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Comparison of Properties and Experience with the Use of Thermomechanical and Normalized rolled Steels for the Building of Apollo Bridge on Danube in Bratislava

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Abstract

The paper summarizes the experience with use of thermomechanically rolled ML and normalized rolled NL steel plates in fabrication of steel structure of Apollo bridge from the year 2003 till 2005. Basic data about the bridge, used steels and their properties in compliance with EN standard as well as supplementary requirements on chemical composition and mechanical properties, especially toughness of steels and welded joints are described. The statistic evaluation of properties of used steel plates: carbon content, CEV carbon equivalent, sulphur content, yield strength Re, impact energy KV at $-30^\circ$C are outlined. The required and determined welding procedure specifications WPS are also described. It is recommended using S420ML and S460ML steels and corresponding welding consumables for construction of large steel bridges.

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1. Introduction

The experience on thermo-mechanical and annealed normalized rolled steel plates gained at the building the APOLLO Bridge in Bratislava, Slovakia, is summarised in details. The APPOLLO Bridge is build as an arch steel bridge with a span of the main field of 231 m and a total length of the welding steel construction of 517.5 m. The bridge is designed for a common commuting. The traffic through the bridge is expected to be high, estimated to more than 40,000 vehicles daily while these requirements might increase in future.

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2. Used steels and their properties

The selection of the steels for the APPOLO bridge has been executed according to following requirements:
- a bridge lifetime of 100 years,
- a minimal design temperature for steel construction $T_{\text{min}} = -30^\circ\text{C}$,
- good weldability of the steels,
- a resistance against fatigue and brittle fracture of steel construction.

Four types of steels have been used for the building of APOLLO Bridge, two of them were thermomechanically rolled (ML) steels and two were normalised rolled steels (NL, or respectively NLC a J2G3). Only a small part of steel plates have been supplied in a quality J2G3 for less strained parts of the construction.

The total mass of whole steel construction of the bridge is approximately 7720 ton excluding anchors. The mass of TM steels is approximately 5000 ton of the total mass. The thicknesses of used TM steels are in the range of 14 to 40 mm.

The following data have been given in the inspection certificates:
- chemical composition (C, Si, Mn, P, S, Cu, Cr, Ni, Al, V, Nb, Ti, Mo),
- mechanical properties ($R_e$, $R_m$, $A_5$, $Z$, $K_{VQ}$, $K_{VL}$).

Some of the requirements in bridge documentation plan [1] on ML steels used for the bridge construction have been tightened when compared to requirements given in a standard EN 10113-3. The overview of additional requirements on chemical composition is given in Table 1. Finally, the overview of additional requirements on fracture toughness and impact energy originating from minimal suggested design temperature $-30^\circ\text{C}$ for steel bridge construction is in Table 2.

| Steel | C (%) | Nb (%) | Nb+Ti+V (%) | S (%) | P (%) | CEV | CEV |
|-------|-------|--------|-------------|-------|-------|-----|-----|
| S 355 ML | 0,14  | 0,05   | 0,12        | 0,010 | 0,020 | 0,38 | 0,41|
| S 420 ML | 0,16  | 0,05   | 0,12        | 0,010 | 0,020 | 0,41 | 0,43|
| S 355 NL | 0,17  | 0,05   | 0,12        | 0,010 | 0,020 | 0,41 | 0,43|

Table 1 Additional requirements on chemical composition of steels – the maximum content of elements and the carbon equivalent.

| Steel according to EN 10113 | Detail thickness (mm) | Toughness Fracture $K_{CJ}$ at $T_S = -30^\circ\text{C}$ (MPa$\sqrt{\text{m}}$) | $T_S$ | Impact energy $K_V$ (J) (average / minimal) | Transversal direction | Longitudinal direction |
|----------------------------|----------------------|-------------------------------------------------|-------|-------------------------------------------|----------------------|----------------------|
| S 355                      | $\leq 25$            | 100                                             | $-30^\circ\text{C}$ | 40 / 30                  | 27 / 21               | 45 / 34              |
|                            | 26 to 50             | 125                                             | $-40^\circ\text{C}$ | 60 / 45                  | 45 / 34               | 45 / 34              |
| S 420                      | $\leq 25$            | 110                                             | $-30^\circ\text{C}$ | 50 / 38                  | 40 / 30               | 45 / 34              |
|                            | 26 to 50             | 140                                             | $-40^\circ\text{C}$ | 60 / 45                  | 45 / 34               | 45 / 34              |

Remark: Data for the fracture toughness were decisive in contradictory cases.
3. Statistics of properties of construction steels

Statistical evaluation and comparison of the properties of the supplied ML and NL steels can be carried out since the sheer number of melts as well as a large ensemble of data on the mechanical properties of steel plates used in the construction of APPOLO Bridge and presented in inspection certificates.

It was evident from the analysis of the inspection certificates that a large amount of steel melts have been supplied for bridge construction while different thicknesses of plates have been rolled from some of the melts. The properties of those products were then tested by a supplier. Overview of the number of the melts and ensembles of the mechanical tests found in the inspection certificates is given in Table 4. The data from test results has been statistically evaluated in MS EXCEL.

| Steel       | Number of melts | Number of mechanical tests |
|-------------|-----------------|----------------------------|
| S 355 NL    | 40              | 150                        |
| S 355 ML    | 41              | 90                         |
| S 420 ML    | 42              | 152                        |

3.1. Statistical evaluation of chemical composition of the steels

Chemical composition of steels is one of the crucial factors which determines the material weldability of the steel. Fig. 1 shows a histogram of carbon (C) content in the steels S 355 ML, S 420 ML a S355NL. It is evident that the real content of carbon was significantly lower in the steels of class ML than in the standard EN 10113-3 and in the binding tender documentation [1].

The comparison of carbon equivalent CEV calculated according to the IIW methodology is very similar. There, the ensemble of steels S 355 NL supplied for APOLLO bridge construction have exhibited the largest values except of a few from the set of the steels S 420 ML, which exceeded the value of 0.40%, see Fig 2.

The following conclusions have been derived for the welding of compared steels for APOLLO Bridge:

- The welding of steels S 355 NL required significantly higher pre-heating temperatures then the steels ML for the equivalent thicknesses or it has required application of the pre-heating even in those cases where the steels ML would not need the pre-heating.
- The mentioned risk of appearance of the cold cracks is especially high at the tack welding of the parts, when conditions for quicker cooling of materials occur, than at the own joint welding. There are more unfavourable strain conditions in the area of tack welds.
3.2. Statistical evaluation of mechanical properties of supplied steels

Fig. 3 shows histogram of $R_{eH}$ for the steels S 355 ML and S 420 ML. As seen the yield strength of steels are nearly comparably high and a majority of the steels S 355 ML exceeds relatively largely the minimum assured value of the yield strength for various thicknesses of steel plates. Approximately 70% of the supplied steel plates of the grade S 355 ML has fulfilled the value of the yield strength required for the steel S 420 ML. The steel S 355 NL has fulfilled requirements on the yield strength limit exactly.

Fig. 4 shows histogram of impact energy $KV (J)$ of the plates made of steels S 355 ML and S 420 ML tested at temperature of $-30^\circ C$. The histogram illustrates that the values of impact energy have been extraordinary high for all supplied steel plates which assures very high resistance against brittle fracture. The impact energy has been also high measured across the direction of the rolling.

4. Welding and properties of welded joints

The steel construction of APOLLO Bridge contains approximately 43,000 m butt weld joints and about 274,000 m fillet welds. The four methods of arc welding have been used:
- Manual metal arc welding with a covered electrode MAW (111),
Submerged arc welding SAW (121),
Metal active gas welding with a solid wire MAG (135),
Metal active gas welding with a flux cored electrode FCAW (136).

The supplier of steel construction of the bridge MCE Voest Linz made components of the constructions in their production lines in Slany and in Nyíregyháza. These were then transported to the work site in Bratislava, where the field welding was carried out. The construction of the bridge was performed by Hutní montáže Ostrava and MCE Slaný. The welding consumables were supplied by Oerlikon.

A test weld join has been made by each of supplier for each method of welding, for each used welding material, and for typical thicknesses (16 mm, 25 mm, 40 to 50 mm) of weld joints before the actual welding. The weld joints for "pre-production tests of welds" have been made under the supervision of a welding engineer. All quantities determining quality and properties of weld joint including pre-heating, welding parameters needed for calculation of heat input, interpass temperature, number of layers in welds, etc. were checked, measured and recorded.

Test weld joints have undergone non-destructive tests: visual testing VT, penetrant testing PT and ultrasonic testing UT. Test bars/bodies have been made by mechanical cutting and machining from the test weld joints. The following tests have been carried out:
- Chemical analyses of the weld metal, rarely also of the steel of base material,
- Evaluation of the macrostructure of welded joint,
- Test of hardness of welded joint: base material, heat affected zone (HAZ), fusion line and weld metal according to the standard EN 10043-1 (ISO 9015)
- Tensile test of weld joint— in transversal direction according to the standard EN 895 (ISO 4136),
- Tensile test of weld joint – in longitudinal direction according to the standard EN 876 (ISO 5178),
- Impact bend test KV: base material, heat affected zone and weld metal according to the standard EN 10045-1 (ISO 148), EN 875 (ISO 9016),
- Bend test of weld joint according to the standard EN 910 (ISO 5173),
- Fracture toughness test – $K_C$; $K_{0,2}$ according to the standard STN 42 0347.

During the bridge construction:
- 28 welding procedure have been approved (WPAR), of which 22 were butt weld joints and 6 fillet weld joints [2],
- further 17 production weld joint test were carried out [3].

Tests of weld joints shown:
- all test bars at the tensile test broke in base material far away from the weld joint,
- Measurement of hardness across weld joints did not show practically no decrease of hardness in HAZ, which would signal lowering of strength of base material due to its heating caused by welding,
- All test bars passed the bend test signalling sufficient reserve of plasticity in the whole region of weld joints,
- welding parameters first of all heat input have critical impact on toughness of weld metal,
- a critical region of weld joints from the point of view of toughness was not the HAZ of base material but the weld metal.

The overview of selected characteristics of the steel plates S420ML of thickness of 40 mm is in Table 4.
Table 4  Selected characteristics of the steel S420ML, plate thickness of 40 mm

| Characteristic          | CEV (%) | $S_{ppm}$ | ReH MPa | ReH/Rm$^5)$ | KVW (J)$^4)$ –30 ºC | KV (J)$^4)$ –30 ºC | KVW (J)$^4)$ –30 ºC |
|-------------------------|---------|-----------|---------|-------------|---------------------|---------------------|---------------------|
| Guaranteed by EN 10025-4| 0,450   | 250       | 400     | –           | 40                  | 23                  | –                   |
| Required in the project | 0,430   | 100       | 400     | 0,85$^5)$   | 60/45$^1)$          | 45/34$^1)$          | 55/40               |
| Real $\sigma^3)$       | 0,363   | 33        | 463     | 0,832       | 213                 | 161                 | 112/150             |
| 169 plates 4.ex$^3)$    | 0,388   | 60        | 403     | 0,89        | 68                  | 67                  | –                   |

$^1) TS = –40 ºC$

$^2) \bar{\sigma}$ – average value

$^3) 4.ex$ – 4th extreme (min/max)

$^4) KVW$ – weld metal

$^5) $ later modified to $R_e/R_m = 0,90$

Toughness of the steel plates S420ML and their weld joints highly exceeded required properties so the plates can be evaluated as excellent.

Experience from the APOLLO Bridge construction has shown that increased attention has to be paid to welding procedures in the interest of properties and quality of welded joints. It is necessary:

- limit heat input for welding in order to achieve required toughness of weld metal, not use inadequate high welding currents (mostly at welding methods MAG - 135 and FCAW - 136),
- use such welding conditions for which supplier guarantees high enough impact energy minimally for the lowest design temperature,
- during the welding, to make sure that adequate technological discipline is assured and to have continuous supervision for welders,
- all the welders must pass the required work tests.

5. Conclusion

- Thermomechanically rolled plates made of ML steels have lower content of carbon C and lower carbon equivalent CEV in comparison with normalised annealed steels (normalised rolled steels) and therefore require a lower pre-heating during welding.
- All used steels fulfil requirements for a yield strength limit of ReH. The steels S355ML highly exceeded normalised data of yield strength limits for various thicknesses and were approaching the requirement on the steels S420ML.
- Thermo-mechanically rolled steels ML are distinguished by large toughness (KV as well as KCJ) even at low temperatures. They are commonly tougher than normalised rolled steels of the same strength class.
- The heat affected zone was rather narrow at all used methods of welding (MMAW – 111, SAW – 121, MAG – 135, FCAW – 136). The measurements of the hardness HV 10 have confirmed that the heat affected zone has not been affected by decrease in strength in comparison with the unaffected bas material.
- The heat input of welding is suggested to be regulated with the aim to increase the toughness of weld metal regardless of the method of steel production.
- We recommend using the steels of the higher strength of classes S 420 ML and S 460 ML with respect to assumed thicknesses of designed bridge constructions.

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