength would decrease not much during bluing, although in the case of high carbon steel, it will decrease by about 10 kgf/mm^2. Figure 2 shows the tensile strength for different temperatures for high carbon steel and steel with silicon [5].

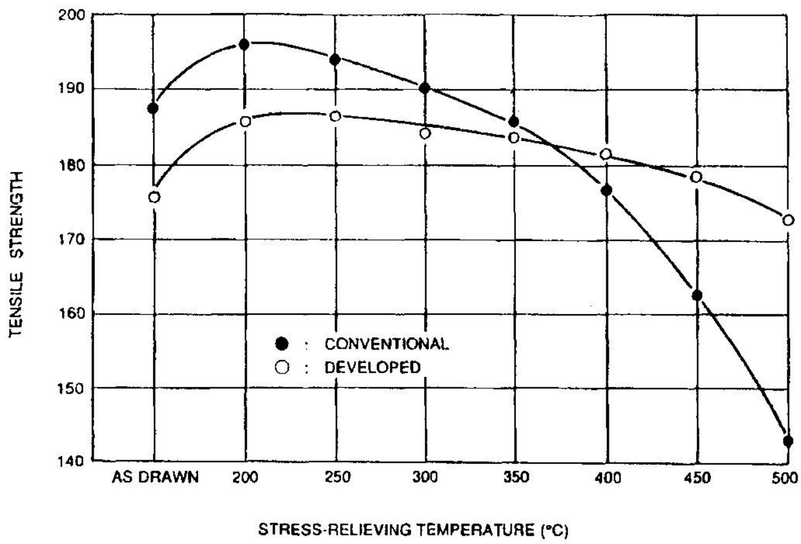

Fig. 2 Tensile Strength of Steel Wire at Stress-Relieving after Drawing Process

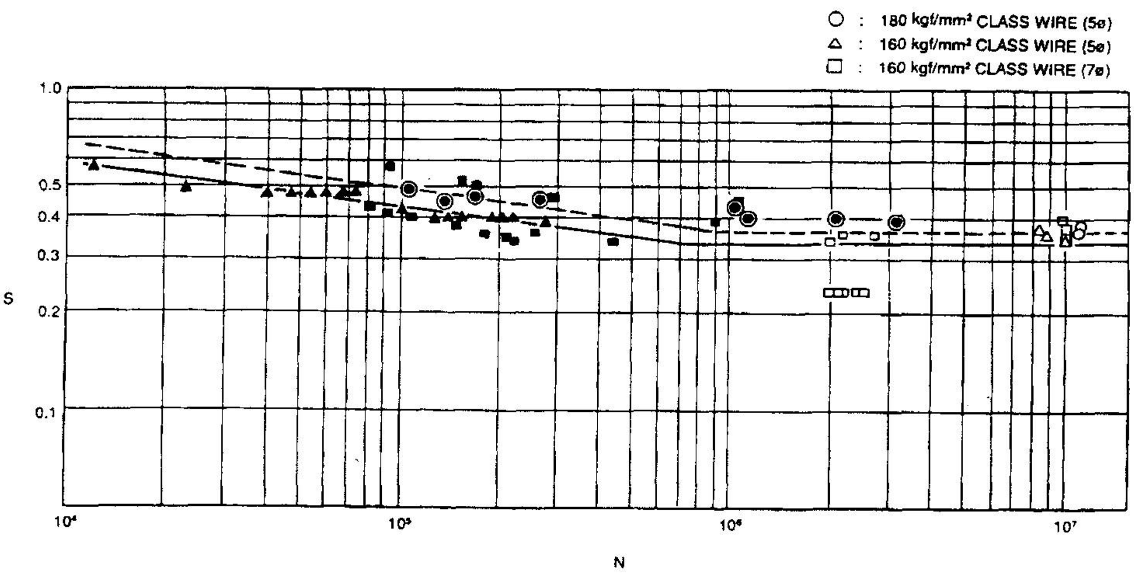

Fig. 3 S-N Curve of Galvanized Steel Wire

In newly developed wire, the strenghth has been improved and also reduction in strength due to the heat applied has been kept to a minimum. Therefore, it has good ductility which increases the fatigue strength (see Fig. 3), shows good results in the delayed fracture test and other mechanical properties are also good. Figure 3 gives a non-dimensional expression ; $S=(S_r f_u/[1-(f_m/f_u)^2])$ which f_u is the ultimate strength S_r is the stress range tested and f_m is the mean stress [6].

CABLE WITH ANCHORAGE

The factors influencing the fatigue fracture of cables are the fretting corrosion and the length deviation in a cable as an assembly of wires, the stress concentration, the fretting corrosion and the heat applied when the cable anchors were installed.

Figure 4 shows the difference between the fatigue test results for wires and cables with anchors. The cables have an impoved zinc socket at both ends which is asuumed to give a better fatigue strength than the conventional type. This difference in fatigue strengths is assumed to arise problems that still exist with anchors such as stress concentration at the fixing front, fretting corrosion in between wires and length variation in wires as well as defects in them.

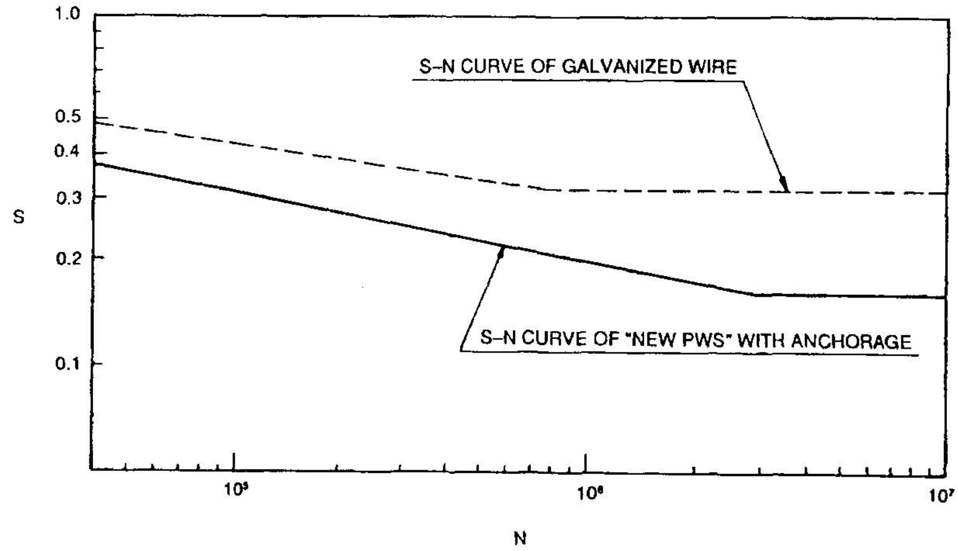

Fig. 4 Comparison on Fatigue Strength between Cable Wire and Cable with Anchor

Regarding the fatigue strength of the cable itself, several models assuming that it is an assembly of wire units have been proposed and discussed. These discussions have mainly concerned themselves with the variation in the amount of defects in wires. However, as mentioned above, the probability of defects basically depends upon the type of wire and cable, so it is important to specify the object of the study. The cable wire used for the Honshu Shikoku Bridge have given good results until now in that the variation in tensile strength (3σ) has been 5~7 kgf/mm^2. In this case, if the variation in fatigue strength could be somehow made proportional to that in the ultimate strength, the variation in fatigue strength in this type of wire would be relatively small.

Besides the wire, the fatigue strength of a cable depends much upon its structure. Table 2 shows the fatigue strengths of several types of cables. It shows that twisted wire rope suffers more from fretting problems than parallel wire cables. Figure 5 shows a failure distribution for wires subjected to the bending fatigue test. It can be seen that the parallel wire cable or similar cable, such as the long lay cable (e.g. NEW-PWS), would be better than wire rope.

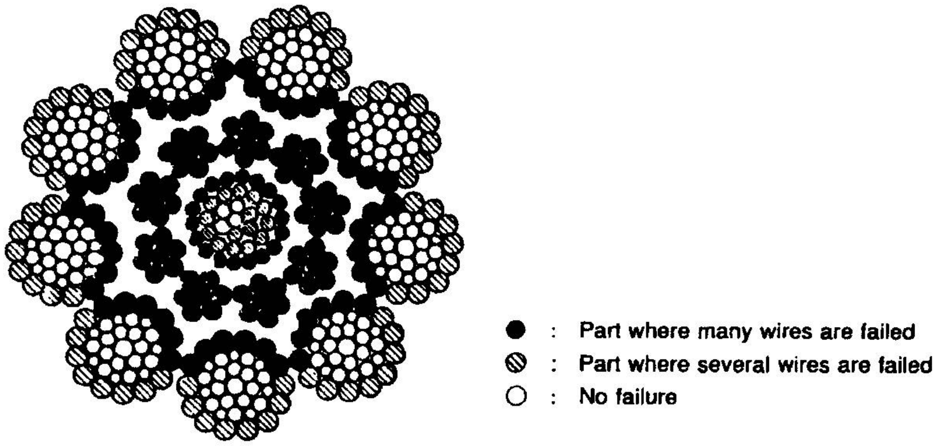

Fig. 5 Distribution of Failed Wire at Bending Fatigue Test of "Center Fit Rope Core" (CFRC)

Table 2 General comparison on Fatigue Strength between Types of Cable [7], [8]

		Fatigue Strength	
		Tension Fatigue ($\Delta\sigma$)	Bending Fatigue (Test Result)
WIRE ROPE	LCP	appr. 15(kgf/mm^2)	3~7% failure until 3×10^6 cicles at $\theta=\pm0.57°$
	SPR	ditto	————
	IWRC	13~14 (kgf/mm^2)	————
	CFRC	ditto	cable failure until 0.8×10^6 cicles at $\theta=\pm0.57°$
PPWS		15~20 (kgf/mm^2)	0.8~3% failure until 4×10^6 cicles at $\theta=\pm0.57°$
NEW-PWS		appr. 25(kgf/mm^2)	no failure until 3×10^6 cicles at $\theta=\pm0.6°$

The typical way installing cable anchors is by spreading out the wires inside a socket and pouring zinc or zinc alloy into it. However, even molten zinc is not capable of penetrating the small spaces between wires and eventually it would become concentrated in certain areas, especially at the outlet of the socket as shown in Figure 6-a. This would cause unequal tension in the wires, concentrating it in certain parts, and might increase the fretting there.

Figure 6-b shows an improved zinc socket which solves these problems. This socket is as resistant to fatigue as the well-known HiAm Anchor. Important features for anchors are a simple structure and ease of installation.

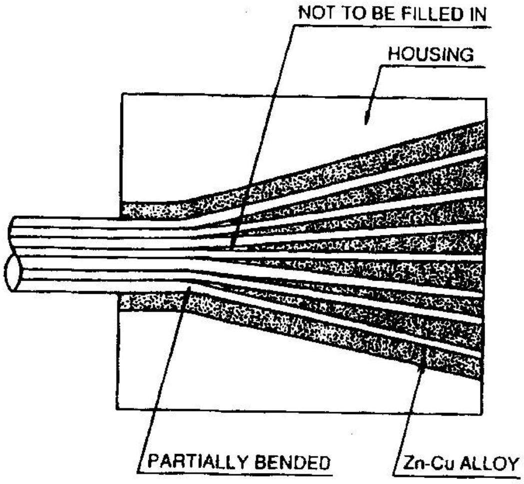

Fig. 6-a
Conventional Zinc Socket

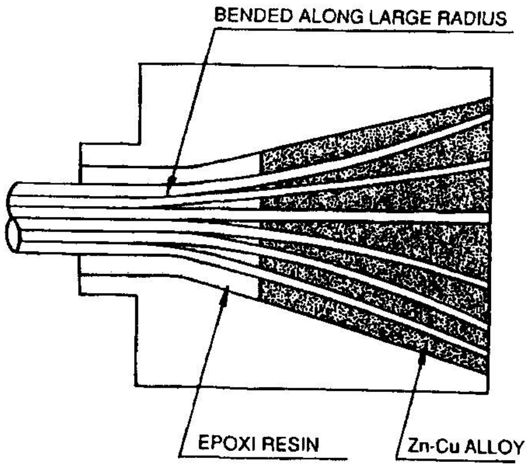

Fig. 6-b
Improved Zinc Socket

OTHER TOPICS

In the case of bridge cables, corrosion protection and easy maintenance may be equally or more important than fatigue because probably we have never heard of bridge cables suffering from serious damage caused by pure fatigue. We can easily give several examples of corrosion problems in the history of cable suspended bridges.

Figure 7 shows the results of fatigue tests on corroded wires which were subjected to a Salt Spray Test (SST) for 50 days, 100 days and 150 days [9]. The results clearly show that the corroded wires have much less fatigue strength than sound wires. A rough wire surface may cause stress concentration lowering the fatigue strength as the amount of drop in fatigue strength becomes less as the wires become more corroded.

Besides the evaluation of corroded wires, it can be said that wire should thus be protected against corrosion, first of all, by galvanizing not by such a way as cement grouting. And methods should be developed for inspecting whether corrosion protectian is adequat or not. The magnetic, ultrasonic and other methods have been reported but being insufficient, still require further study. For this reference, it has been reported in the U.S. that a new method has been adopted to search for corrosion, even right inside of cable [10].

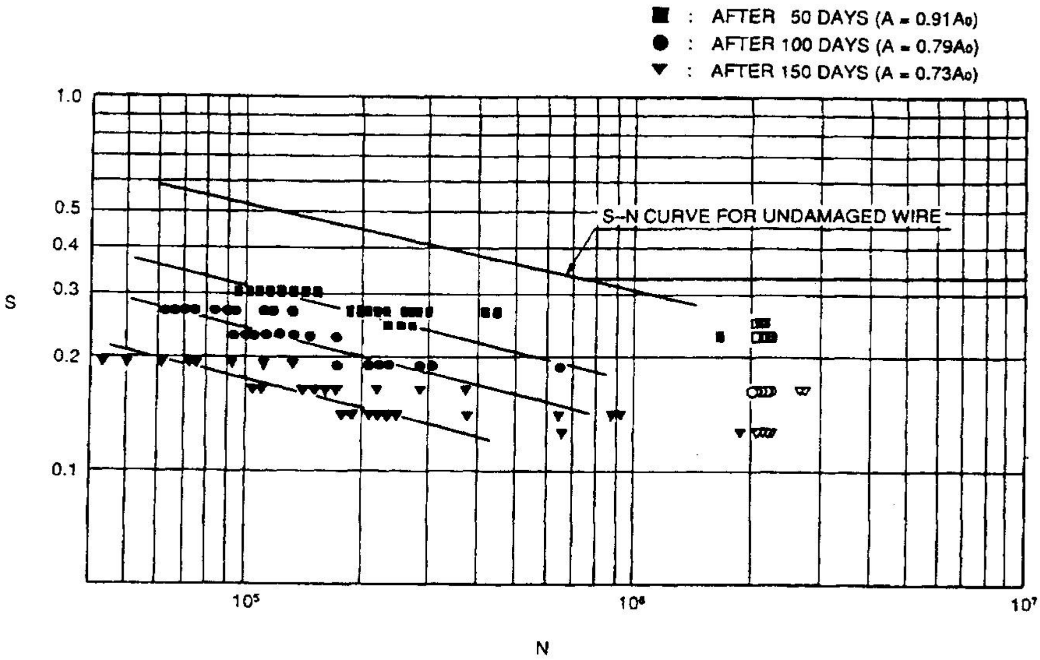

Fig. 7 S-N Curve of Galvanized Steel Wire after Salt Sprayed Test (Test Condition : 0.5 cm^3/min., Salt Water (pH 6.5-7.2)) (Courtesy of Kobe Steel)

CONCLUSION

Recently, much longer suspension bridges have been planned and built, such as the Akashi Kaikyo Bridge in Japan and the Great Belt Bridge in Denmark and the large cable-stayed bridges have been steped forward building. Because of this, an accurate understanging of the fatigue and bending fatigue properties of cables and problems associated with them as well as their tensile strength is extremely important. We should therefore consider the following to ensure the durability and quality of design, construction and maintenance of cables.

1. The higher strength wires so far developed and used for the main cables of the Akashi Kaikyo Bridge have high fatigue strengh and other good mechanical properties. However, concerning cable structure, it should be remembered that the parallel wire system has better fatigue performance and mechanical properties than conventional twisted wire ropes.

2. From the viewpoint of the whole cable system, it should be noticed that that cable anchors tend to be the weak point rather than the cable wires

themselves. Therefore, reliable anchors should be used to improve the design. It is also important that cable anchors should be designed for easy fabrication, and installation in accordance with manufacturing standards, as well as for mass production.

3. Concerning the long term use of cables as in cable-stayed bridges, both better corrosion protection and the easier maintenance are very important points. However, these two points are in conflict with each other and there is also the problem that the inside of the cable is hard to inspect. Polyethylene coverings have been used recently for many cable-stayed bridges which employ long lay cables with zinc coated wires but may still require improvement to make inspection and maintenance easier.

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