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Development and Investigation of High-Strength Galvanized Wire

Développement et recherche sur le fil d'acier galvanisé à haute résistance

Entwicklung und Untersuchung von hochfesten verzinkten Stahlseilen

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SUMMARY
The details of development and material quality of high-strength galvanized steel wire and its effect on bridge design are described. Il will be used for the first time as the main cable for the Akashi-Kaikyo Bridge.

RESUME
Ce rapport décrit en détail le développement et la qualité du fil d'acier galvanisé à haute résistance en tant que matériau, et son effet sur la conception du pont. Ce fil sera utilisé pour la première fois pour le câble porteur du pont d'Akashi-Kaikyo.

ZUSAMMENFASSUNG
In diesem Bericht sind die Entwicklungseinzelheiten sowie die Materialqualität von hochfesten verzinkten Stahlseilen und ihre Auswirkung auf die Auslegung von Brücken beschrieben. Sie werden bei der Akashi-Kaikyo-Brücke erstmals als Tragseile eingesetzt.

1. BACKGROUND TO THE DEVELOPMENT OF HIGH-STRENGTH STEEL WIRE

The Brooklyn Bridge is the first large suspension bridge in history to make use of galvanized steel wire in the main cables. Since then the use of parallel galvanized wires for main cables has become common. As shown in Fig. 1, the tensile strength of the steel wires used in cables has not been improved for more than a half century, remaining at 155-160 kgf/mm^2 since the George Washington Bridge was built. Five-millimeter-diameter steel wires of 160 kgf/mm^2 class have been used for the main cables of many suspension bridges in Japan, including the Honshu-Shikoku Bridges, and loads have reached as much as 75,000 tons. The reasons this particular size of wire becoming popular include the fact that the fabrication of the wire and its processing is easy, prices are relatively low, and the component is such that stable quality can be achieved even in mass production. Little demand has arisen for steel wires of higher tensile strength than 160 kgf/mm^2 for use in the main cables of suspension bridges.

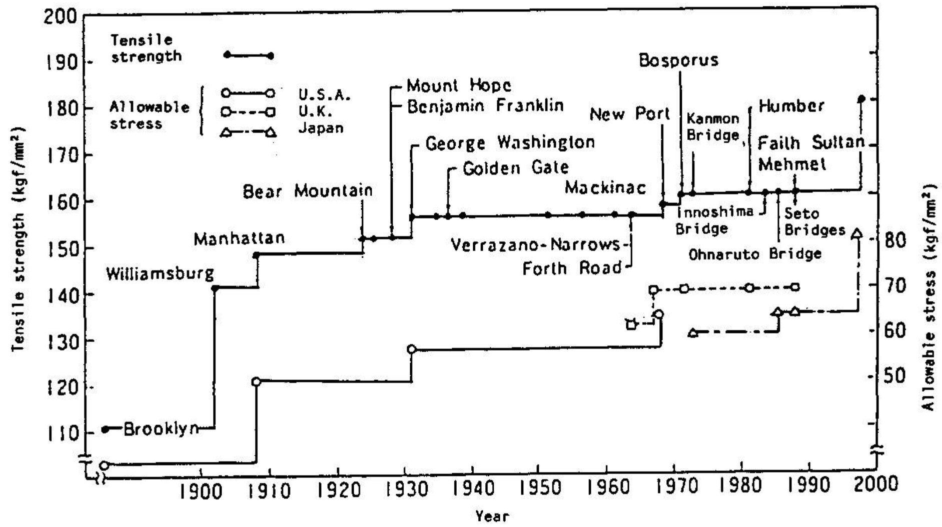


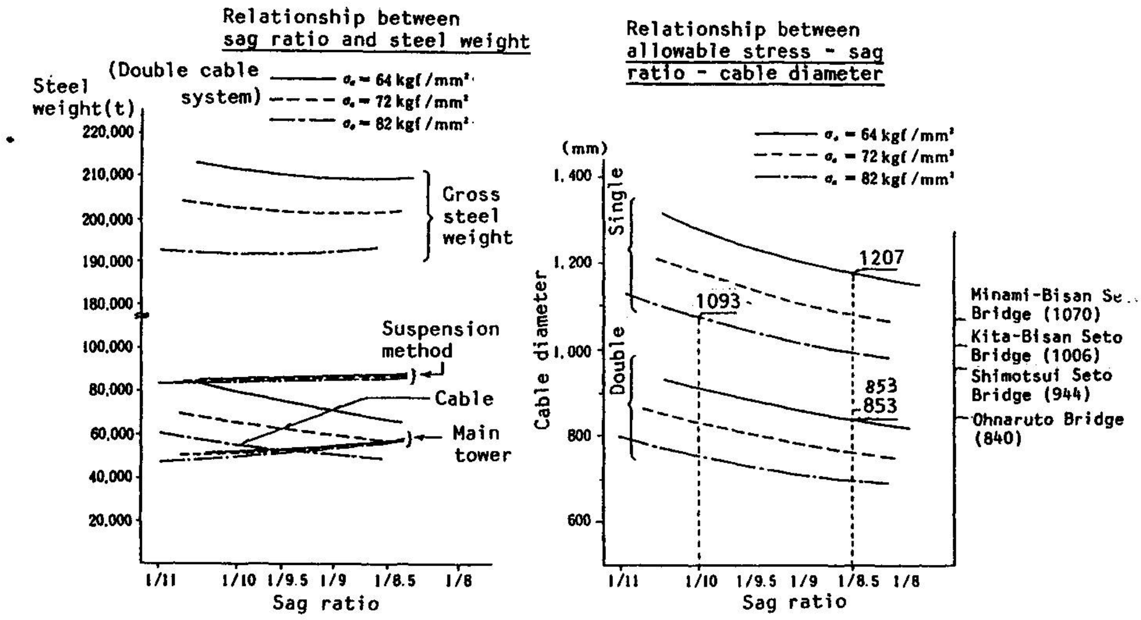
Fig. 1 Improvements in strength of galvanized steel wire

Since the center span of the Akashi-Kaikyo Bridge will be extremely long, at about 2,000 m, the ratio of dead load to total cable tension will be as high as 91%, making reduction of the dead load an important issue.

Other suspension bridges in the Honshu-Shikoku Bridges have adopted steel wires of 160 kgf/mm^2 class (tensile strength: 160-180 kgf/mm^2) and the design was implemented based on the tensile strength to allowable stress ratio (or safety factor) of 2.5 and allowable stress of 64 kgf/mm^2.

Figure 2 shows the relationship of allowable stress in the cable to cable diameter, sag to span ratio (sag ratio), and steel weight. The figure shows that if the allowable stress (σ_a) can reach at about 80 kgf/mm^2 it is possible to use a single cable system with a diameter slightly larger than that used on the Minami-Bisan Seto Bridge with a sag ratio of 1/10.

Table 1 shows a comparison of factors in bridges with a double-cable system (σ_a = 64 kgf/mm^2, sag ratio = 1/8.5) and a single-cable system (σ_a = 82 kgf/mm^2, sag ratio = 1/10). The advantages derived by increasing the allowable stress and using a single cable system are outlined below.



<u>Fig. 2</u> Effect of allowable stress

<u>Table 1</u> Comparison of factors of suspension bridge due to difference in allowable stress of cable.

Allowable stress of cable			82 kgf/mm²	64 kgf/mm²
Basic factors	Span length	Cable (m)	960 + 1.990 + 960	
		Stiffening girder (m)	936 + 1,970 + 936	
	Cable sag ratio		1/10	1/8.5
	Cable center spacing (m)		35.5	38.5
	Number of cables (member/side)		1	2
	Dead load strength	Cable (t/m)	13.60	16.76
		Suspension portion (t/m)	27.57	28.34
		Total (t/m)	41.17 (1.00)	45.12 (1.10)
Cable	Composition of cable section		271st x PWS127	169st x PWS127 x 2
	Diameter of element wire (mm)		ϕ5.27	ϕ5.21
	Sectional area of cable (m²)		0.7507 (1.00)	0.9152 (1.22)
	Diameter of cable (m)		1.093 x 1	0.853 x 2
	Maximum horizontal tension (tf/side)		55,592	51,472
Displacement amount	Horizontal deflection amount (m)		33	38
	Vertical deflection amount (m)		7.0	7.0
	Elongation amount (m)		1.5	1.7
	Horizontal displacement amount, tower top (m)		1.4	1.6

By making the allowable stress about 80 kgf/mm² (sag ratio = 1/10), the following benefits are gained:

(1) The weight of steel can be reduced.
(2) The height of the main tower can be reduced.
(3) Although horizontal deflection, vertical deflection, expansion, and horizontal displacement of the stiffening girder increase as the allowable stress increases, this can be covered by reducing the sag ratio.

By adopting a single cable system the following benefits arise:

(1) The weight of steel can be reduced.
(2) Structure can be simplified.
(3) Load distribution can be clarified as the number of hanger anchoring

points at the girder is reduced from four to two lines.
(4) The relative position of the strand anchoring structure and the anchorage for the splayed section of cable is simplified.
(5) Horizontal deflection of the stiffening girder can be reduced.

2. DEVELOPMENT OF HIGH-STRENGTH STEEL WIRES

2.1 Methods of increasing strength of galvanized steel wire

The galvanized steel wire used for bridge cables is given the necessary strength by heat treatment (patenting) using a high carbon steel, then it is drawn and finally galvanized. Figure 3 shows typical changes in strength of steel wire during manufacturing process.

Three means to increase the strength of galvanized steel wire may be considered as follows.

(i) Increasing the degree of processing during wire drawing.
(ii) Adding small amounts of other elements.
(iii) Controlling strength loss due to the heat reaction during galvanizing.

Although (i) is the simplest method to raise strength, ductility is reduced in the process.

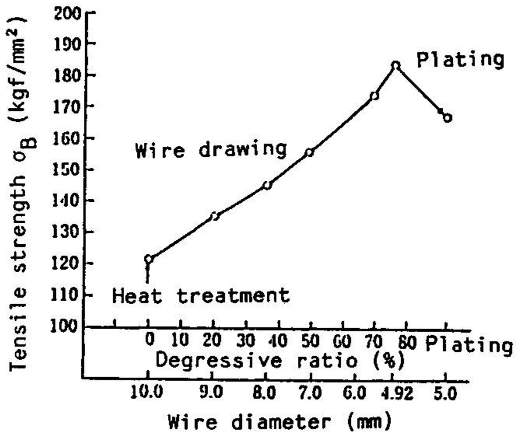


Fig. 3 Changes in strength of steel wire during manufacturing

If method (ii) is used, 1) although the addition of Mn and Cr is effective, the transformation time is much longer, presenting problems in the heat treatment operation, 2) increasing the C content results in reduced ductility because the composition becomes a hyper-eutectoidal, and 3) the addition of Si is effective in increasing strength and the transformation time does not become too long.

Regarding method (iii), if Si is added, reduction in strength due to heat application at the time of galvanizing is smaller.

The above discussion indicates that the possibilities for increasing the strength of the presently-used SWRS77 (JIS G 3501) appear to be limited. Instead, a low-alloy steel must be adopted. One element which could be used is Si, since it is the most effective considering strength, ductility, and heat treatablibity. Such steel has already been put to practical use in the fields of PC steel wires, reinforcement wires for electric power lines, and steel cables, and effort to develop high-strength steel wire have power been based on the Si system low-alloy steel approach.

Before putting steel wires of 180 kgf/mm^2 class into practical use, the following characteristics must be checked:

(i) Mechanical properties, adhesion of plating and linearity as specified in HBS G 3501.

(ii) Creep, fatigue, and stress corrosion cracking.
(iii) Corrosion.
(iv) The effects of lateral pressure, bending, etc., the socket anchorage, and the coefficient of linear expansion.
(v) Effects of fluctuations in Si content, and quality during mass production.

2.2 Test results

With regard to (i), the required strength was obtained and all characteristics proved excellent, including mechanical properties, despite concern that they would suffer as the strength was increased.

With regard to (ii), despite stress increasing in proportion to the greater strength, the creep characteristics were excellent with a creep strain of about 2/3 times of conventional steel wire. In partially pulsating tensile fatigue tests, the fatique characteristics also proved excellent, with stresses about 10 kgf/mm^2 higher being possible. In addition, it was confirmed that the stress corrosion cracking characteristics were better than those of conventional steel wire.

With regard to (iii), corrosion characteristics were checked with brine atomizing tests, accelerated weathering tests, repeated dry and wet tests, outdoor exposure tests, etc., and the results showed no significant difference from the conventional steel wire.

With regard to (iv), the effects of lateral pressure were equivalent to those of conventional steel wire, with no strength reduction as long as the lateral pressure was less than 500 kgf/mm^2. With regard to the effects of bending, there was no strength loss when the wires were bent. No slippage occurred in the socket portion when a conventional socket was used, nor was there any significant difference as compared with conventional steel wire in the tests for coefficient of linear expansion.

With regard to (v), the tensile strength of steel wire as the Si content was varied from 0.73% to 1.01% was in the range of 188.7-196.0 kgf/mm^2, which thoroughly satisfies the requirements while ductility, twisting, and plating characteristics were also excellent.

To confirm quality in mass production, 160 tons of galvanized steel wire (four heats) was manufactured using an actual production line and the quality of its mechanical and plating characteristics was confirmed. It was discovered that the steel wire had fine characteristics and the deviation between heats and processing firms was extremely small.

2.3 Conclusions

High-strength steel wire (180 kgf/mm^2 class) based on Si low-alloy steel has equivalent or superior characteristics to conventional steel wire (160 kgf/mm^2 class) and we judge that application is possible. The main cables for the Akashi-Kaikyo Bridge could be formed with this new high-strength steel wire of 180 kgf/mm^2 class.

3. EXAMINATION OF ALLOWABLE STRESS

Allowable stress of main cables in Akashi-Kaikyo Bridge was re-examined in consideration with following points.

(i) Cables carry a larger ratio of dead load compared with other structural members (tower, stiffening girder, etc.) and have greater allowance for the live load. This is particularly so in the case of the Akashi-Kaikyo Bridge. For example, if the Akashi-Kaikyo Bridge and the Innoshima Bridge were to be designed with the same safety factor, the former would have a large safety margin against the assumed ultimate load even if the safety factor of the bridge were 2.2 as shown in Fig. 4.
(ii) Judging from manufacturing records of steel wire used in existing suspension bridges, the quality of steel wire is highly reliable.
(iii) Secondary stress has little effect on the bearing stress of the cable as a whole.
(iv) Construction management and maintenance can be based on experience gained up to now.

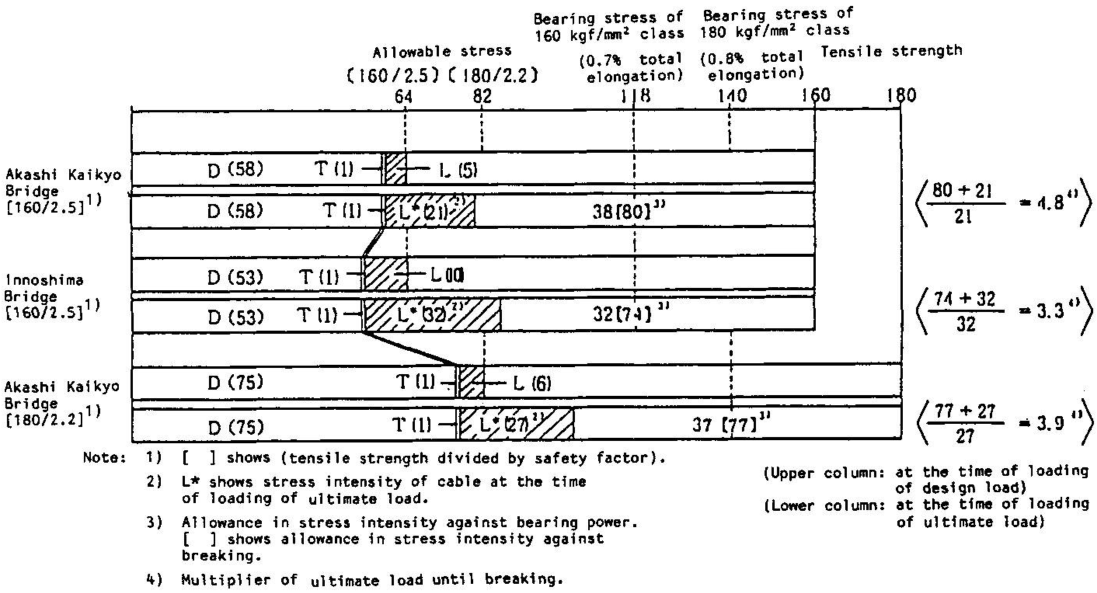


Fig. 4 Cable stress when loaded with the ultimate load (unit: kgf/mm^2)

4. FINAL ASSESSMENT

It has been confirmed that low-alloy steel wire with added Si, a newly developed wire, has characteristics equivalent or superior to conventional steel wire. By using this high-strength steel wire for the main cables of the Akashi-Kaikyo Bridge, it will be possible to use a single cable system and to apply more rational structural designs.

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