THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Opening Minds • Shaping the Future

國家鋼結構工程技術研究中心香港分中心
Chinese National Engineering Research Centre
For Steel Construction (Hong Kong Branch)

Effective Use of High Strength S690 Steel in Construction

国家钢结构工程技术研究中心香港分中心

Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch)

Recent Activities and Achievements
2021

Effective Use of High Strength S690 Steel in Construction

Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch) was established in October 2015 by the Innovation and Technology Fund of the Innovation and Technology Commission of the Government of Hong Kong SAR with an endorsement of the **State Ministry of Science and Technology** of **the People's Republic of China** at **the Hong Kong Polytechnic University.**

CNERC is the only designated Research Centre to promote technological innovations and engineering applications in construction in Hong Kong. Moreover, through the work of CNERC, *a level playing field* is established according to prevailing international practice as well as innovative engineering technology so that the Chinese steel materials are readily adopted for construction projects specified to international standards, and the Chinese Construction Industry is able to compete technically in the international construction markets.

The primary objectives of the technological innovations of CNERC are

- to promote *sustainable infrastructure development* in Hong Kong and various parts of China, in particular, the Greater Bay Area, and
- to promote *advances in structural engineering on modern steel construction*, in particular effective use of high strength steels in construction.

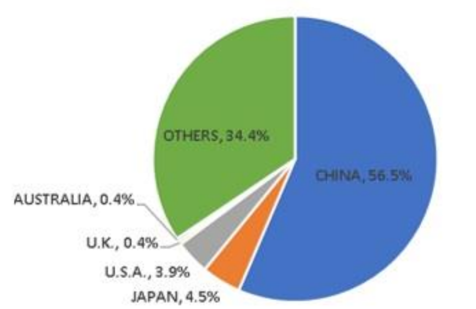
Through technical collaboration with the Development Bureau of the Government of Hong Kong SAR, the Construction Industry Council and various professional institutions in Hong Kong, CNERC supports the Hong Kong Construction Industry to

i) work with the **Chinese Iron and Steel Industry** to demonstrate equivalence of Chinese steel materials to various international materials specifications, and

ii) work with the **Chinese Steel Construction Industry** to participate construction projects which are designed and specified to international engineering and management practice.

STEEL PRODUCTION (MILLION METRIC TONS)

YEAR	CHN	JPN	USA	UK	AUS	World Production
1980	37.1	111.4	101.5	11.3	7.6	**568.5**
1990	66.4	110.3	89.7	17.8	6.7	**616.0**
2000	128.5	106.4	101.8	15.2	7.1	**848.9**
2015	803.8	105.1	78.8	10.9	7.7	**1625.1**
2018	928.3	104.3	86.7	7.3	6.9	**1825.5**
2019	996.3	99.3	87.8	7.2	5.5	**1875.1**
2020	1053.0	83.2	72.7	7.2	6.7	**1864.0**



STEEL PRODUCTION OF 5 CONUTRIES OF INTEREST IN 2020

Fig. 1 World steel production in 2020

High strength S690 steels

In the 1990s, high strength S690 steels are produced in a number of countries with advanced steel-making technology, such as Germany and Japan. Many of these high strength steels are engineering steels with typical thicknesses ranging from 6 to 30 mm. They are commonly used as key members in large lifting equipment and machinery in ports and mines. For many years, these high strength steels cost typically 70% more than the S355 steels, and their use becomes prohibitively expensive in construction when large quantities are used. With advances in steel-making technology in China in the 2010's, a number of leading Chinese steel mills are able to produce high strength S690 steel plates with thicknesses ranging from 6 to 80 mm on a regular basis. As these S690 steels are manufactured with specific compositions of special metallic elements through well controlled heat treatments, they possess excellent mechanical properties, in particular, strength and ductility, as required in both the European and the Chinese Steel Materials Specifications EN 10 025 - 6 and GB 1591.

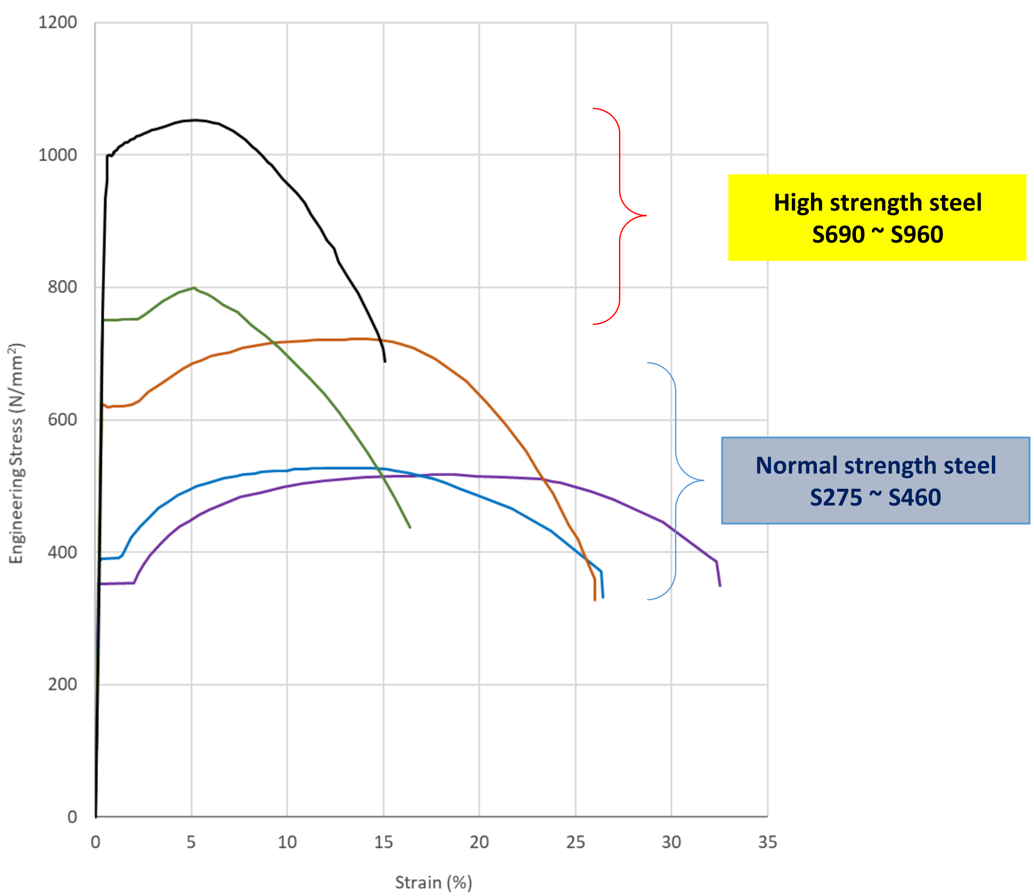


Fig. 2 Stress strain curves

In the recent years, the unit cost of high quality S690 steels is typically 1.3 times of that of S355 steels. A close examination reveals that for a given structure under strength design, the amount of the S690 steels is only half of that of the S355 steels. Hence, the total material cost of the S690 steels is only 1.3 x 0.5 or 0.65 of that of the S355 steels, i.e. there is a significant saving at 35%.

What are the problems ?

Despite the high strength S690 steels are commercially available in the 1990s, structural engineers have technical concerns on adopting them in construction because of conflicting reports on their structural behaviour over the past 30 years. It should be noted that the high strength S690 steels are manufactured with a highly controlled heat treatment process known as "Quenching and Tempering" to produce fine grain crystalline forms with high strengths and toughness. However, a heating / cooling cycle induced during welding may initiate *phase transformation*, *re-crystallization* and *grain growth* in microstructures of the welded sections.

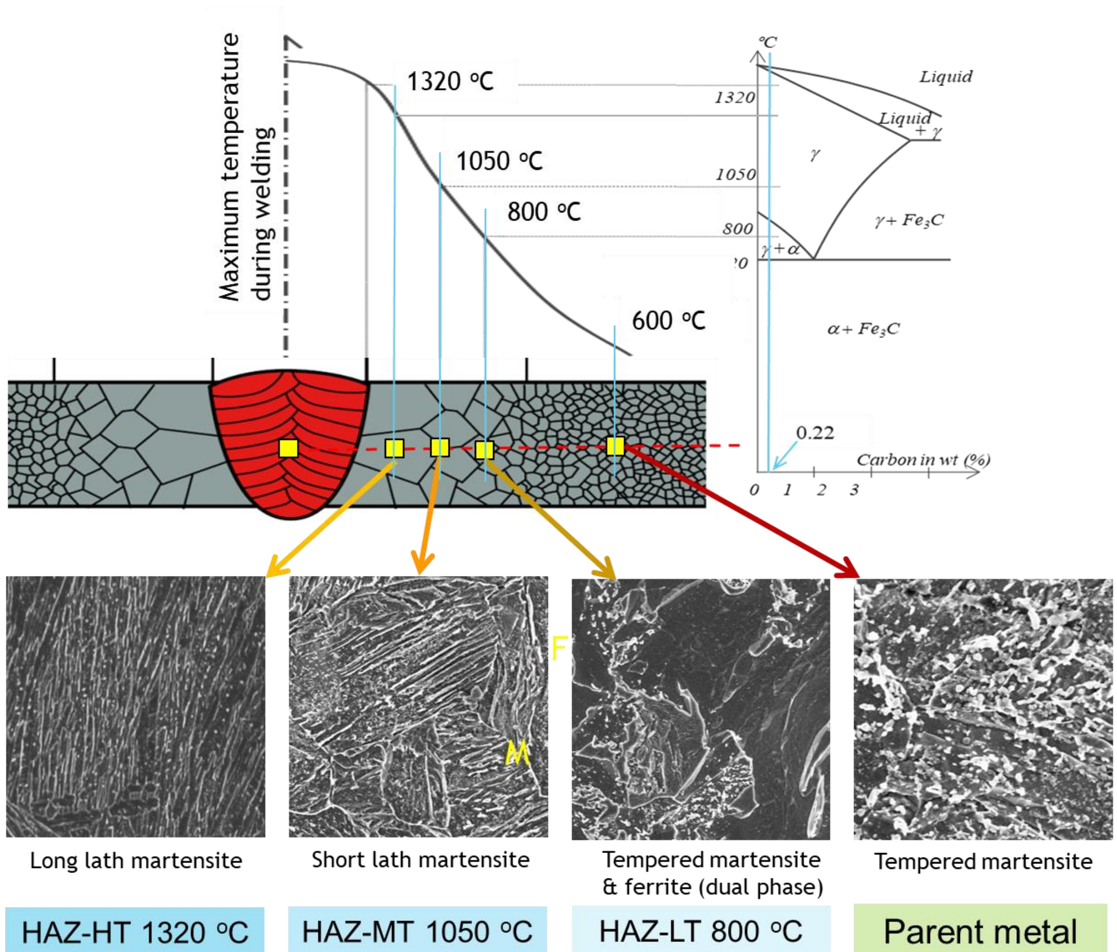


Fig. 3 Microstructural changes in Q690-QT steels after welding

This will cause a significant reduction in their mechanical properties if both the maximum temperatures during welding and the cooling rates after welding are not properly controlled, in particular, in those steel plates with practical thicknesses in construction, i.e. 6 to 80 mm thick. It is highly desirable to assess or predict reductions in various mechanical properties of these welded sections, and more importantly, how to eliminate any such reduction in these welded sections.

Moreover, most modern structural steel codes, such as European Structural Steel Code EN 1993-1-1, are prepared in the 2000's, and their design methods are based on test results of normal strength steels, i.e. S275 and S355. These design methods are found to be over-conservative when they are applied to design S690 steels, owing to the lack of sufficient materials data and test results. More importantly, there is little technical information on welding in the literature for design and construction engineers to specify as well as to appraise welding procedures.

Steel Research at CNERC

In order to promote effective use of high strength S690 steels in construction, CNERC has conducted a number of research and development projects to achieve the following:

i) To raise technical awareness and acceptance of effective use of S690 steels, and their potential advantages and issues in engineering application using high quality Chinese steels.

ii) To generate scientific knowledge and engineering data on mechanical properties of S690 steel plates and welded sections, and their structural behaviour under various practical loading conditions.

iii) To develop efficient design rules for adoption of these S690 welded sections in construction projects, and to obtain acceptance from regulatory agents.

iv) To develop reliable and economical welding procedures for thick S690 steel plates (up to 70 mm) with established quality assurance.

v) To work with structural engineers to develop innovative engineering applications of high strength S690 steels in construction projects.

vi) To work with steel producers on how to improve various mechanical properties of high strength steels for seismic resistant structures, and to develop new steel products for marine engineering.

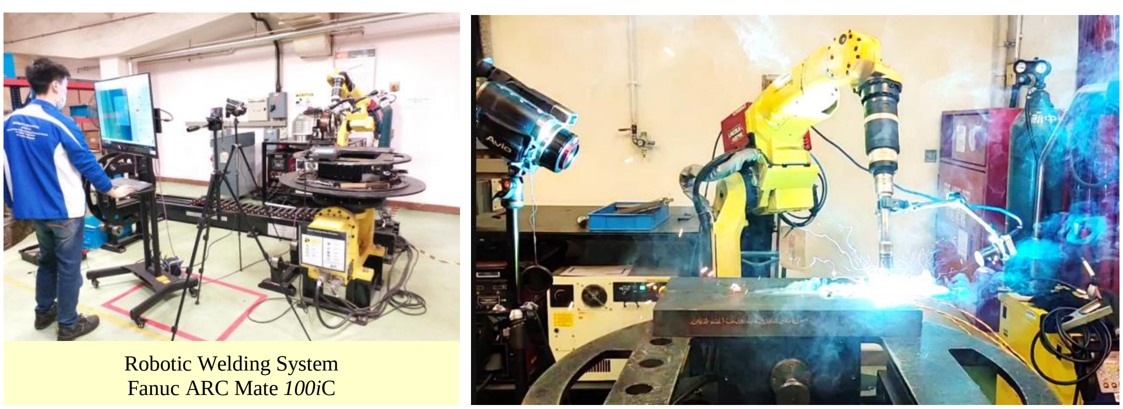

Robotic Welding System
Fanuc ARC Mate *100i*C

Fig. 4 Robotic welding system at CNERC

Key achievements of various steel research at CNERC include:

- to publish over 100 technical papers on world leading journals and conference papers in international conferences on structural engineering and modern steel construction technology;
- to contribute to development of technical design guides and codes of practice in Hong Kong and China;
- to provide scientific understandings and experimental results on structural behaviour high strength S690 members and welded sections to the Technical Committee of the European Structural Steel Code EN 1993-1;
- to conduct academic courses at a Master's level on structural steel design to European Structural Steel Design using high quality Chinese steel materials; and
- to conduct professional short courses to both design and construction engineers on practical structural steel design using Chinese steel materials.

Specific tasks completed

The following tasks have been completed:

a) a full range true stress-strain model for S690 steels undergoing non-uniform deformations up to fracture
b) a thermomechanical numerical simulation of practical welding process for S690 welded sections to determine transient temperature distribution history during welding, and residual stresses after welding
c) determination of mechanical properties of S690 welded sections with various welding parameters under tension
d) hysteretic deformation characteristics of S690 welded sections with various welding parameters under cyclic actions of different target strains and loading frequencies
e) compression resistances and ductility of S690 welded H-sections with full penetration welds over section splices
f) mechanical properties and structural behaviour of S690 welded H-sections under different heat treatments and microstructural changes
g) structural behaviour of stocky and slender S690 welded H-sections and cold-formed circular and square hollow sections under i) compression, and ii) combined compression and bending
h) resistance assessment of partially restrained S690 welded I-sections under lateral loads
i) advanced numerical simulation on transverse bending and longitudinal welding in cold-formed circular and square hollow sections
j) deformation characteristics of T-joints between cold-formed circular hollow sections under i) brace axial forces, and ii) brace in-plane bending
k) advanced thermomechanical simulation analysis on profile welding on T-joints between cold-formed circular hollow sections
l) design rules and parameters for structural design of columns and beams of S690 welded sections in according to European Structural Steel Code EN 1993-1
m) welding technology for S690 steel plates, and complementary certified welding procedure specifications for various joint details

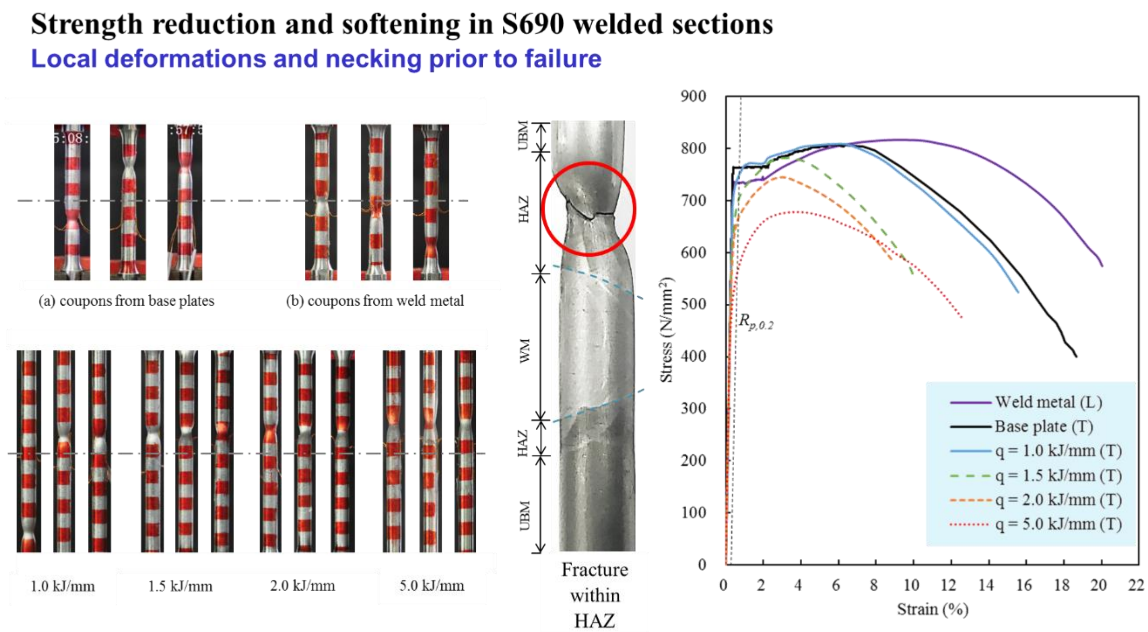


Fig. 5 S690 welded sections under tension

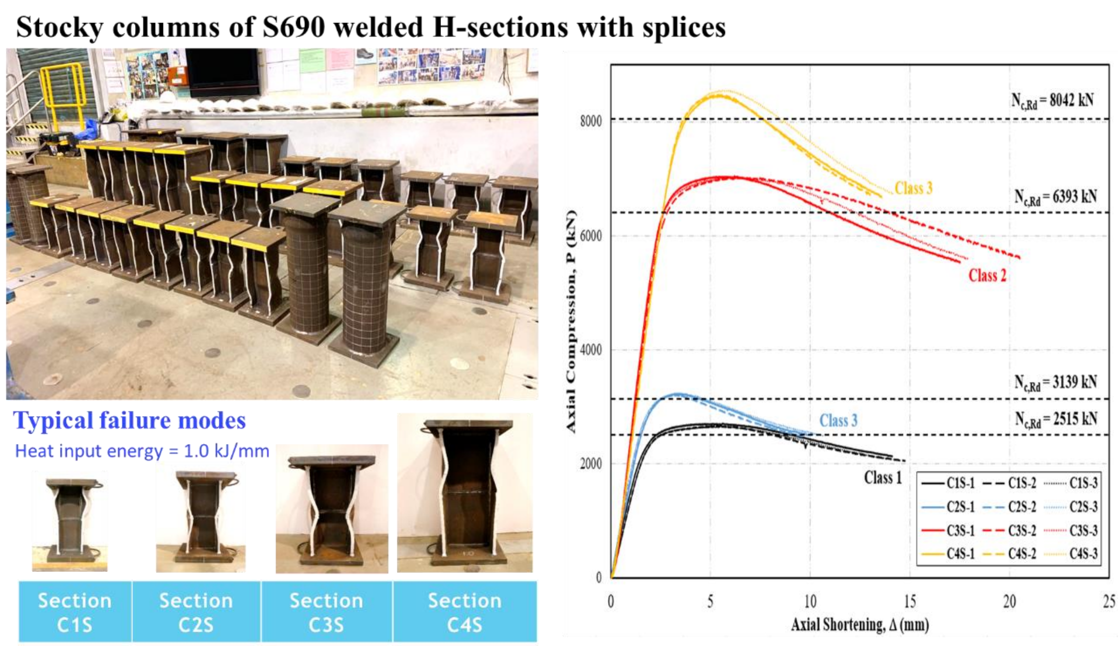


Fig. 6 S690 welded sections under compression

Hence, all the steel research at CNERC is considered to be highly valuable to generate scientific understandings, engineering data and design guidance to facilitate engineers to adopt these high strength S690 steels in construction. A number of technical papers, practical design guides and typical welding procedures for construction using these S690 steels become available as definitive reference documents to pave the way for general acceptance of these S690 steels in construction.

Innovative engineering applications

The high strength S690 steels have an excellent strength-to-self-weight ratio, and they are highly efficient to be used in heavily loaded structures. Typical applications include piles and columns in buildings and supporting members in bridges.

An exemplary application of these high strength S690 steels is the construction of the **Eternity Arch** of the **Cross Bay Link** in Tseung Kwan O by highly skillful design and construction engineers.

Cross Bay Link at Tseung Kwan O, East Kowloon, Hong Kong SAR

Located in the Junk Bay of Tseung Kwan O, East Kowloon, the **Cross Bay Link** was part of a major infrastructure development in the East Kowloon Region in Hong Kong. The project was administrated by the **Civil Engineering and Development Department** of the Government of Hong Kong SAR. The 1.8 km long Cross Bay Link was designed to receive traffic from the 3.8 km long tunnel from Lam Tin to Tseung Kwan O. In additional to a number of concrete bridge segments spanning across the sea, there was a 214 m long steel bridge with a double arch of **S690 steels** which was considered to be the key segment of the Cross Bay Link.

Fig. 7 Cross Bay Link in Tseung Kwan O area

After a 3 stage public engagement exercise to solicit public views on the Cross Bay Link in 2009 and 2010, the concept of a double arch was adopted, and the design of the "Eternity Arch" was implemented by one of the world leading bridge designers, **AECOM** in Hong Kong. Hence, the use of high strength S690 steels was introduced to the bridge design because of its structural efficiency in both materials and costs.

The Steel Bridge

The 214 m steel bridge comprised of the bridge deck, the cables and the double arches which were designed to be fabricated with high strength S690 steels. The double arches were curved box-sections which were 230 m long with a maximum rise at about 40 m at their mid-spans above the bridge deck. The cross-sectional dimensions of the arches were 3.5 x 3.5 m at both ends with a thickness of 70 mm, and they were decreased to 3.0 x 3.0 m at their mid-spans with a thickness of 50 mm. The total weight of the two arches was 4,400 tonnes.

Fig. 8 Eternity Arch with double arches of S690 steels

In June 2018, the construction contract of the main bridge of the Cross Bay Link was awarded by the Civil Engineering and Development Department to **China Road and Bridge Corporation** after a rigorous tendering process. The overall construction cost of the main bridge of the Cross Bay Link was HK$2.5 billion. The construction commenced in August 2018, and the scheduled completion date was 2022. Owing to the high quality of Chinese steel construction, the steel bridge was decided to be fabricated in the **Shanghai Zhenhua Heavy Industries** while high quality high strength Q690 steels were supplied by **Jiangyin Xingcheng Special Steel** in Jiangsu.

Fig. 9 The complete steel bridge: Double arches, cables and bridge decks (*Courtesy of CRBC*)

Together with the steel decks and the cables, the total weight of the steel bridge was 10,000 tonnes. It was decided to fabricate the entire steel bridge in the fabrication yard in Nantong near Shanghai so that all welding work were carried out by experienced welders, and inspected by qualified NDT personnel. This ensured the highest quality of workmanship achieved for the steel bridge. The entire fabrication process took a total period of about 18 months, and about 170 experienced welders and 30 NDT personnel were involved at the peak period of fabrication.

The completed steel bridge was then towed to Hong Kong by a semi-submersible barge to the site in Junk Bay over a distance of about 900 nautical miles. The sea voyage took place in February 2021 as this involved the lowest risk of encountering a typhoon based on 60 years of climatic records. The steel bridge departed Nantong in the early morning of 8 February 2021, and it took 8 days for the steel bridge to arrive the site on 16 February. The steel bridge was installed onto two per-fabricated and pre-installed piers during the high tide in the morning of 26 February 2021, and it was lowered onto positions precisely and safely over a period of five hours.

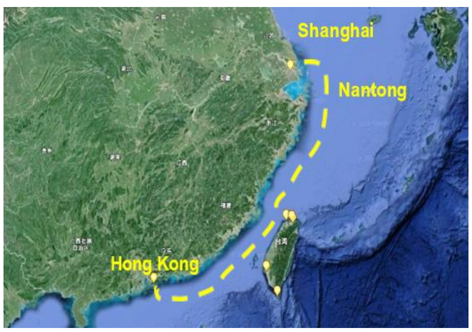


Fig. 10   The sea voyage from Nantong to Hong Kong (*Courtesy of CRBC*)

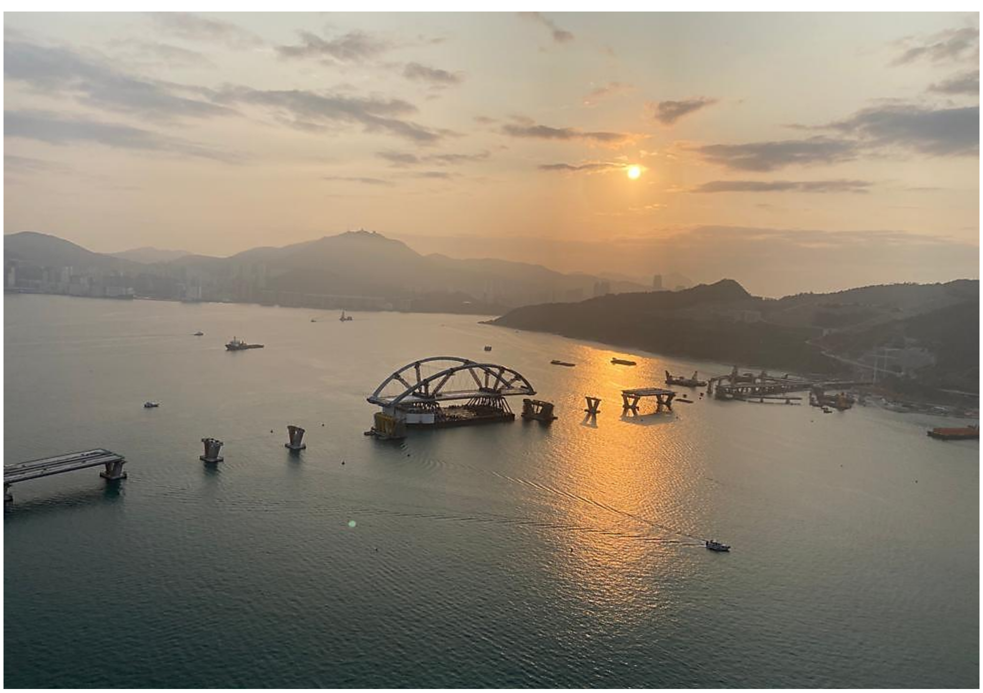


Fig. 11   Arrival of the steel bridge

Contribution of CNERC

Through technical collaboration with the China Road and Bridge Corporation, CNERC has made the following contributions to the general applications of high strength S690 steels in construction:

- to present scientific understandings, experimental results and engineering data for general acceptance of using high strength S690 steels in Hong Kong;
- to assess as an independent expert the welding procedures specifications proposed by fabricators, in particular, joint design and welding procedures and parameters; and
- to examine welding quality and structural adequacy of selected S690 welded sections.

This technical collaboration provided essential engineering data on practical application of thick S690 steel plates, and developed a highly cost efficient construction technology ready to be used in Hong Kong and beyond.

Achievements of the Steel Bridge using High Strength S690 Steels

a) The construction of the steel bridge is a record breaker in Hong Kong as well as in China that it is the first long span 214 m double arches using S690 steels across a sea, and after a complete fabrication, it is towed over a sea voyage of about 900 nautical miles for installation. Hence, this innovative engineering solution enables the delivery of the steel bridge to be completed with a significant saving in construction cost and time.

b) The steel bridge is designed to European standards by an international bridge consulting firm in Hong Kong, built by a leading Chinese Contractor, fabricated by a high quality Chinese Fabricator using high quality Chinese steels. Hence, it is a vivid demonstration of the high level capabilities of the Chinese Steel Construction Industry to deliver a high quality construction project using high quality Chinese S690 steels to international standards.

c) The project demonstrates that by working together, Hong Kong is able to establish itself as the International Design Centre for Infrastructure Development while China becomes the International Construction Centre for Infrastructure Development. High strength steel construction provides a niche for both Hong Kong and China to export their construction materials, structural steel design, and construction engineering and management to the international construction markets.

Remarks

CNERC
The Eternity Arch of the Cross Bay Link is an important step for both Hong Kong and China to collaborate on effective use of high strength Q690 steels in bridges and buildings designed and constructed to international standards. Based on the latest technological developments on advanced structural engineering and modern steel construction, CNERC is able to promote a wide adoption of high strength Q690 steels in Hong Kong as well as overseas construction projects.

AECOM
Adoption of high strength Q690 steel in the steel bridge is a major technological advancement in bridge engineering as this makes the entire design highly attractive. The research and development work of CNERC has definitely advanced the adoption of S690 steels in construction by at least 5 to 8 years in the Region. With these Q690 steels, we are currently working on several bridges with similar innovative engineering applications in various parts of the world!

CRBC
The construction of the Eternity Arch is made possible and efficient only by the use of high strength Q690 steels, and it makes many design considerations and construction procedures both feasible and rational ! After going through this unique project, we have experienced the structural as well as the cost benefits offered by these Q690 steels, and we expect more steel bridges and buildings with Q690 steels to come.

CEDD
We are glad to see the success of the design and construction of the Eternity Arch which takes advantages of the high strength Q690 steels – an effective construction material which offers a large load carrying capacity at a reduced cost. We trust this innovative use of the constructional material will be adopted in similar projects.

Fig. 12 The Eternity Arch with 4,400 tonnes of high strength S690 steels

AECOM was established in 1990, and it is a world-renowned professional service provider of comprehensive infrastructure services from planning, design, engineering to consulting and construction management at all stages of the project. It is ranked 163 on the Fortune 500 of the U.S.A. AECOM has operations in more than 150 countries around the world, with 56,000 employees. In the Greater China region, AECOM is located in more than 10 cities including Hong Kong, Taipei, Shanghai, Beijing, Shenzhen, Guangzhou and Chengdu with office establishment and a total of more than 6,500 employees.

China Road and Bridge Corporation (CRBC) was established in the People's Republic of China in 1979. It is one of the first four large state-owned enterprises in China to enter the international engineering contracting market, providing full range of infrastructure construction services including engineering design, construction, management and investment business in Asia, Africa, Europe and America. Its offices were set up in more than 50 countries and regions. In 2005, CRBC restructured as a wholly-owned subsidiary of China Communications Construction Group (CCC). Since 1988, CRBC has undertaken over 100 projects in Hong Kong on large scale civil engineering structures.

Civil Engineering and Development Department (CEDD) is an engineering department of Development Bureau of the Government of Hong Kong SAR. The scope of work includes land and infrastructure construction, port and marine engineering, geotechnical engineering, and environment and sustainable development in various regions of Hong Kong. There are about 2,000 employees in its regular establishment, and about two-third of them are professional and technical personnel, including civil engineers, geotechnical engineers, surveyors and landscape architects.

Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch) (http://www.polyu.edu.hk/cnerc-steel/en/)

The CNERC for Steel Construction (Hong Kong Branch) is established to promote sustainable infrastructure development through effective use of constructional steel materials and modern technology in structural engineering. The core objectives of the CNERC are:

- To establish a high level technological platform to enable effective design and construction of modern building and civil engineering structures to promote sustainable infrastructure development in Hong Kong.

- To advance technological capabilities of the Hong Kong Construction Industry in design and construction of super high-rise buildings, long span bridges and buildings of large enclosure using high performance materials in Hong Kong and overseas.

The CNERC is dedicated to promote technological developments and internationalization of the steel construction industry in both Hong Kong and China. It is actively engaged with international as well as national exchanges in research and development of steel construction.