Istanbul Bridge Conference
August 11-13, 2014
Istanbul, Turkey

STATE-OF-THE-ART OF NEW MATERIALS AND FUTURE PERSPECTIVES ON SUPER LONG SPAN BRIDGES

T. Yamane[1], A. Takaue[2], T. Ikeda[3], Y. Z. Gundogdu[4]

ABSTRACT

In this study, feasibility of using new materials for super long bridges to extend the length of center span will be discussed. First, Carbon-Fiber Reinforced Plastic (CFRP) material will be introduced. When examined in contrast, superiority of CFRP material's structural properties, such as unit weight, tensile strength etc., over conventional steel wire will be emphasized. Then a trial concept design, 5,000m center span length, will be exhibited, followed by addressing the technical issues of CFRP material to be solved. Furthermore, practical state-of-the-art and recent advances in high-strength steel wire will be presented. Thermo-Mechanical Controlled Process (TMCP) and conventional steel wire production technologies will be reviewed. Two types of high performance steel produced by using TMCP which show improved yield strength, welding workability, formability and fatigue life when compared to conventional steel will be investigated. Finally, future super long bridge project plans in Japan will be introduced.

[1]Structural Bridge Engineer, MSc., Chodai Co., Ltd., 730, Higashi- Hiratsuka, Tsukuba, Ibaraki Japan 305-0812
[2]Structural Bridge Engineer, PhD., Chodai Co., Ltd., 1-20-4, Chuo-Ku, Tokyo, Japan, 103-0014
[3]Structural Bridge Engineer, MSc., Chodai Co., Ltd., 1-20-4, Chuo-Ku, Tokyo, Japan, 103-0014
[4]Structural Bridge Engineer, MSc., Chodai Co., Ltd. Representative Office, Kozyatagi, Istanbul, Turkey, 34744

Yamane T, Takaue A, Ikeda T, Gundogdu Y. Z. State-of-the-art of new materials and future perspectives on super long bridges. *Proceedings of the Istanbul Bridge Conference*, 2014.

Istanbul Bridge Conference
August 11-13, 2014
Istanbul, Turkey

State-of-the-art of New Materials and Future Perspectives on Super Long Span Bridges

T. Yamane[1], A. Takaue[2], T. Ikeda[3], Y. Z. Gundogdu[4]

ABSTRACT

In this study, feasibility of using new materials for super long bridges to extend the length of center span will be discussed. First, Carbon-Fiber Reinforced Plastic (CFRP) material will be introduced. When examined in contrast, superiority of CFRP material's structural properties, such as unit weight, tensile strength etc., over conventional steel wire will be emphasized. Then a trial concept design, 5,000m center span length, will be exhibited, followed by addressing the technical issues of CFRP material to be solved. Furthermore, practical state-of-the-art and recent advances in high-strength steel wire will be presented. Thermo-Mechanical Controlled Process (TMCP) and conventional steel wire production technologies will be reviewed. Two types of high performance steel produced by using TMCP which show improved yield strength, welding workability, formability and fatigue life when compared to conventional steel will be investigated. Finally, future super long bridge project plans in Japan will be introduced.

Introduction

How much long a span length of a suspension bridge can be extended? The Messina Strait Bridge was designed with a center span length of 3,300m. How can we extend the span length of suspension bridge over 5,000m? This study summarizes the investigation [1, 2] of the feasibility of CFRP suspension bridge with center span length 5,000m. CFRP material is used for all bridge components; cables, deck and tower, in the case study. Its design concept was presented and some technical issues to be solved were pointed out. Furthermore most recent advanced steel materials will be introduced as they are to be used as steel plate bridges. Comparisons between the characteristics of the CFRP material and advanced steel materials are presented.

Characteristics of CFRP Material

Fiber reinforced plastic includes three types; CFRP (Carbon Fiber Reinforced Plastic), GFRP (Glass Fiber Reinforced Plastic) and AFRP (Aramid Fiber Reinforced Plastic). Figure 1 shows the characteristics of tensile strength for both conventional steel and FRP (Fiber Reinforced Plastic) materials. As a well-known fact, FRP materials do not have a plastic range in contrast to steel wires.

---

[1]Structural Bridge Engineer, MSc., Chodai Co., Ltd., 730, Higashi- Hiratsuka, Tsukuba, Ibaraki Japan 305-0812
[2]Structural Bridge Engineer, PhD., Chodai Co., Ltd., 1-20-4, Chuo-Ku, Tokyo, Japan, 103-0014
[3]Structural Bridge Engineer, MSc., Chodai Co., Ltd., 1-20-4, Chuo-Ku, Tokyo, Japan, 103-0014
[4]Structural Bridge Engineer, MSc., Chodai Co., Ltd. Representative Office, Kozyatagi, Istanbul, Turkey, 34744

Yamane T, Takaue A, Ikeda T, Gundogdu Y. Z. State-of-the-art of new materials and future perspectives on super long bridges. *Proceedings of the Istanbul Bridge Conference*, 2014.

Further comparison between the CFRP and steel material is provided. As shown in Table 1, the prominent advantages of CFRP wires are unit weight, tensile strength and thermal expansion coefficient. The unit weight of CFRP wire is 80% lower, the tensile strength is 25% higher and thermal expansion coefficient is 90% lower when compared to conventional steel wire. In addition, CFRP is an anti-corrosive material. It should also be noted that the tensile strength of the CFRP wire shown in Table 1 is comparatively underestimated because it is used for bridges [1, 2].

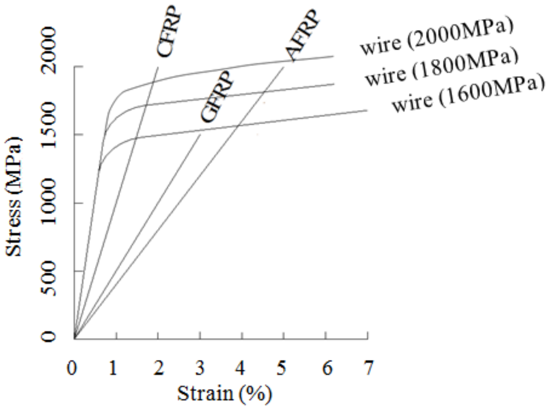


Figure 1. Comparison of CFRP wire with steel wire.

On the other hand, there are some technical issues of CFRP material wire that must be improved in the future to be used for bridges. The shear strength of CFRP wire is very low as shown in Table 1. Moreover the compression strength is also low which is not shown here. Furthermore, as depicted in Figure 1, CFRP has no plastic range with a maximum strain of 2%. In addition the material cost of CFRP is 10~20 times higher, the erection cost is 50% lower and the total construction cost is 1.2~2.0 times higher than the steel wire option [1, 2].

Table 1. Comparison of CFRP wire with steel wire in design.

	CFRP	**Steel Wire**
Unit weight (kN/m^3)	**16**	77
Tensile Strength (MPa)	**2450**	1570~2250
Shear Strength (MPa)	236	801
Elastic Coefficient (GPa)	160	195
Thermal Expansion Coefficient (1/°C)	**0.6x10^{-6}**	12x10^{-6}
Fractural Elongation (%)	1.6	4

It is a well known fact that, the critical span length in the design depends on the sag ratio of a catenary curve and loads acting on the cable. Furthermore, the allowable tensile stress of the wire and the unit weight of the cable have also a direct effect on the critical span length.

Case Study

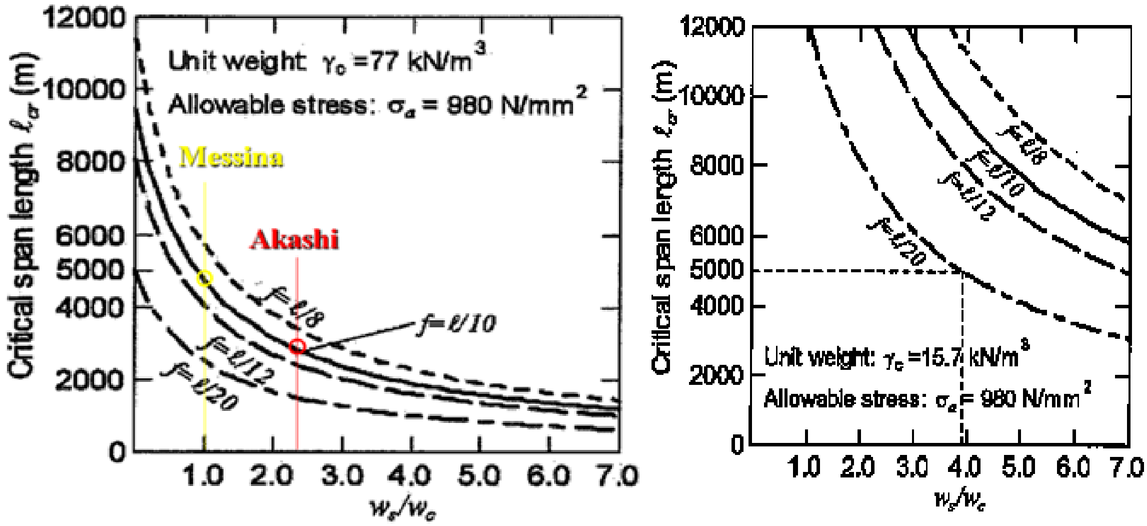
The properties of CFRP wire and steel wire used in the case study [1, 2] are depicted in Table 2. Here, it is important to note that 2450 MPa tensile strength is comparatively a lower value than reality as it is explained previously. Moreover, the safety factor of CFRP bridge was adopted as 2.5 instead of 2.0 since it is an uncommon material for bridges. Finally the same value of allowable tensile stress was obtained for both of the materials.

Table 2. Unit weight and allowable tensile stress of cable.

	CFRP	**Steel Wire**
Unit weight γ_c (kN/m^3)	16	77
Tensile Strength (MPa)	2450	2250
Safety Factor	2.5	2
Allowable tensile Stress σ_a (MPa)	980	980

Figure 2a for steel cables shows the relationship between a critical span length to the vertical direction and a load ratio of w_s/w_c (w_c: dead load of the cable / w_s: dead and live loads of the suspended structure) to the horizontal direction on steel cables according to the sag f. The figure is based on the assumption that the allowable stress is 980MPa. A higher value is given compared with existing practical wires. Furthermore, usually a 1/10 of sag ratio is applied for the steel cables. Around 1/10 of the sag ratio is a favorable value not to increase tension forces for the steel cable. For reference, the load ratio values of w_s/w_c of the Messina and Akashi Bridges are also shown in the Figure 2a. The critical length of sag ratio 1/10 will be 9,000m theoretically; however, height of the tower will become so high like 1,000m which is not a practical height. Hence, upper limit will be dominated by the height of the tower and the huge compression forces acting to the tower from the cable tension. The design of the tower such a height will not be possible. Moreover, in case of a sag ratio 1/20, the height of the tower will be nearly less than 400m as a practical height, a maximum critical span is 5,000m as shown, but the load is 100% cable weight. Finally, it has been found that 5,000m span by sag ratio 1/10 is impossible in reality with steel wires.

On the other hand, the allowable stress of CFRP 980MPa is assumed as same as the steel wire. However, when CFRP wires are applied for the main cable, the possibility to expand the critical span length will be so much improved compared with steel wires. The distinguishing fact is that the sag ratio 1/20 is applicable to the 5,000m span as shown in Figure 2b. This is due to the reason of a lighter weight of CFRP wire. It can be seen that crossing 5,000m span length is possible with the designed load ratio of nearly four. If the dead and live load acting on the suspended structures become lighter, it is found that the critical span can be expanded more as shown in Fig. 2b.



(a) Steel Cable (b) CFRP Cable

Figure 2. Critical span length for steel (a) and CFRP (b) cables.

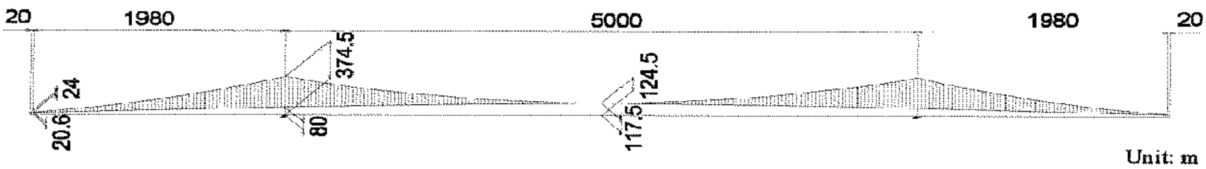


Figure 3. General view of the 5000m span suspension bridge.

The sag ratio of 1/20 is selected to obtain a practical tower height for the case study [2]. As shown in Fig. 3, the tower height of the 5000m span bridge is about 374m. Furthermore, material properties used in each structure are shown in Table 3. Characteristically, the flexural compressive strength of CFRP is quite low when compared with flexural tensile strength. Accordingly, the same value of 1,020MPa is used for both flexural compressive and tensile strengths for the design of the deck. The compressive strength is only a half of tensile strength; therefore the applied compressive strength for CFRP is 510MPa in tower design. Furthermore, the design loads are also shown in Table 4.

The deck in Fig. 4 is a two lane carriageway to each direction and is completely covered by a shield to protect cars from strong winds. The cross section of tower is depicted in Figure 5. The height of the tower is 374m above the sea level. Because of lower compressive strength of CFRP, inside of the tower shaft is filled with a concrete.

Table 3. Material properties used in the case study.

	Cable	Deck	Tower
	CFRP	**CFRP**	**CFRP/Concrete**
Unit weight (kN/m^3)	16.0	16.0	16.0/23.0
Elastic Coefficient (GPa)	160	65	65/30
Elastic Shear Coefficient (GPa)	-	30	30
Tensile (Compressive) Strength (MPa)	2450	**1020**	1020(**510**)/60
Safety Factor	2.5	**6**	6.0/3.3
Allowable Stress (MPa)	980	170	170/18

Table 4. Design loads used in the case study.

	Cable		Deck	
	Center Span	**Side Span**	**Center Span**	**Side Span**
Dead Load (kN/m/Br)	26.7 *(308)	27.2	80.5 *(234)	80.5
Distributed Live Load (kN/m/Br)			20.0	

*( ) shows the values for the Messina Strait Bridge

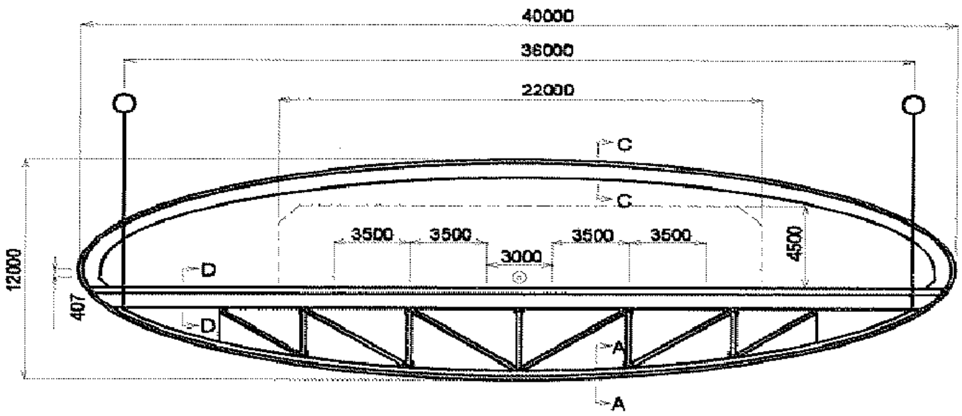


Figure 4. Cross section of the deck.

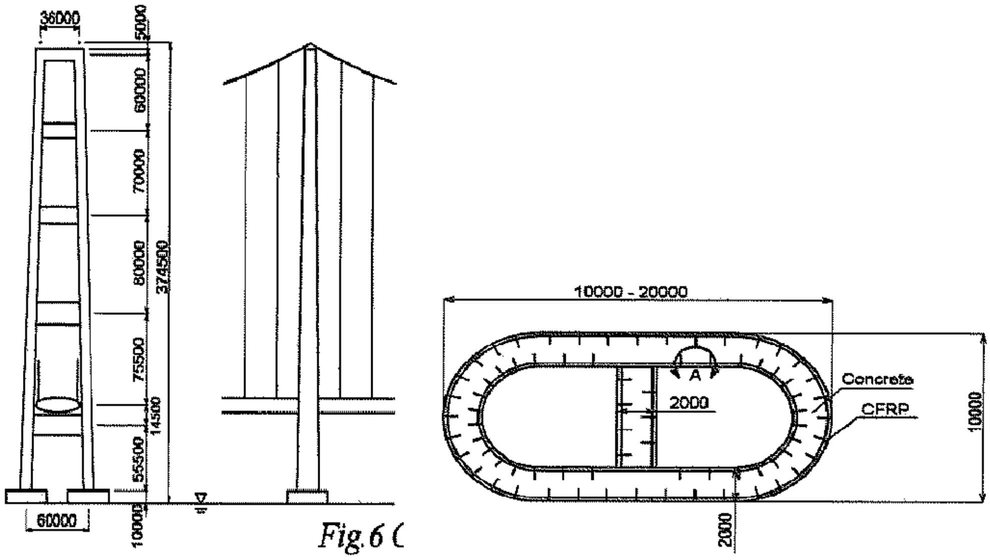


Figure 5. Cross section of the tower.

Recent Development of High-Strength Steel Wire

Aside from the research topic that has been presented, recent developments of high-strength steel wire will be presented in this section. 100 years ago steel wires with 1300 MPa strength was used. With the improvement of control process and advancement in material components, high-strength steel wires are provided to society to be used in especially bridges. For example lately, practical application of 2250 MPa steel wire, which was manufactured by Nippon Steel & Sumitomo Metal Corporation (NSSMC) and it is confirmed and used in design of Gunkai-gawa Bridge on New Tomei Expressway in Japan [6]. In this section, firstly, a development of steel production technology which is called "Thermo-Mechanical Controlled Process (TMCP)" will be introduced. Then two types of steels, namely; Bridge high performance steel (BHS) and Fatigue crack arrester (FCA), produced by using the TMCP technology will be introduced.

Thermo-Mechanical Controlled Process (TCMP)

Thermo-Mechanical Controlled Process (TMCP) [3] is one of the micro-structural control techniques, which combines the controlled rolling and cooling. Normalizing method is the conventional control process which includes rolling, quenching and tempering. On the other hand, TMCP utilizes the CR-OLAC line. First controlled rolling (CR) at a lower temperature is applied and then the on-line accelerated cooling (OLAC) is applied.

The rate of cooling in the transformation temperature range dominantly affects the metallographic structure as well as the strength of steel. As the speed of cooling rate increases, the metallographic structure (reduction of grain size) as well as the strength improves drastically. Hence, it is now possible to manufacture thick steel plates that have the same strength while having drastically lower carbon equivalent with TMCP [7].

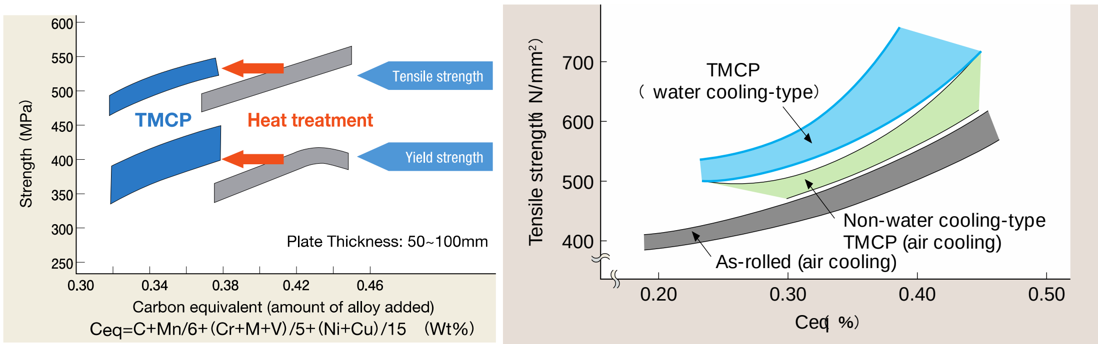


Figure 6. The effect of TMCP and comparison with conventional manufacturing process [7]

By utilizing this method, excellent properties of steel plates are obtained. For example, toughness has been improved as the carbon equivalent decreases. Furthermore, welding workability of steel is drastically improved by: a) lower preheating temperature during welding depending on the low P_{CM} level (weld crack sensitivity composition); b) Decreased maximum hardness of HAZ and improved toughness of the welded joints; c) improvement of the properties of the material in the lamellar-tearing direction. Furthermore, ductility of steel is enhanced by the increased Charpy absorbed energy [7].

600MPa class high-performance steel can be obtained by, the direct quenching and tempering (DQ-T) after the controlled rolling at a lower temperature by TMCP. Furthermore, by using Heat-treatment on-line process (HOP) with TMCP, further higher strength over 780 MPa can also be obtained. HOP is applied for tempering after DQ-T to accelerate the heating process. The heating rate is 10 times more with HOP than the process without HOP. Furthermore, it has been concluded that cementite distribution, which affects the ductility of steel, is much improved with the HOP technology.

Bridge High Performance Steel – BHS500 and BHS700W

The Bridge High Performance Steel [3] is one of the advanced steel produced by using the new technology Thermo-Mechanical Controlled Process (TMCP). The steel has already been in the market and included into the Japan Industrial Standard. When BHS500, which is produced by TMCP, compared with SM570, which is produced by normalizing process, although the tensile strengths are of about the same value (570~720), the yield strength of BHS is higher, about 9 to 19%, than SM570. The distinguishing fact is that no strength lowering is found by a plate thickness in BHS. Furthermore, BHS500 shows superior welding workability & formability since it does not require pre-heating when the weld cracking parameter P_{cm} is less than 0.2. Similarly, BHS700W have also superior yielding strength and welding workability than its counterparts, such as HT780, which are produced by conventional manufacturing process. BHS's unit weight is smaller than conventional steel. Figure 7 shows the superior engineering properties of BHS when compared their conventional counterparts.

Steel grade	490N/mm² Class Steel				570N/mm² Class Steel				780N/mm² Class Steel			
	SBHS400 SBHS400W		Conventional steel SM490Y SMA490W		SBHS500 SBHS500W		Conventional steel SM570 SMA570W		SBHS700 SBHS700W		Conventional steel HT780	
Yield strength (kgf/mm²)	≧400		t ≦ 16 mm	≧ 365	≧500		t ≦ 16 mm	≧ 460	≧700		8 ≦ t ≦ 75	≧ 685
			16 < t ≦ 40	≧ 355			16 < t ≦ 40	≧ 450			50 ≦ t ≦ 75	≧ 665
			40 < t ≦ 75	≧ 335			40 < t ≦ 75	≧ 430				
			75 < t ≦ 100	≧ 325			75 < t ≦ 100	≧ 420				
Tensile strength (kgf/mm²)	490−640		490−640		570−720		570−720		780−930		780−930	
Elongation (%)	6 ≦ t ≦ 16	≧15	t ≦ 5	≧19	6 ≦ t ≦ 16	≧ 19	t ≦ 16	≧ 19	6 ≦ t ≦ 16	≧ 16	8 ≦ t ≦ 50	≧ 17
	16 < t	≧19	5< t ≦ 16	≧15	16 < t	≧ 26	16 < t	≧ 26	16 < t	≧ 24	16 < t ≦ 25	≧ 23
	40 < t	≧21	16 < t ≦ 50	≧19	20 < t	≧ 20	20 < t	≧ 20	20 < t	≧ 16	20 < t ≦ 75	≧ 17
			40 < t	≧21								
Charpy absorbed energy (J)	0°C	≧ 100	0°C	≧ 47	−5°C	≧ 100	−5°C	≧ 47	−40°C	≧ 100	−40°C	≧ 47

Figure 7. Comparison of BHS and conventional steel [8]

Fatigue Crack Arrester (FCA)

FCA steel [4] is newly developed as a functional material with superior resistance against fatigue fracture. It is developed by adjustment of chemical composition and using TMCP technology.

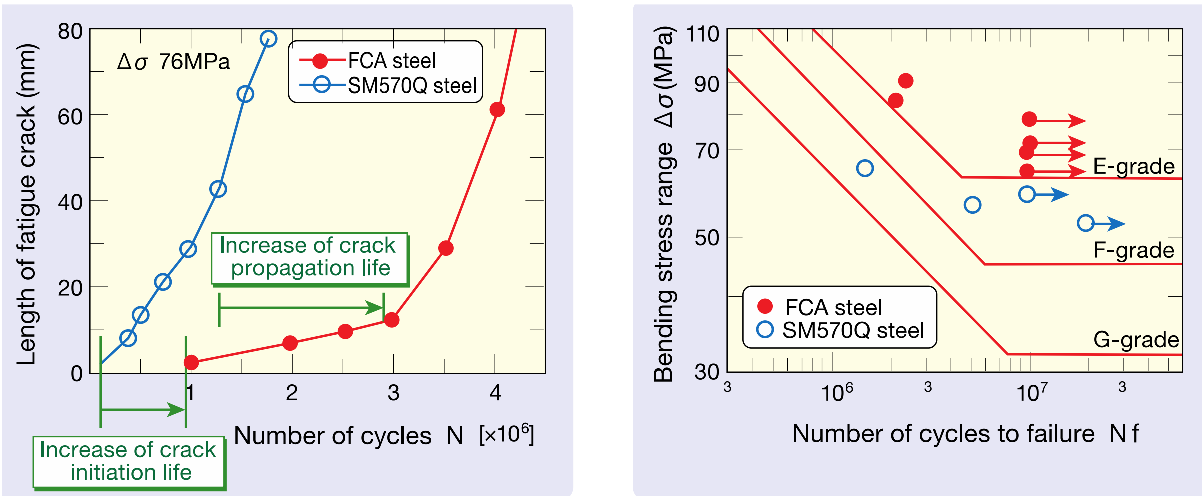


Figure 8. Comparison of fatigue strength of FCA and conventional steel.

FCA steel plate provides controlled fatigue crack initiation since the metal constituent is changed to initiate cracks under higher stress when compared its ordinary counterparts and hence to delay crack extension. In case fatigue cracks occur, the FCA steel plate arrests fatigue crack growth due to its metallographic structure and chemical composition and hence slows down subsequent fatigue crack propagation [9]. As a result, the fatigue life span of structures is substantially prolonged. For example, based on the test results presented by Nippon Steel & Sumitomo Metal, the fatigue strength of the FCA steel was increased by one or higher grade, Figure 9, in the Japan Road Association's fatigue design curve. Moreover, FCA steel also improves the crack initiation life as depicted in Figure 8. [8] Furthermore, FCA steel is either equal to or better than conventional steels in properties such as welding workability, formability, and corrosion resistance required for steel. It is also important to note that there are also application examples of FCA steel in bridge design. For example, 570-N class FCA steel was used at the corners of the intersections of elevated bridge steel piers of KadomaViaduct West by West Nippon Expressway Company Limited. [9]

Conclusions and Future Bridge Projects in Japan

Advances in structural material, such as CFRP, will provide further development in bridge engineering and new projects will be put into practice such as the future strait-crossing projects in Japan as depicted in Figure 9.

The maximum of center span length of 2100m can be seen in Figure 11 for the planned future projects. Because extending the main span more than 2100m provided no significant improvement since even if the span length is more than 3000m the foundations are still in the water. Multi-Span Suspension Bridge can be advantageous when total length of the bridge is long and water is deep. For example, two multi-span suspension bridges under construction in China, Maanshan Yangtze River Bridge and Taizhou Yangtze River Bridge, which both have the same main span length of 2x1080m. In Japan Ko-naruto Bridge is opened to traffic. However, cable slippage at the saddle on the middle tower should be concerned. Hence, stiffness/rigidity in the bridge longitudinal direction must be increased to prevent the slippage at the top of the middle tower.

Based on the case study presented here, it has been shown that the prominent advantages of CFRP wire is 80% lower unit weight, 25% higher tensile strength and 90% lower thermal coefficient when compared to conventional steel wire. Here, it is also important to note that, the allowable tensile stress and unit weight of the wire directly affects the critical span length. With lower unit weight and higher tensile strength, CFRP can enable longer span lengths over 5000m as shown by the case study presented.

There are also some technical issues to be solved for design of CFRP suspension bridge. The low compressive strength, which is roughly 50% of the tensile strength, need to be improved for the design of compression members of the bridge structure. Low shear strength, ~236N/mm^2, needs to be improved about 2 times. Furthermore, low elastic shear coefficient needs to be improved about 2 times hence the aerodynamic stability of deck structure against torsional deflection be improved. As the development in structural material grows with careful approach to the technical issues need to be improved, future super long span bridges with longer center span lengths are possible in the near future.

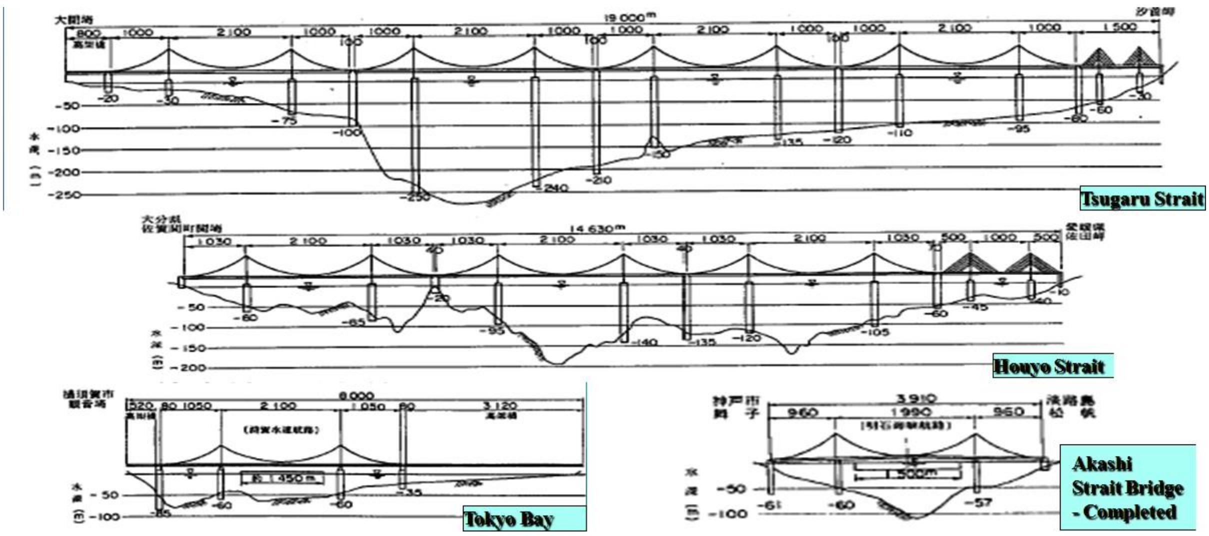


Figure 9. Future strait-crossing projects in Japan.

References

1. Ikeda T, Nakamura H, Maeda K, Hayasi K. Chap.9.4, FRP Bridge, Japan Society of Civil Engineers, 2004.
2. Maeda K, Ikeda T, Nakamura H, Meiarashi S. Feasibility of Ultra Long-Span Suspension Bridge Made of All Plastics, *Towards a Better Built Environment-Innovation, Sustainability, Information Technology IABSE Symposium Report*, Melbourne, September 2002: Vol.86.
3. Homma K, Tanaka M, Matsuoka K, Kasuya T, Kawasaki H. Development of Application Technologies for Bridge High-performance Steel (BHS), *Nippon Steel Technical Report* Jan 2008: No97.
4. New Technology/FCA (Fatigue Crack Arrester) Steel Plates, Sumitomo Metal's website
5. Next Strait Crossing Projects in Japan, *Strait Crossing*, Vol.3 Oct. 95, Vol.4 Jan. 96, Vol.6 Jul. 96, Vol. 7 Nov. 96, Vol.9 Jul. 97
6. Hidefumi T, Yoko K, Masami K, Kenichi N, Masamichi Y, Hiroaki T. Design and Construction of the Gunkai-gawa Bridge on New Tomei Expressway, *Nippon Steel & Sumitomo Metal Corporation Technical Report: Bridge and Foundation Engineering*, 2014: Vol. 3 (In-Japanese)
7. Steel Plates, Nippon Steel & Sumitomo Metal
8. Turkey Presentation, Nippon Steel & Sumitomo Metal
9. Fatigue Solutions of Nippon Steel & Sumitomo Metal, Nippon Steel & Sumitomo Metal