Falko Schröter and Wolfgang Schütz:

Application of heavy plates in civil engineering

Even if the construction industry is presently not behaving well in plenty of European countries, structures made of steel are becoming more and more popular. The advantages shown by this building material such as high resistance, safe and high-quality fabrication and sustainability are appreciated more and more by architects and civil engineers. Thus steel structures show important advantages against concrete structures such as short erection time and the ability to fulfil high architectural demands.
Also the steel industry supported this process by the development of more efficient steel products. This articles focuses such new developments in one steel product used in construction, heavy plates. In particular, it will be shown on the examples of ultra-thick plates and high strength grades how heavy steel plates can be used for efficient and architecturally demanding steel structures.

Since the first application of steel in steel structures in the 19th century the development of steel construction in civil engineering has been closely linked to the development in material properties and production methods. Significant achievements concerning strength, economy, design versatility, fabrication and erection techniques and service performance would not have been possible without the substantial improvements of steel, especially by the application of new production processes for carbon steel grades with improved characteristics (strength, fabrication properties, durability and so on). Today, the application of these grades is mainly driven by economy, architecture, environment and safety.

Economy. By increasing the strength of steel, the cross-section can be reduced in dependence of the structural problem. This may reduce fabrication and erection cost, an important task in high-wage economies.

Architecture. The size of the structural elements can be reduced by higher strength grades allowing special aesthetic and elegant construction which embed in the environment in an outstanding manner.

Environment. Steel saving construction with efficient steel products also means a more efficient usage of our world's rare resources.

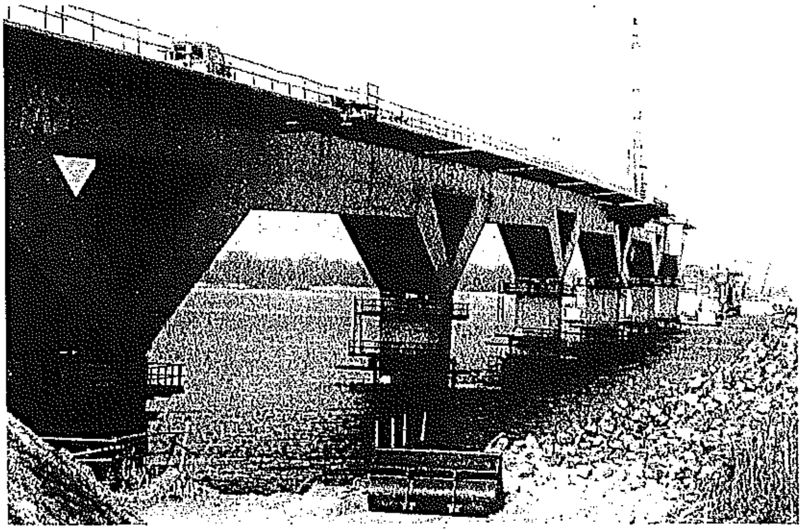


Fig. 1: High-speed railroad bridge Hollandsch Diep

Safety. Modern steel grades do not only offer high strength values. Special grades combine this strength with excellent toughness so that a high safety both in fabrication and application of the structures is applied. This particularly holds for modern offshore steel grades performing at lowest service temperature.

This paper focuses the recent development performed by the steel industry to offer tailor-made steel products for the application in some fields of civil engineering such as bridgebuilding, highrise buildings, stadiums and hydropower stations. Some outstanding examples will be given.

Dimension of heavy plates

Extra-wide plates. Steel fabricators in Western Europe are facing the fact that, in the long term, wages increase more quickly than the prices for the semi-finished products, the steel. Therefore, it is advisable to use plate products by which the efforts for manufacturing (in particular welding) can be reduced.

Today, it is possible to produce heavy plates in widths of up to 5200 mm. By the use of these extra-wide plates additional butt welds in longitudinal or transverse direction can be avoided, thus saving manufacturing costs.

For instance, fig. 1 shows the new high-speed train bridge across the Hollandsch Diep between Brussels and Amsterdam, in which plates up to a width of 4550 mm were applied in order to reduce the number of weldings. Of course, this does not only result in more efficient and quicker manufacturing, but also in a reduced sensitivity to fatigue as the fatigue strength of a weld is always poorer than that of the base material.

Another example for the profitable usage of extra-wide plates is displayed by **fig. 2.** The impressive roof construction for the Olympic Stadium in Athens was designed by the famous Spanish architect Santiago Calatrava. On both longitudinal sides the roof is carried by a lower arch with an inner tube diameter of 3.25 m and an upper main arch with an inner tube diameter of 3.60 m. For instance, the two main arches were assembled from 260 tube segments of 5 m length each. The tubes were made of plates exhibiting thicknesses of up to 100 mm. By using plates in widths of up to 5000 mm, it was possible to assemble the tube segment from only two semi-shells formed on a 6000-t press. Thus, the number of costly and time-consuming longitudinal butt welds was reduced to a minimum on these thick-walled tubes.

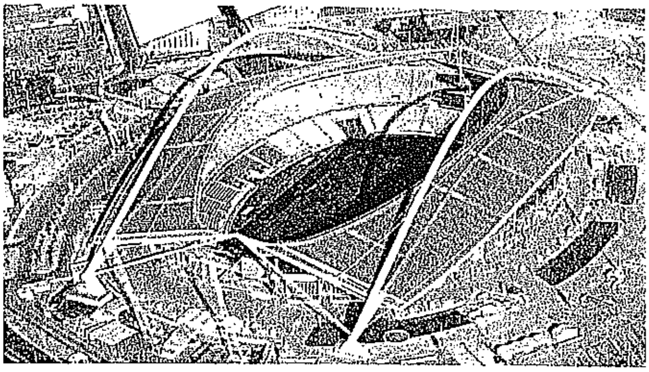


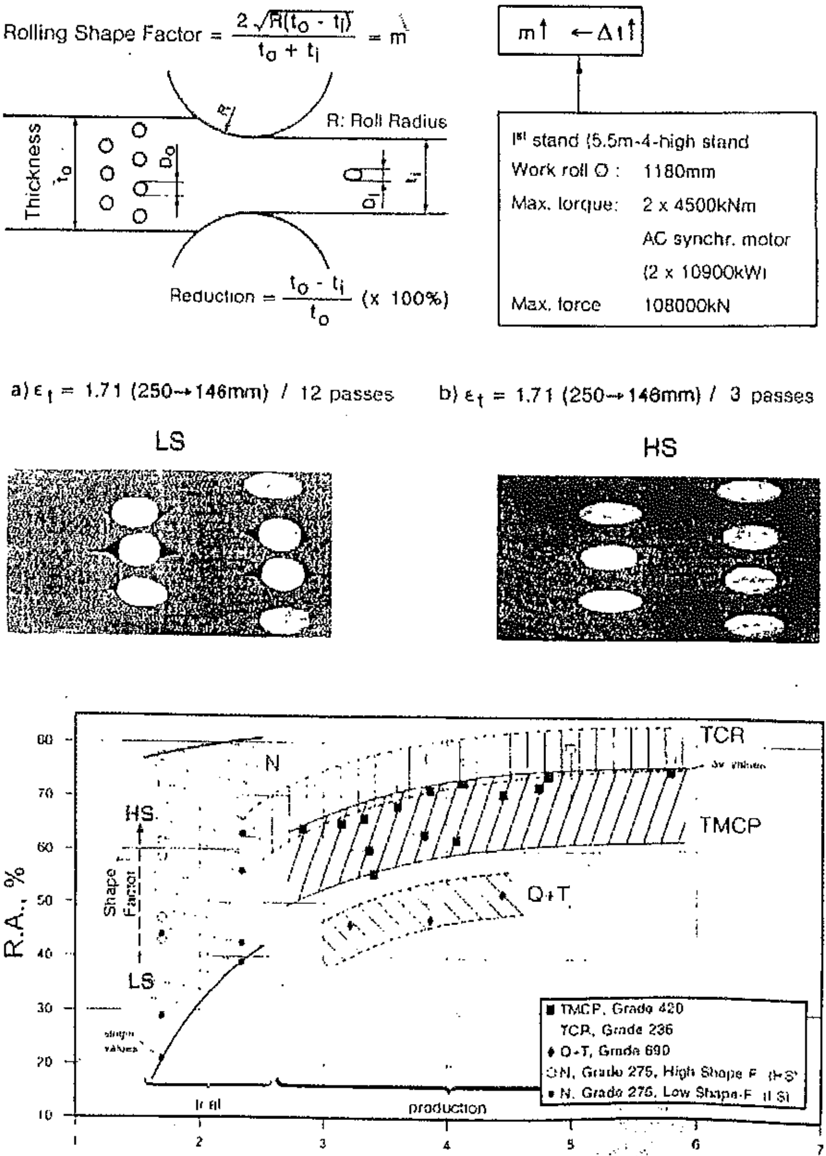
Fig. 2: The roof construction of the Olympic Stadium in Athens (photo: Cimolai Steel Construction)

Ultra-thick plates. Whereas the production of extra-wide plates only shows a secondary influence on the mechanical characteristics of the steel products, these values may be quite significantly influenced by the thickness of the plates. On the other hand, the thicker the steel material used, the higher the requirements on toughness in order to avoid the phenomenon of brittle fracture. This results in the selection of superior steel grades for tendentiously thicker constructions. For instance, the coming European construction code EN 1993-1-10 - Selection of material for fracture toughness and through-thickness properties - defines a maximum allowable plate thickness of 65 mm for a conventional S355J2G3 (that means minimum yield stress of 355 MPa and Charpy-V-test of minimum 27 J at -20 °C), for a reference temperature of -30 °C and a medium load [1]. For the application of thicker constructional elements, a higher grade with improved toughness has to be chosen, for instance an S355NL (that means minimum yield stress of 355 MPa and Charpy-V-test of minimum 27 J at -50°C).

Due to the lack of steel products providing sufficient toughness properties even if thickness was increased, thicker plates were almost banned from use in most countries. For instance, the German construction code DIN 18800 defines a maximum thickness of 50 mm for flange plates. In order to compensate for this shortage, thick flanges were designed comprising additional, reinforcing lamellae on the top of a basis lamella.

However, the steel industry today even succeeds in producing thick plates with appropriate toughness properties due to:

- ♦ modern steel making technology (vacuum degassing, argon stirring etc.) reducing the amount of residual elements, such as sulphur and phosphorus, and minimising the number of non-metallic inclusions;
- ♦ the availability of slabs and ingots with large thickness as the deformation degree, i.e. the ratio between initial slab thickness and final thickness of the plate, strongly correlates with toughness and through-thickness properties;
- ♦ up-to-date rolling technology, for instance HS-rolling (high shape factor rolling) characterised by high deformation degrees during the first rolling passes to improve the core



a) ε_t = 1.71 (250→146mm) / 12 passes

b) ε_t = 1.71 (250→146mm) / 3 passes

Fig. 3: Influence of high shape factor rolling

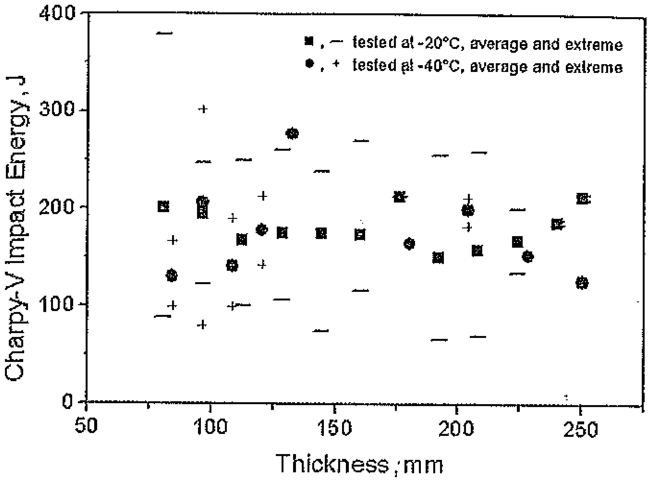


Fig. 4: Charpy-V-results of S355 steel for higher thickness values

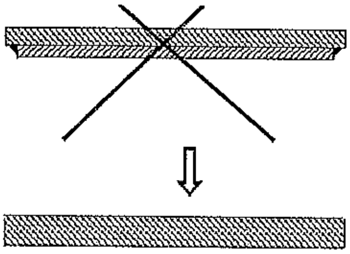


Fig. 5: Reason for using ultra-thick plates

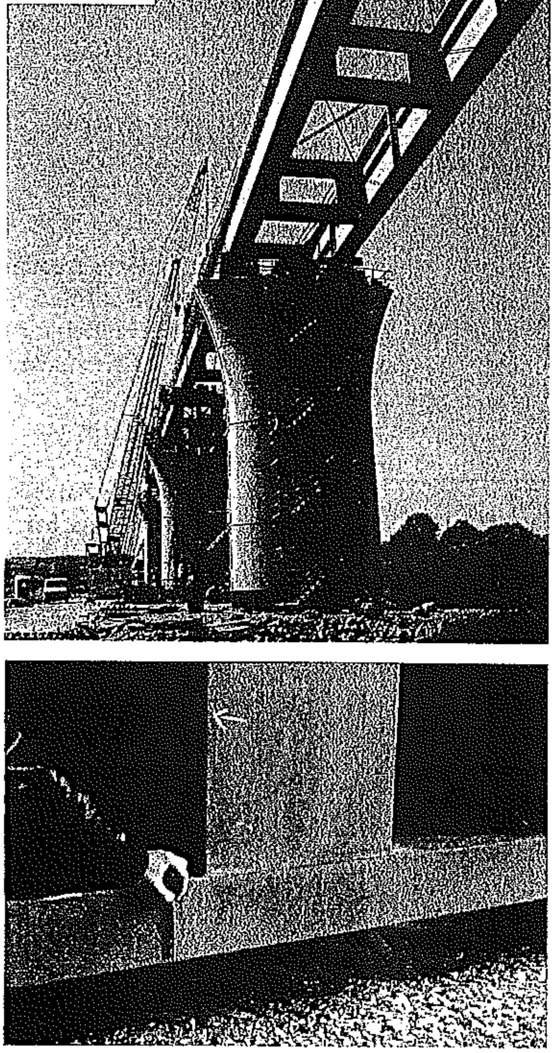


Fig. 6: Bridge across the Mosel valley and application of ultra-thick plates to French composite bridges

properties of the product, see **fig. 3** [2]. Therefore, steel plates featuring sufficient toughness properties to resist brittle fracture are available today. For instance, **fig. 4** illustrates toughness values of plates measuring more than 80 mm in thickness. It can be seen that adequate toughness values can be obtained even with extreme thickness.

Thus it becomes possible for steel construction to benefit from these products by substituting the classical *multiple-lamellae*-type flange construction. Furthermore, the use of thick plates simplifies the fabrication process, **fig. 5**.

A typical example from steel bridge construction is shown in **fig. 6**. For the French fast railroad network (LGV) a kind of composite bridge was developed, which also proves competitive to classical concrete structures. This system mainly consists of two longitudinal girders each with a girder depth of up to 5000 mm connected to each other by diaphragms arranged at distances of 8 to 12 m. A concrete deck was cast onto these girders [3]. Plates with thicknesses of up to 150 mm form the flanges of the girder (see fig 6, bottom). In order to fulfill the regulations for brittle fracture steel grade S355NL, that means with a Charpy-V toughness tested at –50 °C, is employed.

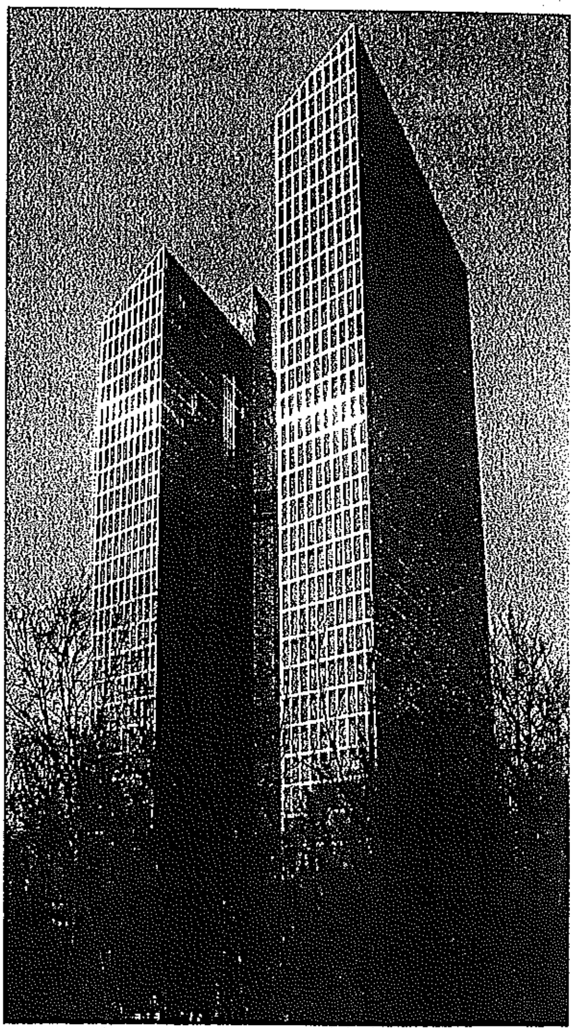


Fig. 7: The Munich Business Towers

A bridge system like this represents a convincing alternative to prestressed concrete bridges usually prevailing in the market of bridges for high-speed trains. Note that this composite design was applied to all major bridges within the latest French fast railroad line, the LGV Est from Paris to Metz/Nancy which will be opened for traffic mid-2007. The bridge across the Mosel valley presented in fig. 6 is one example in the course of this new line.

An example for the application of ultra-thick plates to multy-storey buildings is displayed by **fig. 7**. The twin towers of the new Munich Business Towers in the northern part of the city have a height of 126 m respectively 113 m. The structure consists of an innovative steel-concrete composite structure. The main supporting elements are composite columns built up of massive steel profiles which are inserted into concrete-filled steel tubes. The steel core of the composite columns is formed by joining plates with a thickness of up to 160 mm.

This construction stands on foot plates measuring up to 250 mm in thickness, fig. 8. These plates serve for distributing the forces into eight high-strength anchoring bars. Thus, the plates are dimensioned properly to transfer loads of up to 93000 kN (compression) and of up to 30000 kN (tension). It is essential to ensure best deformability in thickness direction (Z35 according to EN 10164) due to the high load in the through-thickness direction.

welded joints are reduced, thus lowering both manufacturing and inspection costs, and paving the way for special architectural demands [4].

Table 1: Chemical composition (mass contents in %) of high-strength steel, 50 mm thick, in comparison to S355J2. Excerpt from the standard requirements and examples of actual values

	S355J2		S460ML		S690QL	
	EN 10025 Part 2	typical analysis	EN 10025 Part 4	typical analysis	EN 10025 Part 6	typical analysis
C	≤ 0.22	0.17	≤ 0.16	0.08	≤ 0.20	0.16
Si	≤ 0.55	0.45	≤ 0.60	0.45	≤ 0.80	0.30
Mn	≤ 1.60	1.50	≤ 1.70	1.65	≤ 1.70	1.30
P	≤ 0.025	0.018	≤ 0.025	0.011	≤ 0.020	0.012
S	≤ 0.025	0.015	≤ 0.020	0.002	≤ 0.010	0.005
Nb	-	-	≤ 0.05	< 0.04	≤ 0.06	<0.04
V	-	-	≤ 0.12	-	≤ 0.12	
Ti	-	-	≤ 0.05	-	≤ 0.05	
Mo	-	-	≤ 0.20	-	≤ 0.70	0.37
Ni	-	-	≤ 0.80	0.19	≤ 2.0	0.15
Cu	≤ 0.55	-	≤ 0.55	0.17	≤ 0.50	0.08
Cr	-	-	≤ 0.30	-	≤ 1.50	0.40
B	-	-	-	-	≤ 0.0050	<0.003
CE	0.47	0.42	0.47	0.39	0.65	0.54
P_{cm}	-	0.26	-	0.19	-	0.29
CET	-	0.32	-	0.26	-	0.35

carbon equivalents:

$CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$

$P_{cm} = C + Si/30 + (Mn + Cu + Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$

$CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40$

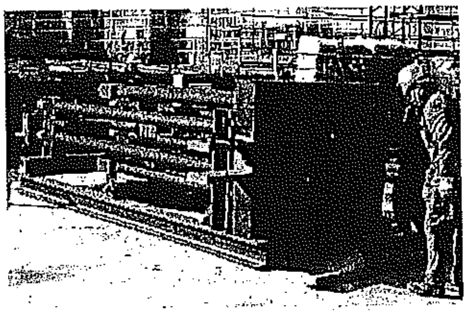


Fig. 8: The anchorage plates of the Munich Business Towers

High-strength steel grades

Benefits in steel construction. The development of new steel grades for steel construction was driven by the users' demand for materials showing good mechanical characteristics, such as yield strength and toughness as well as proper manufacturing properties ensuring efficient manufacturing in the workshop and during on-site erection of the steel structure.

Though the classical constructional grades S235 and S355, that means steel grades with a nominal yield stress of 235 MPa respectively 355 MPa, are still most widely applied to steel buildings and bridges, higher strength grades have significantly gained market shares during the past decade. The benefit of using high strength steel in steel construction is obvious: in comparison to normal strength steel the size of the cross-section of the structure can be reduced resulting in a decrease in the dead weight of the structure, from which the substructure and the erection profit. Simultaneously, the cross-sections of

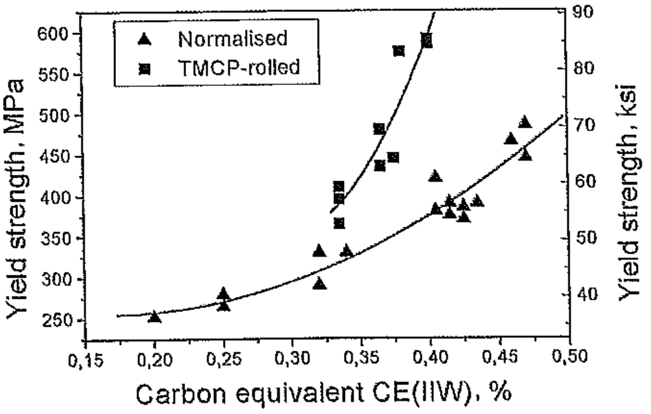


Fig. 9: Carbon equivalents obtainable by normalised and TMCP-rolled steel grades

However, it has to be taken into account that smaller cross-sections also lead to reduced stiffness of the construction. This can hamper the usage of higher strength steel, as not only maximum load criteria but also maximum deflection criteria are often applied to steel construction. Furthermore, steel manufacturers demand for steel products easy to process. Here, weldability even under harsh conditions, e.g. on site, is a major concern. Therefore, quenched and tempered heavy plates, which are today produced with yield strengths of up to 1100 MPa, are rarely used for steel bridges and buildings. As far as higher strength grades are concerned, the thermomechanically rolled plates with best welding properties and yield stress levels of up to 500 MPa are used preferentially.

TMCP-rolled steel. The aim of the thermomechanical control process rolling(TM or TMCP) is to create an extremely fine-grained microstructure. This is done by a sophisticated combination of rolling steps at selected temperatures and a close temperature control. The gain in strength obtained by the grain refinement allows the effective reduction of the carbon and alloy content of the TM-steel compared to normalised steel of the same yield strength categorygrade. The improved weldability that results from the leaner steel composition is a major advantage of the TM-plates. The rolling schedule is individually compiled depending on the chemical composition, the required strength and toughness properties and the plate thickness. Arranging for some *accelerated cooling* after the final rolling pass is beneficial to achieve the most suitable microstructure, especially with thick plates, as it forces the transformation of the elongated austenite grains prior to any occurrence of recrystallisation. For very thick plates and higher yield strength grades a tempering process can be used after the accelerated cooling.

TM-rolled plates with minimum yield strength values of 500 MPa were supplied in thicknesses up to 100 mm for hydropower, offshore platforms and special ships [5].

TMCP-steel represents a material with optimum working point in the contradictory context between strength and processing properties. As already mentioned, weldabilty is positively affected by the alloying content, which is usually expressed in so-called carbon equivalents in order to assess weldability. Usually, the weldability is the better the lower these carbon equivalents are. **Table 1** summarises some typical chemical compositions for 50 mm thick plates of the classical construction steel S355J2, for the TMCP-rolled plate S460M (nominal yield stress of 460 MPa) and for the high-strength quenched and tempered plate S690 (nominal yield stress of 690 MPa). It can be seen that the higher strength TMCP-steel S460M shows an even better carbon equivalent than the conventional S355J2 steel. This is again expressed by **fig. 9** which compares the attainable carbon equivalents CE for classically normalised steel grades and TMCP grades. It can be seen that steel plates with outstandingly low carbon equivalents can be obtained by TMCP rolling.

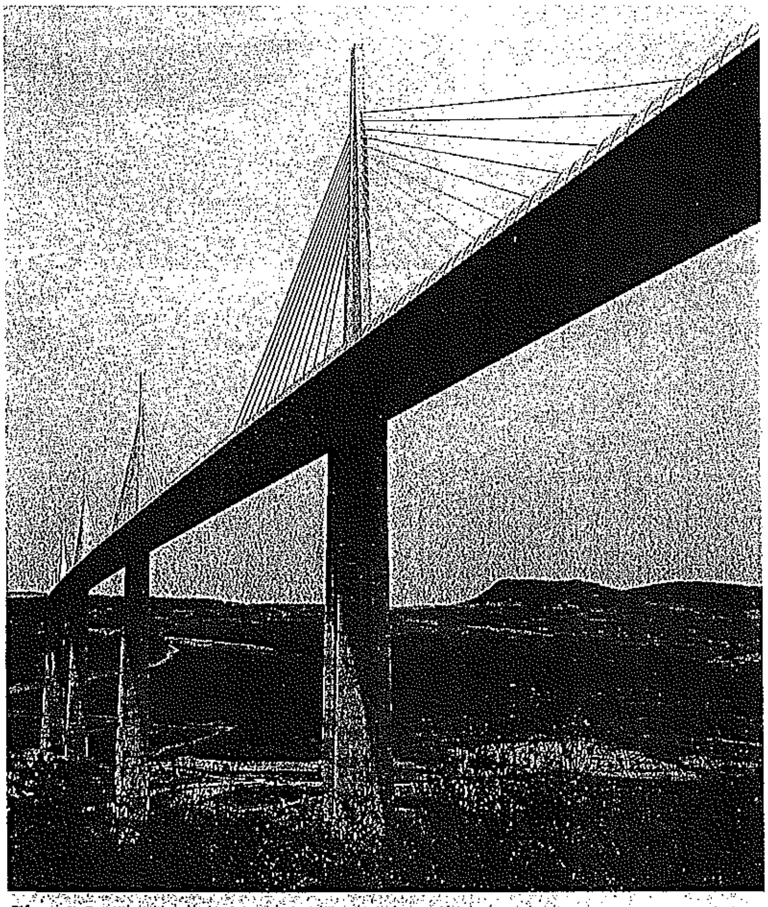


Fig. 10: The Millau Viaduct (France)

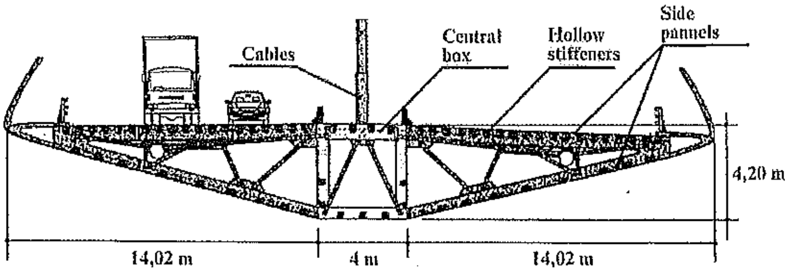


Fig. 11: Cross-section of the steel deck of the Millau Viaduct

More information about TMCP-rolled steel can be found in [6...7].

Application of high-strength steel plates

Bridges. A very impressing example for the use of higher strength grades in bridgebuilding is shown by **fig. 10.** The Millau Viaduct in the South of France, which was opened late 2004, is the highest bridge in the world comprising a total height of 343 m, a deck height of up to 270 m and a length of 2460 m. The deck with 6 equidistant spans of 342 m each and two outer spans of 204 m each is held by stay cables fixed on seven steel pylons. The total weight of the steel plates used for this extraordinary bridge is 43000 t, among this 18000 t of higher-strength TMCP-rolled S460M.

The main element of this bridge is formed by a box girder which contains another central box onto which side panels are fixed, **fig. 11.** S460M plates of up to 80 mm thickness are used for the central box, whereas the side panels are formed by plates of up to 16 mm thickness. A very efficient manufacturing of the deck was possible thanks to plate widths of up to 4200 mm. From these plates and trapezoidal stiffeners approximately 2100 stiffened panels were made in the workshop of Eiffel Construction Métallique in Lauterbourg (Alsace/France). Following transportation to the site these elements were welded together until a total length of 171 m was reached. This work was done at the two preassembly yards located on each abutment of the bridge. The central box sections were preassembled at Fos-sur-Mer.

The bridge was erected by incremental launching from the North and the South abutment. As soon as a new 172-m long segment was finished, this already existing part of the deck was pushed forward. Auxiliary piers bisecting the span length helped to reduce the cantilever effect during launching, **fig. 12.**

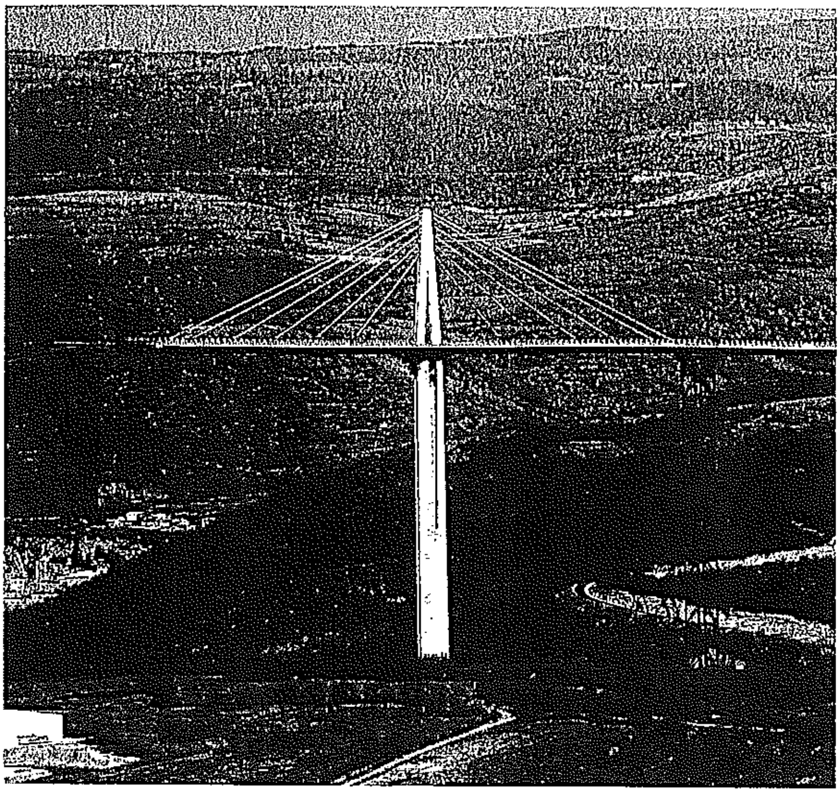


Fig. 12: Cantilever effect during the erection of the Millau Viaduct

A huge amount of high-strength steel S460M was again employed for the deck structure, in particular for the inner box girder, in order to reduce the dead weight of the girder and, thus, the cantilever deformation during the launching procedure.

Two other examples for the application of S460M TMCP-rolled plates are shown in **figs. 13** and **14.** The new Rhine-bridge in the North of Düsseldorf (Germany), which was opened for traffic mid-2002, is a cable-stayed bridge with a central span length of 275 m. The height of the pylons had to be restricted to 34 m due to their situation in the entry lane of the nearby airport, see fig. 13. As a result, high forces arise in the pylon heads. Selecting the high-strength steel S460ML for these structural elements was the only way to cope with this challenge. Nevertheless, plate thicknesses of up to 100 mm had to be used for the central parts of the pylon heads. In order to have the highest degree of material redundancy [8] against brittle fracture, the toughness requirement was defined by a Charpy-V test at –80 °C.

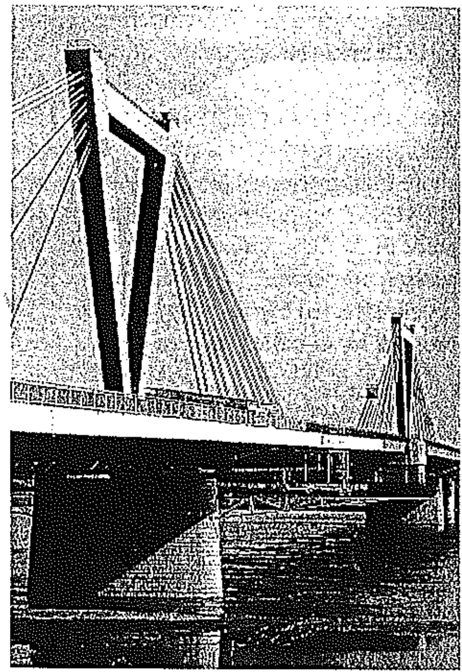


Fig. 13: Rhine bridge Düsseldorf-North (Germany)

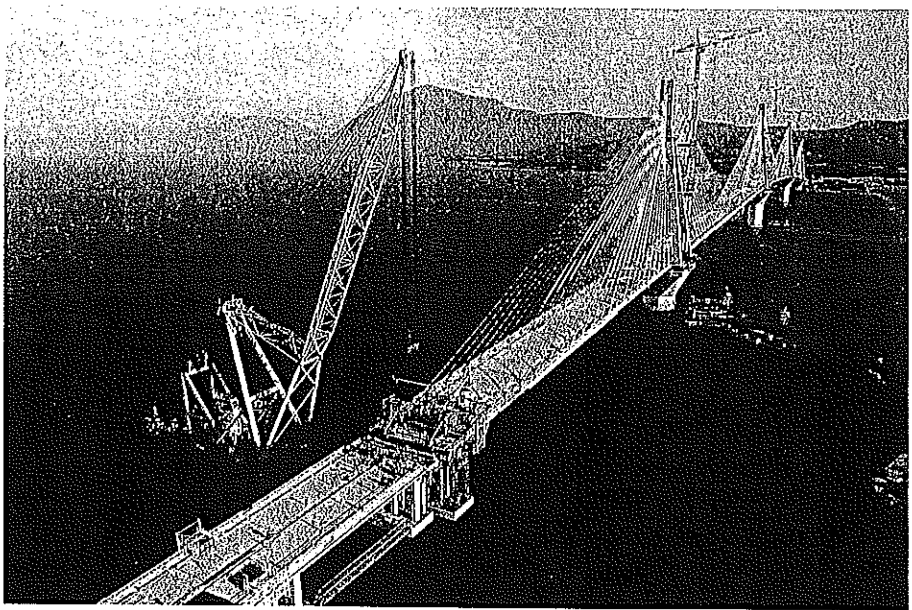


Fig. 14: Harilaos Trikoupis bridge (Greece)

The Harilaos Trikoupis across the Gulf of Patras in Greece is a cable stayed bridge with three central spans of 560 m and two side spans of 286 m each, fig. 14. S460M (TM-rolled) was used for the plated girders of the composite deck the thickness of which amounts up to 80 mm. S460Q (quenched and tempered) was used for thicker plates. Furthermore, the pylon heads were designed of S460M in plate thicknesses reaching up to 110 mm and a total weight of 700 t.

Buildings. Apart from bridges, there are more sectors to profit from the recent developments in metallurgy. Due to the very high requirements of architects on the aesthetics of multi-story buildings, heavy steel skeleton constructions have more and more been used during the past 10 years. With these constructions it becomes possible to reduce the cross-section of heavy columns by applying high strength steel, in order to allow for an efficient manufacturing and erection process but also to optimise the ratio between gross and net surface of the floors.

A typical example is the Commerzbank Tower in Frankfurt/Main with a height of more than 298 m [9]. Its steel framed structure contains about 18000 t of heavy plates. Here, steel S355M is employed in plates the thickness of which exceeds 30 mm, whereas S460M was applied to highly loaded girders and columns. **Fig. 15** shows the mega-column, where, especially, the latter grade is applied to. Thus, manufacturing costs can be reduced by this proper selection of heavy plates.

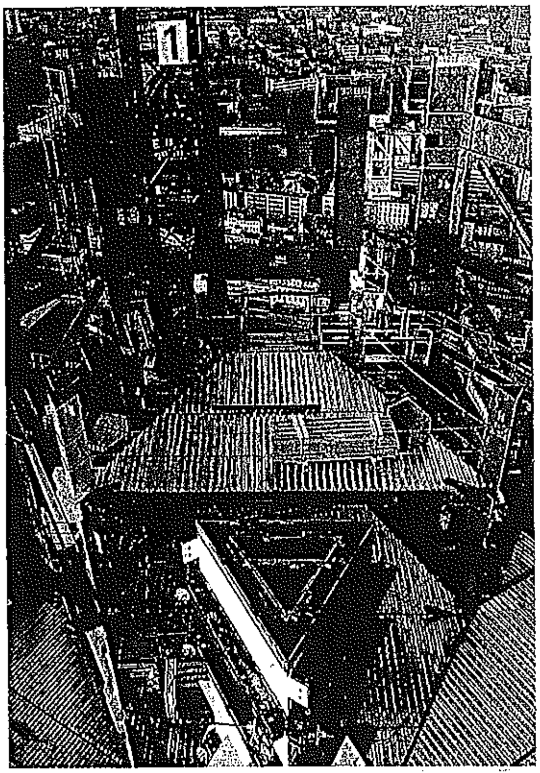


Fig. 15: The mega-column of the Commerzbank-Tower in Frankfurt/Main (Germany)

Examples in hydropower. Due to the globally increasing demand for energy, investments in energy production are also growing. Particularly, emerging markets tend to invest in hydropower energy.

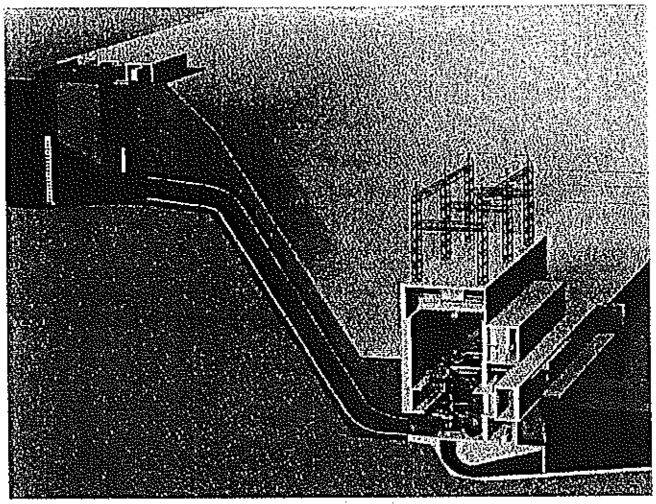


Fig. 16: Scheme of a pump-storage hydropower plant (photo: Voith Siemens Hydro)

A general scheme of a pump-storage hydropower plant is shown in **fig. 16**. Here, two fields of application are of interest for the usage of heavy plates:

- the penstock lining, a large-diameter pipe (up to 6 m in diameter) either installed on the surface of the dam or in a tunnel in the inner of the mountains and often embedded by concrete,
- the pipeworks and machine components in the powerhouse around the turbine such as spiral casings, stay rings and the exit pipe.

The major requirement set on the heavy plate products used for the penstock pipe is the efficient manufacturing not only in the workshop but also under the hard environmental conditions for on-site welding. Today, steel plates in grades up to S690 in quenched and tempered condition are used for such pipes. In the last year also TMCP-rolled steel with up to 500 MPa yield stress was developed for this application. This grade, of course, requires a design with thicker plates compared to S690Q. However, this disadvantage is compensated for by the much better weldability of the TMCP grades. This does not only result in a higher efficiency of the welding process in the workshop and on site, but also in improved safety of the weld due to better toughness properties.

Fig. 17 shows an example for a TMCP-rolled S500 steel in the bifurcation of a penstock lining.

Furthermore, high-strength steel plates are used for powerhouse components, such as spiral casings, **fig. 18**. These plates measuring up to 250 mm in thickness are quenched and tempered. Accordingly, they offer highest deformation properties in thickness direction, what makes them suitable for stay rings.

Fig. 17: Bifurcation of a penstock lining made of TMCP-rolled S500

Conclusion

This article highlights the recent developments made by the steel industry in order to supply steel products for efficient construction in civil engineering. Many examples from bridgebuilding, stadiums and high-rise buildings are presented.

Today, the designers of constructional steelwork can choose from a nearly unlimited range of heavy plates as far as dimensions and steel grades are concerned. Thus, designers are attracted by these almost boundless possibilities of combining optimum dimensioning with an appealing design of a building, rounded off by efficient manufacturing properties with regard to a construction proving economical and competitive especially when compared to pre-stressed concrete and wood. The current delivery programs for plate products considers both the demands and desires of the next coming decades.

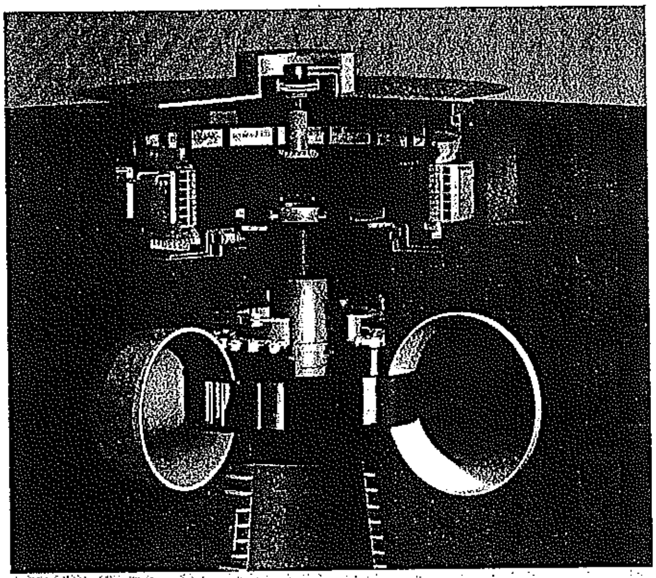


Fig. 18: Stay-ring made of 220 mm thick S550Q plates (photo: Voith Siemens Hydro)

The future developments in heavy plate technology for steelwork are governed by the user's desire for continuing to reduce manufacturing costs. This can be reached by further improving heavy plates. In addition, higher requirements on the uniformity of the mechanical properties, the chemical composition and on the dimensional tolerances represent a great challenge for the processing and rolling technologies of heavy plates

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