Effective use of high-strength S690 steel in construction

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SYNOPSIS

With advances in metallurgy and steel-making technology, structural steel with yield strengths up to 690N/mm^2 is produced regularly in many modern steel mills in different countries, such as China, France, Germany, India and Japan. The yield strength of S690 steel is almost twice that of the commonly used structural S355 steel.

High-strength steels are used in a wide range of structures, such as heavy-duty lifting equipment in mines and ports, frames and members in wind turbines, as well as container trailers and passenger trains. Use of high-strength steels is highly advantageous for these moving structures because they can carry increased payloads and hence use less energy during operation. For civil engineering and building structures, the use of S690 steel allows a significant reduction in the self-weight of a structure and also a reduction in the loads to be imposed on supporting structures and foundations.

In recent years, the cost per tonne of S690 steel in many parts of the world has decreased steadily, which has improved its competitive position with respect to S355 steel. In China, the unit cost of S690 steel has varied typically from 1.25 to 1.35 times that of S355 steel over the past five years. It may be argued that owing to the increased strength of S690 steel, only half of the steel tonnages are needed, compared with S355 steel. Hence, the steel material cost becomes roughly 1.3 times 0.5, or 0.65, of that of S355 steel, leading to a significant saving in material costs.

Research work on mechanical properties and structural behaviour of welded sections made from S690 steel conducted at the Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch) has shown that provided the welding processes are properly controlled, it is possible to minimise or even eliminate any reduction in *strength* and *ductility* which might occur due to microstructural change.

Extensive research and development work have also been conducted to promote application of high-strength steel for construction. A steel bridge with two arches using 4400 tonnes of S690 steel in Hong Kong, and a steel bridge with mega trusses using 1625 tonnes of Q690 steel in Macau are briefly described. In addition, the initiative of the Development Bureau of the Government of Hong Kong SAR in promoting the use of high-strength S690 steel is highlighted.

Introduction

Since the 1980s, steel with a yield strength of 355N/mm^2, i.e. S355 steel, has been widely employed in construction worldwide. It is commonly referred to as normal-strength steel. Owing to advances in metallurgical science and steel-making technology, high-strength steels with yield strengths of 690N/mm^2 are now successfully produced, designated as S690 or Q690 steel. Many steel mills are able to produce these high-strength steels in large quantities, conforming to BS EN 10025-6[1] and GB/T 19879[2] with consistent chemical composition and mechanical properties.

Structural engineers in Hong Kong and China, in particular, are eager to exploit these high-strength steels in multistorey buildings and long-span bridges because of their excellent mechanical properties; in particular, their high strengths per unit weight.

It is anticipated that, with the adoption of innovative structural forms, S690 steel may be used more widely in buildings and bridges, resulting in significant reductions in the amount of steel used, and hence the loads acting onto supporting structures and foundations. Additional advantages include reduced welding resources in terms of electrodes and man-hours because of reduced plate thicknesses, enhanced ease of handling and transportation, and improved site safety during both shop fabrication and site erection.

In general, these welded S690 sections are highly effective acting as columns. Despite the increased strengths, the Young's modulus of S690 steel remains at 205kN/mm^2, i.e. the same as that of S275 and S355 steel. Hence, in cases where they are employed as long-span beams, pre-cambering is commonly used to reduce deflections under permanent loads. Design rules for both cross-section and member resistances of welded S690 H-sections and box-sections, though conservative, are readily found in Eurocode 3[3].

It is interesting to note that while S355 steels are widely considered to be the most commonly used structural steel in construction today, they were introduced into the construction industry as high-strength steel in the 1970s, when many steel structures were built with S235 steel.

Multidisciplinary research on high-strength steel

Established in 2015, the Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch) (CNERC) has been involved in promoting the effective use of high-strength S690 steel in construction. Key research and development activities of CNERC[4,5] on promoting the effective use of high-strength steel in construction include:

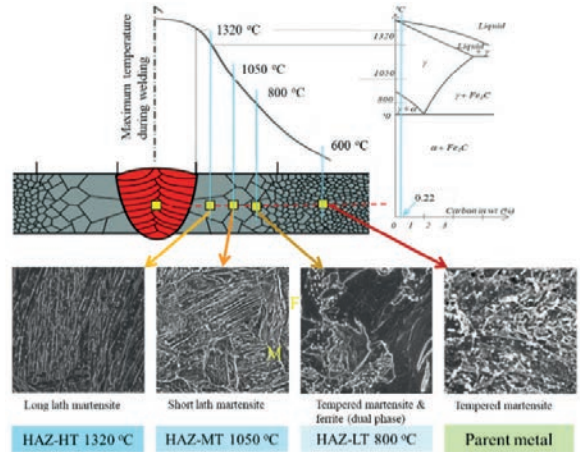
- raising technical awareness and acceptance of the effective use of S690 steel, and its potential advantages and issues in engineering applications
- generating scientific knowledge and engineering data on the mechanical properties of S690 steel plates and welded sections, and their structural behaviour under various practical loading conditions
- developing efficient design rules for adoption of S690 welded sections in construction projects, and demonstrating compliance to regulatory agents
- developing reliable and economical welding procedures for S690 steel plates (up to 70mm thick) with established quality assurance
- working with structural engineers to develop innovative engineering applications of S690 steel in construction projects
- working with steel producers on how to improve various mechanical properties of high-strength steel for seismic-resistant structures, and to develop new steel products with enhanced mechanical properties.

A comprehensive review on the research and development activities of CNERC on high-strength S690 steel is available in a technical report by the Steel Construction Institute[6]. To facilitate structural design of high-strength S690 steel in Hong Kong and neighbouring countries in Asia, technical guidelines for effective design and construction are also available[7–9].

Welding of high-strength steel

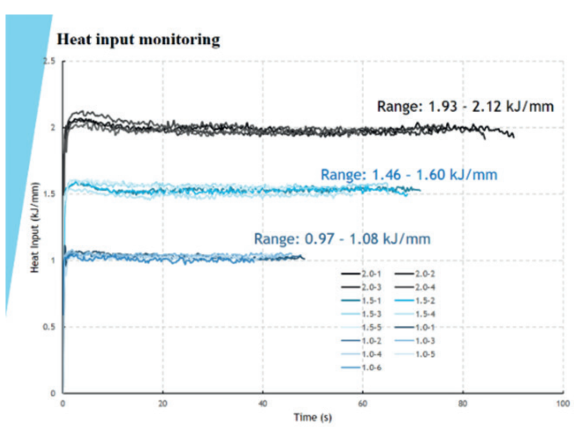
High-strength S690 steel is commonly manufactured with two different heat treatments: i) the quenching and tempering (QT) process; and ii) the thermo-mechanical controlled (TM) process. Through precise control of temperature and time during the production process, it is possible to control the microstructure to obtain the required mechanical properties, primarily strength, toughness and ductility.

However, during welding, the steel is heated up to 1350 to 1500°C, and this will initiate microstructural changes in the heat-affected zone (HAZ) of the steel **(Figure 1)**. To minimise any reduction in the mechanical properties of the HAZ of S690 steel, any metallurgical change in



↗FIGURE 1: Microstructural change in high-strength S690 steel under effects of welding

↗FIGURE 2: Robotic welding system providing good control during welding



↗FIGURE 3: High level of precision and repeatability on heat energy input *q*

> **"IT IS ANTICIPATED THAT S690 STEEL MAY BE USED MORE WIDELY**

the steel should be minimised or even prevented. Hence, the process of phase transformation, recrystallisation and grain growth within the HAZ should be carefully controlled. This is readily achieved with a suitable choice of the heat input energy q during welding according to the plate thickness and various geometric details of the weld joints.

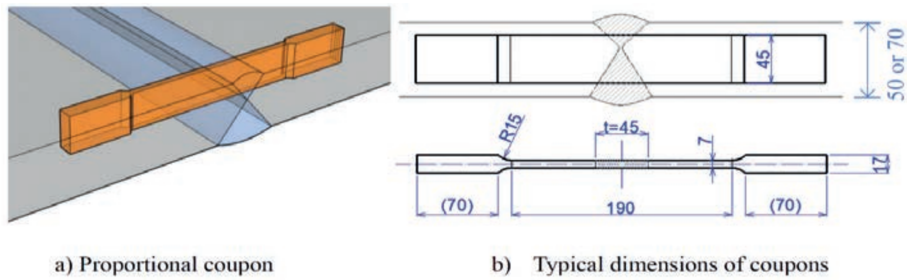
Through the use of a robotic welding system **(Figure 2)**, an extensive experimental investigation into the effects of welding on the mechanical properties of 6 to 70mm thick S690-QT and S690-TM steel was conducted. It should be noted that by adjusting various welding parameters, namely, voltage and current as well as welding speed, a wide range of the heat input energy q values were generated with a high level of precision and repeatability **(Figure 3)**.

Typical standardised coupons were extracted from welded sections of the S690 steel plates **(Figure 4)**, and were subject to standard tensile tests to BS EN 6892[10]. Typical modes of failure of these coupons are illustrated in **Figure 5**[11].

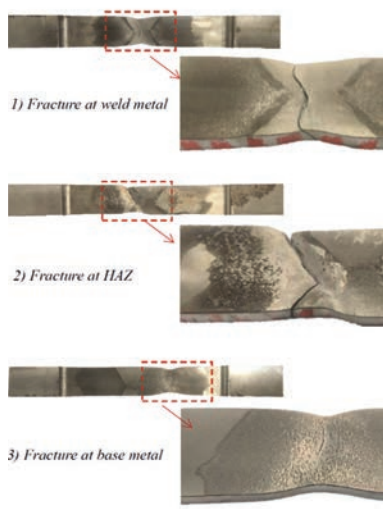
Investigations into the microstructural evolution within the HAZ of S690 welded sections show that phase transformation occurs during and also after welding when the maximum temperature exceeds the transformation temperature Ac_3 of the steel (which depends primarily on the chemical composition). Provided that the cooling rate of the steel within the HAZ from a temperature of 800 to 500°C, known as $t_{8/5}$, is not allowed to exceed 15 seconds for these steel plates with practical dimensions, microstructural changes within the HAZ are not expected to be significant, i.e. there is little or even no reduction in the mechanical properties of these welded sections **(Figure 6)**.

It should be noted that advanced numerical simulations incorporating phase transformation[12] have been performed to assess effects of welding on mechanical properties of the S690 steel with different plate thicknesses. These simulations provide scientific data to improve understanding on microstructural change on the S690 steel after welding.

According to current practice, welding procedure specifications (WPS) should be established for various welding details and joint types according to relevant standards and specifications, such as BS EN ISO 15607[13] and BS EN ISO 15614[14], for all steels. Reference should be made to technical handbooks on welding published by professional welding institutes and associations for further information. The use of effective WPS ensures a high structural efficiency on all the S690 welded sections and, more importantly, a full mobilisation of both their cross-section and member resistances.



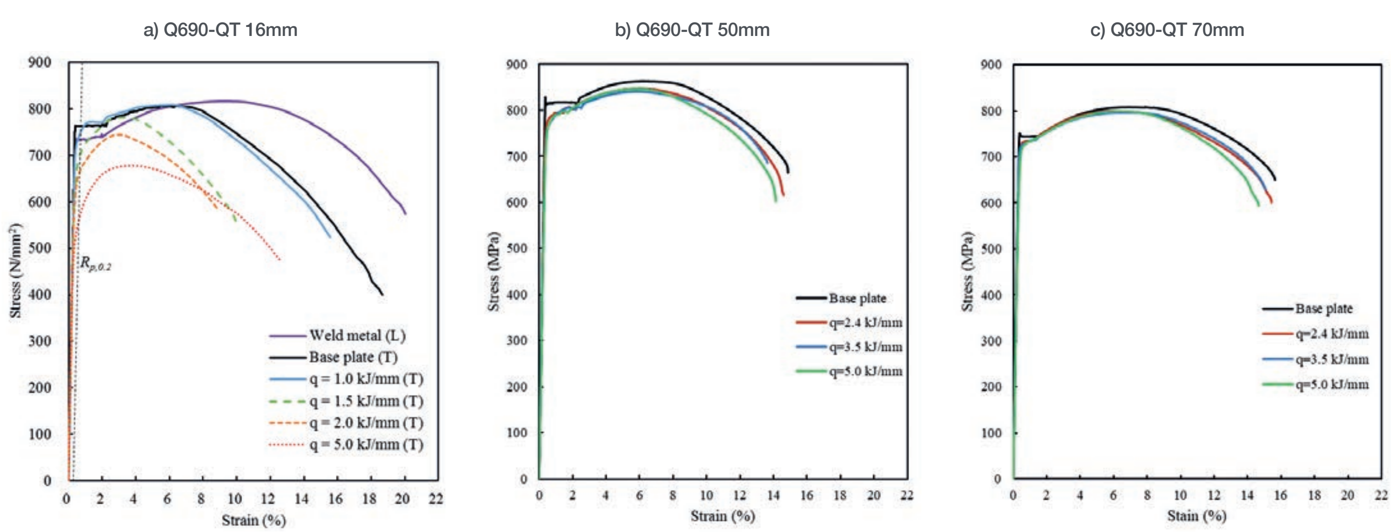
↗FIGURE 4: Typical proportional coupon of welded sections of S690 steel plates



↗FIGURE 5: Fractured coupons of 70mm thick S690-QT welded sections

Construction of road bridges using high-strength S690/Q690 steel

High-strength S690/Q690 steel has an excellent strength-to-self-weight ratio, and can be a highly efficient solution in heavily loaded structures. Examples of the use of high-strength steel are the construction of the Cross Bay Link in Hong Kong, and the Macau Bridge in Macau. CNERC provided technical



↗FIGURE 6: Typical stress–strain curves of S690 welded sections with different plate thicknesses and heat input energy

FIGURE 7: Cross Bay Link in Tseung Kwan O, Kowloon East, Hong Kong

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FIGURE 8: Fabrication and delivery of double-arch steel bridge of Cross Bay Link

advice on the use of S690/Q690 steel, in particular, on both welding and structural design of both bridges.

Cross Bay Link in Tseung Kwan O, Hong Kong SAR

Located in the Junk Bay of Tseung Kwan O, the Cross Bay Link was part of a major infrastructure development in the East Kowloon Region in Hong Kong **(Figure 7)**. Constructed on behalf of the Development Bureau of the Government of Hong Kong SAR, the project was administrated by the Government's Civil Engineering and Development Department. The 1.8km long Cross Bay Link was designed to receive traffic from the 3.8km 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 214m long steel bridge with two arches, and S690 steel was used to reduce the self- weight and hence cost of this bridge.

Double-arch steel bridge

The 214m steel bridge comprised the bridge deck, the cables and the double arches, which were designed to be fabricated with high-strength S690-QT steel. The double arches were curved box-sections which were 230m long with a maximum rise of about 40m at their mid-spans above the bridge deck. The cross-sectional dimensions of the arches were 3.5 × 3.5m at both ends with a thickness of 70mm, and they decreased to 3.0 × 3.0m at their mid-spans with a thickness of 50mm. The total weight of the two arches was 4400 tonnes.

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 the China Road and Bridge Corporation after a tender process. The overall construction cost of the Cross Bay Link was HK$2.5bn. Construction commenced in August 2018, and the scheduled completion date was 2022. The steel bridge was fabricated by Shanghai Zhenhua Heavy Industries **(Figure 8)** while the S690-QT steel was supplied by Jiangyin Xingcheng Special Steel in Jiangsu.

Together with the steel decks and the cables, the total weight of the steel bridge was about 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 could be carried out by experienced welders, and inspected by qualified non-destructive testing (NDT) personnel. This ensured the highest quality of workmanship. The entire fabrication process took around 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

FIGURE 9: Completed Cross Bay Link

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 eight days for the steel bridge to arrive at the site on 16 February. The steel bridge was installed onto two prefabricated and preinstalled piers during high tide in the morning of 26 February 2021, and it was lowered onto positions precisely and safely over a period of five hours. The Cross Bay Link was opened to the public on 11 December 2022 **(Figure 9)**.

The use of 4400 tonnes of S690 steel in the bridge was estimated to have saved about 4400 tonnes of steel, compared with the use of S355 steel. This resulted in a saving of HK$100M in the overall construction cost, and a saving of 12 000tCO_2.

Macau Bridge, Macau SAR

Formerly referred to as the Macau–Taipa Fourth Bridge, the Macau Bridge is a steel bridge with mega (or very large sized) trusses. Its total length is 3.1km while its length across the sea is 2.9km **(Figure 10)**. There are a total of eight spans, and the lengths of the two main spans are 280m. The overall construction cost of the bridge is about HK$5.2bn. The design and construction of the bridge was in strict accordance with the public infrastructure requirements of the Government of Macau SAR. The main contractor was the China Civil Engineering Construction Co., Ltd. Construction of the bridge started in August 2020.

The Macau Bridge was also fabricated by Shanghai Zhenhua Heavy Industries, while the Q690-TM steel was supplied by Baowu Steel in Wuhan. A total of 1625 tonnes of Q690-TM steel in 28 to 44mm thick steel plates was used in the heavily loaded members of the bridge structures **(Figure 11)**. Owing to a rational selection of various steel grades, no site welding on the Q690 steel was necessary. The Macau Bridge was opened to the public on 1 October 2024 **(Figure 12)**.

Construction of civil engineering works using high-strength S690 steel

The Development Bureau of the Government of the Hong Kong SAR is keen to adopt new materials, advanced design and highly efficient construction methods. It encourages all public works departments to adopt innovative construction technology in civil engineering projects. In 2021, the Task Force on Applied Research and Development in Public Works Projects was established to

↗FIGURE 10: Macau Bridge linking Macau and Taipa

promote technological innovation in construction, and high-strength S690 steel was endorsed as one of the priority products to pilot in public works projects as follows.

- **Footbridges** with reduced self-weights to achieve a single lift into position overnight using mobile cranes.
- **Long-span roof structures** with reduced site welding as well as reduced requirements for lifting capacities during site installation.
- **Socketed H-piles** with an increased resistance per pile and, hence, a reduction in the total number of piles in a project.
- **Large-scale noise barriers** with an increase in resistance per frame and, hence, reduced total numbers of steel frames and piles.

CNERC was appointed by the Project Strategy and Government Office in November 2021 to provide technical advice to project teams for selected projects of various works departments; these include material selection and supply of S690 steel, comparisons of different structural schemes, design of connections and joints, and welding and associated quality control. Moreover, a review of various standards and specifications of the works departments was carried out to propose revisions to facilitate adoption of Chinese Q690 steel in civil engineering works.

To date, S690/Q690 steel has been adopted in the design and construction of about 30 public buildings and civil engineering projects. Welding of S690 steel had been performed under site conditions satisfactorily with both pre-heating and post-heating treatment, as necessary. Qualified welding procedure specifications for site welding S690 steel have also been certified by accredited laboratories.

Pilot project using high-strength S960 steel

After the successful introduction of S690 steel, another initiative explored by the Government is the use of high-strength S960 steel, which has a unit cost about 1.7 times that of S355 steel, despite the ratio in their yield strengths being approx. 3. As only a third of the steel tonnage is then needed, the steel material cost becomes roughly 1.7 times 0.3, or 0.51, compared with the use of S355 steel.

In October 2023, the Civil Engineering and Development Department decided to use S960 steel in the construction of two footbridges (F4 and F6) in the form of box girders, in the Fanling North area of the New Territories, Hong Kong, as a pilot project.

Following rational structural analysis and design, a total of 630 tonnes of S960 steel was used. The structural performance of these box girders with multiple longitudinal and transverse stiffeners was found to be highly satisfactorily in both the ultimate and serviceability limit states, including deflection and vibration.

Compared with the original design of a concrete box girder, the self-weight of Footbridge F4 **(Figure 13)** was successfully reduced by more than 70% due to the use of S960 steel, and the number of piles was also reduced by 30%. The overall construction cost for Footbridge F4 was estimated to be reduced by HK$2.8M, i.e. about 28% of the original design cost, with a time saving of about three months. Qualified welding procedure specifications for site welding of the S960 steel using robotic welding have been also certified.

Footbridge F6 is expected to be delivered and erected later this year, with both footbridges scheduled to open to the public before the end of the year. This project has provided valuable opportunities for design and construction engineers and various technical personnel in Hong Kong to gain experience in working with S960 steel. It serves as preparation for construction of large-scale civil engineering structures and bridges in the next few years.

Conclusions

With an ever-increasing demand for infrastructure development in many parts of the world, structural engineers are regularly challenged to design and construct multistorey buildings and long-span bridges with reduced materials, time and money. Our experiences in Hong Kong confirm that high-strength S690 steel offers very attractive solutions with direct reductions in both steel tonnages and construction costs. Structural engineers are strongly encouraged to consider using high-strength steel to provide modern and efficient solutions to their clients with reduced embodied carbon.

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↗FIGURE 13: Lifting and installation of segment of Footbridge F4 with length of 34.1m

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↘↗FIGURE 11: Fabrication and installation of mega trusses of Macau Bridge

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↗FIGURE 12: Opening of Macau Bridge to the public

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